OLEDS, OXIDE TFTS, AND DISPLAY WEEK PREVIEW ISSUE

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So you work in displays? You may soon be working in flexible electronics too. Author Jason Heikenfeld, associate professor with the School of Electronic and Computing Systems at the University of Cincinnati, looks at several of the most interesting developments in flexible electronics.

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editorial



The Future Awaits and SID Can Be Your Guide

by Stephen Atwood

Welcome to the March/April 2013 issue of *Information Display* magazine. Last-minute preparations are well under way for the 50th annual SID Display Week event in Vancouver. With all the excitement around OLED technology, we could not have predicted a better convergence of topics for this issue: OLED and Oxide-TFT technology, the

SID Symposium preview, and our cover story on the SID Honors & Awards recipients for 2013. It's one of the biggest issues we have ever produced and with our new bi-monthly schedule we wanted to make sure you had plenty to read between now and Display Week.

As I worked on this issue and also attended some recent SID activities, it occurred to me that this may be the best time ever to be an SID member. Not only is there an amazing array of new technology innovations going on in our industry, but the opportunities to learn about those innovations through the resources available to members have never been better. For example, the SID on-line webinar program is now gaining traction with almost a dozen recent additions covering topics such as 3-D stereoscopic displays, oxide TFTs, user interfaces (UIs), and the latest advances in LCD technology. These presentations come from some of the most widely respected experts in the field and are available online only to SID members.

Also in this issue you can read about the recent San Francisco Bay Area chapter conference on display technologies for the future. These types of local programs are loaded with presentations by the highest caliber of technology experts and are available to all SID members. They provide invaluable opportunities to make new contacts and leverage the knowledge base of the industry for your own company's benefit.

You can also read about the upcoming papers being presented at the SID Symposium as part of Display Week 2013. If you are not sure about becoming a member, plan on coming to Vancouver and taking in the papers and exhibitions. Spend the next year exploring what your new membership can do for you and I'm certain you will become a believer like me.

Our cover story this month is about the SID 2013 Honors and Awards, recognizing the many achievements of those who have invested so much of their careers to furthering the field of displays. As I have written previously, while the honors are being bestowed on them, the real honor is to those of us who have the privilege of knowing them, working with them, learning from them, and using their innovations to build better products that enrich people's lives. Each year we do our best to capture their achievements in the biographies and citations thoughtfully compiled by our own Jenny Donelan. But nothing we write can come close to documenting a lifetime's worth of ideas, challenges, setbacks, inspirations, and successes that these individuals have given to our industry. All I can say is that in those moments when you look at a great new product or technology, take a moment to reflect on all the human effort that has probably gone into making the "overnight success" happen. Great innovation never really happens overnight and so much of the technology that we take for granted today was built layer upon layer, almost like a brick wall, with each new advancement leveraging the achievements of the previous level for its support. I'm sure you, as you read this story, will come away with something from the award recipients' lives and work you can relate to. Take the time to reach out to them and say "Congratulations and (continued on page 55)

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industry news

Panasonic Closes Plasma-TV Assembly Plant in Shanghai

Earlier this year, news-media outlets including *The Wall Street Journal* and *The Japan Times* reported that Panasonic Corporation was closing its plasma-TV assembly plant in Shanghai, China. Panasonic media representative Jim Reilly later confirmed this news with *Information Display*. The Shanghai operations have been relocated to Panasonic AVC Networks Shandong Company, Ltd., an existing LCD monitor-making facility in Shandong, China. "The plasma and LCD operations will both be consolidated at that location," said Reilly.

Panasonic's move to streamline operations is not surprising in the face of steadily declining plasma-TV sales worldwide. "In the great scheme of things, it's not that big of an impact," says Paul Gagnon, Director of Global TV Research for NPD DisplaySearch. Gagnon believes the closure is more a reflection of market conditions than a game changer for plasma.

However, as has been the case for years, reports of plasma's demise are premature. Panasonic showed 16 new plasma TVs at CES 2013. The Shanghai plant that closed was assembling TVs rather than making the panels, says Gagnon, noting that Panasonic continues to manufacture PDPs in Japan. Panasonic is not actually the biggest producer of plasma TVs; that honor goes to Samsung, according to Gagnon. These two companies, plus LG, are the last manufacturers of plasma TVs in the world.

– Jenny Donelan



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See Us at Display Week 2013, Booth 715

guest editorial



The Challenges and Opportunities of Large OLED TVs

by Ho-Kyoon Chung

OLED TVs were the talk of the Consumer Electronics Show in 2012, and this year's CES featured attentiongetting OLED televisions as well: 55-in. curved OLED TVs from Samsung Display and LG Display and a 56-in. 4K OLED TV from Sony and Panasonic. These were impres-

sive demonstrations, and it was encouraging to see more players, such as Sony and Panasonic, coming into the game. However, there are customers anxiously waiting to buy these TVs at affordable prices. And what happened to earlier promises that large OLED TVs would be in production by the second half of 2012?

It is difficult to tell exactly what's happening at each company and what its future future plans are in terms of investment and production volume. Obviously, manufacturing challenges remain, especially for high yields. Another challenge is how, from a marketing perspective, to differentiate OLED TV from the LED-backlit LCD TV, which has excellent picture quality and is becoming ever thinner.

Challenges of Manufacturing OLED TVs

It is interesting to note that the two leading OLED-TV companies, Samsung Display and LG Display, have taken different approaches to TFT backplanes as well as to OLED RGB color patterning. The details of the technology are described in the articles, "Oxide TFTs for AMOLED TVs" by Jin-Seong Park and "RGB Color Pattering in AMOLED TVs" by Jang Hyuk Kwon in this issue of *Information Display*.

You may ask why each company chose their different path and which one will be the winner. In my opinion, one company has chosen an approach that is an extension of a well-established process for small-OLED mobile displays, and the other has chosen a cost-effective and relatively easy approach to manufacturing large OLED TVs – even though it has not been fully proven for mass production. It is probably too early to tell which one will be the eventual winner.

However, considering the recent success of LED-backlit LCD TVs, the manufacturing process for OLED TVs must meet the following requirements in order to compete with these incumbents. First, the cost of manufacturing must be lower than (or at least equivalent to) the cost of LCD TVs because most consumers will not pay a high premium just for the sake of owning an OLED TV. In order to reduce the cost, the first priority of OLED R&D should be the development of processes and equipment that use the entire motherglass without cutting, from TFT to OLED fabrication. Second, the manufacturing process should be readily extendable to ultra-high-resolution TVs. This requirement necessitates careful consideration when choosing the TFT-array technology and OLED color-patterning method. In order to drive as many as 24 million subpixels for 4K TV; for example, not only the TFT but the metallization process must be developed to meet the requirements. Also, the color patterning must have the scalability to handle the subpixel resolution down to ~100 μ m in large substrates, and the top emission structure needs to be developed for large OLED panels.

Future Outlook of OLED TV

There is good news regarding OLED TV in that people now see the potential of large OLED TV as the ultimate television — something they want to have in their living room. As far as a consumer transition from LED-backlit LCDs to OLED TVs is concerned, there are two schools of thought; it will be abrupt or gradual. Those who

(continued on page 55)

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2013 SID Honors and Awards

This year's winners of the Society for Information Display's Honors and Awards include **Dr. Isamu Akasaki,** who will receive the Karl Ferdinand Braun Prize for his seminal contributions to the development of high-quality single-crystal GaN-based semiconductors and their PN-junction blue LEDs and lasers; **Dr. Marc Baldo,** who will receive the Jan Rajchman Prize for his outstanding contributions to the discovery of phosphorescent-OLED devices; **Dr. Hoi-Sing Kwok,** who will be awarded the Slottow-Owaki Prize for providing education and training in display technology to many students and professionals in the Asia region through the creation of a display research center; and **Dr. Shigeo Mikoshiba,** who will receive the Lewis & Beatrice Winner Award for his sustained exceptional contributions to SID for over 30 years.

by Jenny Donelan

HE RECIPIENTS of the Society for Information Display's 2013 Honors and Awards may be diverse in terms of the display technologies they pursue - GaN-based semiconductors, phosphorescent OLEDs, LCDs, PDPs - and in geographical location - Japan, Massachusetts, Hong Kong - but they have at least two things in common: vision and a clear sense of purpose. As a young researcher in Tokyo, Isamu Akasaki became intrigued by gallium nitride's potential for blue-light emitters, despite the fact that the technology was considered yesterday's news by many scientists — another promising piece of research that had not worked out. Akasaki saw something more in the material – specifically, he saw tiny, well-formed crystallites - but he also saw that it might someday contribute to display systems in a major way. After years of hard work, he, and the rest of the world, discovered he was right.

Another young researcher, Marc Baldo, then a graduate student at Princeton, fell under

Jenny Donelan is the Managing Editor of Information Display Magazine. She can be reached at jdonelan@pcm411.com. a spell after he built his first OLED in the lab. The deep red color of the OLED he made both surprised and entranced him. He continued to focus on OLEDs and went on to contribute to the development of the first phosphorescent OLEDs.

Slottow-Owaki Prize recipient Hoi-Sing Kwok and Lewis & Beatrice Winner Award recipient Shigeo Mikoshiba are both highly respected scientists, but their awards from SID this year reflect their vision for education and community-based efforts. Kwok saw the need for a display-based research center in Hong Kong and went on to create it, which included raising the all-important funds. Mikoshiba, a busy educator and researcher, recognized the importance of volunteering his time to the display industry, and devoted many efforts to the furthering of SID. His vision and continued sense of purpose - he has volunteered continuously for more than 30 years raised up not only SID, but the industry as a whole. Besides, as he told Information Display, such efforts are ultimately as enriching to the volunteer as to those he helps.

The SID Board of Directors, based on recommendations made by the Honors &

Awards Committee, grants these annual awards based upon outstanding achievements and significant contributions to the display industry. This year's winners should take pride in this acknowledgment of their tremendous accomplishments.

The 2013 award winners will be honored at the SID Honors & Awards Banquet, which will take place Monday evening, May 20, 2013, during Display Week at the Vancouver Convention Centre. Tickets cost \$75 and must be purchased in advance – tickets will <u>not</u> be available on-site.

Visit www.displayweek.org for more information.



Dr. Isamu Akasaki

Karl Ferdinand Braun Prize

This award is presented for an outstanding technical achievement in, or contribution to, display technology.

Dr. Isamu Akasaki, Professor at Meijo University, will receive the Karl Ferdinand Braun Prize "for his seminal contributions to the development of high-quality single-crystal GaN-based semiconductors and their PNjunction blue LEDs and lasers."

In 1969, researchers succeeded in growing single-crystal gallium nitride on a sapphire substrate. Two years later, the first blue LED with an MIS structure was created. These advances prompted excitement about the development of GaN-based blue-light emitters, but just several years later, most galliumnitride researchers had withdrawn from the field. They could neither grow electronicgrade high-quality GaN single crystals nor control their electrical conductivity. Both features were key to the development of highperformance blue-light emitters and highpower high-speed transistors.

About that time, an engineer named Isamu Akasaki, then working at Matsushita Research Institute Tokyo (MRIT), became intrigued by GaN's potential for use in blue-light emitters. With the idea in mind that electronic devices and the materials used to make them must be robust, he thought GaN could be the best candidate since it is very stable physically and chemically, even though it was difficult to form high-quality crystals with it. Said Akasaki, "I realized the great potential of GaN as a blue luminescent material when I found tiny yet high-quality crystallites embedded in HVPE-grown crystals containing many cracks and pits. I was intuitively convinced that conductivity control could be achieved if this kind of quality could be made over an entire wafer."

His eventual success with GaN-based semiconductors ultimately contributed to display systems ranging from traffic lights to cell phones, to high-resolution TVs, digital signage, and more. "Akasaki transferred these basic technologies to industry and made fundamental contributions to information-display technology," says Yasushi Nanishi, a Professor at Seoul National University.

It is one thing to pursue a brilliant idea, but it is another to pursue it and eventually succeed after others have dismissed it. "That a single scientist's determination and dedication overcame a barrier that researchers throughout the world had become resigned to, and the impact of the multiple applications derived from this achievement, make this a truly great invention," says colleague Maseo Ikeda.

Akasaki received his undergraduate degree from Kyoto University and doctoral degree from Nagoya University. In 1952, he joined Kobe Kogyo Corp. (now, Fujitsu, Ltd.). In 1959, he moved to Nagoya University, where he worked as a research associate and an associate professor. In 1964, he became Head of the Basic Research Laboratory IV and General Manager of the Semiconductor Department, both at MRIT. He returned to Nagoya University in 1981. Akasaki has authored and/or co-authored more than 700 international journal/conference papers and 30 book chapters and has been awarded 123 Japanese patents (including 110 patents related to group III nitrides) and 90 foreign patents related to nitrides.

Jan Rajchman Prize

This award is presented for an outstanding scientific or technical achievement in, or contribution to, research on flat-panel displays.

Marc Baldo, SID member and Professor at the Massachusetts Institute of Technology, will receive the Jan Rajchman Prize "for his outstanding contributions to the discovery of phosphorescent-OLED devices."

While a graduate student at Princeton, Marc Baldo helped develop phosphorescent OLEDs. Prior to this development, all



Marc Baldo

OLEDs were fluorescent, but fluorescence harnesses only spin 0, or singlet, excitons. Since singlets represent only 25% of the total number of excitons generated by electrical excitation, successful exploitation of the remaining 75% promised to increase OLED efficiencies by a factor of 4.

According to Russell Holmes, Associate Professor with the Department of Chemical Engineering and Materials Science at the University of Minnesota, "This work by Marc (and co-workers in the groups of Professors Stephen Forrest and Mark Thompson) permitted an immediate quadrupling in the efficiency of these devices by harvesting typically dark triplet exciton states. This work, published in *Nature* in 1998, represented a key enabling step for the development of an OLED-display industry and sparked an explosion of research into highly efficient phosphorescent emitters."

The materials and structures Baldo worked on were later commercialized by Universal Display Corp. Phosphorescent materials are now found in many commercial products, especially cell-phone displays.

Baldo received his bachelor of engineering degree from the University of Sydney and his Ph.D. from Princeton University. When asked what led him to his chosen field, he says, "I was very interested in the novelty of building devices based on molecules. I liked the idea of designing materials and devices atom by atom. I found that it was possible to make a device in an afternoon. It was an exciting

SID's best and brightest

time. When I built my first OLED, I remember the shock of the beautiful deep red color. I was hooked."

OLEDs have been the "next big thing" for a long time, and while each year brings progress in terms of commercial devices, that progress has been slower than initially surmised by many enthusiasts. Baldo says, "The challenge for OLEDs has been that they are an entirely new technology, unlike any previous semiconductor device or display technology. Consequently, the industry has not been able to draw on many existing technologies. From the devices themselves, to the packaging, to the manufacturing process, to the backplanes that drive the displays, everything has had to be developed specifically for OLEDs. Even today, with devices that are stable and efficient, we are still working on the manufacturing process. I think the advantages of OLEDs will make it all worthwhile, but it has been a lot of work. We still do not know all that is possible with OLEDs."

Slottow-Owaki Prize

The Slottow-Owaki Prize is awarded for outstanding contributions to the education and training of students and professionals in the field of information displays.

Dr. Hoi-Sing Kwok, SID fellow and Professor at Hong Kong University of Science and Technology, will be awarded the Slottow-Owaki Prize, "for providing education and training in display technology to many students and professionals in the Asia region through the creation of a display research center."



Dr. Hoi-Sing Kwok

Dr. Hoi-Sing Kwok established the Center for Display Research (CDR) at the Hong Kong University of Science and Technology in 1995. Many scientific institutions have a specific program of research in semiconductors, he explains, but not many have programs for displays. "Yet, displays are a large market that is one-third to one-half that of semiconductors," he says. "There are a lot of opportunities in display research." Initially, Kwok was able to convince the government to provide about US\$2 million to start CDR.

CDR has since evolved to become a center of excellence in display research, generating

many noteworthy research results and training numerous doctoral and postdoctoral students for work in the display industry. Kwok and his students have also produced significant intellectual properties in these research fields, obtaining 65 U.S. and Chinese patents thus far

"Professor Kwok is an anchor of the display community in the Hong Kong, Taiwan, and China regions," says Ching Tang, Doris Johns Cherry Professor of Chemical Engineering at the University of Rochester. "He has contributed to a wide range of display technologies, from LCOS to OLED, and from

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The grade of fellow is conferred annually upon SID members of outstanding qualifications and experience as scientists or engineers whose significant contributions to the field of information display have been widely recognized.



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ing devices. Dr. Käläntär is a senior scientist at Global Optical Solutions. He has Ph.Ds in Optics from Toyohashi University of Technology and Tohoku University.



Takatoshi Tsujimura, "For his contributions to the development of AMOLED displays and and OLED lighting." Mr. Tsujimura is General Manager and OLED

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Electronics at Southeast University. He received his Ph.D. in electronic engineering from Southeast University.



Gopalan (Raj) Rajeswaran, "For his pioneering contributions to the development, manufacture, and commercialization of AMOLED displays. Dr. Rajeswaran

is Chief Executive Officer with Moser Baer Technologies. He earned his Ph.D. in electrical engineering from SUNY Buffalo.

creating new device architectures to advancing display-manufacturing processes. The direct impact is that a large group of professionals of diverse skills from his research group are now making their own contributions in both academics and the display industries."

Former student Dr. Haiying Chen of APT Electronics writes, "Fourteen years ago, I joined Prof. Kwok's group as a Ph.D candidate. That was a big challenge for me, a graduate with materials science and engineering background only. Prof. Kwok was very nice and patient. He gave me enough space and freedom to learn, to think, to plan, and to try. I benefited quite a lot during the four-year study and research under Prof. Kwok, especially in learning how to think and to work independently."

Throughout his professional career, Kwok has supervised 42 Ph.D. dissertations, 20 master's theses, and 80 B.S. senior projects. He has co-authored one book, "Photoalignment of Liquid Crystalline Materials: Physics and Applications (Wiley/SID series)," and over 380 journal papers

His greatest satisfaction as a teacher? "To see the students grow and contribute to the industry. And sometimes to see them becoming more knowledgeable than I and teaching me back."

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The Lewis & Beatrice Winner Award for Distinguished Service is awarded to a Society member for exceptional and sustained service to SID.

Dr. Shigeo Mikoshiba, SID Life Fellow, Jan Rajchman Prize winner, and Professor Emeritus at The University of Electro-Communications in Tokyo, Japan, will receive the Lewis & Beatrice Winner Award "for his sustained exceptional contributions to SID for over 30 years."

Dr. Shigeo Mikoshiba is a life-long researcher, educator, and gifted scientist who received SID's Jan Rajchman Prize in 2007

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his B. E. and M. E. degrees in electrical engineering from Saga University.



Ryuichi Murai, "For outstanding contributions to the development of the 145-in.-diagonal super-highvision (8K x 4K) plasma display panel." Mr. Murai is a researcher at Panasonic Corp. He received his B.E. and M.E. degrees in electronic engineering from Osaka University.



In-Byeong Kang, "For his leading contributions to the development of manufacturable filmpatterned-retarder 3D displays and in-planeswitching-based liquid-crystal panels." Dr. Kang is Senior Vice President and Head of the LG Display Laboratory at LG Display Co. He earned his Ph.D. in electronic engineering from the

University of South Australia.



Isao Kawahara, "For his contributions to the research and development of the movingpicture-resolution metric for display panels." Mr. Kawahara has retired as a senior manager for image quality at Panasonic Corp. He received his M.E. degree in electric engineering from Kyoto University.



Qun (Frank) Yan, "For the development of the calcium-magnesium-oxide protective layer for high-luminous-efficacy plasma display panels." Dr. Yan is Chief Scientist of the plasma display panel (PDP) business unit within Changhong Electronics Group. He holds a Ph.D. in physics from Vanderbilt University.



Takehiro Zukawa, "For the development of the calcium-magnesium-oxide protective layer for high-luminous-efficacy plasma display panels." Mr. Zukawa is a Staff Engineer with Panasonic Plasma Display Corp., Ltd. He received his M.S. degree in engineering from Toyama University.



Hidefumi Yoshida, "For his significant contributions to the science and technology of liquidcrystal displays, including the multi-domain vertical-alignment mode." Dr. Yoshida is a Chief Technical Research Fellow with Sharp Corp. He has a Ph.D. in engineering from Tokyo Institute of Technology.

SID's best and brightest



Dr. Shigeo Mikoshiba

for contributions to PDP and LCD backlighting technology. Yet he has also through the years found time to serve and promote the Society for Information Display. He joined SID in 1975, and since 1981 has continuously served SID, its Japan Chapter, Japan Display, and IDW. He has been President and Secretary of SID, as well as chair and member of countless committees. He has also served as an associate editor for both the *Journal of the SID* and *Information Display*.

"I have known and worked with Prof. Mikoshiba for a great many years," says SID member Alan Sobel. "He has worked tirelessly and indefatigably for SID in a number of capacities."

Mikoshiba says it has not always been easy to find the time to volunteer, especially while balancing university research, education, and administrative duties (not to mention family

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obligations). "Nevertheless, I enjoyed my volunteer activities very much," he says. Through these volunteer activities, Mikoshiba says he got to know many people who were helpful not only in terms of those activities but for his research work. Last but not least, volunteer work enriches one's personality, says Mikoshiba. Mikoshiba earned his bachelor's and master's degrees in plasma physics at the Tokyo Institute of Technology. His doctoral degree, also in plasma physics, is from the University of Alberta. Mikoshiba says he became interested in display technology while working for Hitachi starting in 1973, at about the time that PDPs, LCDs, and FEDs were all emerging.



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RGB Color Patterning for AMOLED TVs

RGB color patterning is one of the key technologies for manufacturing large-sized AMOLED *TVs.* Two competing approaches are currently being used to realize RGB subpixels. One requires a more difficult manufacturing process but has better color purity; the other is easier to manufacture but requires optimization in algorithms to overcome some weaknesses.

by Jang Hyuk Kwon

LL COLOR TVs sold today realize color images through combinations of pixels that, in turn, consist of RGB subpixels. Liquid-crystal-display (LCD) TV uses backlighting as the light source and color filters for the RGB subpixels, which are patterned by photolithography or ink-jet printing. Since organic light-emitting diodes (OLEDs) are self-emissive, we can realize RGB subpixels by direct deposition of RGB emission materials for each subpixel (RGB side-by-side) or by filtering white-OLED light through RGB color filters (WOLED + CF). Currently, there is much debate with regard to which approach will be the winner in the large-sized OLED-TV market. This article describes the pros and cons of each technology and presents an outlook for future OLED technology development.

RGB Side-by-Side Patterning by Shadow Mask

Currently, the active-matrix organic lightemitting-diode (AMOLED) pixels for mobile applications are manufactured by evaporation of small-molecule light-emitting materials through metal shadow masks. When onecolor material is being deposited, the other color areas are blocked by this mask. Figure 1 schematically shows the shadow-mask technology for red, green, and blue pixel patterning of AMOLEDs.

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Fig. 1: A typical shadow-mask technology for pixel patterning shows green and blue pixels being blocked. The table at bottom shows the dimensional capability of the shadow-mask process to date.

Current shadow-mask technology is already mature and does not present any serious difficulties when used on substrates up to 750 mm \times 650 mm (which represents ¼ of a Gen 5.5 substrate of 1500 mm \times 1300 mm). However, this technology cannot be used for Gen 8 substrates for AMOLED-TV production because glass and mask sagging become critical issues.

A new process technology called Small Mask Scanning (SMS) has been developed by Samsung for large-area TV manufacturing. In order to circumvent the sagging problem of the substrate and the mask, the glass substrate is moved during pixel deposition while both the small-area shadow masks and the linear evaporation sources are kept stationary (see Fig. 2). The merits of the SMS process are (1) practically, the same small-molecule materials used for mobile application can be used for TVs, and therefore good synergy exists between the two applications, and (2) the benefits of low power and long lifetime and the color purity of the RGB side-by-side pixel configuration are maintained.

One major drawback is that achieving pattern accuracy becomes more difficult for

larger substrates (such as Gen 8 and above) and higher resolution [ultra-definition (UD) and above], which are both necessary for next-generation TVs. To be more specific, any misalignment will result in color mixing and non-uniformity of the subpixels. Mask window variation with multiple patterning processes can also be a serious problem for real mass production. Further technology development is needed in order to increase manufacturing yield as well as to improve scalability in substrate size and high resolution.

White OLEDs with Color Filters

The approach of white OLEDs with color filters (WOLED + CF) has received a great deal of attention because of its simpler process and attendant benefit of using the existing color-filter infrastructure.¹ This method can easily overcome the inherent complexity of RGB side-by-side patterning with the shadow masks. White emission can be achieved by mixing three primary colors (red, green, and blue) or two complementary colors (yellow and blue) in the emissive layers. Generally, WOLEDs consisting of small organic molecules have a multilayer structure with two or more emitting layers in a simple stack or tandem OLED structure.

Figure 3 shows several structures developed to realize white-OLED devices. Among these, the tandem OLED structure has merits in terms of longer lifetime and higher efficiency; however, the manufacturing process is a bit more complicated. The tandem device with two emissive layers as shown in Fig. 3 can greatly reduce current level to achieve the required brightness value of each pixel and more than doubling lifetime. The tandem device can also easily achieve very high efficiency because both efficiency values of each single cell are combined.¹ In the beginning of 2013, LG Electronics announced commercial production of 55-in. AMOLED displays that use the tandem WOLED + CF approach. (In the CES Review in this issue of ID, author Steve Sechrist notes that LG planned to begin shipping these units in Korea in February of 2013.)

One problem with the WOLED + CF approach is that light-output efficiency is reduced to 30% of the efficiency of RGB side-



Fig. 2: The OLED RGB process using SMS (left) is compared with the WOLED + CF process (right) in terms of pixel structure, methodology, and pros and cons.

frontline technology



Fig. 3: Above are shown the merits and demerits of various WOLED structures (EML = emissive layer).

by-side because of the light absorption induced by the color-filter pigments. This problem can be minimized if the RGBW four-pixel color system is employed. Theoretically, the RGBW system can have about ~50% light output due to the mixing of white colors for bright images and thereby compensate this for the light loss.² However, there is a trade-off between the reduction of power consumption and the degradation of color purity. More circuitry to drive the white pixel is needed and light output efficiency to each RGB subpixel depends on the white spectrum of WOLEDs. Therefore, the light output efficiency of actual displays may not reach this ~50% theoretical level. Another issue lies in the color variation on viewing angle because thick organic layers in the tandem structure result in several possible optical paths, which can distort color. Overall, a more than two-times-higher power consumption and a much shorter lifetime can be a real concern in AMOLED TVs using the WOLED + CF system. However, a combination of new OLED materials and optimum color-rendering algorithms may be able to solve the lifetime, power consumption, and color characteristics issues, as discussed in Ref. 2.

Future Prospects in Color Patterning Several companies are trying to develop alternative technologies to replace the current shadow-mask process used for large-area TV applications. Solution-process printing technologies such as ink-jet printing³ and nozzle printing^{4,5} have been proposed as pixelpatterning methods. These processes will be the ultimate objective for pixel-patterning methods for AMOLED displays since using them is fairly simple and does not require any vacuum equipment.

Several material companies are developing soluble materials for these solution processes. However, it is not an easy task to develop good soluble materials because OLED lifetime is very sensitive to impurities, film quality, and environmental conditions. (One such possible solution is discussed in the Industry News story, "Merck to Use Epson Ink Technology for Large OLED Displays," in the January/February issue.) Among the RGB materials, blue has the shortest relative lifetime. Device lifetimes of red and green OLED devices with solution printing processes are sufficiently extended to be of practical use. Consequently, a process involving blue thermal deposition of the entire active area with an open mask after the solution printing of red and green subpixels is being developed to overcome these lifetime issues. Recently, significant progress has been made in the development of soluble materials and the process for AMOLED fabrication. Hence, it is expected that solution printing processes will be available in the near future.

Laser-printing technologies have also been proposed as pixel-patterning methods, suitable for large-area displays. Laser-induced thermal-imaging (LITI) technology⁶ was first reported by Samsung. This technology uses donor films with a laser-light-absorbing layer and a transfer organic layer. Laser light is converted into thermal energy as it shines on the light-absorbing layer. Subsequently, the transfer layer melts and transfers to the substrate. The company is focusing on this method only for small-sized high-resolution display applications. This process is very sensitive to particles because any contaminated particles can fix onto the substrate during the transfer process. Small-sized applications are better with regard to minimizing yield loss.

Laser-induced pattern-wise sublimation (LIPS) technology⁷ has also been reported as an alternative to LITI technology. Both technologies are fundamentally very different. In LIPS technology, emissive organic layers on the light-absorbing metal layer are deposited on glass and then attached to two substrates, one organic deposited substrate and one active-matrix backplane under vacuum. Finally, a laser scans the organic layer to form a pattern through sublimation transfer from the organic layer to the active-matrix backplane. Sony reported this process and demonstrated a 25-in. AMOLED panel at Display Week 2007. In this process, similar thermal evaporation temperatures for host and dopant molecules are required. Patterning of phosphorescent materials using this methodology is difficult because phosphorescent materials have much higher evaporation temperatures originated by high molecular weights. To date, no additional progress has been shown with this process.

Refinements Needed for Progress in Both Processes

Currently, the two main patterning processes, SMS and WOLED + CF, are being intensively developed for commercialization. Gen 8 lines for both technologies have been already invested in for the production evaluation of 55-in. AMOLED-TV applications. Both technologies are rapidly improving. Additional possible processes such as solution printing and LIPS are also being investigated. In the near future, significant progress in solution printing processes in particular is expected.

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Oxide TFTs for AMOLED TVs

AMOLED TVs using promising oxide semiconductor and thin-film transistors (TFTs) have been unveiled. This article will present the issues, challenges, and concerns of oxide TFTs for AMOLED TVs.

by Jin-Seong Park

INCE flexible and transparent amorphous In-Ga-ZnO (indium gallium zinc oxide or IGZO) thin-film transistors (TFTs) were reported in 2004¹, tremendous progress has taken place with regard to amorphous-oxide semiconductor devices as TFT backplanes. These devices enable high-performance flatpanel displays (FPDs), including activematrix organic light-emitting-diode displays (AMOLEDs).² Many FPD manufacturers such as Samsung, LG, Sharp, and AUO have already announced significant investment in large-sized AMOLED panel production based on oxide-semiconductor devices in 2012. Although small-sized AMOLEDs for cell phones using low-temperature polysilicon (LTPS) TFTs are already in large-scale production at Samsung, it is quite significant to hear announcements about adopting oxidesemiconductor devices as backplanes for larger-sized AMOLEDs. According to recent press reports, LG Electronics will sell 55-in. AMOLED TVs to consumers in the first quarter of 2013 (see the CES review in this issue).

For several decades, wide-bandgap oxide materials, including ZnO, Al-doped ZnO, Ga-doped ZnO, SnO₂, In₂O₃, InZnO, and InSnO, have been intensively investigated for sensor, optoelectronics, photovoltaic, and transparent-electrode applications due to their high trans-

Jin-Seong Park is a professor at Hanyang University. His research focuses on oxidesemiconductor materials and devices, flexible AMOLEDs, and thin-film encapsulations. He can be reached at jsparklime@hanyang. ac.kr. parency: > 80% at visible range and carrier concentrations of 10¹⁸/cm³. Interestingly, those materials have been reported to have good semiconducting behavior under a range of deposition parameters, doping elements, and post-annealing processes. The amorphous structure in the oxide semiconductor is also important in avoiding the problems of carrier trapping and low mobility caused by a polycrystalline structure. The key property that enables the formation of an amorphous structure is "crystal frustration" -i.e., the three materials (In, Sn, and Zn) all tend to form different crystal structures on their own, so together will not permit the formation of polycrystalline structures. Thus, based on a number of papers and reports,2-4 amorphousoxide-semiconductor TFTs combining In, Sn, and/or Zn elements have generally exhibited reasonable field-effect mobility (μ_{fe} , greater than 10 $\text{cm}^2/\text{V-sec}$), a high on/off ratio for the drain current, and very low leakage current (less than 10 fA). Accordingly, amorphousoxide semiconductors may be considered the ultimate solution for producing large AMOLED TV panels at low cost.

Many researchers and engineers still have concerns regarding certain critical device issues of oxide-semiconductor devices. These are required further improvements in mobility, stability, pixel design, and electrodes.

The Need for High Mobility

High mobility, greater than 100 cm²/V-sec in LTPS TFTs, is very important for small-sized AMOLED panels because the pixel-driving TFT and the embedded circuits need to oper-

ate at relatively high speed and high current within small pixel dimensions.

For large-sized AMOLED TVs, the mobility requirement is generally predicted to be over 30 cm²/V-sec, depending on display resolution and pixel-circuit designs, because OLED pixels need high current in order to emit light through electrical current injection. Many researchers have reported various oxidesemiconductor materials and structures that can achieve high-mobility TFTs. Interestingly enough, as we learn about the electronic nature of oxide semiconductors, we find the mobility may be controllable in the $1-30 \text{ cm}^2/\text{V-sec}$ range, as long as the device instability is not a concern. Also, a few results have been demonstrated with a mobility of almost 100 cm²/V-sec with a TFT as a unit cell, showing an indium tin oxide (ITO)/IGZO or indium zinc oxide (IZO)/IGZO tandem active structure.5

Robust Oxide TFTs

Instability is perhaps the most important issue that may block the practical application of oxide TFTs to AMOLED displays. Recent efforts have been focused on understanding device instability and improving long-term stability. To investigate the stability of oxide TFTs, many researchers have considered four practical stress conditions: negative/positive bias, temperature, illumination, and environment (humidity).^{6,7} Upon application of the four stresses, the oxide TFT generally only exhibits a V_{th} shift without a change in mobility, as shown in Fig. 1(a). This may occur by either charge trapping at the channel/gateinsulator interface or charge injection into the gate-dielectric bulk. Occasionally, it has been observed that the devices spontaneously recover their initial state after a relaxation period without any thermal annealing.

It is also critical to accelerate the V_{th} shift by applying two stress conditions simultaneously.⁸ Although several groups have reported possibilities such as oxygen vacancy, hole trapping, and electron injection, the origin of the degradation mechanism is still under investigation.

In order to improve the stability of oxide TFTs, researchers have taken steps including optimized structure,⁹ suitable gate-insulator materials,¹⁰ impermeable passivation layers,¹¹ robust semiconductors,¹² and post-annealing treatments.¹³ By comparing bottom-gate TFTs with a back-channel-etch (BCE) or an etch-stopper (ES) structure [Fig. 1 (b)], researchers showed that the stability of an ES-type device was superior to that of a BCEtype device, which may be attributable to the formation of defective interfacial layers. For gate insulators, the superior stability of the SiO_x or AlO_x gated devices can be attributed to the suppression of hole injection or trapping in the gate dielectric, owing to relatively large valence-band offset and less hydrogen content. In addition, low-permeable passivations such as AlO_x and SiON_x exhibited better stability in devices under stress conditions.

In oxide semiconductors, robust oxide TFTs have a higher oxygen content in the active layers during the deposition process and post-treatment. In general, in terms of materials and structures, robust oxide TFTs had less hydrogen and higher oxygen compositions to suppress a V_{th} shift under four practical stress conditions.

It is very difficult to design oxide-TFT structures with a selection of proper materials based on large-sized mass-production equipment. Therefore, it may be impossible to fabricate perfect and stable oxide TFTs by using conventional processes, structures, and equipment because the electronic conduction mechanism in oxide semiconductors depends on controlling defect systems such as oxygen vacancy and hydrogen incorporation, as well as cation composition. TFT structures are very well suited to existing a-Si TFT production lines, but various process factors still need to be closely considered. Making stable oxide TFTs that perform well in the final application requires very tight control of the processes, materials, and equipment.

A Pixel-Circuit Design for Oxide TFTs Besides the mobility and stability issues, there is another problem to solve in order to realize large-sized AMOLED panels: the pixel-circuit design. It is well known that the use of oxide TFTs can result in an AMOLED panel with

the simplest pixel circuit, as shown in Fig. 1(c), because of the amorphous nature of the materials and the resulting highly uniform electrical properties. If the TFTs are uniform (long range and short range) and stable (bias stress), a simple circuit structure is the only thing that is needed. If the TFTs are non-uniform and unstable, non-uniform OLED luminance may occur due to the different parameters of the switching TFT on each pixel. These problems can be fixed by using circuit-design technologies such as a compensated circuit (5T+2C, etc.). Grain boundaries and device instability are important factors to consider in regard to non-uniformity. When AMOLEDs based on oxide TFTs are demonstrated, the oxide TFTs should exhibit no significant variation in V_{th} and μ_{fe} during prolonged operation.

Unfortunately, as mentioned above, the degradation of oxide TFTs is unavoidable under stress conditions. While the variation of μ_{fe} and V_{th} is less important in an AMOLED

switching transistor, the current-induced threshold-voltage shift should be seriously considered for AMOLED driving transistors. It has been reported that a V_{th} shift of the driving transistor by 0.1 V induces variations in the resulting luminance of the OLED pixels by approximately 20%, which reflects the fact that the brightness of each pixel strongly depends on the drain current.¹⁴ Therefore, OLED displays should employ complex compensation circuits that have four or more TFTs, such as 4T2C, 5T2C, and 6T2C circuits, with 4T2C meaning that the circuit involves four transistors and two capacitors.³ In addition, an oxide semiconductor exhibits n-typelike properties, indicating that the major carrier in a channel is an electron. In an average OLED pixel circuit, a compensation circuit such as that shown in Fig. 2 should be employed in order to utilize n-type oxide TFTs, unlike the case for p-type LTPS TFTs, where this is not required.

Low-Resistivity Electrodes

Regarding large-sized AMOLED panels, the proper material for gate, source, and drain electrodes must be chosen. Large, highresolution, and fast-frame-rate panels require



Fig. 1: (a) Gate-voltage vs. drain-current chart represents the evolution of a transfer curve as a function of bias-temperature-illumination stress. (b) The schematics of etch-stopper (ES) and back-channel-etch (BCE) structures are illustrated. (c) This conventional pixel design for an AMOLED panel uses two transistors and one capacitor.

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Fig. 2: This circuit diagram of a pixel (AMOLED panel based on a-IGZO TFTs) shows examples from (a) Samsung Display and (b) Sharp and Semiconductor Energy Laboratory (SEL).

electrodes with low resistivity, such as Al and Cu. However, Al has poor adhesion and easily oxidizes during the AMOLED processes. The Cu element easily diffuses and incorporates into the oxide semiconductor and gate insulator through thermal annealing and electromigration, as is well-known, while showing the degradation of electrical properties such as mobility and stability. Recently, AUO applied Ti/Al/Ti electrodes to 37-in. AMLCDs, and Samsung Electronics applied Cu-based bus lines to a 15-in. AMLCD.^{17,18} Also, LG Display has adopted Cu-based electrodes in its 55-in. AMOLED-TV product.

Oxide-TFT Prospects for AMOLED TVs

From a market perspective, some observers in the display industry have deep concerns about the competitiveness of AMOLED TV based on oxide TFTs. As shown in Table 1, oxide semiconductors have promising possibilities; these initially led to a great deal of attention. Phrases such as "low-cost-based AMOLED backplane technology" or "like amorphoussilicon (a-Si:H) TFT technology for AMOLEDs" were used to describe progress toward the commercialization of AMOLED TV panels. Today, many companies have struggled to reduce fabrication costs in order to compete not only with AMOLED TV panels based on LTPS TFTs, but also with high-quality active-matrix liquid-crystaldisplay (AMLCD) TV panels based on a-Si:H TFTs.

To minimize the fabrication cost of an active-matrix backplane, it is important to reduce the number of photolithography masks. Current a-Si:H LCDs employ 4–5 masks, using a gray mask (also called a halftone mask) to pattern the source/drain electrodes and the channel in a single mask step. Samsung Display recently demonstrated AMOLED displays based on oxide TFTs, employing seven masks with an ES structure.¹⁹

As mentioned above, the ES-type device not only has superior stability, but also has excellent uniformity in the electrical properties because the ES layer can prevent the degradation of active layers during the following dry- or wet-etch process. The ES process in oxide TFTs is the contradictory factor with regard to fabrication cost and production yield. Thus, Sharp and LG Display have demonstrated mass-produced AMLCD and AMOLED backplanes with ES-type structures to guarantee the quality of the panels with uniform device performance. However, these companies have intensively developed a process with fewer mask steps (e.g., a BCEtype structure), resulting in a high-selective wet-etchant and self-passivation layer. To balance fabrication cost and yield in largesized AMOLED displays, a BCE-type device may be an inevitable selection. While the high-quality gate-insulator process may deteriorate the uniformity and performance of devices by damaging the active layer, a topgate device configuration can be a possible solution in reducing the number of masks and parasitic capacitance for large-sized AMOLEDs.

Oxide TFT: A Solution Awaiting Solutions

Since small-sized AMOLED displays have been successful in the display marketplace, there is no doubt that AMOLED displays have the potential to become a superior display technology for TV. However, as far as the backplane technology is concerned, it is not yet clear which technology is suitable for large-sized AMOLEDs. Since 55-in. AMOLED TV panels were first demonstrated in 2012, many manufacturers and researchers have struggled to realize solutions to the following problems: mobility, stability, and yield.

 Table 1: Shown is a comparison of AMOLED panel designs based on polysilicon, amorphous silicon, and oxide TFTs.

AMOLED Panel	Poly-Si TFT	a-Si:H TFT	Oxide TFT
Semiconductor	Poly-crystalline Si	Amorphous Si	Amorphous IGZO
TFT uniformity	Poor	Good	Good
Pixel circuit	Complex (5T + 2C etc.)	Complex (4T + 2C, 5T + 2C)	Simple/Complex $(2T + 1C/6T + 2C)$
Channel mobility	$\sim 100 \text{ cm}^2/\text{V-sec}$	1 cm ² /V-sec	>10 cm ² /V-sec
TFT type	PMOS (CMOS)	NMOS	NMOS
TFT mask steps	5 ~ 11	4~5	5~7
Cost/Yield	High/Medium	Low/No data	Low/Medium

Recently, some research groups have reported a c-axis-aligned IGZO layer as a robust active layer, a large-sized (over Gen 8) sputtered target, and a high-mobility oxide material such as InZnSnO. Although device degradation and electronic-conduction mechanisms have been investigated in oxide TFTs, interdisciplinary researches from theoretical calculation to device engineering have increased drastically in recent times. As we gain deeper understanding into oxide semiconductors and processes, they will no doubt become the solution to realizing large-sized AMOLED TVs in the marketplace.

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Zinc-Oxynitride TFTs: Toward a New High-Mobility Low-Cost Thin-Film Semiconductor

Demands for high-performance, low-cost, and low-energy-consumption displays continue to drive the development of new semiconductor materials. The success of the metal-oxide semiconductor IGZO for display backplanes has triggered even more activity, and zinc oxynitride is proposed as a possible solution.

by Yan Ye

HE CARRIER MOBILITY of a semiconductor material, which is a measure of how fast mobile electrons or holes can move in the material under an applied electric field, is a key parameter for determining the performance of an electronic device. For activematrix thin-film-transistor (TFT) displays, high mobility is related to high resolution, high refresh rate, low energy consumption, and high manufacturing yield.

This article will look at the achievable performance of indium-gallium-zinc-oxide (IGZO) as well as that of other metal-oxide semiconductor materials for TFT applications. Efforts to make IGZO TFTs prevalent in display manufacturing are still ongoing as are searches for even better semiconductor materials that will match the high performance of low-temperature polysilicon (LTPS) TFTs and the low cost of amorphous-silicon (a-Si) TFTs. Zinc oxynitride (ZnON) is described here as one possible path to realizing these performance and cost goals.

a-Si and LTPS

a-Si is widely used as a TFT channel material. Although the field-effect mobility of an a-Si

Yan Ye has been working on the development of new technology at Applied Materials for more than 20 years. He can be reached at yan_ye@contractor.amat.com. TFT is below 1 cm²/V-sec, the low cost of the material and its TFT fabrication set a benchmark for cost-effective production. LTPS typically has a mobility of 50-150 cm²/V-sec.

However, because the cost to fabricate LTPS TFTs is much higher than that for a-Si TFTs, LTPS is used today mostly for high-end smallarea display products. Recently, amorphous



Fig. 1: The Hall mobility of a-IGZO films is shown before and after annealing at different temperatures.

indium-gallium-zinc-oxide (a-IGZO), one of the metal-oxide semiconductors developed in the last decade, has been used to successfully make display backplanes with a mobility higher than that of a-Si TFTs at a cost lower than that of LTPS TFTs.

It is of interest to know whether the mobility of an IGZO TFT can reach a level similar to that of an LTPS TFT through process optimization. A wide range of measurements of the field-effect mobility of IGZO TFTs, which are extracted from I-V measurements, have been reported in the literature. Although TFT fieldeffect mobility is a key parameter for validating channel-layer performance, its intrinsic limit is difficult to establish based on existent data. In fact, accurate field-effect-mobility assessment relies on precise measurements of the I-V transfer curve, channel width and length, capacitance, *etc.* It is sensitive to TFT fabrication, measurement, calculation, and human error.

Hall mobility, the carrier mobility attained from Hall-effect measurement, is a more direct measurement of the material itself. Therefore, Hall mobility is more suitable for comparing different materials, although certain limitations or errors can also exist. Figure 1 plots the Hall mobility of amorphous-IGZO of a composition of about 1:1:1:4 attained in a test. These data suggest that mobility achieved by a-IGZO should be higher than that of a-Si, but not LTPS.

Single-Metal Oxides

Several mechanisms limit electron or hole transport inside n- or p-type semiconductors. Single-metal oxides, such as ZnO, In₂O₃, and SnO₂, have been studied intensively as transparent conductive oxides (TCOs) for decades and as semiconductors for TFTs in the last decade. Figure 2 shows the Hall mobility at different carrier concentrations for doped and undoped ZnO films. It is clear that two mechanisms limit carrier transport in the material: grain-boundary-limited transport and ionized impurity scattering. ZnO is normally polycrystalline. The boundaries between the crystalline grains can trap charges, deplete the carriers around them, and interrupt the electron transport across them, presenting potential barriers with respect to the conduction-band minimum [Fig. 3(a)]. The barrier height decreases with increasing carrier concentration until Coulombic ionized impurity scattering dominates as the mechanismlimiting electron-carrier transport.

As shown in Fig. 2, the transition point at which the ionized impurity scattering mechanism becomes dominant is at a carrier concentration of $\sim 10^{20}$ cm⁻³ in ZnO. It is worth noting that in single-crystal Si, the transition point at which ionized impurity scattering becomes dominant compared to phonon scattering is at a carrier concentration of $\sim 10^{17}$ cm⁻³.

For other single-metal oxides, it is observed that high mobility can be achieved at high carrier concentration where the material is more like a conductor than a semiconductor. For example, In_2O_3 :H films attain a mobility above 100 cm²/V-sec at a carrier concentration over ~10²⁰ cm⁻³, characterizing as conductors. In fact, it is difficult to make a single-metal oxide film with a high mobility and a low carrier concentration as desired for TFTs. Therefore, it is necessary to search for other options.

Multi-Metal Oxides

The grain-boundary-limited transport problem encountered in single-metal oxides can be addressed effectively by forming multi-metal oxides, as shown in Fig. 3(b). Since multiple metals are involved in forming the crystalline structure of the film during deposition, under a balanced ratio, preferential growth of a crystalline structure from any metal used can be interrupted by the presence of other metals. a-IGZO, with a composition of about 1:1:1:4, is a good example in this category.

However, it is observed that even though there is no clear grain boundary in a-IGZO, electron transport is still limited by a potential barrier just as it results from grain-boundarylimited transport, showing an increase in mobility with an increase in carrier concentration [Fig. 3(d)]. The barrier remains the dominant mechanism limiting the mobility at carrier concentrations up to $\sim 10^{20}$ cm⁻³ with



Fig. 2: Mechanisms limiting Hall mobility are shown based on the Hall-mobility measurement of various doped or undoped ZnO films at different carrier concentrations.

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no signs of Coulomb scattering or defect reduction taking over. Therefore, the mechanism resulting in this barrier is strong. Notably, the mobility-carrier concentration relationship remains the same even for singlecrystalline IGZO as shown in Fig. 3. A percolation conduction model has been used to explain the barrier.

Conceptually, the potential barrier in IGZO may also be explained based on the model of s-orbital wave-function overlap. In an ideal case for a multi-metal oxide, as illustrated for IGZO in Fig. 3(b), the distance of the interaction between s-orbitals of neighboring metal cations should be larger than that of cation sites. However, it may not occur everywhere in reality. Even by excluding the complexity of randomness in an amorphous phase, it may not be thermodynamically favorable to pack cations of different metals at an equal distance, as described in the ideal case. In addition, different metals may interact with others differently, making the interaction distance between cations from different metals more complicated. Therefore, it is very likely that there will be some locations where the site distance is larger than the interaction distance between cations, causing interruptions on the conduction-band minimum that will give rise to potential barriers. This model may also explain why mobility is reduced in a highly doped single-metal oxide, even though no significant grain-boundary-limited transport is present, and why a ternary compound such as IGO or IZO may result in a higher mobility as reported due to less complexity than other quaternary compounds.

It is possible to achieve a higher mobility by changing the composition of a multi-metal oxide, *i.e.*, making an IGZO with a different ratio. When making a film with an unbalanced ratio, crystalline structures grow rela-



Fig. 3: The barrier resulting from grain boundary commonly encountered in a single-metal oxide (a) can be suppressed by forming either a multi-metal oxide (b) or a single-metal oxynitride (c). Data plotted in (d) show that the mobility of a-IGZO or c-IGZO increases as carrier concentration increases, indicating that a potential barrier, similar to that due to grain-boundary-limited transport, exists. Data plotted in (e) show that several as-deposited ZnON films attained from a 50°C process follow a different trend compared with IGZO.

tively easily if the defect level is kept low, and thus barriers associated with grain-boundarylimited transport return. Besides, barriers associated with multi-metal cations still exist, just as in a ternary compound or a highly doped binary compound. Therefore, the improvement in mobility thus far with a carrier concentration suitable for TFTs is limited.

Zinc Oxynitrides

The barriers resulting from both grain boundary and multi-metal cations can be suppressed by forming a single-metal cation (Zn) and multi-anion (O and N) metal oxynitride such as zinc oxynitride (ZnON), as shown in Fig. 3. Since both oxygen and nitrogen are used as anions, which require different crystalline structures in the compound, the arrangement of zinc cations in the film is disordered. The film can be deposited through a reactive sputtering process using a metallic zinc target and reactant gases such as oxygen and nitrogen. Composition and crystalline structure of the film can be varied by controlling the competition of reactions between zinc and nitrogen and between zinc and oxygen, which can be achieved by adjusting the flow rate ratio of oxygen and nitrogen along with the associated pressure, temperature, and power used in the process. Figure 4 shows films deposited at different oxygen flow rates under a high nitrogen flow rate of 500 or 300 sccm in a reactive sputtering process. When no oxygen gas is introduced and oxygen unintentionally remaining or is carried into the chamber is minimized, a Zn_3N_2 film is produced. Zn_3N_2 film is polycrystalline as observed by X-ray diffraction (XRD) and grazing-angle XRD (GXRD). When a small amount of oxygen gas is introduced, the growth of the Zn_3N_2 crystalline structure is interrupted because the reaction between zinc and oxygen starts to compete with the reaction between zinc and nitrogen. For a flow rate of oxygen between 5 and 40



Fig. 4: Shown is the change in Hall mobility and crystalline structure in the films deposited at different oxygen flow rates in a reactive sputtering process using a Zn- or Al-doped Zn target. In the sputtering process, the flow of nitrogen gas remains high. By adjusting a dominant reaction from between Zn and N to between Zn and O, zinc nitride (Zn_3N_2) , zinc oxynitride (ZnON), nitrogen-doped zinc oxide (ZnO:N), and zinc oxide (ZnO) films can be produced. High mobility is attained in the films in which crystalline structures of Zn_3N_2 and ZnO are suppressed.

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sccm in the test (Fig. 4), crystalline structures for both Zn_3N_2 and ZnO crystalline structures have been significantly suppressed and films deposited are either amorphous or highly disordered nanocrystalline ZnON films. The amorphous fraction and composition of ZnON films vary depending on reactions involved in the film-deposition process.

As the oxygen flow rate is increased to about 50 sccm, the reaction rate of zinc with oxygen becomes higher than that of zinc with nitrogen, and ZnO crystalline structures emerge. However, nitrogen is still embedded in the film, as indicated by the shift of ZnOcrystalline peaks in XRD and GXRD measurement. Since the film has a clear zinc-oxide crystal-line structure, it is often called nitrogen-doped zinc oxide (ZnO:N). The reaction between zinc and oxygen becomes dominant as oxygen flow further increases or nitrogen gas decreases, and the film becomes a ZnO film even though a lot of nitrogen is still present in the process. It is evident that the reaction rate between zinc and oxygen is much higher than the reaction rate between zinc and nitrogen in the reactive sputtering process. This also explains why an abnormally high ratio of nitrogen over oxygen is often needed to produce a ZnON film, why the transition regime from Zn₃N₂ to ZnON is very small, and why a Zn₃N₂ crystalline structure can be suppressed even by a small amount of residual oxygen.

Although the films made from the process can be Zn_3N_2 , ZnON, ZnO:N, or ZnO, Halleffect measurements show all of the films produced are n-type semiconductors. Therefore, the mobility of the films should rely on the conduction band of the materials. The result in Fig. 4 shows a clear trend that the higher mobility is achieved in the films in which the Zn_3N_2 and ZnO crystalline structure is suppressed. The variation of mobility in a ZnON film depends on its composition, amorphous fraction, and possible defects in the film. Table 1 shows the mobility of a ZnON film before and after annealing. It is clear that mobility increases significantly from 38 to 135 cm²/V-sec, while the carrier concentration is reduced, most likely due to defect reduction in the film through annealing.

Another interesting difference between IGZO and ZnON is illustrated in Fig. 3(e). Several ZnON films tested have shown an increase in Hall mobility as carrier concentration decreases in the region to below 10²⁰ cm⁻³, which is different than the trend reported for IGZO. This indicates that in the ZnON films, ionized impurity scattering remains dominant even in a region where it is relatively weak, which, in turn, indicates that the potential barrier on the conduction-band minimum in the ZnON films is relatively low.

Actually, ZnON should be closer to the ideal model shown in Fig. 3(b) if the disordering from the multi-anions is not too severe. Since only Zn serves as the cation in the ZnON films, the interactions between neighboring cations are more uniform, and the distribution of metal cations is less complex, despite their amorphous arrangement. This increases the probability of maintaining an interaction distance larger than the distance between the cation sites. Therefore, the degree of interruptions on the conductionband minimum, or potential barriers, in the single-metal oxynitride should be reduced compared to that of IGZO film. As a result, a higher mobility than IGZO can be achieved.

ZnON has some unique characteristics compared to other metal oxides. For example, the wet-etch rate of ZnON is at least 10 times faster than that of IGZO. However, ZnON is more resistant to dry plasma. Under typical plasma dielectric etching or metal-etch process conditions, the etch rate of ZnON is about 10 times slower than that of IGZO.

It is also observed that the surface of ZnON is more hydrophilic than other oxides. It can absorb moisture and pollutants in the air and form weak acids or bases that accelerate oxidation of the film from the top surface

 Table 1: Hall mobility and carrier concentration of a ZnON film are shown before and after annealing.

Film	Resistivity Ohm-cm	Hall Mobility cm ² V ⁻¹ S ⁻¹	Carrier Concentration cm ⁻³
ZnON as deposited (50°C process)	2.7E-02	38.5	-9.06E+18
After anneal at 400°C for 1 hour	1.6E-02	135	-2.82E+18

down in a catastrophic way. Typically, the shelf life of ZnON is about several weeks if it is exposed to air without any passivation or protection. Annealing, however, can significantly extend the shelf life of ZnON film from several weeks to several years. ZnON TFTs are often less sensitive to ambient conditions tested against other TFTs of the same structure. However, the threshold voltage, V_{th} , of ZnON TFTs is often more negative compared to other metal-oxide TFTs. As experienced with any other new semiconductor, the integrated process to fabricate ZnON TFTs will be different from that for IGZO, and some changes will have to be implemented. Some of these features are challenges that need to be addressed, but some of the unique film properties can be utilized to improve the TFT stability and reduce the costs for manufacturing TFT backplanes. So far, ZnON activematrix TFT backplanes for a 3.8-in. QVGA display have been tested with yields close to 100%. A field-effect mobility of about $100 \text{ cm}^2/\text{V-sec}$ has also been achieved by groups with ZnON TFTs.

In summary, IGZO TFTs have successfully demonstrated higher mobility than a-Si TFTs and lower cost than LTPS TFTs. Even though efforts to fully implement IGZO TFTs in display manufacturing are still ongoing, searches for even better semiconductor materials have clearly already started. In order to make TFTs with a performance as high as that for LTPS TFTs and as low cost as that for a-Si TFTs, breakthroughs are needed. ZnON TFTs have been demonstrated here as one candidate to achieve this goal, but more progress is expected in the future.

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AMOLED Production: Entering a New Era?

Active-matrix organic light-emitting-diode (AMOLED) displays have many attractive features that have led companies to attempt to manufacture them, but one country – Korea – currently accounts for the vast majority of AMOLED-display manufacturing capacity. Ambitious investment plans in China, Japan, and Taiwan could change this balance over the next several years.

by Paul Semenza

MONG the many compelling features of active-matrix organic lighting-emittingdiode (AMOLED) displays are image quality (wide color gamut, viewing angle, and high contrast), thinness, and weight (no backlight and the potential to be made on a single substrate, which could be plastic or metal), and manufacturing process (simple stack, small amounts of materials, and few optical films). During the decade since the first AMOLED displays were produced, dozens of companies have made at least some efforts toward mass production. Despite the promise of the technology, the reality has been that developing the equipment, materials, and manufacturing processes to make OLED displays at high yield rates has been very difficult. Even the dominant firms, Samsung Display and LG Display, have struggled to scale the technology to make TV panels. At the same time, TFT-LCD technology has continued to improve, most recently in the form of $4K \times 2K$ panels.

Through 2012, the vast majority of AMOLEDdisplay manufacturing capacity has been in Korea, primarily with Samsung Display but increasingly with LG Display as well through investments in Gen 8 fabs for TV panels (Fig. 1). There is a great deal of uncertainty with regard to future production plans, but it is likely that there will be several new fabs in

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China, as well as a resurgence from companies such as Japan Display, Inc. (JDI), Panasonic, AU Optronics Corp. (AUO), and Innolux, all of which have implemented restructuring and consolidation of existing AMOLED-display fabs. The key to building out new capacity will be to master manufacturing technologies that enable scaling to large substrate sizes. Korea: Samsung Display and LG Display Samsung Display, the result of the merger of Samsung Mobile Display and Samsung Electronics's LCD business, is the dominant producer of AMOLED displays, starting mass production in 2007 and accounting for more than 95% of shipments in 2012. The company's capacity thus far has been built around



Fig. 1: AMOLED-display manufacturing capacity has been centered in Korea, but new or expanded production is expected in other countries over the next few years. Note: Taiwan capacity includes AUO's Singapore fab. Source: DisplaySearch Quarterly FPD Supply/Demand & Capital Spending Report.

Gen 4 and, starting in 2011, Gen 5.5 lines, which focus on displays for smartphones and other mobile devices.

These lines use the low-temperature polysilicon (LTPS) approach for the fabrication of the active-matrix backplanes, which are then cut in half (for the Gen 4) or guarters (for the Gen 5.5) for organic-material deposition. Vapor deposition of RGB subpixels is achieved primarily via fine-metal-mask patterning. Samsung has been using its Gen 5.5 A2 line, which consists of five phases, to experiment with new manufacturing technologies, including laser-induced thermal imaging (LITI) for materials deposition, flexible substrates, and thin-film encapsulation. (For more about current large-area OLED-display manufacturing processes, see the article "RGB Color Patterning for AMOLED TVs" in this issue.)

LG Display did not start mass production of AMOLED displays for mobile devices until 2011, as it focused on high-resolution and wide-viewing-angle LCDs for mobile devices. The company also started out with Gen 4 production, but within one year, pilot Gen 8 production began, focusing on AMOLED-TV panels. The company began shipping 55-in. TV panels at the end of 2012, but is not expected to manufacture in large volumes until 2014, when it starts deposition on full Gen 8 substrates (it is currently using half Gen 8 sheets for organic-material deposition) in its M2 fab.

LG Display has adopted two new approaches in its Gen 8 fab – oxide-TFT backplanes and white OLEDs with a color filter. Both of these approaches are believed to enable scaling to larger substrate sizes – the oxide-TFT approach because it can use modified a-Si TFT processes and the white-OLED approach because it does not require the deposition of individual red, green, and blue organic emitters on the subpixels. In order to fabricate RGB subpixels, color-filter material is then patterned on top of the white-OLED emitting area. The process to add color filters is much easier than the process to deposit RGB organic materials.

Samsung Display has also announced that it will begin Gen 8 production, although the exact timing is not clear. This new fab will cut the LTPS backplane into six sheets for organic-material deposition. Samsung has been developing a proprietary evaporation technique called small-mask scanning, in which a linear vapor-deposition source is scanned along the mask, which is believed to allow for scaling to larger substrate sizes than is the case when using a fine metal mask with a point source. Samsung is also believed to be developing oxide-TFT backplanes and white-OLED deposition for future Gen 8 production, as it may be easier to scale than LTPS backplanes.

While Samsung will have the largest AMOLED-display manufacturing capacity through 2014, it is possible that LG Display could catch up in 2015 if it continues on its current Gen 8 investment path. Samsung would likely maintain its market share for some time, however, as it continues to increase smartphone-display production and is moving toward the production of panels for tablet PCs and other larger-screen sizes. The outcome may depend on whether Samsung pursues OLED TV as rapidly as LG Display or focuses instead on smaller, mobile displays.

Japan: Fewer, Larger Players

Japan Display, Inc., (JDI) was formed via the merger of the mobile-display businesses of Hitachi, Toshiba, and Sony, and produces AMOLED displays using Gen 2 (formerly Hitachi) and Gen 4 (formerly Toshiba) fabs; Sony did not transfer its AMOLED-display assets to the new company. JDI is planning to add new capacity to the Gen 4 line (organic deposition on half-substrates), with the capability to process WOLED or RGB. JDI has also acquired Panasonic's Gen 6 a-Si LCD line and will install equipment to convert the fab to LTPS production in 2013, with organicmaterial deposition on the substrate cut into sixths.

Sony, historically a leader in AMOLEDdisplay production, previously produced AMOLED displays for its Clie PDAs, as well as the first AMOLED TVs. Sony has maintained its facilities and integrated into Sony Semiconductor and is currently producing very-high-end AMOLED monitors for master video and medical applications.

Panasonic has been developing AMOLEDdisplay production for years at its R&D center. In 2012, it installed ink-jet tools at a line in Himeji for AMOLED-TV pilot production. The company has been pursuing AMOLEDdisplay production with oxide backplanes, ink-jet printing, and Sumitomo Chemical's (much of the original patent portfolio was acquired from Cambridge Display) soluble polymer AMOLED materials (as opposed to more common small-molecule materials that are vapor deposited through a fine metal mask). In July 2012, Panasonic announced a joint development program with Sony based on printing technologies.

Other companies in Japan with ongoing AMOLED-display efforts include Epson, Ortus, and Sharp; however, none are anticipated to begin mass production in the near future.

Taiwan: Consolidation, Limited Production

AUO has two OLED lines for the production of small-to-medium OLED products, based on LTPS backplane and evaporation color patterning, a Gen 3.5 line, and a half Gen 4 line (AFPD in Singapore). In 2012, the company started a Gen 6 line using oxide-TFT backplanes and the full deposition of white OLEDs; it is believed that Sony's 56-in. RGB $4K \times 2K$ AMOLED TV was produced by AUO. Innolux owns a former TPO Gen 3.5 fab that uses LTPS backplanes with white OLEDs and a Chimei EL Gen 3.5 fab that previously produced bottom-emission AMOLEDs. Wintek has also been developing AMOLED-display production.

China: Many Announcements, Little Capacity Thus Far

There are many panel makers in China that have built R&D lines for AMOLED production, including BOE, CCO, Shenzhen China Star Optoelctronics, IRICO, Tianma, UDT, and Visionox. Most of these fabs are Gen 2, with the exception of Shenzhen China Star Optoelectronic Technology's (half Gen 4) fab, and all use LTPS backplanes and RGB patterning. BOE, China Star, Hehui Opto, IRICO, Lai Bao, and Truly have announced their intention to go into production with Gen 4 fabs over the next few years; BOE, China Star, Tianma, and Visionox are planning Gen 5.5 fabs, and Foxconn has announced its intention to build a Gen 6 line. Finally, BOE is planning a Gen 8 AMOLED-display fab for making TV panels in Beijing, using oxide TFTs and white OLEDs.

For a number of these companies, the schedule and probability of success are uncertain. Many are driven by provincial initiatives to develop high-technology manufacturing, but the supply chain and human-resource pool are limited in some cases. However, a steady stream of new ventures is targeting AMOLEDdisplay production. Among the newest players are IMEC, which announced that it intends to

display marketplace

build a Gen 3.5 AMOLED fab in Nanjing, with help from JGroup. Blue Excited Technology (BEX) plans to produce small AMOLED displays based on blue-coating technology developed at Xinyang Normal University; the company plans to build a Gen 4 fab using oxide-TFT blue OLED material and color conversion for color patterning.

Scaling Up to Larger Substrate Sizes

Most existing AMOLED-display fabs are Gen 4 or smaller. This is due to limitations in scaling both the TFT backplane array and organic materials deposition to larger substrate sizes. As with TFT-LCDs, there is an imperative in the AMOLED-display industry to move to larger fab sizes in order to increase revenues and reap economies of scale; so much of the industry focus is in these two areas of manufacturing technology.

In the past, AMOLED backplanes have been limited to Gen 4 substrates. This was because LTPS was the only TFT technology

that was able to drive the OLED devices, which are diodes, with sufficient levels of current density. LTPS fabs were limited to Gen 4 because of the need for an annealing step that typically uses excimer lasers. Due to limitations in laser power, the Gen 4 substrate was the largest area that could be annealed by the laser in a reasonable amount of processing time. However, developments over the past recent years have reduced some of these barriers. First, more powerful excimer lasers, as well as multiple scanning, have enabled Gen 6 and potentially larger LTPS backplanes. Second, oxide-TFT technology, which is similar to standard a-Si TFTs but provides higher levels of current density, has been brought into mass manufacturing, enabling Gen 8 AMOLED backplanes to be produced.

It is common in AMOLED-display manufacturing to cut the TFT-array substrate down to a smaller size for the back-end process of organic-material deposition. This is due to limitations in the standard process for evaporating organic material from a point source through a fine metal mask to define the subpixels. The use of this technique at Gen 4 and larger sizes has been difficult, due to issues such as sagging of the mask, shadowing and angular-distortion induced by the large angles, and the necessity of cleaning the masks. Samsung has recently been working on scanning a linear source across a mask, which could address some of these challenges; another approach is vertical scanning, in which both the mask and substrate are oriented vertically.

To scale up to very large substrate sizes, however, it is likely that new approaches are needed (Fig. 2). Two that have been in development for some time are LITI and ink-jet printing. In LITI, the organic material is embedded in a sacrificial film that is put on top of the substrate and then exposed to a laser, which causes a transfer of the organic materials to the substrate. In ink-jet printing, the organic materials are suspended in solu-

	Evaporation: Fine Metal Mask (FMM)	Laser Printing: Laser Induced Thermal Imaging (LITI)	Soluble: Ink-Jet Printing	White OLED + CF
Schematic	Substrate Fine Metal Shadow Mask Source Vacuum Deposition	Laser Beam Donor Film Substrate	Piezo Inkjet Heads	Encapsulation Cathode WOLED Layers (Tandem by Kodak) Pixel Electrode = Anode R G B W
Performance	Good – Very Good	Excellent	Very Good	Good
Width of Pattern	15 µm	2.5 µm	10 µm	2.5 µm
Resolution	250 ppi	300-400 ppi	200 ppi	300-400 ppi
Aperture Ratio	40-50%	70-80 %	60%	60-70%
Advantages	 Verified (currently in mass production) 	Large sizeHigh resolutionMulti layer	 Large size Minimal material usage 	Large size Superior productivity
Limitations	 Large area production Equipment and process issues (mask sagging, alignment) 	 B phosphor problem Donor film cost Requires delamination	 Poor material performance Limited material suppliers Not verified (productivity) 	 Additional process (color filter) High power consumption Not verified (productivity)

Fig. 2: While the use of a fine metal mask is the most prevalent method for deposition of the organic material layers in AMOLED displays, newer larger fabs are pursuing other approaches that might be more easily scaled to large sizes. Source: DisplaySearch.

tion, which is then forced through ink-jet print heads onto the substrate. While these techniques show great promise, neither has been put into mass production. (The January/February Industry News section of *ID* magazine discusses new ink technology developed by Merck and Epson for the manufacture of large OLED displays.)

The newest approach to be tried is the white-OLED approach combined with the use of color filters, which LG Display is using (as described earlier); in this approach, a single layer of white-emitting material is deposited on the substrate and a color-filter layer is used to define the RGB (sometimes RGBW) subpixels. This approach eliminates the need for separate deposition steps for each of the primary colors, a source of many of the challenges with fine-metal-mask deposition. A downside is the added complexity of a color-filter layer and the potential for lower efficiency due to absorption losses.

Next Steps

Several upcoming fabs are planning to adopt both oxide-TFT backplanes and white OLEDs, as these technologies appear to be most easily scaled to larger substrate sizes. It should be noted that both of these techniques are new to mass production, and it is likely that there are unforeseen barriers to mass production that could impact schedules and output. Finally, it cannot be forgotten that AMOLED displays currently face competition from TFT-LCDs in virtually every screen size and application. Thus, it is imperative that AMOLED-display manufacturing costs, currently a multiple of equivalent LCDs in large sizes, come down dramatically. In some cases, notably in China, AMOLED displays are viewed as an entry into the FPD industry that has greater potential than LCD manufacturing, which has become mature and extremely competitive.

A different approach to the production of AMOLED displays could be in flexible displays. It is extremely difficult for LCDs to be made in fully flexible, or even curved, formats, due to challenges with cell-gap maintenance and backlighting optics. Technologies such as electrophoretic technology are very amenable to flexible formats, but do not have the visual performance required for video and other key applications. AMOLEDdisplay technology is one of the few display technologies that has demonstrated the ability to be made in thin, flexible formats with little diminution of display performance.

Both Samsung Display and LG Display are working on the production of AMOLED displays on flexible substrates and face a different set of manufacturing challenges; notably, manufacturing yield and performance of the TFT backplane on flexible substrates and the requirement for some sort of thin-film encapsulation to protect the organic materials. Neither of these challenges has been surmounted in mass production, and it is likely that we will see a series of steps, first using flexible substrates to make fixed, possibly curved, displays, and then moving to full flexibility in future product generations.



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Flexing and Stretching

So you work in displays? You may soon be working in flexible electronics too. Author Jason Heikenfeld, associate professor with the School of Electronic and Computing Systems at the University of Cincinnati, looks at several of the most interesting developments in flexible electronics.

by Jason C. Heikenfeld

HEN I began my academic career in 2005, I thought my display days were over. The dominance of LCDs was clear; what research was there left to do? Was I ever wrong, as displays have remained a rich area of work for me and countless other people, and there continues to be numerous needs for novel display technologies. Since I became involved with displays more than a decade ago, I have worked with and published on just about every display type: plasma/liquid/solid, emissive/transmissive/ reflective/transparent, flexible/rollable, 3-D, *etc.*

More and more, I find myself working in flexible electronics too, and the segue into flex has been quite natural. Why? Well, like many of us "display folk," I have always been intimately familiar with low-cost and largearea microfabrication, hybrid integration of organic and inorganic materials, low-temperature processing, and print-based patterning. Furthermore, to make something rollable, the foremost enabler is often to make the entire device as thin as possible, typically $<100 \ \mu m$ thick. Display engineers are constantly looking for ways to thin down the materials in a display to bring about better aesthetic appeal, impact resistance, and the thinness and lightness required for devices such as smartphones. The point is that if you work in displays, you are

Jason C. Heikenfeld is an Associate Professor in the School of Electronic and Computing Systems of the University of Cincinnati; telephone 513/556-4763, e-mail: heikenjc@ ucmail.uc.edu. often highly qualified to work in flexible/ rollable electronics as well.

In this article, I hope to show that others in the display community a few things they may have not seen before by touching on some of the interesting things happening in flexible/ stretchable electronics. This is not a comprehensive review by any stretch (or flex); rather, I hope to convince readers that flex is a growing and exciting area with applications that might complement more traditional work in displays by citing some examples of this work being done in the industry.

PARC: A logical place to begin this sampling is the Palo Alto Research Center (PARC), a prime source of display and print experts flexing their muscles (or devices) in the flexibleelectronics area. PARC was an early pioneer in the late 1990s in flexible-display technology, due, in part, due to efforts in Gyricon's bichromal ball technology for electronic paper (a rotating charged ball with black on one side and white on the other), and also, in part, to its deep expertise in print-based patterning. If you look at PARC's activities today (Fig. 1), you will see a broad spectrum of flexible electronic technologies ranging from flexible batteries with a bend radius of <3 mm and a capacity >5 mA-hr/cm², jet-patterned activematrix backplanes (680-µm pixels), and a flexible 75-dpi PIN image sensor array, just to name a few. PARC develops these technologies through a variety of projects ranging from basic materials science all the way to full systems prototyping/demonstration. According to Janos Veres, Program Manager for Printed Electronics at PARC, "Flexible and printed electronics is a field rich in opportunities for PARC to deliver high-value innovation by combining its expertise in material science, device and circuit design, process technology, and prototyping. Our clients range from chemical companies to makers of consumer products." A great deal of PARC's pioneering work in printed displays is now being deployed in exploring the limits of printed circuits and their use, for example, in smart sensor systems. PARC has recently demonstrated printed, disposable, blast dosimeters that monitor traumatic brain injury in soldiers on the battlefield. The tape-like blast dosimeter records the severity and the number of blast events during 1 week in order to enable early administration of medical care. The fully functional sensors are fabricated by methods such as lamination, die cutting, solution processing, and printing - all compatible with inexpensive roll-to-roll processing.

American Semiconductor and MC10: Let's say that you are a display integrated circuit or row/column driver expert, and you are excited about chip-on-glass, but think that flex has nothing to do with you or with a traditional CMOS foundry. Think again! Today, the very high temperatures and ultrahigh-resolution capabilities found in Si foundries can be realized in rollable form. Compared to conventional flexible thin-filmtransistors (TFTs), you can obtain a few 100× improvements: an increase in the best mobili-



Fig. 1: PARC's wide spectrum of foundational flexible electronic components and systems include a growing library of additively printed devices and circuits, novel approaches for compliant packaging of components, and flexible sensor arrays. Source: PARC.

ties for amorphous transistors on plastic from ${\sim}1~cm^2/V\text{-sec}$ to ${\sim}100\text{s}$ of $cm^2/V\text{-sec}$ for crystalline Si and a reduction in the feature sizes from approximately 5 to15 μm for display lithography down to approximately 50–150 nm. The key enabler for flexing is the same: make the CMOS film as thin as possible.

As shown in Fig. 2, American Semiconductor uses a wafer-thinning process on silicon-oninsulator (SOI) substrates to make flexible ICs with from 10 to 10,000s of chips per wafer. However, to reduce fragility, the company applies a polyimide film before the thinning process is performed to remove the thick Si support wafer. CMOS wafers thinned to $<20 \ \mu m$ have been demonstrated to achieve a bend radius of 5 mm with no change in the electrical characteristics after flexing. American Semiconductor is a flexible electronics and services provider that performs

flexible hybrid systems development as well as design engineering, including design, verification, layout, and testing. It now also provides FleX Silicon-on-Polymer technology for flexible CMOS. Initial production runs of its FleX technology have begun, and regarding future volume product, Richard Chaney, General Manager at American Semiconductor, notes, "FleX is a repeatable, manufacturable process demonstrated in prototype volumes and is currently supported using a Jazz Semiconductor CMOS foundry silicon. We convert advanced ICs from commercial foundries into flexible chips by using our proprietary low-cost FleX process and integrating them with printed electronics to form flexible hybrid systems. This new technology is ultra-thin, rugged, bendable, and low cost. Our FleX technology provides logic, memory, and wireless capability that is orders of

magnitude faster and smaller than printed TFTs for features that have always been required but never before available in flexible electronics." So, as a side note, if you want to realize a completely rollable display with no rigid parts, you now have every component available to you in order to make this a reality.

Now, can you take flexible Si electronics one step further, making them conformal, stretchable, and biocompatible? The University of Illinois and startup MC10 have answered that affirmatively, demonstrating several exciting new conformal electronics in recent years (Fig. 3). They have shown sophisticated "epidermal electronics" that is applied to the skin in a manner similar to that of a temporary tattoo or expandable electronics on a balloon catheter for sensing or for localized delivery of therapy. The key to moving beyond flex to stretch/conformal is the ribbon-like sections

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Fig. 2: Above (left) are examples of flexible ICs based on American Semiconductor's Flexible Si CMOS (FleX) technology. At upper right are flexible, transparent CMOS foils; at lower right, the company's roadmap for developing and delivering the technology. Source: American Semiconductor.

between functional "islands" of Si. These interconnecting ribbons have a concertina-like geometry and can be stretched by more than 50%, which is also just about how much human skin can stretch. One of MC10's mottos has been "electronics anywhere," and, more recently, the company has been focusing on reshaping electronics to conform to the human body for digital health applications. According to Amar Kendale, MC10's VP of Strategy & Market Development, "Epidermal electronics enable constant medical monitoring everywhere. MC10's ultra-thin skin-mounted sensors can manage conditions continuously so that they do not worsen or reach a crisis." This constant monitoring is made possible by using devices that are so thin that activities such as football, firefighting, or sleeping can be performed without any interference from the device, with medical data provided wirelessly via Bluetooth or other communication means.

Corning: Glass substrates are a familiar area to most of us in the display industry. Corning, Asahi, and several others have now

released super-thin glass that challenges the notion that flex means low-temperature processing and the need for sophisticated moisture/gas barrier layers. Flex electronics that require dimensional and thermal stability, hermeticity, transparency, and a high surface quality on which to build may work better with flexible glass than with plastic substrates. Even polyimide substrates are not compatible with conventional poly-Si temperatures, and stainless steel has its own host of issues (such as the need for planarization). Glass, on the other hand, can be made with the fusion draw process invented at Corning, such that the outer glass surface is never touched during forming, providing a pristine surface. Dr. Sean Garner of Corning notes that "Corning Willow Glass is an enabling component for both display and non-display applications that allows for thinner, lighter weight, or conformal device designs."

Willow Glass allows processing up to 500°C and is available in samples down to a thickness of 100 μ m. This certainly satisfies flexibility and bending down to several centi-

meters in radius and allows roll-to-roll processing (see examples performed by ITRI in Fig. 4). However, at the present time, it is not yet thin enough for personal foldable or rollable applications, a capability that currently only plastic substrates can provide. When it comes to substrates for flexible applications, your options are as follows: you can now process on conventional transparent PEN/PET flex substrates at <150°C, you can use yellow-colored polyimide which allows a bit higher temperature processing up to ~350°C and is the workhorse of all flexible electronic interconnects in the electronics industry, and now you have access to transparent glass that allows all the processing temperatures and materials that can be found in a conventional modern LCD manufacturing facility. Furthermore, as mentioned previously, the world of crystalline Si is now flexible, so there are many options.

Flex Tech: In flexible electronics, there is room for everyone (Fig. 5). Organizations such as the FlexTech Alliance (formerly the



Fig. 3: State-of-the-art medical applications for flex Si incorporate specially designed "ribbons" in between functional Si "islands" to allow fully conformal, even stretchable, electronics.

U.S. Display Consortium) and the market research firm IDTechEx in Europe broadly cover flexible electronics, and, not surprisingly, many of their reports include developments in displays. FlexTech's view of major flexibleelectronics opportunities is two-fold: (1) flexible and printed electronics enable human-scale products – conformable, portable, or wearable – for healthcare, energy, and displays/e-books and (2) new, distributed manufacturing with printed electronics is possible for customized, diversified products. These will be manufactured closer to the end user and will be accessible to both large and small manufacturers. There is no doubt in the market either. Consider these highly compelling market forecasts by IDTechEx: "The market for printed and thinfilm electronics will be \$9.46 billion in 2012; 42.5% of that will be predominately organic electronics such as OLED display modules. Of the total market in 2012, 30% will be printed. Initially, photovoltaics, OLED displays, and e-paper displays grew rapidly, followed by TFT circuits, sensors, and batteries. By 2022, the market will be worth \$63.28 billion, with 45% printed and 33% of that on flexible substrates."¹

So How Close Are We?

Compelling, exciting, and transformative are all good descriptors of some the technology demonstrations now being seen in flexible electronics. So what is holding us back? Well, as we know for applications such as displays, in some cases it is a technological hurdle (stable TFTs and no moisture penetration for flexible OLEDs) and sometimes it is market pull. (Polymer Vision's beautiful rollable displays relied on E Ink's monochrome reflective technology, which in those days lacked the response time suitable for video rates. This



Fig. 4: Above are examples of roll-to-roll processes implemented by ITRI (Taiwan) on Corning's flexible Willow Glass, and, at right, a plot of bend stress vs. bend radius.

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Fig. 5: A view of flexible/printed electronics materials, products, and markets as shown by the *FlexTech Alliance*.

shortcoming may have allowed touch-screen smartphones and tablets with full-color LCDs to absorb consumer demand for the potential rollable product.) Since the polarizers used for LCDs cause the panels to be too thick for use in a rollable display. The future may be limited to rollable OLED displays or e-Paper; however, smartphones do not need to wait for rollable displays to switch over to simple flex for thinness and impact resistance.

Other technologies such as flexible electronics for medical applications have great momentum toward commercialization, but gaining acceptance and approval in medical devices involves a long pathway with numerous regulatory and other hurdles that must be cleared. Roll-to-roll manufacturing has been fully proven as well, including ITRI's demonstration several years ago of all the electronics needed to enable a smart-card device. The fundamentals and infrastructure for flexible electronics are quite sound, and continued work is needed in finding the right applications. You often have to provide something highly desirable to consumers that they will pay extra for, since at the time of market entry, the competition is rigid electronics, which have beaten the difference between manufacturing cost and price down to a razorthin margin. Only in the longer term will lowcost arguments such as roll-to-roll manufacturing potentially allow for more flex products to win market share based on cost alone.

So, again, do you work in displays? How long will it be before you work in flexible electronics too? It may be sooner than you realize. It is quite clear that whether your interest is in displays or in other areas of flexible electronics, exciting enabling technologies are now available, and flexible electronics and displays will become ever more pervasive in our work and daily lives.

Reference

¹http://www.idtechex.com/research/reports/ printed-organic-and-flexible-electronics-forecasts-players-and-opportunities-2012-2022-000301.asp

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show review

Alpha and Omega: Most Exciting Display Technologies at CES

Giant TVs, ultra-high definition, IGZO, and more were among the display showstoppers at this year's Consumer Electronics Show in Las Vegas.

by Steve Sechrist

ONE of the best things about being part of SID is the opportunity to see the "alpha and omega" of the display industry. This includes products or technologies that start in the lab or are just the germ of an idea to product concepts and then to shipping displays. Pixeldense UHD TVs, anti-reflective materials, and almost any display technology that is breaking news today was first dreamed of, then discussed, then prodded and poked at during SID's Display Week; sometimes years before making it to the CES show floor in January. Let's take a look at the "omega" side of displays and some key trends uncovered at this year's CES.

UHD Thunder: China Struts Its Stuff The unmistakable display technology of note at CES was ultra-high definition (UHD). Just as 3-D was all the rage 2 years ago, most vendors this year had UHD offerings, including all tier-one companies, the Taiwanese LCD makers, and almost every Chinese mainland brand. Remarkably, it was the 84-in. UHD TV that seemed to be near-mandatory in Las Vegas, with almost every brand showing multiple TVs boasting a large-screen 4K x 2K set.

Among the China-based notables showing 84-in. UHD sets were TCL (also with a 110-in. model) Skyworth (see Fig. 1), Westinghouse, Haier, and Hisense with five models, making

Steve Sechrist is a display-industry analyst and contributing editor to Information Display magazine. He can be reached at sechrist@ucla.edu or by cell at 503/704-2578. that China-based company the one with the most 4K sets. The Hisense units ranged from 50 in. to an eye-popping 110 in. on the diagonal with a pixel resolution of 3840×2160 (see below). The products looked very close to commercial status – they were not just prototypes. To get a look at the competition

tier-one brands are facing from Chinese companies, see the specifications for Hisense's flagship XT900 4K models, which it calls U-LED TVs.

- Hisense XT900 U-LED 4K TV Specifications
- UHD (3840 × 2160) native resolution, 120 Hz



Fig. 1: This 4K China Skyworth UHD TV is sourced from CMI Display Taiwan. Photo courtesy Steve Sechrist.

- · WiFi enabled
- · Smart TV with Google TV
- 65-, 84-, and 110-in. screen sizes
- 3-D
- Smart-TV functionality
- · Precise local dimming
- "Mega" dynamic contrast ratio (the backlight can be completely turned off in local regions to greatly extend the dynamic range)
- · Multi-screen play
- Detachable camera (Skype calling, gesture, and facial recognition)
- Voice-control remote that allows voice activation for on-off and channel changing.

As far as LCD fab sources for the giant 110-in.-diagonal panels is concerned, I was told in the TCL booth by product manager Jain Peng "Konan" Jiao that the fab used by TCL was a result of its Joint Venture Gen 8.5 with Samsung, called China Star Optoelectronics Tech (CSOT). Other panel makers with a 4K offering at CES included Sharp (using its IGZO technology), Samsung, LG, Sony, Panasonic, and Toshiba.

4K Monitors at CES will Probably Ship First

It's interesting to note that the Panasonic UHD-class 20-in. hybrid tablet/display with a 15:9 aspect ratio could be used as a tablet or desktop monitor. The device includes an IPS $4K \times 2K$ panel and was shown at CES running Windows 8 with an Intel i5 Core (1.8 GHz) and up to 16 GB of memory.

With this technology, Panasonic seems to be looking to extend desktop monitors into a new class of device that can also serve double duty as a tablet (albeit in this case, a mighty big one.) The company said it is targeting professionals who need very high resolution (photographers, engineers, and architects.) Perhaps another way to look at the product is as a portable "all-in-one" desktop PC with the advantage that it can be taken into the field.

LG, Sharp, and ViewSonic all showed examples of smaller 4K displays with 30-in. panels, and while the LG 30-in. unit was a prototype (found nested in a window wall in the booth), specs include 153 ppi, 500 nits, and 99% of the RGB color gamut. This panel is probably aimed at OEM customers.

Meanwhile, Sharp claimed the "world's thinnest" 4K monitor with its 32-in. diagonal model, which is less than 1.5 in. thick and is based on its new zinc-oxide-TFT technology.

This panel also sports a 10-point discrete touch screen, as IGZO allows for more discrete sensors. According to Sharp, IGZO can cycle the power-down state of the panel at a very high rate, enabling a far "quieter" electromagnetic environment. This allows the use of much higher sensitivity devices that cannot work with conventional AMLCD panels (see the IGZO write-up below.)

This Sharp monitor was announced in November 2012 prior to CES. It has a pixel density of 137 ppi and will retail at around \$5000. ViewSonic showed its 32-in. 4K monitor at CES and said the product will launch "sometime in 2013" with pricing to be announced.

4K Empowers 3-D

In the booth of Hisense, based in Qingdao, China, the company was using a 60-in. UHD to show off its autostereoscopic 3-D technology. Hisense went so far as to give the product a model number (GF60XT980), while at the same time calling it a "proof-of-concept model," with no price or ship date. "By using a Hisense ultra-high-definition 2160p panel, even at half the normal screen resolution, viewers can still enjoy a truly high-definition picture," according to Peter Erdman, Hisense Group VP.

In terms of the images used at the show, the company did a very good job of simulating depth with its autostereoscopic prototype. It's important to note it was not displaying commercial 3-D film content, but rather multi 3-D layering content that demonstrated the technology in a subtler way. On-axis viewing was discernably better than viewing from the sides. Hisense did say it was using a face-tracking technology to adjust the 3-D sweet spot, and this may have been "overloaded" with the large crowds viewing the screen at the show.

Hisense also showed a transparent 3-D display for digital-signage applications (Fig. 2). The company used an LCD frontplane with passive 3-D capabilities and a mounted backlight with a 1-m (or so) gap in between where merchandise can be placed. The objective was to demonstrate how to use the LCD with current 3-D virtual content over any real merchandise in the background. In a storefront configuration, a window with merchandise behind it can be displayed. Hisense sees applications in real-estate demos, window advertisements, showcases, and around the home.



Fig. 2: Hisense showed transparent 3-D technology for digital-signage applications at CES. Photo courtesy Steve Sechrist.

show review

Most UHD TVs shown at CES were 3-D capable. Some of the vendors were using UHD to create an autostereo TV image. These included Dimenco, showing an 11.6-in. switchable prototype using the company's "Nabla" lenticular lens and new liquid-crystal cell design with low-voltage switching. Dimension Technologies, Inc. (DTI) also had an autostereoscopic technology on hand, with an 8-view, glasses-free display using a unique time-multiplex backlight system. Dolby showed a new autostereo panel they developed with Taiwan-based CMI by using a Philips lenticular lens along with stereo image processing by Dolby, converted to multi-view and streamed over a Vudu encoding format. Stream TV showed a set (UHD 60 in. at 2160p) with a non-lenticular 3-D stack combining diffractive and refractive optics to guide light in the right direction within an established viewing distance.

On the standard (glasses-based) 3-D side, most major players (Sony, LG, Samsung, *etc.*) continued to show their active and passive



Fig. 3: Sharp Moth-Eye display shows technology introduced at SID in 2011. Photo courtesy Steve Sechrist.

3-D technology, including Vizio, which demonstrated passive technology in two sets: 65- and 70-in. models in its XVT (UHD TV) Smart-TV series.

Content is Still King, But Where Is It?

What was interesting at CES was that 4K glass (UHD TVs) seemed more prevalent than the content needed for viewers to take advantage of the high-pixel-density displays. It is the familiar Catch-22 cycle: there is no content, so no one buys the displays, so no one makes the content since no one is waiting to view it.

One way HDTV overcame this content hurdle was through the DTV transition and through over-the-air broadcasts of HD content. In that vein, LG did show a 2012 joint pilot venture with KBS (Korean Broadcasting System) that used 4K over the air. The antenna technology used for this venture was on display in LG's booth.

This, along with full-HD up-scaling and of course producing (or re-mastering) original film content to air on giant, high-pixel-density screens will eventually fill the 4K content pipe and help drive demand as we move from full-HD into new UHD-display frontiers. It's hard to imagine the 500 lines of last century's SDTV lasting for more than 50 years in light of the DTV transition, full-HD broadcasts, and even the (albeit limited) 3-D sports and event broadcasts of today. (For more about the timeline for UHD broadcasts, see NHK's article, "Super Hi-Vision as Next-Generation Television and Its Video Parameters" in the November/December 2012 issue of ID.)

Biomimicry: Sharp's Moth-Eye Technology

An example of the aforementioned alphaomega technology progression from SID to CES is the Moth-Eye nanotechnology described at SID 2011 in a presentation showing how it enabled a dramatic reduction in glare. At this year's CES, prominent in the Sharp booth was none other than a Moth-Eye demonstration of how this "biomimicry" antiglare technology will be used by Sharp to remove glare from indoor screens, with an aim toward tuning it for outdoor purposes in the long term (Fig. 3).

Moth Eye creates nanohexagonal patterns of bumps on a film surface (spaced 300 nm apart) that are smaller (200 nm) than the wavelength of visible light, creating a continuous refractive-index gradient (removing the air-lens interface.) Moth Eye gets its name from nature, which uses this strategy in common night-flying moths to prevent light reflection and thus help the moths conceal themselves from predators. Early reports of the technology go back as far as 2003, with development credited to MacDermid Autotype (Autoflex film) and Fraunhofer Institute for Solar Energy in Germany.

Truth be told, commercial Moth Eye was first revealed by Sharp at CEATEC in Japan last October, when the company announced its Aquos Quattron (3D XL vintage) with sizes ranging from 46 to 80 in., all due to feature the new technology in 2013 product roll-outs.

The Move to Giant TVs

At the pre-show press conference, Sharp (and others) indicated the company will continue its large-and-larger display strategy, selling displays that top out at 90-in. on the diagonal. At the press conference. Sharp said it will migrate to the 90-in. sets from the current 80-in. ones based, in part, on U.S. consumer numbers that show the plus 60-in. category is the fastest growing size in the TV space. In 2011, 60-in. sets were just 4% of the LCD-TV market in terms of revenue, according to Sharp. That number has grown to 20% of LCD-TV revenue. The company plans to offer 21 models that are 60 in. and up, at prices as high as \$10,000. Look for more big sets from all major LCD players as they transition to UHD sets in the middle of this year.

China's Full-HD Mobile Displays

Even with the Mobile World Congress event taking place just weeks after CES, the China smartphone brands all used CES to launch full-HD handheld displays that are sure to dominate the wireless smartphone and tablet space in 2013. Tier-one brands such as Samsung and LG only hinted at these new higher-pixel-density models. Case in point was Huawei, which announced a 5-in. 1080p display with an impressive 443-ppi pixel density in its new flagship Ascend D2 Dream Phone. The Grand S (flagship model) from ZTE is a 440-ppi 5-in. 1080p display. Other China-based brands to offer a full-HD handheld included the Vizio Via (5-in. full-HD screen), the Alcatel Scribe X (with a 1080p 5-in. display), and the Lenovo K900 with a 5.5-in. 1080p IPS display that uses an LG AMLCD panel.

Sony's new flagship Xperia Z smartphone (Fig. 4) attracted lots of attention on press day at CES. The phone features a 5-in. 1080p display and a remarkable water-resistant design. Meanwhile, Sharp announced its continuousgrain-silicon (CGS) 5.1-in. smartphone for the Japanese wireless market that boasts 443 ppi. Sharp said its CGS LCD panel is also available for the OEM market. It first showed the technology in October at CEATEC, where its IGZO technology took the Top Innovation Award in electronic components. The CGS backplane is based on crystalline silicon, with an electron mobility up to 600 times faster than that of ordinary amorphous silicon and up to 6 times faster than that of low-temperature polysilicon (LTPS), the current technology in the iPhone retina class iPhone 4, according to Sharp. The panel is being made at Sharp's Mei Plant No. 3, using technology jointly developed along with Semiconductor Energy Labs (SEL) in 1998. SEL is the same company that helped Sharp with IGZO. Sharp said its new full-HD



Fig. 4: Sony's Xperia Z, a water-resistant 5-in. full-HD smartphone, stole the show in the mobile space. Photo courtesy Steve Sechrist.

show review

5-in. set also achieves a brightness of 500 $\mbox{cm/m}^2.$

OLEDs Almost Eclipsed by UHD

Sony and Panasonic, along with LG and Samsung, all had an OLED TV story to tell at CES and most (except for LG) were still singing the old "sun will come out tomorrow" song with beautiful images and no specific launch date. Meanwhile, LG did take the plunge, announcing just prior to CES that it had begun taking pre-orders for its 55-in. (55EM9700) TV. A February 2013 delivery was scheduled for the new OLED 55-in. ultraslim sets in Korea (for about \$10,000 a piece). They are due to ship to the U.S. in the March 2013 time frame – finally, some progress.

LG will be using its white OLED (WOLED) and color-filter approach to get to market with what some call a simpler approach to solving some OLED materials lifetime issues. This approach is based on solutions the company developed, in part, by using Kodak patents. Meanwhile, Samsung is using the tried-andtrue RGB color OLED approach that brought the company OLED display dominance in the small-to-medium display space. To date, no one sells more AMOLED panels than Samsung. (For more about the two different approaches, see the article "RGB Color Patterning for AMOLED TVs" in this issue.)

Japan-based Sony and Panasonic were both present at CES with new 56-in. OLED panels, therefore claiming the "world's largest" title from Korean manufacturers. But at this late state in the OLED-TV game, one may rightly ask whether without a model number or ship date, does this have any real meaning?

E Ink Displays at CES

E Ink was a Best of CES display winner with an interesting prototype from a Russian-based company, Yota Devices. This was a two-sided Android device, the "Yotaphone," with a 4.3-in. 720p HD LCD on one side and a power-saving E Ink monochrome display on



the other. This configuration allows the device to act as a regular smartphone, but also an e-Book reader and platform for applications not requiring the more memory-hungry color LCD. The company also had flexible displays at an evening post-show event; one prototype was Central Standard Timing's "CST-01" bendable watch display that's worn on the wrist. While multiple E Ink tablets were present at CES, we were told by Marketing VP Sriram Peruvemba to look for the technology to begin moving more rapidly in the digitalsignage space, as bi-stable, low-power, and ultra-thin displays empower a growing class of signage that includes retail shelf labels, hybrid static/dynamic posters, and rugged outdoor displays.

IGZO and New Life for LCDs

Finally, this report would not be complete without mention of the ground-breaking IGZO technology shown at CES by Sharp. In an extended meeting with Sharp engineers, I learned that the technology transforms displays using its indium gallium zinc oxide with "far superior" electron mobility and much smaller thin-film transistors (TFTs) to boost the pixel aperture ratio (or the amount of light that can go through an R, G, or B subpixel).

This development is creating a ripple effect throughout LCD fab design and should enable not just lower power from fewer backlights, but the ability to modulate the panel power (with cycles down to 1 Hz) depending on content - something Sharp calls "variable refresh." This, plus an off-state panel, will create a virtually electromagnetic (EM) noisefree sensor environment allowing the panel to integrate not just discrete multi-touch sensors, but an entire array of new sensor technology (think bio/cellular, as well as UV sensors, atmospheric, olfactory, you name it ...). In addition to sensor-integration enablement, IGZO allows for deep pixel integration shown in some Sharp models of up to 1000 points per inch.

Suffice it to say, the best and brightest were on display at CES, with China beginning to show major strides not only in keeping pace, but in leading the display industry in key technology fields. As 2013 dawns, we are beginning to see the rise of Chinese display technology dominance and perhaps the reassertion of the tried and true LCD (*via* UHD and IGZO) that are sure to be major factors in the display industry going forward.

FIRST LOOK

Society for Information Display SID INTERNATIONAL SYMPOSIUM, SEMINAR, AND EXHIBITION



May 19–24, 2013 Vancouver Convention Centre, Vancouver, British Columbia, Canada



Announcing Special Topics of Interest on OLED TV & Oxide TFTs & Touch & Interactivity & 3D & Lighting

Visit www.displayweek.org

The Evolution of Displays through Innovation

Electronic information displays touch nearly all aspects of modern life. Display Week's 2013 Keynote addresses will provide a vision of how the evolution of display technology through innovation will change the shape and look of the displays of the future.

KEYNOTE SPEAKERS

Dr. Kinam Kim, President & CEO, Samsung Display Co. "Displays and Innovation: An Exciting Future"



Our industry is forced to re-invent itself as users are in need of better and more exciting uses for displays. They want rich, dynamic, immersive experiences, which will require innovations in user interface/interaction as well as advancements in panel technologies. Challenges along the path to this exciting future will be presented.

Mr. Bill Buxton, Principal Researcher, Microsoft Research, Microsoft Corp. "The Social Life of Devices"



Just as we are learning to manage the complexity imposed upon users by individual devices, the problem is shifting to that imposed by the ecosystem. Welcome to the shifting sands of ubiquitous computing! Managing this complexity is critical to the continued growth of our industry. The means of doing so lies in social computing – amongst the society of appliances.

Professor John F. Wager, *The Michael and Judith Gaulke Endowed Chair Professor of Electrical Engineering, School of EECS, Oregon State University*

"Exciting Developments in Oxide-TFT Technology"



Amorphous-oxide semiconductor thin-film transistors (TFTs) are transitioning towards commercialization for active-matrix liquid-crystal-display (AMLCD) applications. They also appear well-positioned to meet the more demanding challenges associated with active-matrix organic light-emitting devices (AMOLEDs). The objective of this talk is to review the origins and current status of amorphous-oxide-semiconductor (AOS) TFTs for display applications.

2013 SID TECHNICAL PROGRAM TO INCLUDE SPECIAL TECHNOLOGY TRACKS

The Society for Information Display's annual Symposium at Display Week offers a wide selection of presentations on display technology that simply cannot be found anywhere else. This year's technical program consists of 68 technical sessions with over 250 oral presentations and an additional 150 papers to be presented at the Thursday afternoon Poster Session. Join us in Vancouver (Tuesday, May 21 – Friday, May 24) to hear the latest developments in the display industry. This year's special areas of focus are OLED TV, Oxide TFTs, Touch and Interactivity, 3D, and Lighting. Here is just a sampling of those topics and other innovations you can expect to find at this year's symposium:

OLED TV

This Special Topic will cover OLEDs specialized for TV applications. Papers on advanced OLED TV technologies will be included. OLED-based displays have several unique attributes that continue to drive interest for television applications. Also, the explosion in portable video-capable devices such as tablets and smartphones place high demands for the displays. 3D television application puts a higher demand on display power, response times, and high dynamic range. Papers in this session include:

- Progress and Commercialization of AMOLED TV
- * A 55-in. AMOLED TV Using Oxide TFTs and WRGB Design
- A 65-in. Amorphous-Oxide-TFT AMOLED TV Using Side-by-Side and Fine-Metal-Mask Technology

Oxide TFTs

Oxide-semiconductor technology is emerging as a strong competitor to thinfilm silicon technologies for active-matrix backplanes. However, there are several critical issues related to oxide materials and these are associated with the overall characteristics of mass-produced devices, including stability (over time, temperature, and light), uniformity, mobility, *etc.* Clearly, to be viable these devices need to be made at costs comparable to that of conventional Si-based TFTs. Sessions related to oxide-based TFTs and displays driven by oxidebased TFTs include:

- Oxide TFTs I & II
- Oxide-TFT Reliability
- OLED and Oxide-TFT Manufacturing
- Oxide-TFT Manufacturing

Touch and Interactivity

Since the launch of touch-enabled mobile devices several years ago, touch has become an increasingly crucial component for numerous display products. Touch is in an evolutionary phase now, and this year's papers reflect the diversity of applications, advanced sensors and materials, and touch integration and applications. The topics to be covered include:

- Touch User Experience
- Touch Integration and Controllers
- Touch Applications
- Touch Sensors, Materials, and Manufacturing

3D

Possibly the biggest commercial story in displays in recent years is the arrival of 3D-ready TVs. Now that they have arrived, the story is far from over. Researchers continue to pursue the different approaches of active-shutter vs. passive glasses technology, and glasses-free viewing is a major challenge that many experts believe must be met in order to make 3D displays truly successful. This year's presentations also cover topics such as autostereoscopic 3D displays, 3D and perception, volumetric and holographic displays, and stereoscopic and display applications. The symposium includes the following sessions:

- ✤ Autostereoscopic and Multi-View I & II
- ♦ LC Technology for 3D I & II
- Holographic and Volumetric Displays
- Light-Field Displays
- Perception in 3D Displays
- 3D Algorithms and Driving
- 3D Applications
- 3D Projection Screens

Lighting

Solid-State lighting has begun to fulfill its promise with regard to saving energy and providing design flexibility. However, LEDs have made more commercial inroads in this area than OLEDs, which are currently available only in high-end architectural applications. OLED papers therefore form the bulk of this year's solid-state-lighting sessions, as the industry pushes to develop higher-efficiency, higher-performing OLED panels. Other solid-state-lighting papers will focus on trends in LED illumination. The symposium includes the following topics:

- ♦ OLED Lighting I & II
- Human Factors on Lighting
- Lighting Designs

MARKET FOCUS CONFERENCES

After a very successful debut in 2010, the Market Focus Conferences will once again be held in conjunction with Display Week. They will cover the following two topics:

- Touch Gesture Motion (Wednesday, May 22, 2013)
- High-Performance Displays (Thursday, May 23, 2013)

Each Market Focus Conference will concentrate on the critical market development issues facing each of these technologies. Developed in collaboration with IHS, the conference will feature presentations and panel sessions with executives throughout the display supply chain. Conference fees include a continental breakfast, lunch, refreshments, access to the Exhibit Hall and Symposium Keynote Session on Tuesday morning, and electronic copies of the presentation material. Registration for the Market Focus Conferences does not require a current SID membership.

Touch Gesture Motion: The 2013 SID Touch Gesture Motion Conference will focus on next-generation touch, gesture, and motion-based technologies applicable to the display industry. The conference will focus on future technology and interactivity trends - and not so much on what is currently available in the marketplace. Interactive display technologies are one of the most intriguing aspects of the display industry - helping to enable completely new usage models in multiple applications. Highlights of the conference will include actual demonstrations from some of the leading-edge innovators, bringing together many of our senses - sight, touch, motion, sound ...

This event builds on the three prior events presented at past Display Week Conferences, as well as three separate 2-day TGM conferences. The primary goal is to assure that the events are complementary - with minimal overlap. The objective is to establish a series of non-duplicative events such that delegates can easily justify repeat attendance with the assurance of highly differentiated programs.

High-Performance Displays: The 2013 SID High-Performance Displays Conference will highlight next-generation display technologies that offer significant opportunities to enhance the visual experience. The event will focus on performance parameters, more so than the specific display technologies. The technologies necessary to promote improved performance will be highlighted. The event will enable delegates to consider various performance trade-offs related to the future of vision-based devices.

This event is a new event - but directly focuses on one of the biggest opportunities for both display makers and device manufacturers - to truly differentiate their product offerings. The event is expected to garner considerable interest and discussion as various performance parameters are presented and compared. For further updates visit www.imsconferences.com/sidfti/html

SID BUSINESS ENTERPRISE (BUSINESS **CONFERENCE AND INVESTORS CONFERENCE**)

Business Conference: The 2013 SID Business Conference will be held on Monday, May 20, at the Vancouver Convention Centre. It will provide a unique forum where attendees will gain insight from leading minds from both Wall Street and the display industry and focus on the theme "Paths to a Healthier Display Industry." Inspirational presentations from industry leaders and IHS analysts will take an integrated view assessing the current health of the industry and focus on what it would take to improve the health of the industry, identifying some specific exciting trends, and its impact on the display supply chain. The Business Conference will feature keynotes and presentations from industry leaders, lively panel sessions, and ample networking opportunities.

For further updates visit www.imsconferences.com/sidbc.html

Investors Conference: Co-sponsored by Cowen & Co., LLC, a securities and investment banking firm, this Conference, to be held on Tuesday, May 21, will feature company presentations from leading public and private display companies, intended to appeal primarily to securities analysts, portfolio managers, investors, M&A specialists, and display company executives.

For further updates visit www.cowen.com

2013 SID SEMINAR SERIES

Sunday Short Courses

The Society for Information Display presents four 4-hour short courses on diverse topics related to information display on Sunday, May 19. The tutorials are characterized by technical depth and small class size. The classes will cover the fundamentals of electronic information displays and will be held on the morning and afternoon of the Sunday preceding the Symposium. Full-color tutorial notes will be distributed to all participants and are included in the fee. Ample time will be provided for questions from the audience. The speakers are leaders in their respective fields and bring an international perspective to information display.

- S-1: Fundamentals of OLED Technology
- S-2: Fundamentals of 3D Computer Vision and Applications to Interactive Devices
- S-3: Fundamentals of TFT Backplane Technologies and Progress Made on Metal-Oxide TFTs
- S-4: Fundamentals of Touch Technologies

For further details visit www.displayweek.org/Program/SundayShortCourses

Monday Technology / Applications Seminars

The SID Technology / Applications Seminars to be held on Monday, May 20, present lectures on diverse topics related to electronic information displays. These seminars are tutorial in nature, and an attempt is made to provide information at

three levels. First and foremost, the technical foundations of the topic are treated in detail. Next, recent technical advances are discussed, and, finally, the current state of the art and the projection of future trends are analyzed. The Applications Seminars focus on the application and evaluation of information displays. These seminars benefit both newcomers and experienced professionals. Engineers new to assignments in information display find them especially helpful in getting up to speed quickly. Experienced professionals attend to keep up with recent developments in fields closely related to their specialties. Managers attending the seminars obtain a broad perspective of the display field and a sense of its recent dynamics. Attendees will receive an excellent set of full-color notes, consisting of the instructor's presentation slides replete with references and illustrations. Ample time is provided for questions from the audience in each session. The speakers are leaders in their fields who bring an international perspective to information display.

Track 1: Display Marketplace

- *M-1:* The Next Big Thing *M-6:* Display Market Trends
- Track 2: Mobile Displays
 - * M-2: Advanced Mobile-Display Technologies
 - ✤ M-7: Mobile Multimedia Displays

Track 3: Touch and Interactivity

- * M-3: Status and Future of Touch Technologies
- ✤ M-8: Touch-Display Integration
- Track 4: Liquid-Crystal Technology
 - * M-4: Fast-Field-Switching (FFS) Mode and Its Applications
 - * M-9: Fast-Switching Technologies for LC Devices toward Low-Power Display Systems

Track 5: OLED Displays

- * M-5: Challenges of AMOLED TVs and Flexible AMOLED Displays
- ✤ M-10: OLED Technology

Track 6: Display Components and Metrology

- * M-11: Optical Coatings and Films
- * M-16: Display Measurement Basics and Practical Considerations

Track 7: Lighting

- * M-12: Backlighting LEDs in General Illumination
- ✤ *M-17:* OLED Lighting
- Track 8: 3D Technology
 - M-13: LC Technology for 3D Applications
 - * M-18: Signal Processing for Stereoscopic 3D Displays

Track 9: Oxide TFTs

- M-14: Oxide TFTs: Technology Trends in Materials and Processes
- * M-19: Device Structures and Stability of Oxide TFTs

Track 10: Flexible-Display Technology

- * M-15: Flexible OLEDs for Display and Lighting Applications
- * M-20: A Critical and Current Review of the Present and Future Prospects for e-Paper

For further details visit www.displayweek.org/Program/MondaySeminars

ANNUAL AWARDS LUNCHEON

The annual SID Awards Luncheon will take place at 12:00 Noon on Wednesday, May 22, in Room 301/305 of the Vancouver Convention Centre.



This year's luncheon speaker will be Prof. Ronald A. Rensink from the Departments of Computer Science and Psychology at the University of British Columbia, Vancouver, Canada

Professor Rensink will discuss "When Vision Science Met Information Display."

Also, the 2013 Display Industry Awards honoring the best of the industry in 2012 and the 2013 SID Best-in-Show and I-Zone award winners will be announced. Also, the

SID 2013 honors and award recipients will be acknowledged.

SPECIAL EVENT

The Vancouver Aquarium – Sponsored by Henkel



Come join us on this special event on Wednesday evening to the Vancouver Aquarium, the largest in Canada and one of the five largest in North America. The Vancouver Aquarium was the first aquarium in the world to capture and display an orca. For more

details regarding the Vancouver Aquarium, please visit www.vanaqua.org

Display Week 2013 Overview

Vancouver Convention Centre, Vancouver, British Columbia, Canada May 19-24, 2013

TIMETABLE	Sunday, May 19	Monday	, May 20	Tue	sday, May	21	Wedne	sday, May	22	Thur	rsday, May	23	Friday, May 24
	Course	Seminars	Bus Conf	Symp	Exhibits	Inv. Conf.	Symp	Exhibits	MFC	Symp	Exhibits	MFC	Symp
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8:30 PM - 9:00 PM		Awards											
9:00 PM - 9:30 PM		Banquet											
9:30 PM - 10:00 PM													

Display Week 2013 Symposium at a Glance

			2013 SID Displa	y Week Symposium at	a Glance – Vancouver	Convention Centre			
	Times	Ballroom A	Ballroom B	Ballroom C	Room 118	Room202	Room 205	Times	
	8:00 - 10:20	3	SID Busir	ess Meeting and Keyr	note Session (Concour	se Hall)		8:00 - 10:20	
Nay 21	10:50 – 12:10	Autostereoscopic and Multi- View I (Joint with Systems)	Oxide TFTs I (Joint with Active Matrix)	5 LCD or OLED?	6 e-Paper I	7 Plasma-Display Devices	8 Emerging Displays	10:50 – 12:10	Tue
Tuesday, I	2:00 - 3:20	9 Autostereoscopic and Multi- View II (Joint with Systems)	10 Oxide TFTs II (Joint with Active Matrix)	11 4K x 2K Displays	12 e-Paper II	13 Plasma-Display Protective Layer	14 Human Enhancement and Diagnostics	2:00 - 3:20	sday, May 2:
	3:40 - 5:00	15 LC Technology for 3D I (Joint with Liquid Crystal)	16 Oxide-TFT Reliability (Joint with Active Matrix)	17 Blue-Phase LCDs I	18 Flexible AMOLEDs	19 Phosphors and Quantum- Dot LEDs		3:40 - 5:00	1
	5:00 - 6:00			Author Interview	s (Exhibit Hall)			5:00 - 6:00	
	9:00 – 10:20	20 LC Technology for 3D II (Joint with Liquid Crystal)	21 OLED TV (Joint with OLEDs)	22 Blue-Phase LCDs II	23 Flexible TFTs	24 Novel Measurement Topics	25 Advanced LCD Electronics	9:00 – 10:20	
day, May 22	10:40 - 12:00	26 Holographic and Volumetric Displays (Joint with Systems)	27 OLED Displays I	28 Advanced Displays	29 Flexible Barriers and Substrates	30 Challenges in 3D Characterization, Motion Blur Analysis, and Monitor Callibration	31 High-Speed Driver Technologies	10:40 – 12:00	Wednesday,
hee	2:00 - 3:30			Designated Exhibit	Time (Exhibit Hall)			2:00 - 3:30	Maj
Wec	3:30 - 4:50	32 Light-Field Displays (Joint with Systems)	33 OLED Displays II	34 Fast-Switching LCDs	70 Late-News Papers: Flexible OLEDs and Printing Techniques		35 OLED Pixel and Driving	3:30 - 4:50	y 22
	5:00 - 6:00			Author Interviews	s (Exhibit Hall)			5:00 - 6:00	
Thursday, May 23	9:00 – 10:20	36 Perception in 3D Displays (Joint with Applied Vision)	37 OLED Materials	38 Film and Alignment	39 Touch User Experience	40 Automotive and Head-Up Displays (HUD) (Joint with Projection)	41 Colors and Image Quality	9:00 - 10:20	
	10:40 – 12:00	42 3D Algorithms and Driving (Joint with Systems)	43 OLED Devices I	44 Liquid Crystals with Reactive Mesogen	45 Touch Integration and Controllers	46 OLED and Oxide-TFT Manufacturing (Joint with OLED, Active Matrix, and Manufacturing)	47 Human Factors on Lighting (Joint with Applied Vision)	10:40 – 12:00	Thur
	1:30 – 2:50	48 3D Applications (Joint with Applications)	49 OLED Devices II	50 Low-Power and Sensor- Integrated Displays	51 Touch Applications	52 Oxide-TFT Manufacturing (Joint with Active Matrix and Manufacturing)	53 Lighting Designs (Joint with Applications)	1:30 - 2:50	sday, May 23
	3:10 - 4:30	54 Projection Screens (Joint with Projection)	55 OLED Manufacturing	56 TFT Applications	57 Touch Sensors, Materials, and Manufacturing (Joint with Manufacturing)	58 Advanced Substrates and Manufacturing on Flex (Joint with e-Paper/Flexible)	59 Novel Backlighting Systems	3:10 - 4:30	
	4:30 - 5:30			Author Interview	s (Exhibit Hall)			4:30 - 5:30	
	5.00 - 8.00			1 03(61 36531011		1	1	5.00 - 8.00	
, May 24	9:00 – 10:20	60 Projection Light Sources	61 OLED Lighting I (Joint with OLEDs)	62 TFTs for Mobile Display		63 Mechanical Reliability Testing for Displays	64 Near-to-Eye, Transparent, and Floating Displays	9:00 – 10:20	Friday, I
Friday,	10:40 - 12:00	65 Projection-Display Components	66 OLED Lighting II (Joint with OLEDs)	67 TFT Driver Circuits		68 Advances in Materials for Manufacturing	69 Energy-Efficient Displays (Joint with Electronics)	10:40 - 12:00	May 24
	12:00 – 1:00			Author Interview	s (Exhibit Hall)			12:00 – 1:00	

		TECHNOLOGY	TRACKS KEY		
3-D	Active-Matrix Devices	Applications	Applied Vision	Electronics	Emissive
e-Paper/Flexible	Lighting	Liquid Crystal	Manufacturing	Measurement	OLEDs
Oxide TFTs	Projection	Systems	Touch		

Plan Ahead for the 2013 Symposium

Make the most of Display Week 2013 with an advance look at this year's technology sessions.

by Jenny Donelan

HE Society for Information Display's annual symposium is the foundation of Display Week. Each year, hundreds of papers are presented that convey vital research and development information, both forward-looking and immediately practical, in numerous areas of display technology. The information you will obtain at this year's Symposium in Vancouver, Canada, is not available at any other venue or from any other industry organizations.

As in previous years, sessions are organized by subcommittees, whose members have chosen the most exciting and informative papers in their focus areas of display technology. Those areas include active-matrix devices, applications, applied vision, display electronics, display manufacturing, display measurement, display systems, emissive displays, e-paper and flexible displays, liquidcrystal technology, OLEDs, and projection.

In addition to these regular topics, SID has designated special display topics of interest that are especially timely and important to our industry: OLED TV, oxide TFTs, 3-D, lighting, and touch and interactivity. Attendees at Display Week 2013 have the opportunity to gain comprehensive knowledge of each of these special topics not only by attending the presentations during the four-day technical symposium, but also through the special Sunday Short Courses and Monday Seminars. SID also offers a display-centric business perspective with the Business and Investors Conferences and the Market Focus Conferences. In addition, be sure to catch this year's

Jenny Donelan is the Managing Editor of Information Display Magazine. She can be reached at jdonelan@pcm411.com. stellar line-up of keynote speakers (highlighted throughout this article) on Tuesday morning immediately before the exhibition opens.

The following session highlights are but a small portion of what awaits attendees at Display Week 2013. Come join us to find out what's happened in our industry over the past year – and what's going to happen in the years to come. See you in Vancouver!

Active-Matrix Devices: Oxide TFT Starts to Hit Its Stride

Last year's Active-Matrix Devices (AND) sessions covered topics such as IGZO and 8K × 4K LCDs - providing advance notice of technology later shown in products at CES this year. The 2013 AMD papers will continue representing some of the most interesting and important news at the Symposium, according to subcommittee chair Tohru Nishibe. Among the most newsworthy, he says, are two invited presentations on oxide semiconductors. The first is "Electronic Structure, Carrier Transport, Defects, and Impurities in Amorphous Oxide Semiconductors," by Toshio Kamiya of the Tokyo Institute of Technology. "This is a good tutorial and basic analysis that includes new findings," says Nishibe. The second is "Development of IGZO-TFT and Creation of New Devices Using IGZO-TFTs," by Hajime Imai of Sharp Corp, in collaboration with SEL (Semiconductor Energy Laboratory Co.). "This look at the world's first IGZO product [shown at CES] will attract a huge audience," says Nishibe. "Moreover, we'll have intriguing invited papers from LG Display, Samsung Display, and others."

Other papers of interest are "A 55-in. AMOLED TV Using InGaZnO TFTs Using WRGB Pixel Design," by Woo-Jin Nam of LG Display Co. and "Negative-Bias Photodegradation Mechanism in SnO TFTs," by Masashi Tsubuku of the Semiconductor Energy Laboratory Co., Ltd. According to Nishibe, both these papers will address key factors for improving IGZO reliability.

Applications: Expanded Interaction, Emerging Displays

As is often the case in the applications sessions at Display Week, this year's papers cover an extremely wide range of topics. Of particular note are two invited papers on "auditory" displays in the session titled Human Enhancement and Diagnostics. "Sonification: Multimodal and Auditory Display of Data," by Bruce Walker of the Georgia Institute of Technology, and "Development of Auditory and Cross-Modal Displays for Assistive Technology," by Tony Stockman of Queen Mary University of London, describe displays that both speak and listen (as well as display visual imagery). They may thus prove useful to vision-impaired users, in addition to other applications, notes subcommittee chair Adi Abileah. "The idea is that there is more than one way to interact with displays," says Abileah. "We think this is a direction that SID will head toward in the future."

As is also usual for applications, there are too many interesting papers to cite here, but one of note in the Emerging Displays session is the invited paper "Optical and System Considerations for Mobile Touch-Screen Applications," by Steven Bathiche of Microsoft, which Abileah describes as an excellent review presentation that will cover different considerations for mobile-display parameters including pixel density, optical effects, ambient-lighting influence, touchscreen weight, and power. The paper analyzes the significance of these parameters based on the human eye's acuity, contrast sensitivity, and focusing ability in different lighting conditions. The paper "Semi-Transparent Inverted Quantum-Dot Light-Emitting Diodes," by Jin Jang of Kyung Hee University, will describe a new display technology, a semi-transparent inverted quantum-dot lightemitting diode (QLED) that uses tri-layered quantum dots. "Blur-Free Transparent LCD with Hybrid Transparency," by Chia-Wei Kuo of AU Optronics Corp., outlines a 65-in transparent LCD in which the author controlled LC orientation to suppress image blurring behind the transparent LCD.

Applied Vision: Night-time TV Watching

"This year there are a lot of Applied Vision papers related to 3-D and lighting," says subcommittee chair Yi-Pai Huang. "These are the trends." Two interesting invited papers from the joint session with lighting that address real practical marketplace issues are "Displays as Light Sources: Resolving the Conflict between Gamut and Color Rendering," by Lorne Whitehead of the University of British Columbia, and "Opportunities with LEDs for Increasing the Visual Benefits of Lighting," by Mark Rea of the Rensselaer Polytechnic Institute.

One slightly different paper that Huang recommends is "The Impact of Watching Television on Evening Melatonin Levels," by Mariana Figueiro of Rensselaer Polytechnic Institute. For at least a decade, some researchers (and the media) have suggested that night-time TV viewing suppresses human melatonin levels and thus interferes with sleep. Figueiro's paper investigated whether the blue light from television does in fact suppress melatonin. Readers will have to attend the session to find out the answer, as well as the author's recommendation.

Display Electronics: OLED Drivers Lead the Pack

The scope of papers in Display Electronics this year is diverse but very relevant, according to subcommittee chair Seung Woo Lee. "We do have many OLED-driving papers, but except for this area, the topics are widespread," he says. One trend that Lee did note for 2013



Dr. Kinam Kim, President & CEO, Samsung Display Co., will give a Keynote address on "Displays and Innovation: An Exciting Future"

is a larger number of papers from academia rather than private industry.

There is a full session focused on OLED Pixel and Driving as well as interesting papers in other areas include "Capacitively Coupled 13.56-MHz Resonance-Controlled Wireless Power Transfer System for e-Paper Modules," by Reiji Hattori of Kyushu University, and "ESD and EOS Impact During Module Assembly Processes of Display Panels," by Ming-Dou Ker of the National Chiao-Tung University, both from the advanced LCD Electronics session. Hattori's paper describes a development that could enable electronic paper that works without batteries. Ker's presentation will address the phenomena of electrostatic discharge (ESD) and electrical overstress (EOS) as they occur in production processes, as well as their effect on product reliability. He will suggest ways to control ESD and EOS so as to improve overall vield.

Display Manufacturing: Timely Problem Solving

Manufacturing is an exciting R&D focus topic these days. We are witnessing doubled-down efforts for solving manufacturing process and materials challenges to enable the long-held promise of OLED use in TVs, as well as to accelerate the adoption of oxide-semiconductor TFTs for high-performance display applications. With that in mind, the Display Manufacturing subcommittee is highlighting three papers from this year's impressive selection. The first, "Ink-Jet-Printed 17-in. AMOLED Display with Amorphous-IGZO TFT Backplane," by Ze Liu of BOE Technology Group Co., is an invited paper that reports on the successful integration of ink-jet processed OLEDs with amorphous-oxide TFTs as a path to cost-effective manufacturing of large-sized panels. "It is very exciting to see this technology at the manufacturing stage," says Subcommittee Chair Ion Bita. "BOE is a relative newcomer," he says, "but their rapid advances in technology development and manufacturing are very impressive."

The paper "Advanced Glass Substrate for the Enhancement of OLED Lighting Out-Coupling Efficiency," by Nobuhiro Nakamura of Asahi Glass Co., reports on a substrate designed to improve efficiency in lighting and with potential for display applications. This substrate incorporates a glass-scattering laver that greatly improves efficiency, as demonstrated by the paper's author using OLED lighting panels. "Roll-to-Roll Process on Ultra-Thin Flexible Glass for Manufacturing a Multi-Touch Sensor Panel," by Chia-Sheng Huang of ITRI, demonstrates the advantages of roll-to-roll manufacturing on thin-glass substrates, in which the set of processes and equipment developed by the authors enabled fabrication of ITO-pattern-based touchsensor panels from 0.1-mm rollable thin glass.

Display Measurement: IDMS Gains Traction

As was the case for the last several years, 3-D is a hot topic for Display Measurement in 2013. This is because 2-D measurement just doesn't cover all of what needs to be measured in 3-D, explains subcommittee chair Frank Rochow. What is new in measurement papers this year is that authors have begun adopting the IDMS, the display measurement standard released in 2012 by the ICDM (International Committee for Display Metrology). "The IDMS methods are definitely being implemented in the papers being presented," says Rochow. "The IDMS is being seen as a success and is widely respected."

A good paper to check out for the latest in 3-D measurements is the invited "Techniques and Challenges in the Measurement of Stereoscopic Displays," by Adi Abileah of Planar

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Systems. Another interesting paper that takes on the newest types of displays is "Viewing-Angle Measurements on Flexible Reflective e-Paper Displays," by Dirk Hertel of E Ink Corp. Displays that are curved and reflective make it difficult for researchers to obtain repeatable, consistent measurements, explains Rochow.

Display Systems: Deep Views

With nine separate sessions, Display Systems has a lot going on this year. 3-D continues to be a popular topic, but within 3-D the types of displays have grown increasingly diverse. This year's 3-D sessions include Autostereoscopic and Multiview I and II, Holographic and Volumetric Displays, Lightfield Display, and 3-D Algorithms and Driving.

Other Display Systems sessions include Augmented Reality and Near-to-Eye Displays, Novel Backlighting Systems, Automotive and Head-Up Displays, and Energy-Efficient Displays. Of special interest is the invited paper. "Augmented-Reality Head-Up Display for Car Navigation System," by Toshiki Kaneko of Japan Display, Inc., which uses a laser projector and microlens array to create what the authors say is the first such display that creates augmented reality beyond the windshield. Another invited paper, "Extending Battery Life of Ultrabook through Use of Panel Self-Refresh Technology," by Kamal Shah of Intel Corp., describes an interesting new powermanagement technique for mobile devices.

Emissive Displays: Lots of Late-News for Quantum Dots and Phosphors

Probably the most intriguing aspect of the Emissive Display sessions this year are the number of late-news papers in the Phosphors and Quantum-Dot session - three out of a total of six. These are "Development of Stable Alkaline-Earth-Sulfide LED Phosphors for LCD Backlights," by Ravi Rao of Specialty Phosphors, Inc.; "High-Efficiency and Long-Lifetime Quantum-Dot Light-Emitting Diodes for Flat-Panel-Display Application," by Paul Holloway of the University of Florida; and "How to Fabricate Much Brighter AC Electroluminescent Lamps: Optimizing the Alignment of the Emitting ZnS:Cu Phosphor Particles to the AC Field," by Jack Silver of Brunel University. According to the committee, an exceptional paper in this session is "Characterization of Electron-Hole-Pair Migration and Trapping in Rare-Earth-Doped



Mr. Bill Buxton, Principal Researcher, Microsoft Research, Microsoft Corp., will give a keynote address on "The Social Life of Devices"

YBO₃ under Vacuum-Ultraviolet Excitation," by Anthony Diaz of Central Washington University, in which the author's analysis suggests a correlation between electron-hole trapping efficiency and the energy of activator electronic states relative to the host conduction band.

The other two emissive sessions are devoted to plasma. An invited plasma paper of special interest is "Progress in Luminous Array Film with Plasma-Tube Technology for Seamless-Tiling Super-Large-Area Display," by Terukazu Kosako of Shinoda Plasma Co., which discusses a new flat-sealing process that can enable extra-large curved displays. The late-news paper "New, Thinner Phosphor Layer Fabrication Process for ACPDPs," by Ryuichi Murai of Panasonic AVC Networks Company, describes a process for achieving a 3-µm-thick phosphor layer in the PDP cells.

e-Paper and Flexible Displays

The six e-Paper and Flexible Displays sessions this year include one composed entirely of late-news papers on the topic of Flexible OLEDs and Printed Electronics. These five papers, covering topics such as barrier films, ink-jet printing, and plastic substrates, will obviously provide an exciting look at the state of the art.

A notable paper from AU Optronics is "A 9-in. Flexible Color Electrophoretic Display with Projected-Capacitive Touch Panel and Integrated a-Si Gate Driver," by Yen Lai. This paper, highly recommended by the subcommitee, describes how the authors developed a prototype and concept design for what they describe as the next-stage e-reader: combining a flexible color electrophoretic display (EPD), flexible projected-capacitive touch panel (TP), and amorphous-silicon gate driver circuit on array (GOA) technologies.

Liquid-Crystal Technology: Meeting the Challenges of a Changing Landscape

The LCT subcommittee made a point of inviting what chair Philip Chen describes as the major Asian companies to submit papers this year: Samsung, AUO, LG Display, Japan Display, China Star, BOE, and others. The idea, says Chen, was to get these companies to come to Display Week to share their latest developments and plans for the future, thus providing symposium goers with a complete view of the LC landscape.

Another subcommittee initiative was to organize a session specifically on the topic of OLEDs and LCDs. The three invited papers in the session titled LCDs or OLEDs? include "TFT-LCDs as the Future Leading Role in FPDs," by Yasuhiro Ukai of Ukai Display Device Institute;"AH-IPS, Superb Display for Mobile Devices," by Joun Ho Lee of LG Display Co.; and "LCD or OLED: Who Wins?," by David Barnes of BizWitz. This last, possibly provocative paper will discuss historical trends that point toward a future of increasing technical performance and decreasing financial performance for LCD producers, as well as the feasibility of creating an OLED infrastructure. "This will be a very attractive session," says Chen, "for students and for anyone else in the industry who wants to know about the future direction of these technologies."

Four more notable papers from the LC sessions are "High-Transmission VA-LCD with a Three Dimensionally Shaped Pixel Electrode for 4K × 2K Displays," by Masashi Miyakawa of Sony Corp.;" "LC GRIN Lens Mode with Wide Viewing Angle for Rotatable 2D/3D Tablet," by Masako Kashiwagi of Toshiba Corp.; "Driving Method of FFS-Mode Oxide LCD for Reducing Eye Strain," by Ryo Hatsumi of the Semiconductor Energy Laboratory Co.; and "A Nematic LCD with Submillisecond Gray-to-Gray Response Time," by Daming Xu of the University of Central Florida. **OLEDs: Big TVs and Better Materials**

One trend is certain: OLED TVs, at least OLED TV prototypes, keep getting larger. The most exciting OLED paper this year, according to subcommittee chair Sven Murano, will be "Large-Sized Amorphous-Oxide-TFT AMOLED-TV Using Side-by-Side and Fine-Metal-Mask Technology" by Jen-Yu Lee of AU Optronics Corp. This paper describes a 65-in. panel with a long-range threshold voltage uniformity of 0.34 V. The dam and fill encapsulation process is simple and highly stable, according to the author. The AUO paper is part of a special all OLED-TV session (jointly offered through the OLEDs and Active-Matrix Devices committees) that Murano says may be among the hottest at the symposium.

There is more to OLEDs than big TVs, though. This year has brought many improvements to OLED lighting technology (see the Lighting section below), and also progress in OLED R&D in general. One of the hurdles that OLED technology needs to clear in order to realize its full commercial potential is efficiency in both materials and devices. Two very interesting papers that address this aspect are "Highly Efficient OLED Device with Device Architecture for Reducing Drive Voltage," by Yoshiharu Hirakata of Semiconductor Energy Laboratory, which describes how the author's team developed phosphorescent OLEDs with high efficiency, a long lifetime, and low drive voltage using energy transfer from an exciplex to an emitter; and "Efficiency Improvement of Fluorescent Blue Device by Molecular Orientation of Blue Dopant," by Hitoshi Kuma of Idemitsu Kosan Co., Ltd. Kuma's research suggests how phosphorescent blue devices, which have lagged behind their red and green counterparts in terms of efficiency, can be made to catch up.

Projection: Lasers Loom Larger

Last year, subcommittee co-chair Alan Sobel predicted that 2012 would be the year of the pico projector, in terms of commercial availability. That seems to be true, based on a quick online search for the products, which are numerous and available in some cases for less than \$200. In terms of the symposium, however, the technology is mature. "Surprisingly, there are no [LED-based] pico-projector papers this year," says Sobel. Instead, laserlight engines for projection are the focus of several papers.



Professor John F. Wager, The Michael and Judith Gaulke Endowed Chair Professor of Electrical Engineering, School of EECS, Oregon State University, will give a keynote address on "Exciting Developments in Oxide-TFT Technology"

A standout invited paper in the Projection sessions that Sobel recommends is "High-Efficiency Polarization Preserving Cinema Projection Screen," by Dave Coleman of RealD. This paper describes a polarizationpreserving projection screen that addresses issues of conventional silver screens through substantially increased efficiency (brightness), increased stereo contrast, larger viewing angle, and matte appearance. In addition, the screen enables vastly improved laserspeckle reduction. Says Sobel, "This is potentially a game changer, a big curved screen for digital cinema, with better performance, wider angles, [reduced] ghosting. It will be more expensive than conventional screens."

Special Topics: OLED TV, Oxide TFTs, 3-D, Lighting, and Touch & Interactivity

Each year, the Society for Information Display designates special sessions to explore important and timely display topics. This year's sessions are OLED TV, oxide TFTs, 3-D, lighting, and touch & interactivity. Here are highlights from each:

OLED TV: The four papers in this one session, jointly sponsored by the Active-Matrix Devices and OLEDs subcommittees, will no

doubt be among the most popular at the symposium. AUO's 65-in TV (described in the OLEDs section above) will certainly be an attention-getter, but the other three papers will be fascinating as well. Certainly, no one will want to miss "Technological Progress and Commercialization of AMOLED TV," in which author Chang-Ho Oh of LG Display Co. talks about the art and science behind getting the first mass-produced large-area OLED TVs off the factory floor and into people's living rooms.

Oxide TFTs: A mere four years ago, the idea that oxide TFT could take the place of silicon in display devices was "very new and promising," according to Hyun Jae Kim, the 2009 Active-Matrix subcommittee chair. In 2013, oxide TFT is now a special topic with five sessions devoted to it alone. Those are:

- · Oxide TFT I and II
- Oxide TFT Reliability
- · OLED and Oxide TFT Manufacturing
- Oxide TFT Manufacturing

Several of the outstanding oxide-TFT papers have been described above in conjunction with other technology topics such as Active-Matrix Devices and Display Manufacturing. An additional paper to take note of is "Electrical Properties of Amorphous InGaZnO TFTs Prepared by Magnetron Sputtering Using Kr and Xe Gas," by Tetsuya Goto of Tohoku University. Goto's work explains how the use of certain noble gases in the magnetron-sputtering part of the manufacturing process can reduce film damage caused by ion-bombardment, and thus improve overall thin-film quality.

3-D: This technology area continues to be extremely well-represented in terms of paper submissions – there are 10 3-D sessions in this year's symposium – but the subjects have evolved over the past few years from discussions on passive *vs.* active glasses to a wide range of 3-D displays. The 3-D sessions are

- Autostereoscopic and Multi-View I and II
- LC Technology for 3D I and II
- Holographic and Volumetric Displays
- Light-field Display
- Perception in 3D Display
- 3D Algorithms and Driving
- 3D Application
- Projection Screens

Some of the outstanding 3-D papers are outlined in the sections above, such as RealD's curved cinema screen described

symposium preview

under Projection. Here are some additional ones to check out: "High-Performance Autostereoscopic 2D/3D Switchable Display Using Liquid-Crystal Lens," by Shinichiro Oka of Japan Display, Inc., describes the development of a switchable 2D/3D display with higher luminance and reduced crosstalk. Late-news paper "Real-Time Up-Converter from HDTV to 4K with Super-High Resolution," by Seiichi Gohshi of Kogakuin University, suggests a method for obtaining high-quality 4K resolution from HDTV video, a subject that will become increasingly relevant in the months and years to come.

Lighting: There are four lighting sessions this year, two of them devoted to OLEDs:

- Human Factors on Lighting
- Lighting Design
- OLED Lighting I and II

OLED lighting still has far to go in terms of manufacturing costs, efficiency, and lifetime, but progress is being made. One paper that describes a good advance is the invited "80lm/W White OLEDs for Solid-State Lighting," by Jaemin Moon of LG Chem. These OLEDs were realized by introducing a threestacked tandem structure in conjunction with an internal light-extraction layer. Another exciting paper in terms of getting closer to commercial viability is "Highly Efficient White OLEDs with Over 100-lm/W for General Lighting," by Kazuyuki Yamae of Panasonic Eco Solutions. The author's highperformance all-phosphorescent white devices on a light-outcoupling substrate showed an efficacy of 114 lm/W at 1000 cd/m² and 102 lm/W at 3000 cd/m².

According to Sven Murano, this year's OLED subcommittee chair, "Now is the time when [lighting] companies are starting to invest in manufacturing lines, and I am optimistic that in the coming years OLED lighting will become cheaper and its efficacy will go up."

Touch and Interactivity: Tighter integration and reduction of cost are two major issues surrounding touch in display design and manufacturing, according to Touch & Interactivity chair Jeff Han. (Earlier this year, Han gave the keynote address for the Bay Area SID Chapter's one-day technical conference, Display and Touch Technologies of the Future.) "Touch is still expensive," says Han, also noting that the touch user experience is also increasingly crucial. This year there is a session devoted just to the user experience, and three others as well:

- Touch User Experience
- Touch Integration and Controller
- Touch Application

 Touch Sensors, Materials, and Manufacturing

A touch paper of note is "12.2-in. 1920 \times RGBW × 720 IPS-LCD Integrating In-Cell Touch Panel for Automotive Use," by Chihiro Tanaka of Japan Display, Inc., which suggests solutions to some of the special issues surrounding the design of an in-cell touch panel specifically for automotive use. An interesting paper that addresses the touch user experience is "The Need for Speed in Touch Systems," by Albert Ng of Microsoft. The author shows the impact of touch-to-display latency, frame rate, and motion blur on the touch-user experience. He explains how by using a custom device his team was able to achieve latencies down to ~ 1 msec, with frame rates up to 1000 Hz

A Wealth of Information

In sum total, there is no doubt that this collection of symposium papers represents the most important display industry information you will find all year. Please join the Display Week presenters as they share their research with their friends and colleagues in the display industry.







by Stephen P. Atwood

SOCIETY FOR Information Display

The flyer headline read: "SID Bay Area Announces First One-Day Technical Conference: Display and Touch Technologies of the Future: Jan 16, 2013." So, there I went to attend the first of what I sincerely hope will be an annual event, held in one of the most fertile technology innovation regions in the world. The program was expertly arranged by conference co-chairs Jennifer Colegrove and Rashmi Rao, and I was expecting a small gathering of about 50 or so die-hard display folk. What I encountered instead were over 160 attendees, a virtual sell-out, representing 43 different technology companies and countless different product and display-application interests. What unfolded throughout the day was a wonderful balance of speaker presentations, audience questions, panel discussions, and informal interactions that surely sparked some fresh ideas and seeded some new energy back into our industry.

Keynote speaker Jeffrey Han (Fig. 1) talked about his background at Perceptive Pixel, the company he founded. He described how his effort to create new touch-screen hardware quickly became an endeavor to expand the potential of multi-touch through software as he realized how little capability existed in user interfaces at the time. Now that Jeff as well as his company are part of the Microsoft Office organization, Perceptive Pixel remains



Fig. 1: Conference organizer Rashmi Rao and Perceptive Pixel Founder Jeff Han demonstrate the large-area multi-touch Perceptive Pixel touch screen.

a hardware division with a mission to seed interactive large-screen displays into every possible application, not just conference rooms and presentation arenas.

Repeating a mantra we all know well, Jeff stressed that there is no perfect touch technology for all applications. In fact, Jeff explained that in his view, "Touch is not as good at content creation [as other methods]," and he went on to show some great demonstrations of how the future will be focused on pen and touch working together. For example, in a large-screen application, you might use your left hand for manipulation of the documents and windows and your right hand to draw and write the content.

Modality is also a big problem for touch applications – it's challenging to program the computer to know what you intend when you use your fingers. However, we can use tools to define modality, such as pens for inking content and hands for manipulation. In a good UI design, your hand should be able to rest on the screen while you are inking and you should be able to perform a variety of content creation and context management tasks with no modality switching involved. This is part of what Jeff is working on at the Microsoft Research Center and it is surely a glimpse of what we'll see in Microsoft products someday soon.

In the LCD Technology session, we heard from three speakers whose endeavors and those of their companies are all making fundamental contributions to the field. Candice Brown Elliott, founder of first Clairvoyant and now Nouvoyance, companies dedicated to innovative ways of producing multi-primary color with improved power efficiency and visual performance, presented her vision of key technology trends that are changing the landscape of color displays. "Thank goodness we're moving to 4K resolution displays," she began, talking about all the experiential advantages that users will gain from the ultrahigh-definition formats. She then made a compelling case for the adoption of multiprimary display formats such as red-greenblue-yellow-cyan, which allow a variety of color metamers and creative ways to process and render images with wider color gamuts while avoiding increases in energy requirements.

She then explained how local dimming – using segmented 2-D backlights that enhance dynamic range – can be augmented with field-

sequential color rendering to also greatly expand the boundaries on color and produce high-dynamic-range displays. These methods are much more achievable on consumer displays today due to the very low cost of high-performance processors and the new standards coming for digital-content distribution. Of course, mentioning field-sequential topics invokes fear in technologists used to dealing with color-breakup artifacts and poor user response. Well, not to fear, because as Candice described, the display area can be segmented into small zones where each zone has its own color map and usually much lower color-diversity requirements that, in turn, can be met with virtual primaries (mixes of the actual primaries) that are much less saturated and therefore less likely to produce color breakup in observers.

Professor John F. Wager from Oregon State University took the podium next and presented the technical merits and future potential of oxide thin-film transistors (TFTs) for a variety of display applications, especially where transparency is needed. This is new technology that is just beginning to appear in mainstream OLED and LCD panels, promising a host of advantages and performance improvements. The first published work on oxide TFTs appeared in 2003 and serious interest developed around 2007. TFTs made from oxides are accumulation-mode devices, where electrons flow source to drain with positive gate voltage and positive drain voltage.

Making an oxide TFT with good mobility is challenging because unlike silicon, you want to discourage polycrystalline structures in favor of amorphous. This is because of an effect called "carrier trapping," which causes an overall reduction in mobility in polycrystalline states. However, some combinations of elements such as zinc-tin (ZnSn) can be made amorphous rather than polycrystalline. Today, we see great success using InGaZnOx (IGZO,) which is now in commercial use and is described in several ID magazine articles of late.

The key advantages of oxide TFTs for LCD manufacturing include high mobility, fast refresh, and easy insertion into already existing a-Si plants. By contrast, poly-Si fabrication requires a totally new plant, while oxide technology needs more of an upgrade. Oxide-TFT technology promises to spread into AMLCDs, EPDs, and AMOLEDs. It's not yet ready to become part of flexible displays, but to read about progress being made in this area, see the article "Oxide TFTs for AMOLED TVs" in this issue. Also, see Fig. 2, for a comparison.

Rounding out this trio of speakers was Seth Coe-Sullivan, CTO and co-founder of QD Vision, a company well known for its work in quantum-dot research, especially by those of us in the Northeast U.S. Seth discussed his company's newest innovation, which involves LCD color-gamut-enhancing films with quantum-dot technology that can be installed directly into edge-lit backlights. This technology uses blue LEDs and then converts the blue-light energy into very specific spectrums of red, green, and blue as desired. QD Vision calls this technology "Color IQ," and it was jointly announced with Sony at CES as the innovation behind Sony's new "Triluminous" Displays. The result is what Seth describes as "LCDs with OLED color gamuts." Seth went on to explain that another advantage of quantum dots is that they have worldwide environmental compliance, containing no materials that are known to be hazardous to the environment. In the first embodiment, Color IQ is packaged in a polymer film, but in the future quantum dots might be suitable for inclusion in the LED package itself, eliminating the need for an additional component. This could represent a sub-\$100 solution to the panel designer.

However, there are further development challenges, including increasing total light output, managing heat, and improving lifetimes. Earlier QD optical performance used to degrade significantly at temperatures above 80° C but now is within $\pm 3\%$ up to 140° C. The currently expected lifetimes are greater than 2500 hours at power densities up to 100s of W/cm² with no measureable luminance decay. Seth also believes that while the dots themselves are currently made in "batches," the process itself is completely scalable to high-volume LCD manufacturing.

The next series of presentations focused on OLED technology, leading off with Dennis Kondakov, Principal Scientist at Dupont. Dennis, who compared two options for deposition of OLED materials onto backplanes during OLED manufacturing – evaporation with masks or solution printing and processing. Major considerations in selecting one of these processes include material waste and panel size because OLED materials are very expensive and processes must scale effectively to very large substrate sizes. Dupont believes that nozzle printing will be the approach chosen most often in future because of inherent advantages with the nozzles' high printing rates of 2–5 m/sec and scalability.

Up next was Sean Xia, a research manager with Universal Display Corp., who discussed the short- and long-term potential for phosphorescent OLEDs (PHOLEDs). Xia and his team believe PHOLED materials hold the key to a variety of new innovations in displays as well as lighting applications, owing in large measure to the potential advantage in internal quantum efficiency (IOE) of up to $4 \times$ that of fluorescent OLEDs. This higher optical efficiency naturally reduces heat dissipation in the devices and allows many more creative design concepts than current lighting technologies. Of course, there are numerous advantages to both inorganic as well as organic LEDs for lighting, including wide color gamuts and high optical efficiency, but OLED and particularly PHOLED materials can be printed in large sheets and on many types of flexible substrates while achieving tested performance up to 70 lm/w for 30,000 hours or longer. OLED lighting has been

talked about before at conferences and in *ID*, but I was convinced that significant progress is being made, and it's inevitable that we will see this technology in lighting applications in the not too distant future.

While UDC has been working on large-area OLEDs, Amal Ghosh and his colleagues at eMagin Corp. have been working on OLED microdisplays, packing more and more activematrix RGB pixels onto silicon backplanes with display diagonals in the range of from 0.5 in. to about 0.9 in. Their most stunning achievement is a 0.86-in.-diagonal WUXGA microdisplay with an astounding 7,138,368 RGB pixel elements on it. This translates into a pixel pitch of about 9.6 µm, with each subpixel having dimensions of $3.45 \times 8.5 \,\mu\text{m}$. The application enables full HD 3-D glasses that can be used to create a virtual display experience. With the prototype the people from eMagin discussed, the diagonal field of view was 65°, creating a virtual image of approximately 212 in. on the diagonal at 12 ft. with a luminance of over 150 cd/m^2 . Because it is OLED technology, it has a very fast intrinsic response time and therefore can

	AMLCDs							
Property	a-Si:H	LTPS	IGZO					
Manufacturability	mature, proven	proven, scaling issues	emerging					
Microstructure	amorphous -	polycrystalline	→ amorphous					
V _T uniformity	good ←	fair 🔶	good 🕂					
V _T stability	poor	excellent	good					
Mobility	1	20–100	<u>10–30</u>					
Mobility uniformity	good 🖵	fair 🔶	good					
Device type	NMOS	CMOS	NMOS					
Process complexity	low	high	low					

Fig. 2: John Wager presented this slide comparing the relevant properties of a-Si, low-temperature polysilicon (LTPS), and IGZO for AMLCD TFT fabrication. Credit: John F. Wager, "Amorphous Oxide Semiconductor Thin-Film Transistors for Display Applications," presented at the Bay-Area SID Chapter's One-Day Conference on "Displays and Touch Technologies of the Future," Sunnyvale, CA, January 16, 2013. deliver full 3-D stereo images without flicker, motion blur, or image latency. And, of course, Ghosh promised they are also working on $2K \times 2K$ imagers and beyond.

By this point, you might think we have already covered a full day but, in fact, all the above was presented before lunch! The afternoon sessions began with a keynote from Achin Bhowmik, Intel's Director of Perceptual Computing, who characterized the major weakness of computers today as their limited ability to interact with humans. Although the human brain has a much slower processing speed than even the slowest computers, it can perform massive amounts of parallel processing on multiple sensor inputs at the same time, creating a much broader range of analytical abilities than computers. Intel's focus is to bridge that gap in a series of steps, starting by enabling touch interfaces in all forms of tablets and handheld devices.

As touch and Windows 8 become pervasive, Intel envisions moving to the next level with a system it calls "Perceptual Computing," which is powered by a multi-input 3-D camera system and an SDK that Intel is currently offering for free in beta form. This SDK supports several perceptual modes, including Close-Range Interactions, Hand and Finger Level Tracking, Face Analysis, Tracking and Recognition, Speech Recognition, and 2-D/3-D Object Tracking. As Bhowmik said, this new approach "opens a world to creating applications without developing underlying controls." You can see an interesting demo of these new concepts at http://software.intel.com/en-us/ vcsource/tools/perceptual-computing-sdk

These demos are more interesting than anything I can write about here in a short space. Clearly, we have seen for several years increasing interest all over the industry in new types of 3-D and non-contact interaction modes with computers. Many concepts have recently been discussed at Display Week presentations, some built on the Microsoft Kinect platform. In fact, Intel's product is compatible with the Kinect device as well as its standard depth camera offering, but the Intel SDK focuses on hands and faces rather than the entire body. "If we want computers to be interactive with people, we need to give people the tools to communicate with them," said Bhowmik in closing.

Next, we heard from well-known industry expert Geoff Walker, who spoke about the future of touch technology. Noting that early

sales of Windows 8 have not been encouraging, Geoff said there is a lack of hardware that fully enables the new features and that Windows 8 will soon drive the consumer market as hardware catches up. He also predicted that by 2018, 95% of phones will be touch enabled - something I'm not at all surprised about. Recently, the concentration of touch in some notebook formats such as All-in-Ones (AiOs) actually went down due to fears of pro-cap-only choices for Windows 8 - not because the market doesn't exist. Similarly, with traditional "clamshell" notebooks, increasing touch penetration will require solutions that are easier or more convenient than alternative input methods and, of course, Windows 8!

Meanwhile, Geoff said that large-format touch has huge opportunities, and there are a number of technology options on the market or coming to market soon, including: camerabased, vision-based, FTIR, projected-capacitive (Pro-Cap), "traditional" infrared, and highfinger-count multi-touch infrared. All of these are in various stages of development or deployment now. Not surprisingly, Pro-Cap is the biggest show in town, capturing 83% of the market for screen applications less than 15 in. and spawning a number of R&D efforts on core materials such as metal mesh, silver nanowires, carbon nanotubes, and conductive polymers. However, as Geoff explained, it's really the process to manufacture these screens that determines cost and performance improvements. With the OEM cost of a 13.3-in Pro-Cap screen in the range of \$55–85, there have clearly been many improvements recently.

The other trend that Geoff emphasized was renewed interest in stylus input. Windows 7 was finger-focused because of the perceived failure of stylus input on tablet PCs. However, several recent products have brought back the stylus, which is much better for content creation such as drawing and writing, so Window 8 will likely re-energize stylus input. In fact, the ideal embodiment on larger screens may be just what Jeff Han discussed earlier: hand recognition for control of frames and windows and simultaneous stylus input for actual content creation.

Next in line was Joel Kent from Elo Touch-Systems to explain how surface-acousticwave (SAW) technology may be seeing a rebirth. He explained his company's new edge-to-edge SAW implementation, which can produce a virtually bezel-less design with the sensors and transducers moved to the back of the glass. Until recently, the touch market was predominantly a commercial and industrial application space. As we know, beginning around 2000, the consumer touch market began its expansion way beyond the commercial market. This is important because the user's learning curve in the two markets is very different. Consumers will make the effort to learn how to best optimize their personal devices, but commercial market users are transient and will not invest time to learn; therefore, the touch interface and application experience must still be significantly different. Examples Kent cited included an airport check-in kiosk vs. a smartphone.

Rounding out the trio of touch technology speakers was Zachi Baharav, Manager of R&D from Corning. We're all familiar with the significant and highly innovative role Corning has played in the LCD industry for the last 30+ years, but it was interesting to hear how diverse and nuanced the company's offerings are for touch-sensor development. The diversity in touch-application requirements varies in strength, thickness, chemistry, tolerance to processing, surface texture, etc., in much greater degrees than we might have realized. Baharav brought with him some of the best Corning videos, including the famous "A Day Made of Glass." Famous for their imaginative depictions of transparent tablet displays and augmented reality, these videos pose many interesting questions about user interaction as well as future modalities for information devices. They are, incidentally, also available on youtube but they are more fun to watch on the big screens at a conference like this one.

The final round of talks addressed flexible displays and emerging technologies. Jennifer Colegrove, President of Touch Display Research, spoke about the opportunities for continued technical advances in technologies and commented on the future potential. She said that there are "currently over 10 different technologies that can be made into flexible displays." She went on to make a bold prediction that we will see a "...flexible AMOLED from Samsung in 2013 that will be a phone and a tablet combined, with a screen size >5 in." That certainly got my attention! The market revenue for flexible displays in 2011 was a modest \$400 million (which is larger than I would have even thought), but Jennifer predicts by 2015 that it could be as much as



Fig. 3: Bay Area SID Chapter Conference Organizers. From left to right in back row: Joel Pollack, Steven Huang, and Cheng-Wei Pei; from left to right in front row: Carolyn Marsden, Jennifer Colegrove, Rashmi Rao, John Miller, and Geoff Walker.

- More advanced and efficient interaction between people and their devices.
- A wider range of power-efficient, lowercost, and even flexible devices going way beyond what we have today.
- Displays becoming more fully integrated into all our appliances and devices, with virtual linkage creating a seamless environment for information exchange.
- And best of all, a wide range of new opportunities for invention, discovery, investment, and future careers.

I really enjoyed my trip to the future and it was all due to the outstanding efforts of the BA chapter conference team pictured in Fig. 3. Congratulations to them all for a very successful conference!

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\$2.5 billion Some of the key technology areas that are ripe for further development include OLED flexible barrier layers, color for e-Paper, ITO replacement materials, flexible touch, and better/smaller batteries.

The last speaker was Jian Chen, VP of R&D for Nanosys, a former winner of SID's prestigous Display Industry Awards. Dr. Chen explained that green LED efficiency was one of the factors limiting adoption of RGB LED backlights. Also, differential aging made it hard to maintain white balance over long product life cycles, which explains why phosphor white LEDs have become the de-facto standard for most LED backlight designs. Nanosys provides a film for LCD backlights it calls QDEF, which produces a secondary light emission with quantum-dot technology. These films can be tuned to very specific light wavelengths based on stimulation from 365-nm blue LED sources. Nanosys has demonstrated its process to be very scalable with modest investment, allowing it to partner with companies such as 3M to produce a roll-to-roll manufacturing process. This ensures the product can meet the demands of major LCD-manufacturing customers.

While a great many seemingly diverse topics were covered during the course of this event, it was clear that they all fit together when you step back and try to envision the characteristics of display technology several years into the future:

continued from page 2

Thank You" for everything they have achieved.

Our lineup of technical articles was developed for us by our two outstanding guest editors this month. The OLED articles were solicited by H. K. Chung, who led Samsung's OLED R&D for over 10 years and now is Chair Professor at Sungkyunkwan University. You can read his Guest Editor's note to see what his thoughts are for the future of OLED TVs and related developments. Our first Frontline Technology article comes from author Jang Hyuk Kwon from the Department of Information Display, Kyung Hee University, Seoul, Korea. All color flat-panel displays utilize some form of color subpixel matrix to produce mixed colors and Dr. Kwon describes the prevailing methods for patterning the color filters and/or emitters for those subpixels in his work titled "RGB Color Patterning for AMOLED TVs."

Next, we have our second Frontline Technology feature titled "Oxide TFTs for AMOLED TVs" by author Jin-Seong Park, a professor at Hanyang University. Dr. Park explains the reasons why oxide TFTs are so potentially important for OLED TVs, as well as the current state of the art and some of the remaining hurdles in the way of massproducing oxide-TFT backplanes. Oxide TFTs have turned out to be one of the big stories thus far this year, especially when linked to the future of OLED displays. Guest Editor Dr. Arokia Nathan brought us a great article by Yan Ye from Applied Materials describing the underlying physics and properties of oxide TFTs. In his article, "Zinc Oxynitride TFT: Toward a New High-Mobility Low-Cost Thin-film Semiconductor," we learn much about the different types of possible oxide compounds that are candidates for TFTs and why the amorphous state is actually better for mobility than the polycrystalline state. This is a very detailed article that really filled in the blanks for me about the current state and future potential of this technology.

In this issue's Display Marketplace feature titled "AMOLED Production: Entering a New Era" contributing editor Paul Semenza has put a great deal of effort into detailing the current state of AMOLED manufacturing, the varying pixel architecture approaches companies are pursuing, and the likely forward paths these same companies will follow. Paul is not afraid to name names, and both his industry insight and technical understanding are widely respected for their accuracy. Needless to say, oxide-TFT technology plays a large role in his view of the future.

One application that Paul believes creates a unique opportunity for OLED technology is flexible displays, and so we asked another frequent contributor, Dr. Jason Heikenfeld, Associate Professor at the University of Cincinnati, to look at the state of the art in flexible displays for our Enabling Technology feature that Jason decided to call "Flexing and Stretching." Looking back as well as looking forward, Jason shows us where the most promising work is happening, the key opportunities for future innovation, and also names companies to point out specific embodiments of each key infrastructure component. From Jason's description, which will also likely be updated at his seminar at Display Week in May, it's clear organic electronics, specifically OLEDs, will play a major role in the future of flexible displays.

There were a lot of headlines from this year's Consumer Electronics Show, including a dazzling keynote by Samsung incorporating a new phone concept presented by our own SID President Brian Berkeley. If you were not one of the reported 150,000 people who were there, worry not, because we asked industry reporter Steve Sechrist to give us "Alpha and Omega: Most Exciting Display Technologies at CES." Not surprising, if you have been following our recent issues of ID, was that the major themes were ultra-highdefinition (UHD) TV, OLEDs, oxide TFTs, 3-D, and even transparent LCDs, which I think have a lot more potential than others may recognize. In any case, there is plenty for everyone to get excited about in this show review from Steve.

And so, with this issue finally complete and ready for your enjoyment, I hope I'll see all of you in Vancouver in less than 2 months from now. I want to thank our tireless staff, our guest editors, and all our authors for their dedicated work on this and every issue.



guest editorial

continued from page 4

support the idea of abrupt transition are the optimists who believe that the current manufacturing issues will be solved within 2-3 years, as many companies shift to OLED-TV manufacturing. The gradual transition scenario stems from the consideration that the LCD TV will continue to lead the market because it will take more than 2–3 years for OLED TV to establish a manufacturing technology with both low cost and high yield. Besides, the LCD-TV infrastructures have already been well established. In my opinion, the entry of OLED TV into the marketplace will be driven by the marketing strategy of TV-set makers more than by the economy in the early phase, and the transition could be swift because I believe the learning curve for large-OLED-panel manufacturing will be quicker than that for the small mobile display.

Ho Kyoon Chung led Samsung's OLED R&D for over 10 years and is now Chair Professor at Sungkyunkwan University after retirement from Samsung. He is still continuing his research on core-technology development for flexible AMOLED and OLED lighting on flexible substrates. He is a Fellow of SID and can be reached at hokyoonc@gmail.com.

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