

DISPLAY WEEK 2016 PREVIEW AND FLEXIBLE TECHNOLOGY

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From Flexible to Bendable to Foldable to Rollable

**FLEXIBLE TFTs TO ENABLE
NOVEL APPLICATIONS**

**SID HONORS ITS BEST
AND BRIGHTEST**

**THE ROAD TO FLEXIBLE
AMOLED DISPLAYS**

CES REVIEW

**ROLLING OUT NEW
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ON THE COVER: Researchers are actively working on all forms of flexible displays: rigid, bendable, foldable, and rollable. In order to develop products using these forms of flexible displays, designers have to consider all of their practical limitations which includes the rigidity of electronic components. These limitations are unique to each specific application. As a result, for each form of flexible display, a variety of new forms will also be generated at the product level – flexible displays will come in many forms.



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AMOLED technology is an emerging technology that has gained tremendous attention in part because of its potential for flexibility. This article provides an overview of AUO's progress in AMOLED technology, from fixed curve to bendable, and now moving toward a foldable display.

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The First Days of Spring

by Stephen P. Atwood

Spring is here, and along with the warming of the weather comes a very busy season for our industry. It started with CES in January, when we saw a significant number of new display achievements and continues through May, when we all come together for the annual Display Week gathering – the largest and most complete convergence of display-industry activities in the world. In between these two,

we see many local and regional events (such as the China Display Conference and the Electronic Displays Conference in Germany), all warming us up for Display Week. This year, the big show is in beautiful San Francisco beginning on May 22 and spanning the entire week with short courses, seminars, business and market focus conferences, the International Symposium, some great keynotes, and the world-class Display Week Exhibition. If you have not yet made your plans to visit, it's time!

We will talk more about Display Week shortly, but first let me discuss our technical focus for this issue, which is flexible displays – an area of R&D that is bringing a lot of promising new capabilities to the marketplace. We have already seen curved and flexible displays in numerous consumer products – generally packaged as rigid or mildly flexible solutions such as a phone that will not break if you put it in your back pocket and sit on it. We have also seen a myriad of curved LCD (and a few OLED) TV-size screens shown and sold commercially. So, the concept is becoming more main stream, but a display that you can literally roll up or fold up still eludes us. Thanks to important product segments such as wearables and tablet computers, there is no shortage of commercial interest in the ultimate flexible-display solution.

We start off this month with three excellent Frontline Technology articles that address critical building blocks toward achieving true flexibility, for which we thank our terrific guest editor Ruiqing (Ray) Ma from Universal Display Corp. I recommend that you start by reading Ray's guest editorial titled "Flexible Displays Come in Many Forms" to get his perspective on the context for these three key articles. Then jump right in to enjoy "Enabling Wearable and Other Novel Applications through Flexible TFTs" by Antonio Facchetti and his colleagues at Polyera, whose work in organic electronics has yielded organic TFT backplanes capable of near-endless bending. Their concept product, the "Wove Band," is literally a wearable rectangular wristband with an electrophoretic display and touch screen along the entire length. You put it on just like a bracelet and it functions like a smartwatch and small tablet at the same time. The concept is fairly compelling on its own, but I really think the story is in the underlying work they have done to further the commercial viability of organic backplanes.

Next, we offer an article by Jin Jang from the Department of Information Display at Kyung Hee University in Seoul, Korea, titled "Bulk-Accumulation Oxide-TFT Backplane Technology for Flexible and Rollable AMOLEDs: Part I." The story here is, of course, the goal of achieving flexible TFT backplanes with enough current-switching ability to support OLED pixels. Normally, this is done with multiple high-mobility TFTs, but Dr. Jang and his team have developed a dual-gate bulk-accumulation TFT using n-type amorphous-indium-gallium-zinc-oxide (a-IGZO). The advantages of this over single-gate TFTs are clearly stated as "...drain current that is over three times larger, turn-on voltage that is closer to 0 V, smaller sub-threshold voltage swing, better device-to-device uniformity, and better bias and light stability..." Because he

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OLEDs Shine in Smartphone Displays

In his latest DisplayMate shootout,¹ theoretical physicist (and *ID* contributing editor) Ray Soneira looks at the Galaxy S7 and Galaxy S7 Edge, Samsung's new high-end smartphones with OLED displays (Fig. 1). "Samsung," writes Soneira, "has been systematically improving OLED-display performance with every Galaxy generation since 2010, when we started tracking OLED displays. In a span of just 6 years, OLED-display technology is now challenging and even exceeding the performance of the best LCDs."

Soneira notes that while the Galaxy S7 screen size and resolution are the same as that of its predecessor, the Galaxy S6, display performance has been significantly improved. For example, the display's maximum brightness is 24% higher than that of the Galaxy S6. Contrast and contrast rating for high ambient light have also been improved. He also notes that the Galaxy S7 matches or breaks new records in smartphone display performance for: Highest Absolute Color Accuracy (1.5 JNCD), Highest Peak Brightness (855 nits), Highest Contrast Rating in Ambient Light (186), Highest Screen Resolution (2560 × 1440), Highest (infinite) Contrast Ratio, and Smallest Brightness Variation with Viewing Angle (28%).

The Galaxy S7 also introduces two useful display enhancements. The first is a new, personalized automatic brightness control that learns and remembers the display brightness settings you set or adjust for various ambient light levels. "This not only improves the screen readability in ambient light but also the running time on battery because you will just see the screen brightness levels that you need," writes Soneira. "And there is also a new 'Always On Display' mode that will show a personalized clock, calendar, status messages, notifications, and

images on the main screen whenever the phone is off (in standby), all day and all night, which can be done with very low power on an OLED display, so you can discreetly check it with just a glance."

For more about the Galaxy S7 and S7 Edge, which is almost identical to the Galaxy S7 except that it has a curved, flexible OLED display that extends and bends around to both the right and left side edges of the phone, see the shootout online at www.displaymate.com/Galaxy_S7_ShootOut_1.htm

In summation, Soneira says, "OLEDs have now evolved and emerged as the premium mobile smartphone display technology. There is no better confirmation of this than a series of recent well-founded rumors from a number of prominent publications [*Forbes*, *Tech Times*, *Reuters*] that Apple will be switching the iPhone to OLED displays in 2018, or possibly 2017 for premium models." *Information Display* will follow up those rumors in the next issue.

¹www.displaymate.com/Galaxy_S7_ShootOut_1.htm

Late News: Foxconn and Sharp Deal Hits a Snag

At press time for *ID* magazine, shortly after Japanese display-maker Sharp announced that it would sell a two-thirds stake to Taiwanese display firm Foxconn, Foxconn announced that it was putting the deal on hold for some further research.²

²www.reuters.com/article/us-sharp-restructuring-shares-idUSKCN0VZooZ



Fig. 1: The OLED-based Galaxy S7 (left) and S7 Edge (right) are Samsung's latest flagship smartphones.

Solar-Tectic Receives Patent for Hybrid Thin-Film Solar Cell and OLED Technology

Solar-Tectic LLC, a thin-film specialty manufacturer, recently announced that the United States Patent and Trademark Office has granted it a patent for hybrid organic/inorganic thin-film growth on inexpensive substrates, such as flexible and ordinary soda-lime glass. Solar-Tectic's primary focus is on developing patented technologies for single crystal or highly textured semiconductor films on glass or metal tapes.

The technology was invented by Ashok Chaudhari and is based on the work of the late Dr. Praveen Chaudhari, winner of the 1995 U.S. Medal of Technology. It has applications in various industries such as solar, displays, and OLEDs and OLETs (organic light-emitting diodes and transistors).

Tannas Electronic Displays Becomes Pixel Scientific

Tannas Electronic Displays, Inc., a company devoted to custom-sized LCDs, was recently sold in a majority stock purchase agreement to investors led by Richard McCartney of Scotts Valley, California. The new board of directors named "Dick" McCartney CEO and Chairman

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guest editorial



Flexible Displays Come in Many Forms

by Ruiqing (Ray) Ma

Seven years ago, right around this time, I was busy preparing for my first Display Week Applications Tutorial on flexible displays. You may wonder why a display researcher was asked to talk about applications for one and a half hours. The reason was simple – no one knew much about flexible-display applications back then. Among the 65 slides I

created, the most important one was titled “How Will Flexible Displays Develop?” On it, I described five conceptual phases of flexible-display development, with the first four phases being low power (efficient, thin, rigid), rugged (flat, unbreakable), bendable, and rollable. Let’s be clear: this was not an application roadmap, but a display roadmap based on the levels of difficulty in making such displays.

Looking to the market today, flexible displays are still in the “low power” or “efficient, thin, rigid,” phase. OLED displays and bi-stable reflective displays represent two of the best flexible-display technologies. However, both entered the market not for flexibility, but for the compelling selling points of low power and slim form factor. Two good product examples of these technologies are e-Readers with electrophoretic displays and smartphones with AMOLED screens. For smartphones that demand dimensions down to one-tenth of a millimeter, AMOLED displays clearly have an edge, with their very thin profile and power efficiency. In 2013, the first commercial products based on flexible AMOLED displays were introduced to the world. These displays were built on flexible substrates, but used in rigid designs in either flat or curved models. Even with the rigidity of the products, it is fascinating to see the variety of new forms being generated at the product level: uniform curves on the long or short dimensions, curved edges, circular displays, and displays with even slimmer bezels that take advantage of flexible substrates.

The theme of this special issue is “What’s next for flexible displays – applications and enabling technologies.” Three inspiring articles are featured to provide a clear picture of current R&D efforts in the field of flexible displays.

In the article entitled “Enabling Wearable and Other Novel Applications Through Flexible TFTs,” Dr. Facchetti and his colleagues at Polyera share their vision that flexible TFT technology is a key to enabling mechanical flexibility for the next round of flexible electronic products. Combining their organic TFT (OTFT) based flexible TFT with electrophoretic displays, the Polyera team has built a truly flexible wearable device: the WOVE Band. With an active area several times larger than that of most smartwatches, the display can be bent 50,000 times with a 15-mm radius.

While OTFTs are a good match for electrophoretic displays, LTPS and oxide TFTs are the dominant backplane technologies for AMOLED displays. Because of its amorphous nature, oxide TFTs have an advantage in flexibility. In the article titled “Bulk Accumulation Oxide-TFT Backplane Technology for Flexible and Rollable AMOLED Displays: Part I,” Professor Jin Jang from Kyung Hee University shares the latest results of bulk-accumulation oxide TFT for advanced flexible AMOLED displays. These TFTs can achieve an effective mobility up to 90 cm²/V-sec and show no obvious change in TFT characteristics, even when bent to a tight radius of 2 mm, showing great promise in driving ultra-flexible AMOLED displays.

To get a broad view of the current status of flexible AMOLED research, I would recommend the article titled “Flexible AMOLED Displays Make Progress,” in which

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Enabling Wearable and Other Novel Applications through Flexible TFTs

Mechanical flexibility is a key feature for the next generation of display-based electronic products. An essential component of this capability is flexible TFT technology, which requires a materials set specifically designed to perform optimally under mechanical stress. Progress to this end has been made by several companies, including Polyera Corp.

by Antonio Facchetti, Chung-Chin Hsiao, Edzer Huitema, and Philippe Inagaki

ORGANIC and flexible electronics are revolutionary technologies that enable the fabrication of unconventional electronic devices (including displays) where mechanical flexibility and light weight are essential characteristics.¹⁻⁴ The unique properties of organic materials enable them to be used to fabricate TFT backplanes using either standard fab processes (spin-coating, slot dye coating plus photolithography) or processes borrowed from the graphic-arts industry, such as printing. These are all low-temperature solution-based processes that are potentially compatible with the plastic substrates that enable flexible lightweight displays.

By using the above-mentioned materials and processes, single electronic elements such as transistors (Fig. 1) and capacitors can be made, as well as networks of devices forming circuits¹⁰ such as memories or display driver arrays. In turn, entire devices including

flexible displays,¹¹ radio-frequency identification (RFID) tags, disposable diagnostic devices, rollable solar cells, and batteries could be fabricated with this new materials set. This article will describe how organic

TFTs can be used to create flexible backplanes for displays and other devices, and ends with a discussion of a wearable flexible-display product, the Wove Band, which is now under development.

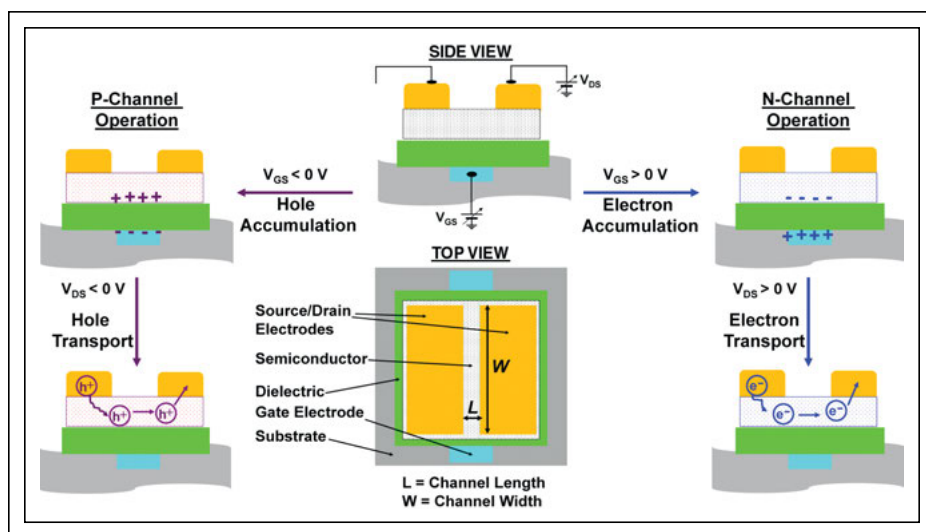


Fig. 1: The structure of a (bottom-gate top-contact) organic thin-film transistor (OTFT) with operation in p-channel (hole transport) and n-channel (electron transport) modes is shown. For driving a display, only one type of TFT (either p^- or n^-) is necessary, but for other devices such as RFID and sensors, complementary circuits based on both polarity OTFTs provide a far better platform in terms of stability and reliability.

Antonio Facchetti is a co-founder and the CSO of Polyera Corp. He can be reached at afacchetti@polyera.com. **Edzer Huitema** is the Chief technology Officer of Polyera Corp. **Chung-Chin Hsiao** is the Head of Display Development of Polyera. **Phil Inagaki** is a Founder & Chief Executive Officer of Polyera Corp.

Options and Obstacles for Organic Electronics

It is important to explain that the aim of organic electronics is not to replace conventional silicon-based electronics. Rather, it offers several opportunities to reduce the cost of certain devices by circumventing production limitations of the conventional semiconductor industry and, specifically for flexible electronics, enabling completely new products impossible to fabricate using silicon technologies because of intrinsic and/or processing limitations.

The conventional obstacle for the realization of this technology has been on the materials side, since solution-processed electronic materials, particularly the gate dielectric and the semiconductor, exhibit poor electrical performance for current standards. Furthermore, it has been challenging to scale up this new material set, formulate it in fab-acceptable solvents, and identify quality-control parameters for solid materials and formulations. Modification and optimization on the production equipment side have been proposed to cope with the different processing parameters of organic materials; however, the electronic industry is reluctant to follow this approach. Finally, new device and circuit design as well as tools to investigate and qualify the performance of devices fabricated for flexibility, on plastic substrates, may be necessary.

Solution Processing and Flexible Electronic Materials

As in the case of conventional electronics, organic electronic devices need a core materials set for charge accumulation, injection, and transport, as well as specific materials to enable particular device functions. For instance, in every type of electronic device there is the need for a certain control of the current flow as well as memory.

For thin-film transistors (TFTs), the key device-enabling multiple electronic technologies (Fig. 1), three fundamental materials are needed: the conductor, the gate dielectric, and the semiconductor (Fig. 2).

Then, depending on the specific device application, additional active materials may be necessary. For instance, for OLEDs, an emissive material is necessary for efficient conversion of electricity to light. For organic photovoltaics (OPVs), besides the materials needed for efficient charge transport, it is necessary to have a photosensitizer and/or an

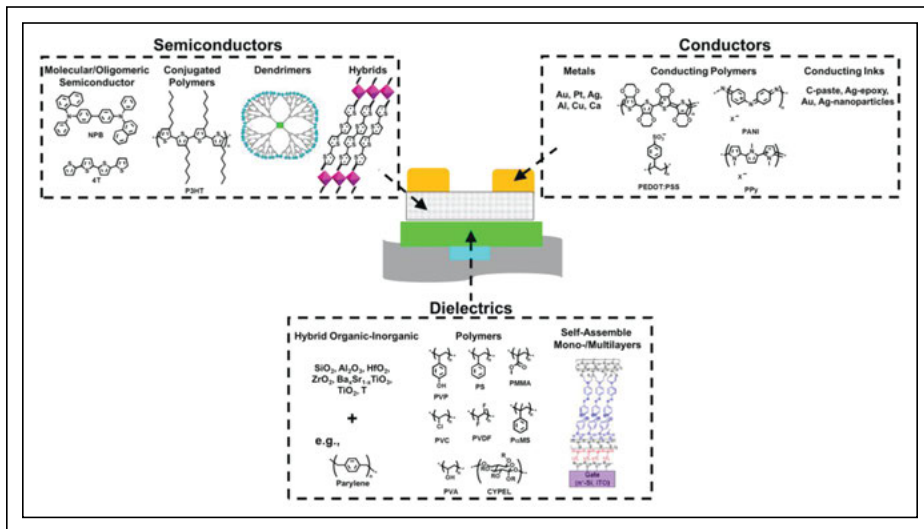


Fig. 2: Electronic materials classes for organic thin-film transistors include those for semiconductors, conductors, and dielectrics

efficient light absorber for photon absorption and dissociation. Displays may be based on different technologies for pixel fabrication including OLED, electrophoretic inks (proper dyes are necessary), liquid-crystal (LC molecules are used), and electrochromic compounds. Many other types of chemicals/materials may also be necessary for device fabrication, including small molecules as interfacial layers for efficient charge injection or surface-energy match, additives used as dopants or stabilizers and polymers for encapsulation.

Tremendous progress has been made during the past 5 years in enhancing the performance of solution-processable electronic materials.⁵⁻⁸ Particularly, organic semiconductors in transistors have achieved exceptionally large field-effect mobilities, approaching those of poly-Si. However, these performances have not been demonstrated with a scalable and fab-compatible materials set. For instance, mobilities of > 10 and > 40 cm²/V-sec have been reported for organic TFTs based on solution-processed polymeric and molecular semiconductors; however, the gate dielectric was an oxide

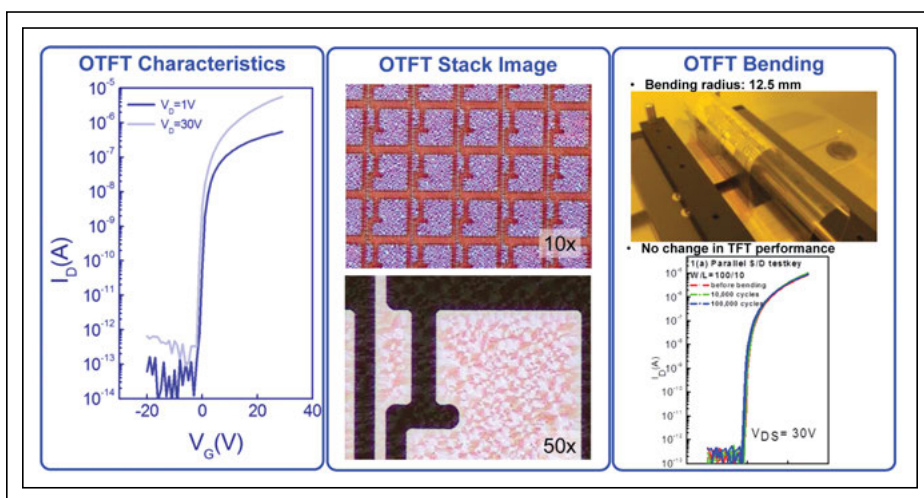


Fig. 3: The authors' organic TFT technology is represented in terms of electrical, morphological, and mechanical characteristics.

Table 1: The properties and performance of selected TFT materials, ranging from metal oxides to polymers, are shown above. Note: s = conductivity; m = charge-carrier mobility; J = leakage current density; BF = breakdown field.

Performance/Needs	Materials					
	Conductor		Semiconductor		Dielectric	
	Metal/Metal Oxides	Polymers	Small Molecules	Polymers	Inorganics	Polymers
Current Materials	Ag, Au, Cu nanoparticles ITO	PEDOT:PSS PANI CNT Graphene	Heteroarenes and acenes Oligothiophenes Perylenes	DPP-based NDI-based Polythiophenes	Oxides-epoxy	PMMA Crosslinked PVP
Current Performance	$\sigma > 10^4$ S/cm	$\sigma > 1$ S/cm ($\sim 10^4$ S/cm)	$\mu = 1\text{--}40$ cm ² /Vs $I_{\text{on}}:I_{\text{off}} > 10^6$	$\mu = 1\text{--}10$ cm ² /Vs $I_{\text{on}}:I_{\text{off}} > 10^6$	$J < 10^{-7}$ A/cm ² BF > 5 MV/cm	$J < 10^{-8}$ A/cm ² BF > 6 MV/cm
Advantage	Good processability High conductivity	Good processability Sufficient conductivity	Easy purification Facile scale-up	Easy ink formulation	Tunable permittivity	Easily solution processable
Limitations	Costly	Low speed applications	Difficult ink formulation for printing Ambient stability	Difficult purification Lower performance Ambient stability	Leaky Rough surface Thick films	Low permittivity High Permeability Thick films
Polyera Materials	-	-	$\mu = 2\text{--}7$ cm ² /Vs $\mu > 1$ cm ² /Vs (FAB, plastic substrate) $I_{\text{on}}:I_{\text{off}} > 10^7$	$\mu = 1\text{--}6$ cm ² /Vs $\mu = 0.5\text{--}1$ cm ² /Vs (FAB, plastic substrate) $I_{\text{on}}:I_{\text{off}} > 10^7$		$J < 10^{-8}$ A/cm ² BF > 6 MV/cm (k > 10)

and/or the solvent used in formulation was unacceptable (Table 1). In addition, most processes were carried out at high temperatures during film deposition or post-deposition, which is unacceptable in standard equipment, and the TFT array area was very small.

The authors' specific work in this area is to provide a total materials set to enable OTFT fabrication via wet process of the key materials components on mechanically flexible plastic foils. Other companies, such as Merck, are also pursuing a similar goal. Our materials set includes a polymeric photocurable buffer to coat the TFT substrate, the organic semiconductor, a photolithography material compatible with our semiconductor channel, a photocurable gate dielectric, a passivation layer, and a planarization layer. The combination of this material enables, in a conventional fab, excellent transistor I - V characteristics and monolithic integration into a TFT array over Gen 2.5 substrates (Fig. 3).

This set of electronic materials has satisfied chemical scalability (they can all be scaled to

commercial kg-scale volumes using safe and environmentally acceptable chemical processes) and stringent electrical performance parameters (acceptable performance variance and negligible bias stress). In addition, the corresponding films, combined into multiple layers that are integrated into a TFT architecture, are mechanically robust and flexible, as demonstrated by our mechanical tests. Therefore, we have made great efforts to develop a materials set with performance equal to or greater than that for amorphous-silicon and processed in a conventional fab infrastructure without any modifications.

For specific applications in flexible displays and wearable electronics, we demonstrated that this material stack is compatible with plastic substrates and the fabrication of flexible displays via bond-debond processes (Fig. 4). The bond-debond processes are the most advanced, and here the plastic substrate is glued to a glass plate that is then processed using standard tools for the fabrication of the TFT backplane and then the front plane.⁹ Cer-

tain plastic substrates such as PET and PEN impose temperature restrictions on the process because they start to deform at temperatures >200°C. Recently, developed PI can withstand far higher temperatures, although it is more expensive. At the end of the process, the display is debonded from the glass plate. If the display is sufficiently bendable, it can be rolled off the glass plate at moderate temperature. The glass plate can then be cleaned and reused.

Flexible Displays

A typical display structure comprises at least a substrate, a TFT backplane driving the pixel, a frontplane enabling the image, and passivation/encapsulation films. Touch is used in nearly every advanced portable display product. Frontplane technologies suitable for flexible displays must be very thin because the display itself must be very thin. Probably the most advanced (and complementary in several aspects) frontplane technologies are electrophoretic¹² and OLED.¹³ Figure 5

shows examples of displays fabricated with these technologies.

Electrophoretic displays have been on the market in e-Readers since 2004. The electrophoretic layer is 20–40 μm , which is relatively thick, but does not require any optical films, a backlight, or extreme oxygen barriers. This is a bistable technology, in which the image remains without the need of refresh. Thus, power consumption is minimal and is ideal for wearable displays. Furthermore, this technology does not need very high-performance transistors to drive the pixel, and the performance of amorphous-silicon is sufficient. This display medium is therefore very well suited for flexible displays where low power is required. Polymer Vision, Seiko-Epson, Sony, AUO, Plastic Logic, and Polyera (among others) have demonstrated flexible electrophoretic displays.⁹

OLED displays do not require a backlighting unit; however, they do rely on an optical stack at the front side that typically includes a polarizing and a retarding film to increase the daylight contrast. The severe sensitivity of the OLED material stack to air during operation requires the use of barrier films with very low permeation to oxygen and water, something that glass and steel films can provide but that plastic substrates cannot unless using organic-inorganic multi-layered coatings. Furthermore, the transistors needed to drive OLEDs have higher stability and uniformity requirements compared to that for electrophoretic displays and LCDs.

Currently, mainly LTPS transistors are used to drive the OLED pixels. For OTFTs to be able to drive OLED pixels, two main requirements need to be fulfilled. The first is a carrier mobility that is high enough to supply the current to the OLED pixels using small enough transistors. To achieve this goal, a mobility higher than 1 $\text{cm}^2/\text{V}\cdot\text{sec}$, preferably higher than 3 $\text{cm}^2/\text{V}\cdot\text{sec}$, is required. The second is TFT stability under electrical stress that is so good that no image artifacts appear on the display, even after years of use. This requires not only a good semiconductor, but also an excellent dielectric material. In general, the state of the art for OTFTs is such that EPDs and LCDs can already be driven, but in order to drive OLED displays, further advances, especially in the area of stability under electrical stress, are needed in the coming years. Once these advances have been achieved, OTFTs will be the prime candidate

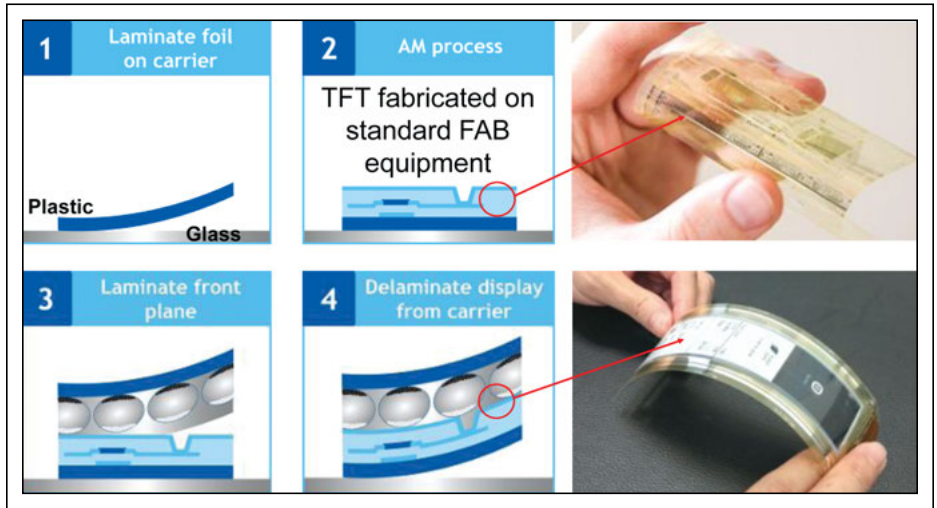


Fig. 4: The process for the fabrication of the display module begins with a plastic substrate and TFT materials.

to realize the full potential of flexible and rollable OLED, which requires a robust TFT backplane solution that is currently missing.

Since OLEDs are current driven, power consumption is a concern for wearable flexible displays, though LG, Samsung, AUO, and Sony have demonstrated flexible OLED

displays. For the above reasons, electrophoretic display technology is ideal for products such as Polyera's Wave Band, which is described in the next section.

Wearing the Flexible Display

The vision behind the Wave Band is to enable

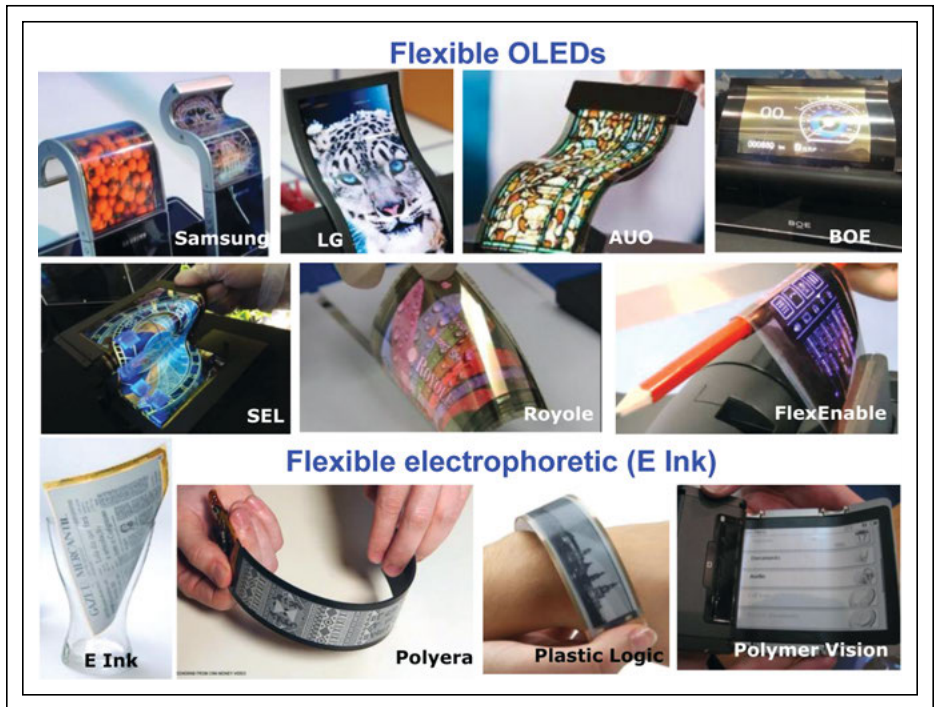


Fig. 5: Examples of flexible displays from different companies include those based on OLED and electrophoretic technology.

a display that forms a natural fabric-based interface with the digital world, summarized in articles like “Digital Goes Material,” which appeared in a recent issue of *Wired*.¹⁴ We believe such a display must be flexible, reflective like fabric, always on, and extremely low power. Polyera has developed a technology that meets these requirements – called Polyera Digital Fabric (see <https://www.youtube.com/watch?v=TsxJMKvtQ98> for an example video).

In Fig. 6, the organic transistor stack (top left) incorporated into the flexible-display module stack (bottom left) is shown. The display module stack benefits from the OTFT stack by giving it a much higher degree of flexibility and robustness than possible when using conventional silicon-based transistors. The display module also incorporates a flexible multi-touch sensor that at the same time is used as the hard-coated top layer of the display. The display module is integrated with a unique mechanical support structure (as shown at right in Fig. 6) that limits the bending range of the display while at the same time minimizing mechanical stress during bending. It consists of an assembly of individual links that are connected in a unique way such that the display does not stretch or compress when flexed in any position.

The specifications of the Wove Band are shown in Table 2. The product uses state-of-the-art electronic components based on the ARM A7 architecture and Bluetooth LE to connect to a phone and runs the Android operating system. This enables receiving messages, alerts, and, in general, content from the Internet, as do other smartwatches. The display area of the Wove Band is six times larger than that of the Apple Watch, as indicated in Fig. 7. This is enabled by, for the first time, using a flexible display in a real flexible product where the digital fabric is wrapped around the wrist of the user. Curved displays have been used in past years by Samsung, LG, and Sony in phones and wearables, but always in a rigid curved configuration. Although this allows the use of a formed cover glass over the display, it greatly limits the use of flexible displays in new product categories. By using a much more robust OTFT stack that uses organic (“plastic”) materials that can handle much more mechanical deformation, we have achieved for the first time the goal of using a flexible display in a dynamically flexible product. The much larger touch-sensitive display improves on the small screens on smartwatches and gives the user the capability of displaying multiple applications simultane-

Table 2: Specifications of the Wove Band include a flexible display with a resolution of 1040 x 200 pixels.	
Operating System	WoveOS (based on Android 5.1)
Processor	Freescale i.MX7 dual core ARM Cortex A7
Memory	4 GB storage and 512 MB of RAM
Battery life	> 24 hours, capacity: 230 mAh
Connectivity	Bluetooth 4.0
Sensors	9 axis motion sensor
Haptic feedback	ERM vibration motor
SDK	Java, HTML5/CSS3/JS and graphical tool
Display	
Type	Electrophoretic, 16 gray
Resolution	1040 × 200 pixels
Size	30 mm × 156 mm; 6.25 in. diagonal
Resolution	170 ppi
Touch	Multi-touch integrated
Thickness	0.23 mm including touch sensor
Flexibility	50k bends at 15-mm radius



Fig. 6: The backplane and stack at left enable flexible-display-based products such as the Wove Band shown at right.

ously on their wrist. This essentially solves two very important problems of current smartwatches. The first is the inefficient methodology in which the user has to swipe through a large number of screens to reach the desired function on the watch. The second problem is the absence of “at-a-glance” information. Current smartwatches are typically not capable of displaying the information that a user needs at any specific moment, due to the small display size and the fact that the display has to be turned off most of the time to conserve power. The Wove Band solves the above problems by offering a much larger display that can show multiple pieces of relevant information in parallel and has a display that is always on. A complete menu can be displayed at once, which enables quick navigation through settings and application menus, very similar



Fig. 7: A typical screen shot includes a variety of information that can be displayed on the Wove Band. Indicated in blue are the relative size of the small (38 mm) and large (42 mm) Apple Watch displays that have a 6.5 and 5.4 times smaller display area than the Wove Band, respectively.

to current smartphones. This is demonstrated in Fig. 7, where a typical content mix appears on the Wove Band. Multiple applications are showing real-time status. Users can change the layout and applications to their needs, such that the most relevant information is shown.

Applications that will be enabled on the Wove Band are the types that are typically found on current smartwatches, such as notifications and messages including full text, music player control, fitness trackers, calendars, and watch faces. On the Wove Band, however, multiple applications typically will be active simultaneously and showing information on different portions of the display.

A Fabric for the Future

The digital fabric created by Polyera to create the Wove Band can also be incorporated into a wide range of products in the near future, such as wristbands, smartphone cases, headphones, bags, and much more. It will also enable software companies (apps, existing social systems, etc.) to re-imagine how their content and services might operate on this alternative surface.

The work carried out by the authors at Polyera Corp. has merged expertise spanning from chemistry, materials science, and applied physics to mechanical, electrical, and software engineering to enable a complete materials solution and product possibilities for unconventional devices – particularly mechanically flexible displays and circuits – that have yet to be imagined.

References

- ¹S. R. Forrest, “The path to ubiquitous and low-cost organic electronic appliances on plastic,” *Nature* **428**, 911–918 (2004).
- ²R. R. Søndergaard, M. Hösel, and F. C. Krebs, “Roll-to-roll fabrication of large-area

functional organic materials,” *Journal of Polymer Science Part B: Polymer Physics* **51**, 16–34 doi:10.1002/polb.23192 (2013).

³M. M. Voigt *et al.*, “Polymer Field-Effect Transistors Fabricated by the Sequential Gravure Printing of Polythiophene, Two Insulator Layers, and a Metal Ink Gate,” *Advanced Functional Materials* **20**, 239–246, doi:10.1002/adfm.200901597 (2010).

⁴H. Yan *et al.*, “A high-mobility electron-transporting polymer for printed transistors,” *Nature* **457**, 679–686

⁵A. Facchetti, “ π -Conjugated Polymers for Organic Electronics and Photovoltaic Cell Applications,” *Chemistry of Materials* **23**, 733–758 (2011).

⁶B. Kumar, B. K. Kaushik, and Y. S. Negi, “Organic Thin Film Transistors: Structures, Models, Materials, Fabrication, and Applications: A Review,” *Polymer Reviews* **54**, 33–111 (2014).

⁷Y. Yuan, G. Giri, A. L. Ayzner, A. P. Zoombelt, S. C. Mannsfeld, J. Chen, C. Nordlund, M. F. Toney, J. Huang, and Z. Bao, “Ultra-high mobility transparent organic thin film transistors grown by an off-centre spin-coating method,” *Nature Communications* (2014).

⁸Y. Fukutomi, M. Nakano, J.-Y. Hu, I. Osaka, and K. Takimiya, “Naphthodithiophenediimide (NDTI): Synthesis, Structure, and Applications,” *Journal of the American Chemical Society* **135**, 11445–11448 (2013).

⁹E. Huitema, “The Future of Display is Rollable,” *Information Display* **28**, 2/3, 6–10 (2012).

¹⁰K. Myny *et al.*, “An 8b organic micro-processor on plastic foil,” ISSCC 2011, session 18.1, February 20–24 2011, San Francisco, CA, USA.

¹¹E. Huitema, “Flexible electronic-paper active-matrix displays,” *J. Soc. Info. Display* **13**/3, (2005).

¹²M. Wang *et al.*, “Electrophoretic Display Platform Comprising B, W, R Particles,” *SID International Digest of Technical Papers*, 857–860 (2014).

¹³M. Noda *et al.*, “An OTFT-driven rollable OLED display,” *J. Soc. Info. Display* **19**/4, 316–322 (2011).

¹⁴Wired.com, “Hands-On With the World’s First Flexible Wearable”; <http://www.wired.com/2015/10/hands-worlds-first-flexible-wearable/> ■

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Bulk-Accumulation Oxide-TFT Backplane Technology for Flexible and Rollable AMOLED Displays: Part I

In the first of a two-part series on a new backplane technology for flexible and rollable AMOLED displays, the author reviews a bulk-accumulation (BA) amorphous indium-gallium-zinc-oxide (a-IGZO) thin-film transistor (TFT) with 3–5 times the drain current of a comparable conventional single-gate TFT. The advantages of BA TFTs include excellent performance from circuits such as ring oscillators and gate drivers and also higher robustness under mechanical bending.

by Jin Jang

FLEXIBLE DISPLAYS based on active-matrix organic light-emitting diodes (AMOLEDs) have been receiving increased attention recently. The thin-film-transistor (TFT) backplane necessary for flexible OLED displays can be realized with low-temperature polycrystalline silicon (LTPS) or oxide semiconductors because of the high performance of these materials. But amorphous-silicon (a-Si:H) TFTs have an inherent issue of threshold-voltage (V_{th}) shift during OLED operations, so they cannot be used for AMOLED displays. Recent AMOLED products on polyimide (PI) substrates have been based on LTPS-TFT backplanes manufactured using the excimer-laser-annealing (ELA) process, which requires high capital investment and high-manufacturing cost (see Fig. 1 for AMOLED products, including smartphones and smart watches, launched in 2015

using PI substrates). Currently, all AMOLED products manufactured on PI substrates use LTPS with excimer-laser annealing.

Another material with promise for use as TFTs on flexible substrates is amorphous oxide. For the last 10 years, a huge number of research groups have joined to work on amorphous-oxide-semiconductor (AOS) TFTs both on glass and plastic substrates. The first AOS TFT product was released in 2002/2003 by Sharp. It was used in the 9.7-in. iPad Retina AMLCD. After that, many LCD products with amorphous indium-gallium-zinc-oxide (a-IGZO) TFT backplanes were launched by Sharp. In parallel with this work, LG Display had succeeded in creating an AMOLED TV with a-IGZO TFT backplanes that used a coplanar structure. And inverted staggered IGZO-TFT structures using etch-stopper (ES) and back-channel-etched (BCE) technology were also manufactured for AMLCDs for tablet and monitor displays by LG Display, Samsung, and Sharp.

Bulk-Accumulation Oxide TFTs

However, a-IGZO TFTs also have challenges.

The low yield, non-uniformity, and bias instability of oxide TFTs limit their application to commercial products. In this article, we explain the device concept of a bulk-accumulation (BA) TFT, which has many advantages compared with conventional single-gate TFTs. LCDs use a single TFT to charge the cell to a prescribed voltage. Once the cell is charged, the TFT shuts off and the LCD material is rotated to the correct driven state. The system remains stable for the rest of that refresh cycle because the LC material response to the charge voltage is stored in the cell. In an AMOLED display, however, the TFT (or array of TFTs) must continuously conduct current at a prescribed analog value for the entire frame time. Thus, issues such as the stability and uniformity of mobility matter a great deal.

For an AMOLED display, we need at least two TFTs; one is a switching TFT, which plays the same role it does in LCD switching, and the other is a driving TFT that is connected in series with the OLED. Therefore, the driving current always has one directional current flow so that the threshold voltage should be stable during OLED operation, but

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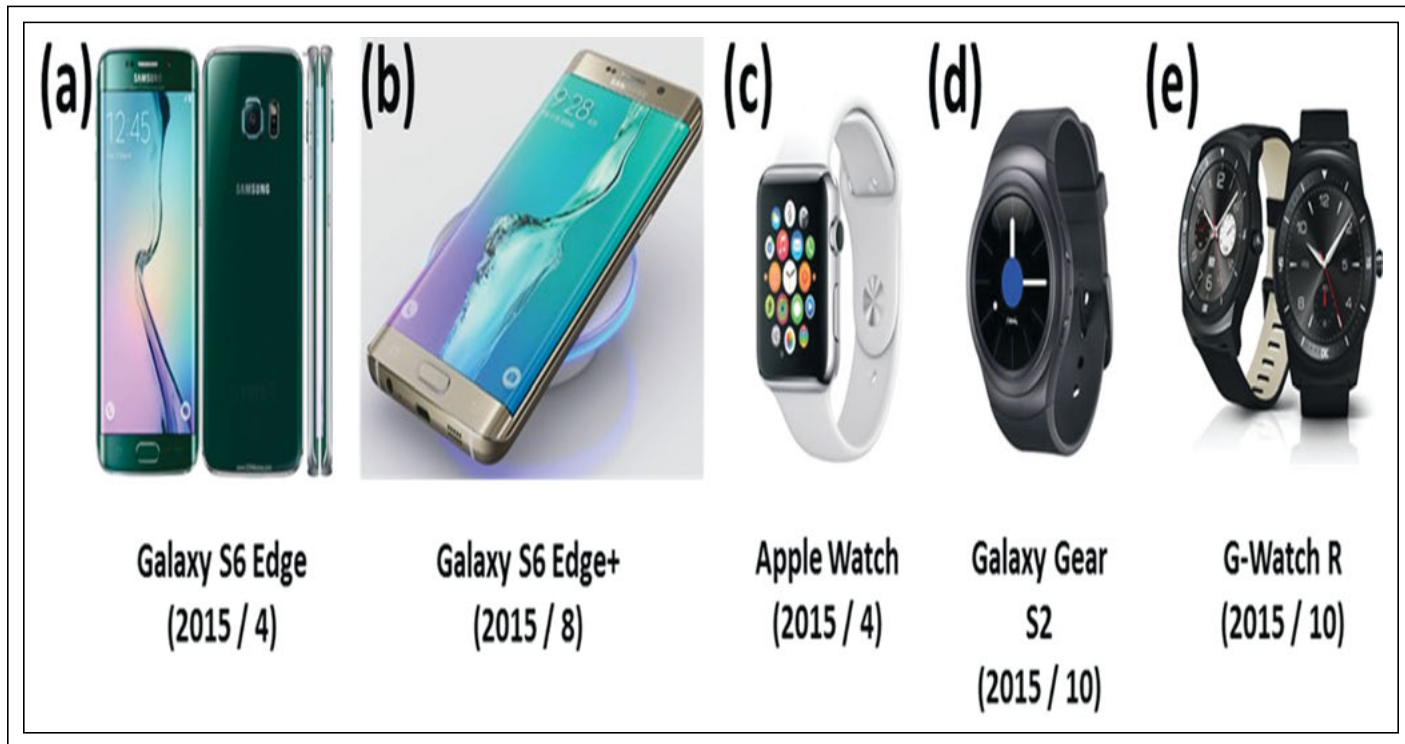


Fig. 1: These commercialized AMOLED products on PI substrates came out in 2015. The AMOLED displays were manufactured by Samsung (a,b,d) or LG (c,e).

an a-Si:H TFT suffers from defect generation via electron accumulation in the channel when the TFT is on, leading to an increase in the V_{th} of the driving TFT, and thus dimming the display screen. This is a fundamental issue that cannot be overcome. Therefore, a-Si:H TFTs cannot be applied to AMOLED displays.

Our university's research teams have made significant progress in overcoming some of these limitations by developing a bulk-accumulation TFT, which employs n-type a-IGZO as its active material, a silicon-dioxide layer as both the gate-insulator and passivation layer, and molybdenum as its metal electrodes [Fig. 2(a)].

A dual-gate TFT has the same device structure as a single-gate TFT,¹ using the bottom as the main gate and the top as an additional gate to control the carrier concentration at the top interface as shown in Fig. 2(a). The transfer curves measured at the bottom gate sweep are shown in Fig. 2(b), where the top-gate potential is controlled from positive to negative. The parallel shift of the threshold voltage is apparent. The electron concentration at the bottom and top interfaces can also

be seen, respectively, in Figs. 2(c) and 2(d), and Fig. 2(e) in bulk accumulation.

The concept of BA is that the induced charges by top- and bottom-gate potentials are placed in the bulk and at the bottom/top interface regions of the channel.² BA is a condition in which the accumulation layer of electrons is not only confined to the semiconductor/gate-insulator interface, but extends to the entire depth of the semiconductor (Fig. 2). We need top and bottom gates because the semiconductor layer is thin – gates cannot be covered at the sides of a transistor's active layer. This is achieved by employing a dual-gate structure in which the semiconductor layer is thin (< 25 nm) and the top gate and bottom gate are electrically tied together [Fig. 2(a)].²

Compared to single-gate-driven TFTs, the benefits of bulk-accumulation TFTs include a drain current that is over three times larger, a turn-on voltage that is closer to 0 V, a smaller subthreshold voltage swing, better device-to-device uniformity, and better bias and light stability [Fig. 2(b)].^{3–5} Better stability is attributed to high gate drive and less carrier

scattering at the interfaces. Because of the bulk accumulation/depletion, the subthreshold swing is always small, the turn-on voltage is always around 0 V, and device-to-device uniformity is much better than that of single-gate TFTs. The increase in the drain currents is partially due to the higher electron mobility with increasing carrier concentration in the channel, as shown in Fig. 2(f).⁶

The requirements for the BA TFT are low density of states (DOS) in the gap of AOS because the accumulation depth from the interface decreases with increasing gap state density and also low density of interface states with bottom- and top-gate insulators. Note that most of the induced electrons accumulate at the interface region when the DOS is high. Another important practical condition is active-layer AOS thickness because the area density of the gap states increases with AOS thickness.

Evidence of bulk accumulation can be seen in the output characteristics of dual-gate TFTs measured under three gate modes: bottom gate (sweeping bottom gate, while grounding top gate), top gate (sweeping top gate, while

grounding bottom gate), and dual gate (synchronized sweep, in which the top gate is connected to the bottom gate) as shown in Fig. 3(a). Given that dual-gate currents are larger than the sum of the bottom-gate and top-gate currents, the device is governed by bulk accumulation. The experimental

evidence of the advantage of BA TFTs is shown in Fig. 3(a), where the currents by dual-gate sweep can be 3–5 times those of single-gate TFTs. The uniformity of the TFT transfer characteristics are compared as shown between Figs. 3(b) and 3(c), where researchers took a bad lot of TFTs to see the

clear difference, using a 15×15 cm glass substrate and showing a large deviation in the transfer curves for bottom-gate TFTs.

The advantage of BA is shown as the increase of mobility with increasing carrier concentration in the channels of oxide semiconductors.⁶ The Hall mobility of oxide semiconductors increases with doping concentration, which is quite different from Si and III-V semiconductors, where mobility drops with increasing doping concentration due to impurity scattering by the ionized impurity atoms.

High-Performance BA Oxide-TFT Circuits

The advantage of BA TFTs can be confirmed by comparing the speed of the ring oscillators made of single-gate (SG) and BA oxide TFTs. The rise and fall times of an example shift register depend on the performance of the TFT used in the design. Our researchers have confirmed the advantage of BA TFTs through a comparison of the TFT circuits of a ring oscillator (RO) and the shift register made of SG and BA TFTs. Note that most AMLCD and AMOLED products with IGZO TFT backplanes have the driver ICs bonded in the peripheral area due to inferior TFT uniformity and performance.

Figure 4(a) shows the equivalent-circuit schematics of an inverter (left) and its 11-stage ring oscillator with output buffers (right). In each inverter stage, the width (W) of the load and driving TFTs are, respectively, 60 and $480 \mu\text{m}$ with $L = 10 \mu\text{m}$. Typical output waveforms of SG-driven and BA-driven ROs are, respectively, shown as symbols in Figs. 4(b) and 4(c) for $V_{DD} = 20 \text{ V}$.⁷ The oscillation frequencies are ~ 334 and 781 kHz , respectively, for SG driving and BA driving. The RO implemented with BA-driven TFTs oscillates at a higher frequency, the speed of which is comparable to that of ROs based on etch-stopper-type TFT structures.⁸ Note that the high oscillation frequency exhibited by the BA-driven RO presented herein is achieved at a lower V_{DD} and with the simple back-channel-etched (BCE) process. This is mainly due to two reasons: (1) the μFE under BA driving is higher than that of the SG TFT; (2) the top gates do not introduce additional parasitic capacitance owing to the $2\text{-}\mu\text{m}$ offsets between TG and the source/drain.^{2,9} The SmartSpice simulation results of the output

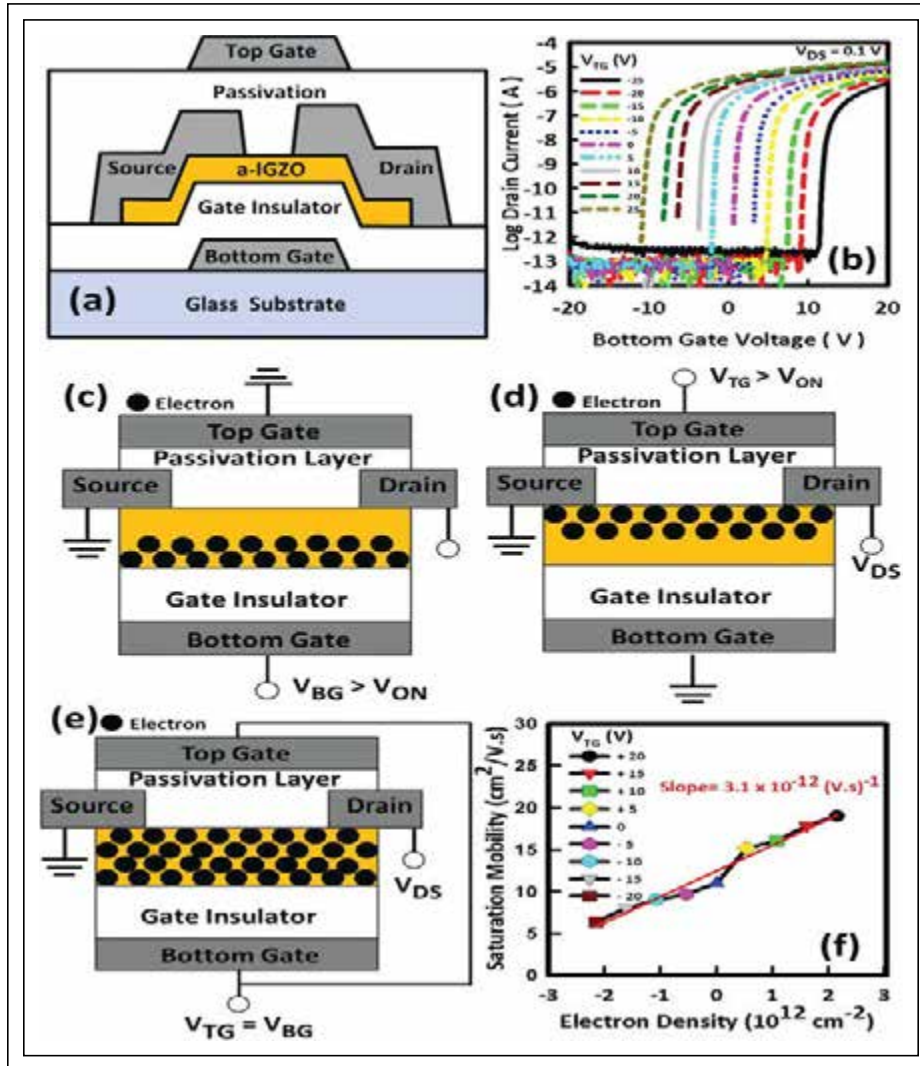


Fig. 2: The structure and characteristics of dual-gate a-IGZO TFTs are shown, including (a) a schematic cross-sectional view of a dual-gate TFT and (b) transfer characteristics measured for $V_{DS} = 0.1 \text{ V}$ with the bottom-gate (V_{BG}) sweep from -20 to 20 V , while biasing the top gate (V_{TG}) with various constant potentials from -25 to 25 V with 5-V steps. In (c), (d), and (e), schematic cross-sectional views of the electron accumulation region are shown in (c) a bottom-gate sweep, (d) a top-gate sweep, and (e) a dual-gate sweep (BG is electrically tied to the TG). Dual-gate driving results in bulk accumulation when the active layer is thin, whereas in single-gate driving TFTs, the channel is confined to the interface regions. The mobility in the saturation region extracted from the bottom-gate sweep vs. the electron density in the channel induced by the top-gate bias is shown in (f).⁶

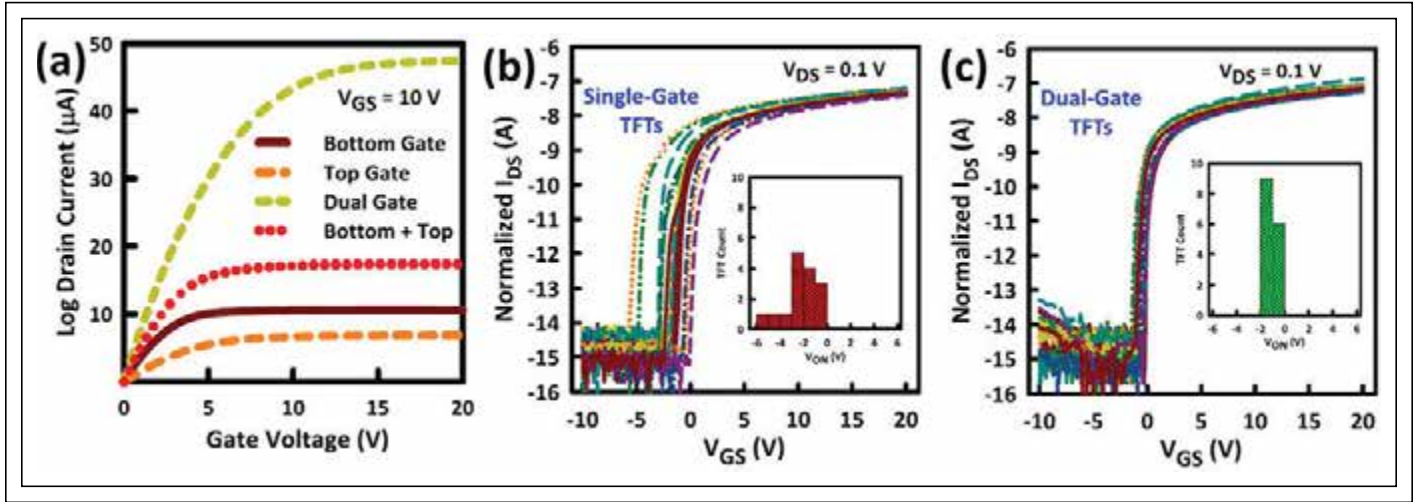


Fig. 3: In (a), the output characteristics of a dual-gate a-IGZO TFT under various gate bias sweep modes is shown. “Bottom Gate” is only the bottom-gate voltage sweep with grounding of the top gate. “Dual Gate” is the gate sweep with the top gate electrically tied to the bottom gate. “Bottom + Top” is the sum of the currents by bottom-gate and top-gate sweeps. Transfer characteristics of 15 single-gate (b) and 15 dual-gate (c) a-IGZO TFTs are shown across a 15×15 -cm glass substrate with TFTs with a channel width (W) = $20 \mu\text{m}$ and channel length (L) = $20 \mu\text{m}$. Dual-gate TFTs are dual-gate driving. Insets of (b) and (c) are the histograms showing the distribution of the turn-on voltages.²

waveforms (solid lines) of the two types of ROs match well with the experimental results. This good agreement is due to the excellent uniformity of fabricated a-IGZO TFTs and the consistency of their dynamic characteristics with static characteristics.

The speed of a-IGZO TFT-based circuits can be further enhanced by proper circuit design. Figure 4(d) shows a proposed pseudo-CMOS inverter (left) and its 7-stage RO with pick-out buffers (right).¹⁰ The advantage of the pseudo-CMOS circuits compared to the ratioed inverters [Fig. 4(a)] can be seen in Ref. 11. Figure 4(e) shows the VDD frequency dependency, including the comparison between pseudo-CMOS-type ROs using SG and BA TFTs with $L = 10$ or $6 \mu\text{m}$. A RO with an $L = 6 \mu\text{m}$ shows faster speed, but both results show much higher speed compared to those of a SG TFT-based RO. This result, therefore, proves that due to the better switching characteristics of BA TFTs, which include higher on-state TFT current and lower switching speed, the switching speed of pseudo-CMOS circuits can also be improved by the implementation of BA TFTs.

The shift registers based on SG and BA a-IGZO TFTs were fabricated. Optical images of the fabricated SG and BA shift register are shown, respectively, in Figs. 5(a) and 5(b). Typical output waveforms of SG and BA a-IGZO TFT-based shift registers are,

respectively, shown in Figs. 5(c) and 5(d) for a pulse height $V_H = 20$ V.

The current levels of driving TFTs are important because they determine the delay time of the gate driver by taking advantage of the high on-currents in BA a-IGZO TFTs. The rise and fall times are 0.83 and 0.84 μsec for the BA-TFT-based shift register and 1.08 and 1.22 μsec for the SG-TFT-based shift register, respectively. It is well known that parasitic capacitance slows down dynamic operation. Here, the top gate does not introduce additional parasitic capacitance (between TG and S/D), due to the $2\text{-}\mu\text{m}$ offsets. Low-level-holding TFTs require good stability under positive-bias stress, given that they are mostly in on-state to maintain the voltage at node Q and output at low during the low-level holding period. However, BA a-IGZO TFTs have been reported to be very stable under positive-bias stress, which indicates a higher yield and longer lifetime. In addition, BA-TFTs give better turn-on voltage (V_{ON}) uniformity compared to that of SG-TFT.⁵ Because of bulk accumulation/depletion, the TFT V_{ON} is always close to 0 V, indicating an enhancement-mode operation, which allows the realization of simple shift-register circuits without the necessity of level shifting or additional low-level signals.

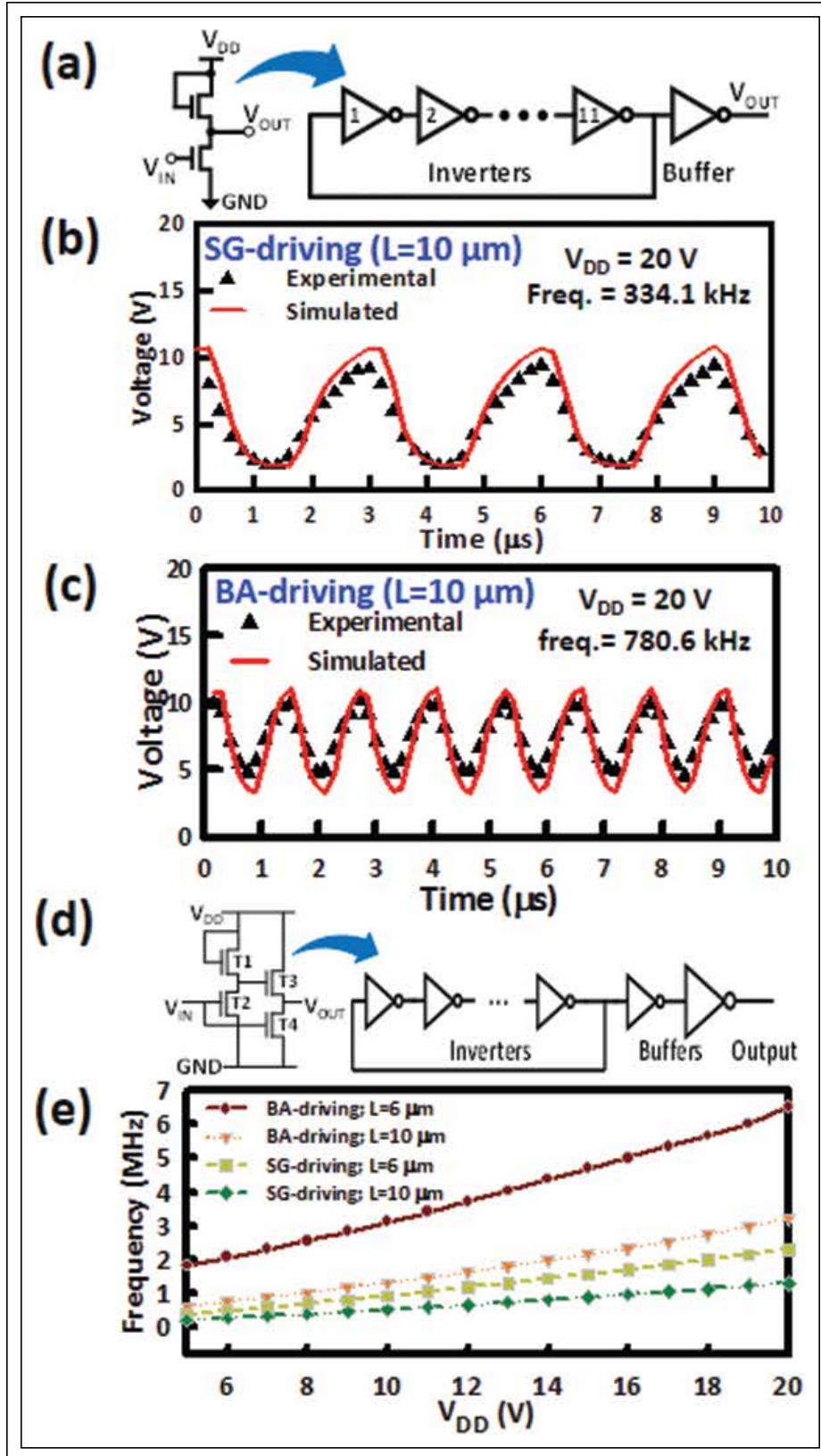
We have confirmed that BA-TFTs with a TG offset structure enhances the speed and

lifetime of the shift register⁵ through advantages such as high I_{ON} and a small sub-threshold swing (SS). We were then able to further reduce the pitch (width) of the BA-TFT-based shift register. Earlier, we had reported a $30\text{-}\mu\text{m}$ -pitch gate driver.¹² The single stage is small in physical size – only $720 \times 30 \mu\text{m}$ – much smaller compared to other oxide-TFT-based gate drivers reported in the literature. Figure 5 (bottom) shows the output waveform of the gate driver for an input pulse V_H of 20 V with a pulse width of 2 μsec . The high-output voltage and rise and fall times are, respectively, ~ 19.7 V, 583 nsec, and 617 nsec.

To this point, we have described the attributes and benefits of BA oxide-TFT backplanes. In part II of this article, we will describe a flexible AMOLED display with integrated gate drivers using BA-oxide TFTs that is demonstrated with a carbon-nanotube/graphene oxide (CNT/GO) buffer embedded in a plastic substrate.

References

- ¹M. J. Seok, M. H. Choi, M. Mativenga, D. Geng, D. Y. Kim, and J. Jang, “A full-swing a-IGZO TFT-based inverter with a top-gate-bias-induced depletion load,” *IEEE Electron Device Letters* **32**(8), 1089–1091 (2011).
- ²M. Mativenga, S. An, and J. Jang, “Bulk Accumulation a-IGZO TFT for High Current



and Turn-On Voltage Uniformity," *IEEE Electron Device Letters* **34**(12), 1533–1536 (2013).

³S. Hong, S. Lee, M. Mativenga, and J. Jang, "Reduction of negative bias and light instability of a-IGZO TFTs by dual-gate driving," *IEEE Electron Device Letters* **35**(1), 93–95 (2014).

⁴S. Jin, T.-W. Kim, Y. Seol, M. Mativenga, and J. Jang, "Reduction of positive-bias-stress effects in bulk-accumulation amorphous-InGaZnO TFTs," *IEEE Electron Device Letters* **35**(5), 560–562 (2014).

⁵S. Lee, M. Mativenga, and J. Jang, "Removal of negative-bias-illumination-stress instability in amorphous-InGaZnO thin-film transistors by top-gate offset structure," *IEEE Electron Device Letters* **35**(9), 930–932 (2014).

⁶M. Chun, M. D. H. Chowdhury, and J. Jang, "Semiconductor to metallic transition in bulk accumulated amorphous indium-gallium-zinc-oxide dual gate thin-film transistor," *J. Appl. Phys.* **5**, 057165/1–6 (2015).

⁷X. Li, D. Geng, M. Mativenga, and J. Jang, "High-speed dual-gate a-IGZO TFT-based circuits with top-gate offset structure," *IEEE Electron Device Letters* **35**(4), 461–463 (2014).

⁸D. Geng, D. H. Kang, and J. Jang, "High-performance amorphous indium-gallium-zinc-oxide thin-film transistor with a self-aligned etch stopper patterned by back-side UV exposure," *IEEE Electron Device Letters* **32**(6), 758–760 (2011).

⁹X. Li, D. Geng, M. Mativenga, Y. Chen, and J. Jang, "Effect of bulk-accumulation on switching speed of dual-gate a-IGZO TFT-based circuits," *IEEE Electron Device Letters* **35**(12), 1242–1244 (2014).

Fig. 4: The comparison of the operational speed of the SG-driving and BA-driving circuit shows (a) equivalent-circuit schematics of a ratioed inverter (left) and its 11-stage ring oscillator (RO). Typical output waveforms include (b) an SG-driven and (c) BA-driven RO at the supply voltage $V_{DD} = 20\ \text{V}$. The SmartSpice circuit simulation results in output waveforms (solid lines) of the two types of ROs that match well with the experimental results (symbols). In (d), the circuit schematics of a pseudo-CMOS inverter (left) and its 7-stage RO. (e) shows the output frequency dependency on supply voltage V_{DD} for SG and BA pseudo-CMOS ring oscillators, with channel length $L = 10$ or $6\ \mu\text{m}$.^{9,10}

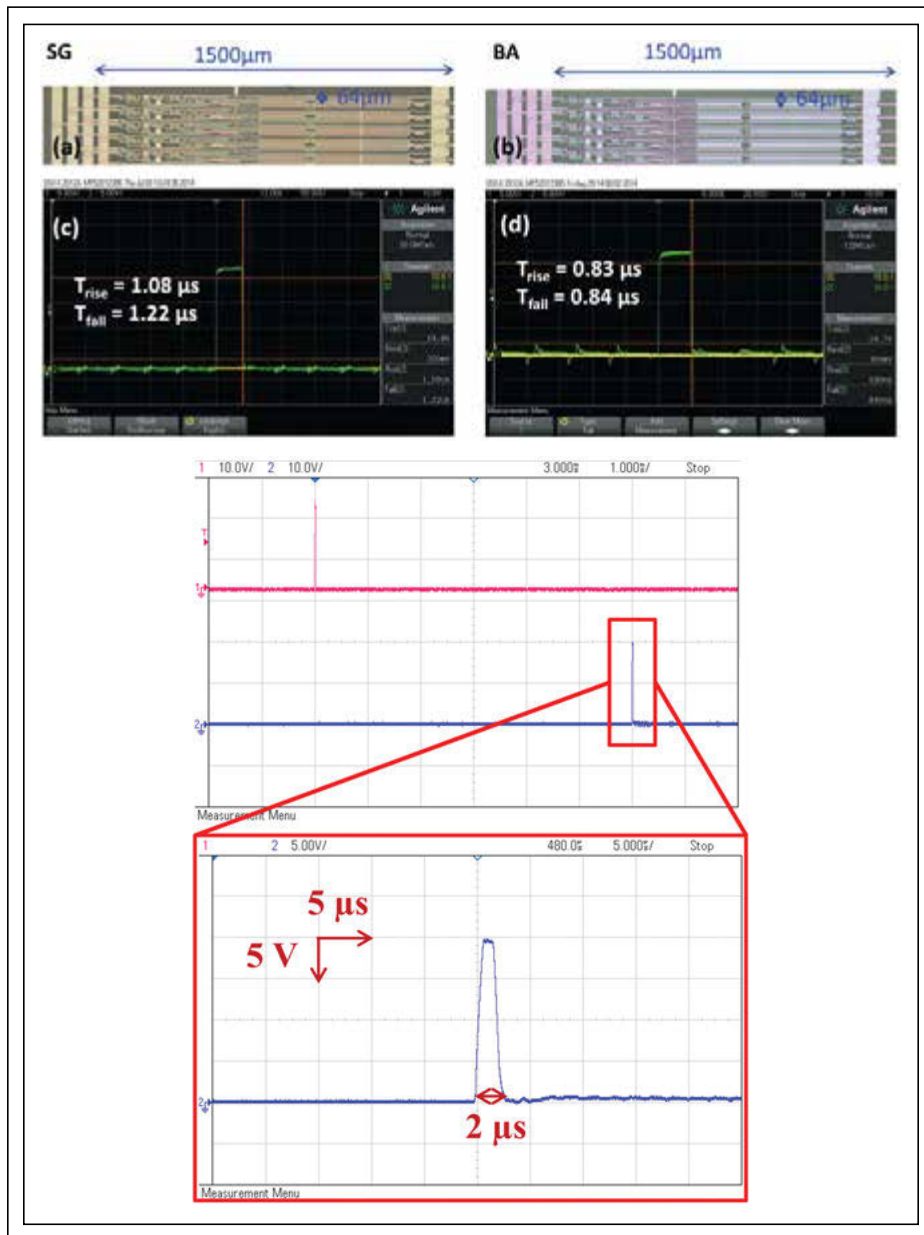


Fig. 5: (a) and (b) are the optical images and (c) and (d) are typical output waveforms for SG and BA a-IGZO TFT-based shift registers, with (a) and (c) for SG and (b) and (d) for BA TFTs. At bottom are output waveforms of the BA shift registers for 30-μm gate drivers with a pulse height of 20 V with a width of 2 μsec.¹²

¹⁰Y. Chen, D. Geng, M. Mativenga, H. Nam, and J. Jang, "High-speed pseudo-CMOS circuits using bulk accumulation a-IGZO TFTs," *IEEE Electron Device Letters* **36**(2), 153–155 (2015).

¹¹T.-C. Huang *et al.*, "Pseudo-CMOS: A design style for low-cost and robust flexible

electronics," *IEEE Trans. Electron Devices* **58**(1), 141–150 (2011).

¹²D. Geng, Y. F. Chen, M. Mativenga, and J. Jang, "30-μm-Pitch Oxide-TFT-Based Gate-Driver Design for Small-Size, High-Resolution, and Narrow-Bezel Displays," *IEEE Electron Device Letters* **36**(8), 805–807 (2015). ■

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Flexible AMOLED Displays Make Progress

AMOLED technology is an emerging technology that has gained tremendous attention in part because of its potential for flexibility. This article provides an overview of AUO's progress in AMOLED technology, from fixed curve to bendable, and now moving toward a foldable display.

by Annie Tzuyu Huang, Chi-Shun Chan, Cheng-liang Wang, Chia-Chun Chang, Yen-Huei Lai, Chia-Hsun Tu, and Meng-Ting Lee

ACTIVE-MATRIX light-emitting diodes (AMOLEDs) are a crucially important and ongoing display research subject for many reasons. They enable, to varying degrees, displays with a slim form factor, fast switching times ($\sim\mu\text{sec}$), energy efficiency, wide color gamut, deep blacks and high contrast, and last, but not least, flexibility, especially compared to that of LCDs. Because LCDs utilize a backlight and require a fixed cell-gap distance, it is difficult for LCDs to achieve flexibility. Because of the recent advances made in both thin-film encapsulation and the thermal resistance of plastic film (see below), we are now moving toward the goal of a truly flexible AMOLED display. In this article, several important technology developments related to AUO's recent work with flexible AMOLED displays will be discussed.

Material Concerns

Encapsulation methods and materials are crucial for AMOLED displays because AMOLEDs degrade rapidly in the presence of oxygen and moisture. Conventional glass-based AMOLED displays use glass encapsula-

tion with frit sealing around the perimeter of the display to prevent moisture and oxygen from entering the OLED panel.¹ In general, this encapsulation needs to achieve a water-vapor transmission rate (WVTR) of $\sim 10^{-6}$ g/m²/day for an AMOLED device to pass its reliability tests, which guarantees 5 years of lifetime. An AMOLED display with glass encapsulation is generally as thick as 7 mm [as shown in Fig. 1(a)]. Even though a thinner panel could be achieved with additional glass-

thinning processes after assembly, the panel would not be flexible, similar to an LCD panel. If glass encapsulation can be eliminated, AMOLED displays gain the advantage of significant flexibility.

Creating Stacks for Flexible AMOLED Structures

Creating a flexible OLED display imposes several additional challenges, including proper backplane selection and elimination of

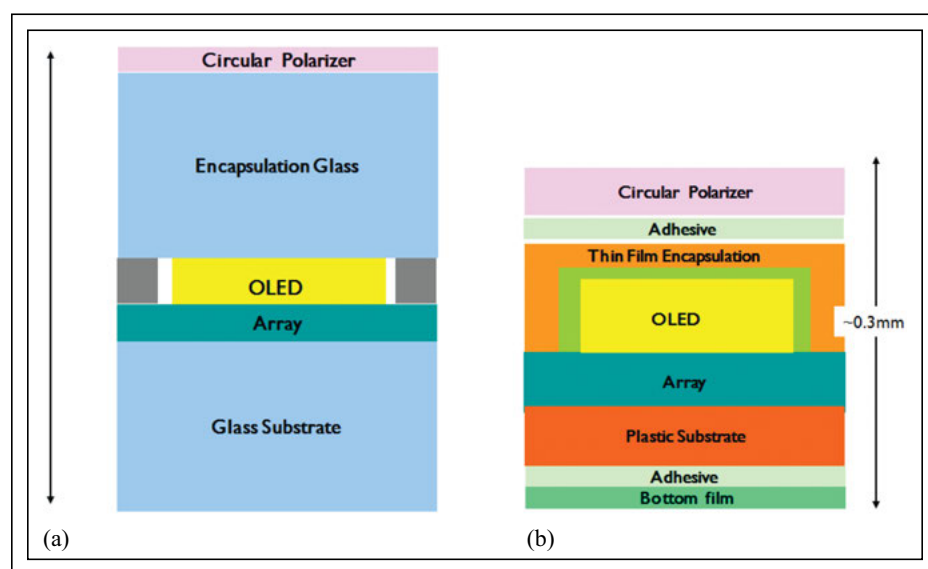


Fig. 1: The structure of a conventional glass-based AMOLED display is shown in (a). The structure of a current flexible AMOLED display (not drawn to scale) appears in (b).

Annie T. Huang and Chi-Shun Chan are senior research engineers, Cheng-Liang Wang, Yen-Huei Lai, and Chia-Hsun Tu are managers, Chia-Chun Chang is a user interface designer of flexible sensors, Yen-Huei and Meng-Ting Lee are currently senior managers, all at AUO. M-T. Lee can be reached at mt.lee@auo.com.

the glass layers, which, in turn, re-introduces the problem of environmental contamination. Special steps must be taken in order to create a flexible-display stack that is also able to achieve sufficient barrier protection. In general, the core of a flexible AMOLED display has the structure shown in Fig. 1(b), where a top-emission AMOLED display is composed of a substrate with a TFT array deposited with OLED layers and thin-film encapsulation (TFE) on the top. Currently, LTPS-TFT is the most common TFT back-plane, due to its higher mobility and better electrical performance compared to other technologies such as amorphous silicon or IGZO.² A circular polarizer is then laminated above the TFE layer and the bottom of the substrate is laminated with a supporting back film. As mentioned earlier, the function of the TFE layer is to protect the AMOLED device from the interaction of oxygen and moisture and obtain the WVTR property of 10^{-6} g/m²/day. Without an additional moisture- and oxygen-blocking layer, none of the plastic layers alone is enough to protect the AMOLED materials properly. Therefore, it is critical to develop a TFE layer structure that can achieve the WVTR requirement.

One of the best-known approaches thus far is to form multiple layers of organic and inorganic thin films, the so-called Vitex technology (after Vitex Systems, the company that developed it).^{3–5} Several authors have reported that flexible encapsulation layers made of alternating Al₂O₃ and polyacrylate layers can achieve 10^{-6} g/m²/day. The inorganic layers act as the primary moisture barrier while the organic layers decouple the pinholes of the inorganic layers. As a result, the diffusion length for water to permeate

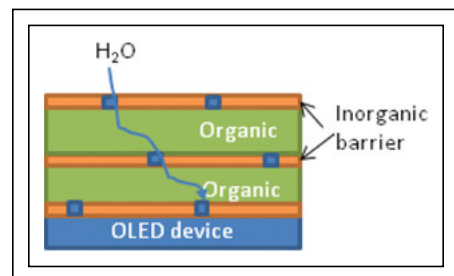


Fig. 2: Inorganic and organic layers are stacked alternately in a thin-film-encapsulation stack that greatly reduces water-vapor transmission rates.

through the stack is extended. In addition, the organic layer works as a planarization layer that provides a smoother surface for the deposition of the following inorganic layer and eases the lamination process applied after the TFE structure is complete. With an alternative stacking approach similar to that shown in Fig. 2 (compared to a single inorganic layer), this type of structure reduced the WVTR dramatically, from 10^{-3} to 10^{-4} or 10^{-6} g/m²/day.

Alternative Approaches to Thin-Film Encapsulation

This Vitex structure is effective, but the fabrication process has proven complicated and costly, and research into lower cost and simpler process TFE has been ongoing. One example is the deposition of hexamethyldisiloxane (HMDSO). Recently, HMDSO has become an attractive material for TFE because it can possess either inorganic or organic properties through simple process tuning using a plasma-enhanced chemical-vapor deposition (PECVD) process.^{6–8} Increasing or decreasing the O₂ content during deposition will cause the film to be more inorganic- or organic-like, respectively.

It is important to consider the optical properties as well as the moisture-blocking abilities of TFE structures, and, accordingly, AUO has recently developed a hybrid structure using HMDSO as a precursor and an optical enhancement layer as shown in Fig. 3. With the application of optical enhancement layers, the performance of OLED displays with TFE

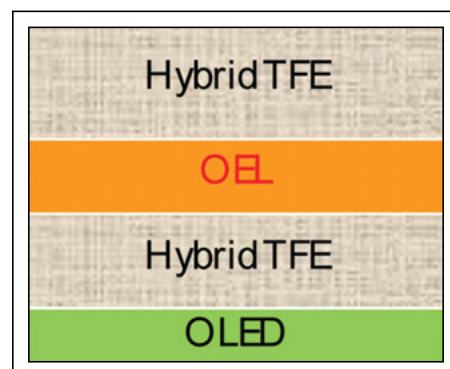


Fig. 3: A recent development from AUO shows a structure incorporating a hybrid TFE with HMDSO as a precursor with optical enhancement layers.

is comparable to glass encapsulation in efficiency and color coordinates as well as viewing-angle properties. More related research is

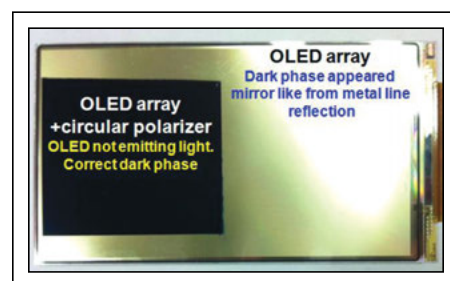


Fig. 4: An OLED panel is shown at left with a circular polarizer and, at right, without one.

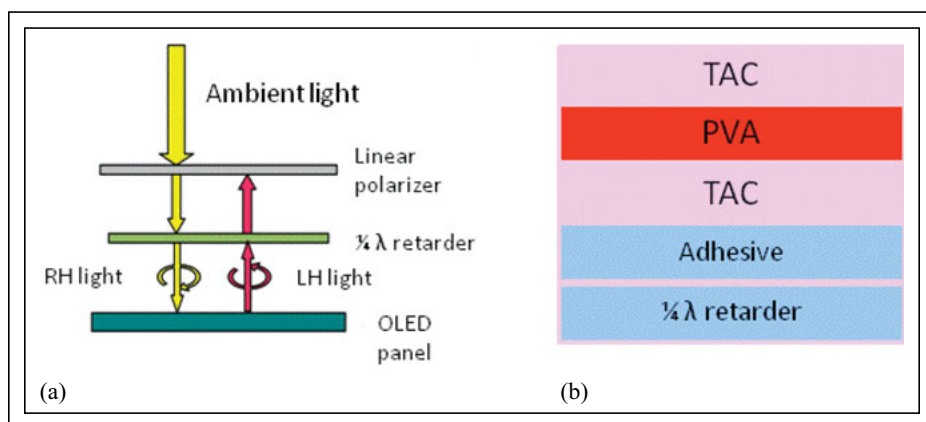


Fig. 5: The basic components of a circular polarizer is shown in (a). For a combination of a linear polarizer and a $1/4 \lambda$ retarder, all ambient light is absorbed. A typical layered structure for a circular polarizer is shown in (b).




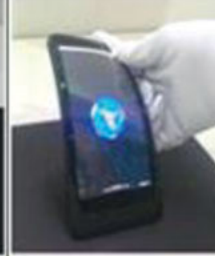
2013	2014		2015
			
	Fixed Curve		Bendable
4.3" (257 ppi) LTS RGB SPR Top emitting	5" (295 ppi) LTS RGB SPR Top emitting R = 30 mm	5" (295 ppi) LTS RGB SPR Top emitting R = 10 mm Curved Lamination	5" (295 ppi) LTS RGB SPR Top emitting Sensor Tech For DUI

Fig. 6: The above photos of flexible AMOLED displays from AUO range from a 4.3-in. fixed curve in 2013 to a 5-in. bendable model in 2015.

under way, and recent development has shown that this structure is able to pass 500-hour aging at 60°C and 90%RH.

Pros and Cons of Circular Polarizers

Adding a circular polarizer to the top of the stack, as shown in Fig. 1, has advantages and disadvantages. The function of a circular polarizer is to filter out ambient light. Because the top of the OLED region consists

of electrodes with high reflection (e.g., Ag) as shown in Fig. 4, at the region without the polarizer, the OLED electrode reflects incident light and the off-state does not appear dark. As a result, contrast ratio suffers. As shown in Fig. 5(a), a circular polarizer consists of a linear polarizer and a $1/4 \lambda$ retarder film. A linear polarizer first allows only linearly polarized light passing through. The $1/4 \lambda$ retarder film then turns the linear waves

to circular waves. When circular rays strike a reflecting surface (e.g., an electrode of a top-emission OLED), their phase relationship is reversed. This results in reflected light that is now in the opposite orientation to the polarizer stack; therefore, the reflected light rays are blocked from leaving the stack. Utilization of a circular polarizer therefore reduces internal reflections and increases the contrast ratio of the display. However, the drawback is that the luminance of the unpolarized light emitted from the AMOLED stack is also reduced by as much as 60%, requiring higher power consumption to achieve the desired luminance levels of the display.

Fixed Curved to Bendable

In 2013, AUO demonstrated a fixed-curve AMOLED panel at Touch Taiwan (International Smart Display and Touch Panel Exhibition) as shown in Fig. 6. The AMOLED display used side-by-side RGB stripe technology with a fine-metal mask to successfully produce a 257-ppi mobile display. The 4.3-in. flexible display incorporated flexible materials and thin-film-encapsulation technology. This display was only 0.2 mm thick and could be formed into a curved shape with a radius smaller than 60 mm. At both Touch Taiwan 2014 and Display Week 2014, AUO showcased a 5-in. flexible AMOLED display using AUO subpixel-rendering technology with an on-cell touch panel on a plastic substrate using TFE technology. This stack allowed a minimum bending radius to less than 10 mm. The panel was also 0.2 mm thick and could be used for smartphones with screens extended to the sides. Users could thus set function keys at desired locations to increase more space for operation and viewing area. To obtain a bent edge, curve lamination was utilized.

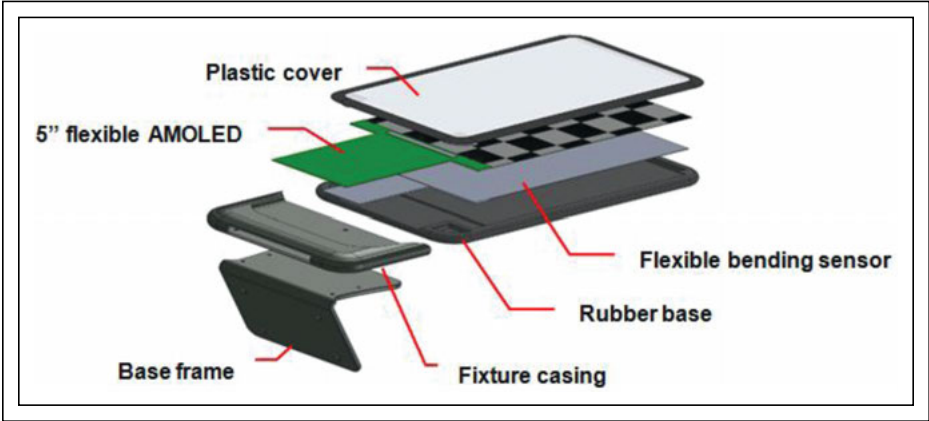


Fig. 7: The structure design of a bendable phone prototype includes both a bending sensor and a touch sensor.

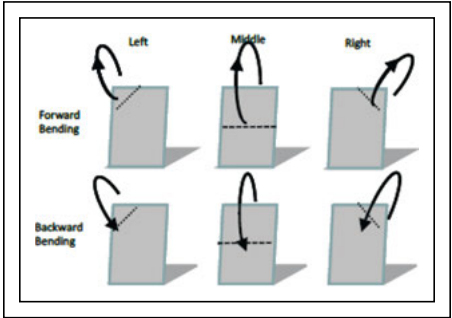


Fig. 8: Six modes of bending operations for a bendable phone are shown.

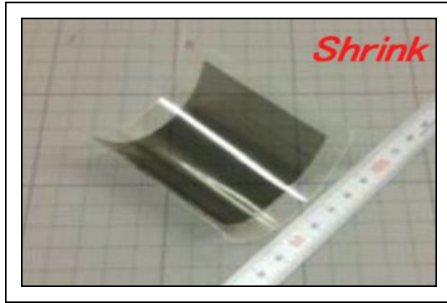


Fig. 9: A polarizer deforms after a reliability test.

AUO then demonstrated a 5-in. 295-ppi bendable AMOLED prototype with a bending sensor at Touch Taiwan 2015 and IWFP (International Workshop on Flexible and Printable Electronics) Korea, as shown in Fig. 6. This flexible AMOLED display incorporates a novel bending interactive interface that works differently from a flat-panel display. It allows users to bend the panel and manipulate the size and direction of the display's active area. The content display on the screen can be manipulated by twisting and bending the unit. The fundamental concept of this technology is to input commands through changing the geometric profile of the display rather than through touch sensing. In other words, the display receives information as it is bent, rolled, twisted, or folded by the user.

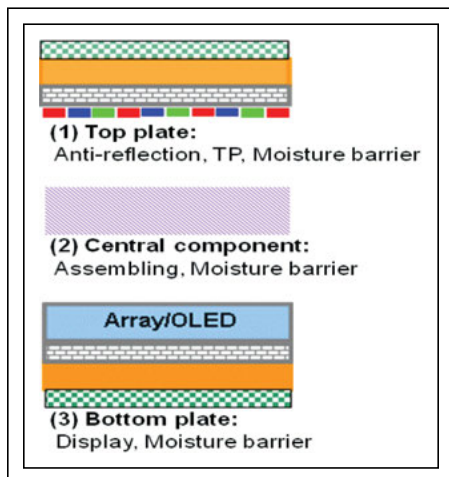


Fig. 10: The layers of an SPS (symmetric panel stacking structure) consist of a top plate and color-filter layer, assembled with an OLED array using a moisture barrier.

The geometric information of the display can be derived from the measurement of the mechanical strain. The relationship of the measured resistance ΔR and mechanical strain ϵ in a strain sensor can be expressed as the following equation:

$$\Delta R/R = F \cdot \epsilon,$$

where R is the initial resistance of the strain gauge when no strain is applied and F is the gauge factor, a constant coefficient depending on the gauge property. The curvature κ along the strain direction is proportional to the measured strain as

$$\kappa = \epsilon/y$$

where y is the distance between the layer of strain gauge and the neutral plane of the flexible display. As shown in Fig. 7, this prototype comprises a 5-in. flexible display with a film-type strain gauge laminated on the back. With precise calibration, we can obtain accurate information of the six bending modes as shown in Fig. 8 from the resistance change measured from the strain gauge of the bending sensor.

Bendability Enables a New Interface

Navigating Google Earth is one possible use for this technology. Bending left or right in forward or backward direction rotates the earth, while bending forward or backward at the middle can zoom in and zoom out the earth, respectively. This bendable phone technology with a flexible AMOLED display provides more intuitive operation and control that bring the user experience to the next level. (For more about this functionality, see the article, "A Flexible Display Enables a New Intuitive User Interface," in the February 2011 issue of *ID*, which discusses research by Toshiba. The difference between the authors' work and Toshiba's is that the former puts multiple sensors on films so that strain can be detected at multiple bending angles.)

Moving toward Foldable Displays

A structure utilizing a polarizer does eliminate the reflectivity of ambient light. However, as mentioned previously, the existence of the polarizer also increases power consumption because the polarizer unavoidably absorbs at least half of the light emitted by the display. As shown in Fig. 5(b), a circular polarizer consists of a multilayered structure with a

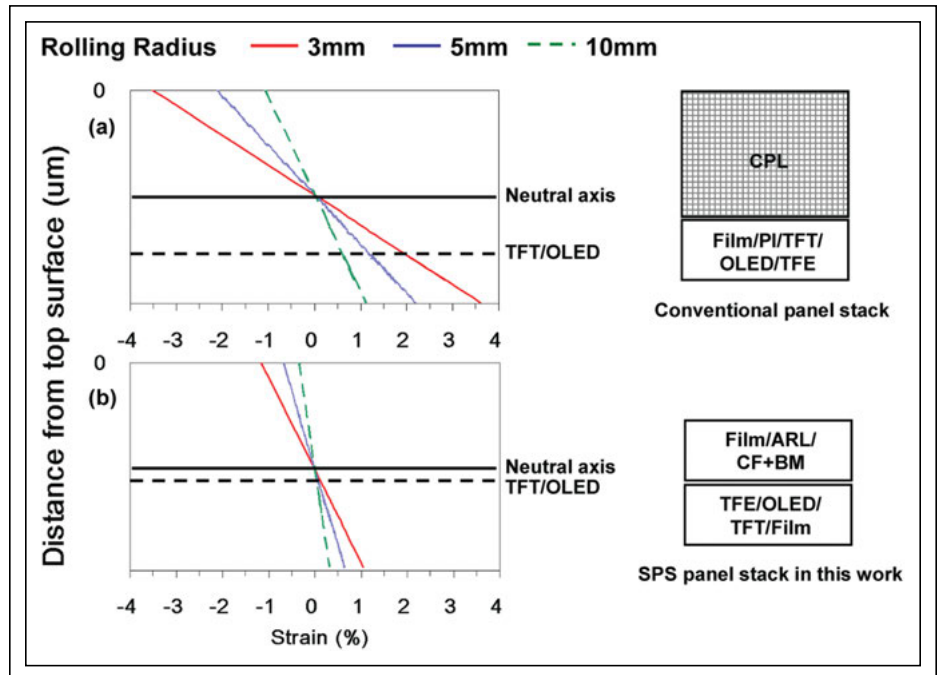
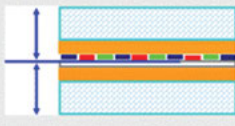



Fig. 11: Strain is shown for different film layers at different rolling radii in (a), an APS structure, and (b) an SPS structure.

Table 1: A comparison of total thickness and stiffness is shown for SPS at left and APS at right.

Stack	SPS	APS
Structure		
Total thickness	<100μm	>300μm
S N/m * E-03	5	14.6

linear polarizer and a $1/4 \lambda$ retarder film. Polarizing properties are usually obtained by straining polyvinyl alcohol (PVA) and fixing this material by laminating it between TAC films. Therefore, it has poor mechanical properties in comparison to alternative polymer films, such as polyethylene terephthalate (PET). Additionally, when this kind of polarizer undergoes environmental reliability tests such as high-temperature storage, it tends to deform as shown in Fig. 9. A coating-type polarizer is a possible alternative, but this type of polarizer has not been mass produced.

Replacing Polarizers with Color Filters

A potential solution to achieve high contrast without as much loss of display luminance is to utilize a color-filter layer instead of a polarizer. As shown in Fig. 10, such a structure consists of a touch sensor and a color filter at the top. The assembly is completed with a moisture barrier. Without the use of a polarizer, the flexible properties of the display are not constrained by the thickness of the polarizer. The thickness of the top and bottom films can be adjusted to obtain a symmetric panel stacking structure (SPS) with the TFT/OLED/TFE located at the neutral plane of the entire structure instead of at the polarizer layer in the original asymmetric panel structure (APS), as shown in Fig. 11.

The color filter utilized was fabricated on a transparent flexible substrate. The black matrix was first deposited, followed by a single color-filter layer with red, blue, and green color coated side by side. The flexible substrate was further laminated with a top film for additional support and to meet optical requirements.

As mentioned earlier, when plastic material such as PET instead of a complex multi-layered polarizer is utilized, the mechanical

property of the flexible AMOLED device is greatly improved in terms of bearing more strain and demonstrating less stiffness. The total thickness can be also reduced to one third of the APS structure, as shown in Table 1. With the application of a color filter, as shown in Fig. 12(a), when the ambient light

first enters the color filter, for example, only red light is able to pass through the red color filter and hits the red OLED layer and is reflected back to the ambient through the red color filter again. As a result, at on-state, the emitted light from the display shows both the red light emitted from the OLED panel plus the red reflected ambient light, not the other colors. Figure 12(b) shows the reflectivity of the SPS structure and the APS structure. Most importantly, as shown in Fig. 13, using the same 5-in. panel, the SPS structure can reduce power consumption by half and double the lifetime.

Recipe for a Foldable Display

With the much improved mechanical properties of SPS as compared to APS, we have obtained a potential candidate for foldable displays. As shown in Fig. 14, a 5-in. panel with an SPS structure was prepared and folded repeatedly at the center. More than 500K folding cycles at a bending radius of

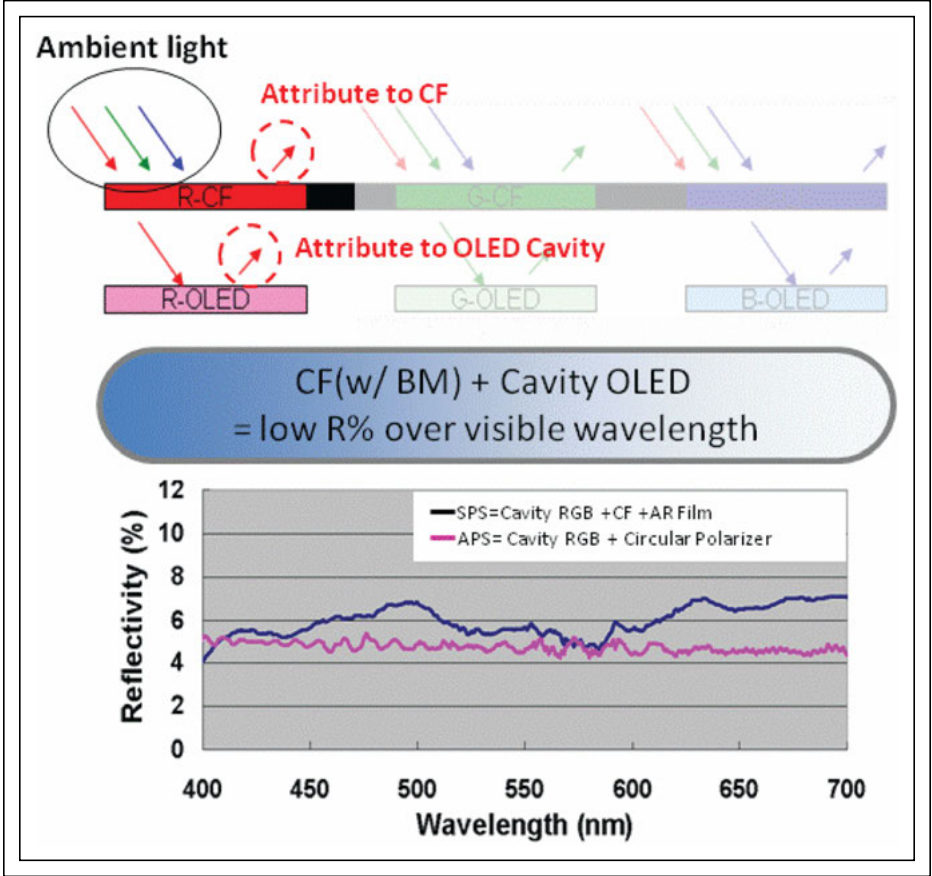


Fig. 12: The path of ambient light into an SPS structure appears at top. At bottom is a comparison of reflectivity for SPS and APS structures.

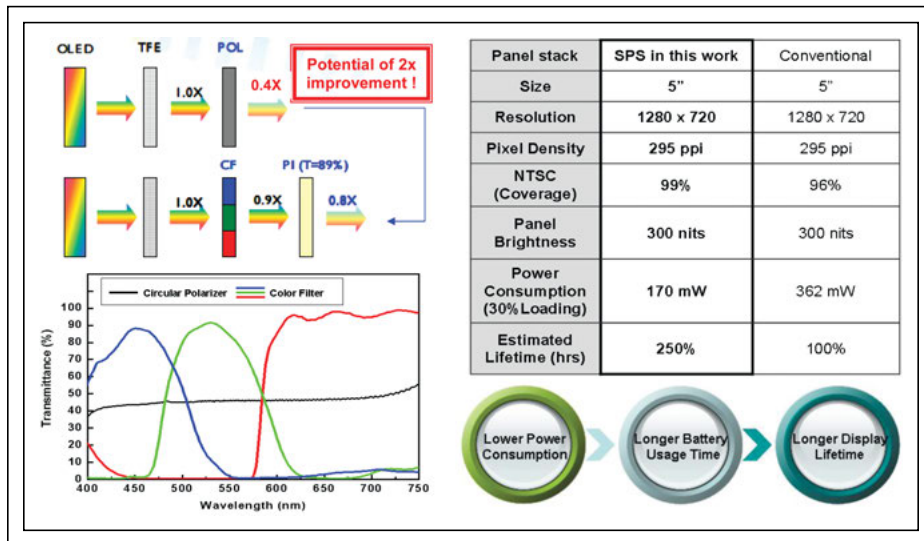


Fig. 13: A comparison of power consumption and light absorption for SPS and APS (conventional) structures shows that the SPS stack consumes less power.

4 mm showed no damage on TFT/OLED/TFE and no effect on the panel's optical property. Flexible AMOLED displays have come a long way from fixed curve to foldable, but more effort is necessary (and currently under way) to realize the latter in terms of taking demo samples from a lab setting to mass production. With continuous effort in materials research,

structural improvements, and additional innovative ideas, it is likely that we are steadily moving toward a bright future with flexible AMOLED technology.

References

¹J. S. Lewis and M. S. Weaver, "Thin-Film Permeation-Barrier Technology for Flexible

Organic Light-Emitting Devices," *IEEE J. Selected Topics in Quantum Electronics* **10**, 45 (2004).

²J. F. Wager, "Flat-Panel-Display Backplanes: LTPS or IGZO for AMLCDs or AMOLED Displays," *Information Display* **30**, No. 2, 26–29 (Mar/April 2014).

³A. B. Chwang, "Thin-film-encapsulated flexible organic electroluminescent displays," *Appl. Phys. Lett.* **83**(1), 413–415 (2003).

⁴M. S. Weaver, L. A. Michalski, K. Rajan, M. A. Rothman, J. A. Silvernail, J. J. Brown, P. E. Burrows, G. L. Graff, M. E. Gross, P. M. Martin, M. Hall, E. Mast, C. Bonham, W. Bennett, and M. Zumhoff, "A single-layer permeation barrier for organic light-emitting displays," *Appl. Phys. Lett.* **81**, 2929 (2002).

⁵C. S. Suen and X. Chu, "Multi thin-film barrier protection of flex-electronics," *Solid State Technology* **51**, 36–39 (2009).

⁶C.-H. Su and T.-C. Wei, "Display Device with Passivation Structure," U.S. Patent No. 7030557 B2 (2006).

⁷P. Mandlik, J. Gartside, L. Han, I. C. Cheng, S. Wagner, J. A. Silvernail, R. Q. Ma, M. Hack, and J. J. Brown, "A single-layer permeation barrier for organic light-emitting displays," *Appl. Phys. Lett.* **92**, 10, 103309 (2008).

⁸L. Han, P. Mandlik, J. Gartside, S. Wagner, J. A. Silvernail, R. Q. Ma, M. Hack, and J. J. Brown, "Properties of a permeation barrier material deposited from hexamethyl disiloxane and oxygen," *J. Electrochem. Soc.* **156**, No. 2, H106–H114 (2009). ■

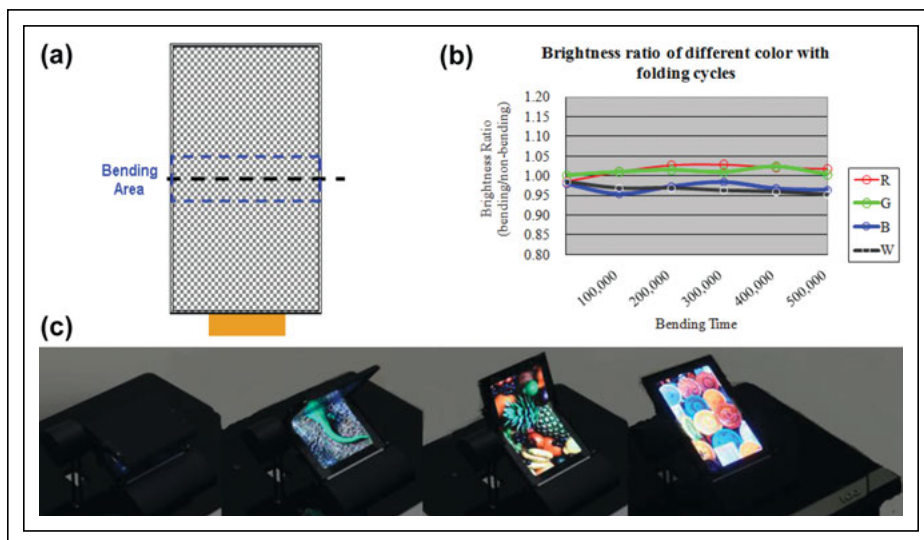


Fig. 14: The bending region of an SPS 5-in. foldable OLED display is shown in (a). In (b), the brightness ratio between bending and non-bending regions is compared after 50K bending cycles. Photos depicting the bending sequence of the 5-in. foldable AMOLED display appear in (c).

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2016 SID Honors and Awards

*This year's winners of the Society for Information Display's Honors and Awards include **Ho Kyoong Chung**, who will receive the Karl Ferdinand Braun Prize for his contributions to the large-scale commercialization and technology development of AMOLED displays; **Seung Hee Lee**, who will be awarded the Jan Rajchman Prize for his invention, product development, commercialization, and basic research of fringe-field-switching LCD devices; **Nikhil Balram**, who will receive the Otto Schade Prize for his outstanding contributions to image, video, and display processing technology and development of objective image-quality benchmarking methodology that helped bring world-class image quality to mainstream consumer displays; **Shunsuke Kobayashi**, who will be awarded the Slottow–Owaki Prize for his long-term outstanding contributions to the education and training of students and professionals in LCD science and technology; and **Anthony C. Lowe**, who will receive the Lewis and Beatrice Winner Award for his outstanding and sustained contributions to the leadership and governance of the Society and the exceptional benefit provided to SID's members throughout his editorship of the Wiley/SID book series.*

by Jenny Donelan

THIS YEAR'S award winners are, as always, an impressive group. In addition to the accomplished new SID Fellows and Special Recognition Award recipients, the major award winners include individuals who have made direct contributions – whether through OLED, LCD, or video algorithm developments – to the TVs, smartphones, and other display devices we use today. Even those being honored for their contributions to education or society activities are accomplished scientists in their own right who have contributed a great deal to display technology.

While there are many qualities these major award winners share – intelligence, perseverance, the ability to work in a team – one quality that really stands out is that they have

paid attention. This is a skill that has been much praised of late. Books such as *The Power of Noticing: What the Best Leaders See* by Max Bazerman describe the power not only of observing a phenomenon but of understanding its significance in relation to everything else. This year's award winners all noticed something different. They also noticed its importance. Inspired by what they saw, they paid further attention – this time to detail – carrying out tasks over years and even decades that achieved results we recognize as brilliant today but that involved many mundane iterations before they could be called successful.

Braun prize winner Ho Kyoong Chung, as a young researcher at Samsung, saw his first OLED in 2001 and understood that it could revolutionize display technology. That vision sustained him through nearly a decade of OLED development, even when the material's

prospects were uncertain, because he had been inspired by what was special about it. Similarly, Rajchman winner Seung Hee Lee, as a graduate student at Kent State University, saw wide-angle-viewing demonstrations that set him on the path of developing fringe-field switching, a technology he and his fellow researchers knew was, in Lee's words, "a game changer." Otto Schade winner Nikhil Balram paid attention not to just one aspect of image processing, but to what he calls "The Visual Pipeline" – from image creation to human reception of the image. Giving considerable attention to all aspects of that pipeline enabled him to create algorithms and semiconductor solutions that were not only technically elegant, but profoundly practical – our video content experience on almost any platform is better today due to his efforts. As a young scientist, Slottow–Owaki winner Shunsuke Kobayashi was intrigued by the

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idea of a truly portable calculator based on LCD technology. As an educator, he shared his enthusiasm for display technology with a passion that helped create many more display scientists. And as an educator he noticed the little things, like that a first-time presenter at the Display Week symposium might be feeling nervous. By helping young researchers prepare for more successful presentations, he set them on a positive path toward creating even greater things. And last, the Lewis and Beatrice Award Winner recipient Anthony Lowe paid attention when he created new chapters in Europe. He could have forged ahead and tried to force the chapters into being, but instead he was sensitive to issues such as national pride and relative average incomes around the world. He paid attention to the contexts in which each country operated and as a result had great success.

Please join us in congratulating this year's outstanding group of SID award winners. They paid attention, both to novelty and to detail. They persevered even when the flow of general opinion might have worked against them. Their efforts created the science, and the Society, that we enjoy today.

2016 Karl Ferdinand Braun Prize

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

Ho Kyoong Chung, SID Fellow and Professor at Sungkyunkwan University in Suwon City, Korea, "for his contributions to the large-scale commercialization and technology development of AMOLED displays."

Those who know Professor Ho Kyoong Chung use words like "passionate" and "tenacious" to describe his approach toward AMOLED development over the past decade and a half. Among his many accomplishments in this area have been the development of mura-free TFT backplane technology, invention of a fine-metal masking technique to deposit RGB pixels uniformly onto TFT backplanes, development of flexible OLEDs using both metal foil and plastic substrates, and work in mirror and transparent AMOLED displays.

"Chung was the driving force behind AMOLED development at Samsung from 2000 to 2008. This was a period when the outlook of AMOLED was at best uncertain," says Ching Tang, a Professor at the University of Rochester and the Hong Kong University of Science and Technology. After receiving



Ho Kyoong Chung

his Ph.D. degree in electrical engineering from the University of Illinois at Urbana-Champaign, Chung worked as a manager of the GaAs Process Development Laboratory in Bloomington, Minnesota, for several years, and then in 1988, embarked on a long career at Samsung. In 2000, he was named Senior Vice-President, Director of AMOLED Technology Development, for Samsung SDI.

Then, in January 2001, Chung saw an OLED for the first time. His team had installed the company's first evaporator with which full-color OLED devices could be made and were able to create a full-color 3.6-in. AMOLED in about a month – an extremely short time, notes Chung. "Our young engineers worked day and night with passion and dedication," he says. Chung felt drawn to the possibilities of the material from the first. "It had such vivid color and a perfect moving picture with a simple structure that did not require any other component," he says. "I felt strongly that it would replace the LCD in the near future."

Chung notes that key advances were needed in order for OLEDs to become viable, including the process optimization necessary to fabricate uniform TFT arrays in the backplane, the development of pixel circuits to compensate for TFT non-uniformity, the fine-metal-mesh manufacturing process development for RGB color patterning, and encapsulation technology using a frit-seal process, which provided a seal to protect the OLED against

moisture and oxygen permeation. "Samsung SDI perfected this seal in collaboration with Corning, and it has become the standard process in AMOLED manufacturing in the world," says Chung. "There are probably a lot more advances which made Samsung SDI successful in AMOLED manufacturing, but I think these four technologies were the key ones."

It is Chung's vision and determination, as well as his technical accomplishments, that have made him successful and impressed others. According to Hyun Jae Kim, Professor with the School of Electrical and Electronic Engineering at Yonsei University, "Back then [in the early 2000s], the display market was dominated by LCDs, and it was hard to imagine that AMOLED displays would emerge as one of the candidates for next-generation display applications. However, Chung saw the potential in AMOLEDs as a next-generation display application and developed a number of fundamental technologies for realization of commercialized AMOLED displays."

These days, Chung is a professor at Sungkyunkwan University, where he pursues research in addition to teaching. His current impetus is the development of roll-to-roll (R2R) processing to improve the productivity of plastic OLED manufacturing.

2016 Jan Rajchman Prize

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

Seung Hee Lee, SID Fellow and a Professor at Chonbuk National University, "for his invention, product development, commercialization, and basic research of fringe-field-switching LCD devices."

As a scientist with the LCD Division of Hyundai Electronics (now Hydis), Seung Hee Lee invented a new wide-viewing-angle technology with high transmittance and low operating voltage. He named this new technology, which overcame the shortcomings of conventional liquid-crystal modes such as TN (twisted-nematic), IPS (in-plane switching), and MVA (multi-domain vertical alignment), "fringe-field switching (FFS)." At present, the FFS mode is used in numerous high-resolution/high-image-quality displays and is employed in devices mass-produced by companies including BOE, Hitachi/Panasonic, LG Display, Samsung, CMI, AUO, Japan Display, CSOT, and more. In addition,



Seung Hee Lee

Apple's iPhone, iPad, and Macbook products use FFS TFT-LCDs.

Lee became interested in the importance of wide-angle viewing after seeing LC device demonstrations by colleagues at Kent State University, where he was pursuing his Ph.D. degree in physics during the early 1990s. After receiving his degree in 1994, he joined the LCD Division of Hyundai in 1995, where his main job was designing LC cells in TFT-LCDs and developing new LC devices. The main problem Lee and his fellow researchers were trying to solve in those days was that of high power consumption on the part of IPS and MVA, the wide-angle viewing solutions of the day. "Both devices showed a much wider viewing angle than that of TN and film-compensated TN mode," says Lee. "However, their transmittance dropped severely and the operating voltage increased." This limited their use to non-portable displays such as monitors and TVs. "We were challenged to develop a new LC device that demonstrates a wide viewing angle and high transmittance simultaneously, so it could be used in both portable and non-portable LC devices," he says.

Lee says he and his team knew early on that FFS would be a game changer. "We had a clear confidence that FFS would show the best performance of all LC modes and that it could be applicable to all types of LCDs, irrespective of size and application, because the FFS mode could overcome long-standing problems in electro-optic performances. In

addition, the LC orientation was the most stable when an external pressure was applied, which made it suitable for touch displays," says Lee. However, he adds that it took longer than he expected for FFS to become a standard mode. "For that, we have to thank the technology trend of LCDs with higher resolution and touch screens, for which the FFS mode was most suitable," he says.

According to Kent State Professor Phil Bos, "It can be said emphatically that Professor Lee's FFS invention is the most influential in the area of displays since the TN mode. His invention is now used in all high-quality smartphones, tablets, and laptop and desktop computers. And it is being rapidly adopted by television manufacturers and has overtaken the TN mode in high-quality display devices. There is a very good chance that most mem-

2016 SID Fellow Awards

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.



Achintya K. Bhowmik "for his pioneering contributions in the fields of interactive computing and displays with natural human interface technologies."

Dr. Bhowmik is a vice-president at Intel Corp., where he leads the RealSense technology and products.



In Byeong Kang "for his many innovative contributions and commercialization of key technologies for large-sized displays, including IPS mode/Cu interconnect, and

advanced future display technologies, including oxide TFTs for large OLED TVs."

Dr. Kang is chief technology officer for LG Display Co. He earned his Ph.D. degree in electronic engineering from the University of South Australia.



Hideo Hosono "for his pioneering research on oxide semiconductors for high-mobility TFTs."

Dr. Hosono is the Founding Director of the Materials Research Center for Element Strategy and a professor in the Materials and Structures Laboratory at the Tokyo Institute of Technology. He earned his Ph.D. degree in applied chemistry from Tokyo Metropolitan University.



Changhee Lee "for his many contributions to the science and technology of OLED displays and quantum-dot LED displays, including highly efficient and stable devices."

Dr. Lee is a professor with the School of Electrical and Computer Engineering at Seoul National University. He received his Ph.D. degree in physics from the University of California at Santa Barbara.



Chung-Chih Wu "for his distinguished contributions to OLED materials and device research and development."

Dr. Wu is a professor of electrical engineering at National Taiwan University. He earned his Ph.D. degree in electrical engineering from Princeton University.

bers of the SID own a display based on his invention, and it is unlikely that this can be said for any other single display invention.”

Lee’s contribution to the LCD community is also notable in that it covers both industrial and academic realms, notes Jae Jin Ryu of Samsung Display. “More than 80 students have graduated from his lab since he joined Chonbuk National University in 2001. Most of these students are now working for LCD-related companies in the display industry,” says Ryu. According to Hyun Chul Choi, Vice-President of LG Display, “The employees from Dr. Lee’s group are well educated not only theoretically but practically. This has been a great help to the Korean LCD industry.”

2016 Otto Schade Prize

The Otto Schade Prize is awarded for outstanding scientific or technical achievement in, or contribution to, the advancement of functional performance and/or image quality of information displays.

Nikhil Balram, SID Fellow and President and CEO of Ricoh Innovations Corp., “for his outstanding contributions to image, video, and display processing technology and development of objective image-quality benchmarking methodology that helped bring world-class image quality to mainstream consumer displays.”

Nikhil Balram has played a pioneering role in inventing video-processing algorithms and implementing them in cost-effective semiconductor architectures that can be adopted in mainstream consumer displays and consumer electronics such as front projectors, TVs, DVD players and recorders, Blu-ray players and recorders, A/V receivers, and more. In essence, he brought high-end home-theater-quality video to mainstream displays. His algorithms, which make use of a novel combination of statistical signal processing and heuristics based on visual perception, and their implementations in silicon have improved viewing experiences at one point or another for anyone reading this article.

Balram also played a pivotal role in developing the first widely accepted benchmarks for video quality. He was the lead technical expert for the Video2000 benchmark, the first major video benchmark for the PC platform. He also helped pioneer a new class of display-processing algorithm for video warping that enables ultra-thin rear-projection and off-axis front-projection displays, and he developed



Nikhil Balram

new display image-quality analysis metrics for LCDs, which have been used in the specification and design of military avionics displays. He is also committed to helping educate and motivate new display engineers.

“Nikhil Balram has made outstanding contributions to dramatically increasing the image quality of video images through advanced electronic signal processing,” says Frederic Kahn, SID Fellow, Braun prize winner, and president of Kahn International. “He has greatly improved the viewing experience of hundreds of millions of viewers through the commercialization of practical, affordable advanced image processors, which eliminate major artifacts that greatly reduce the viewing quality of commercial displays. These artifacts were increasingly disturbing as display resolution and size increased over the last decade.”

Balram became interested in image, video, and display processing starting in graduate school at Carnegie Mellon University, where he earned his Ph.D. degree in electrical engineering. He was working on statistical models and signal processing for 2D and 3D fields of data at a theoretical and general level until about the time he started thinking about getting a job. “Then I focused on the most common and practical examples of these types of fields – images and video,” says Balram. He was hired as a chip architect by IBM’s VLSI group in Boca Raton, where he began thinking about the image pipeline for multimedia system architectures. “The last pieces of the puzzle – the display that showed the

image and the final consumer of it, the human visual system – came together for me when I moved to Silicon Valley to become lead video/graphics VLSI architect for Kaiser Electronics, which was doing head-up, head-down, and head-mounted displays for military aircraft,” says Balram.

The main problem he was trying to solve when he wrote those algorithms was always the same – trying to create the best possible picture for the viewer. “However,” says Balram, “as the old saying goes, ‘Beauty is in the eye of the beholder’ – and so the definition of ‘best possible picture’ depends on the application.” For consumer displays such as TVs, the goal is to make pictures as visually compelling as possible. For military avionics displays, the most important goals are image fidelity and the ability to show the minute detail needed for identification of key features. In systems such as augmented-reality head-mounted displays, there are specific challenges such as compensating for optical distortion and user head movement while displaying video content and graphics appropriately overlaid and aligned to the real world.

Most recently, as President and CEO of Ricoh Innovations Corp., Balram has been leading a number of advanced technology projects involving computer vision, big data, and light-field technology, targeted at markets such as consumer, retail, enterprise, and healthcare. He is also a guest professor of design and innovation, visiting professor of vision science, and adjunct professor of

*The 2016 winners
will be honored at the SID
Honors & Awards Banquet,
which takes place at 8:00 pm,
Monday evening, May 23, 2016,
during Display Week at the
Intercontinental Hotel
in San Francisco.
Tickets cost \$100 and must be
purchased in advance – they will
not be available on-site.
Visit www.displayweek.org
for more information.*

SID's best and brightest

electrical engineering at IIT Gandhinagar, UC Berkeley, and Carnegie Mellon University, respectively.

2016 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.

Shunsuke Kobayashi, SID Fellow, Professor Emeritus of Tokyo University of Agriculture and Technology and Professor Emeritus and Founding Director of the Liquid Crystal Institute at Tokyo University of Science, Yamaguchi “for his long-term outstanding contributions to the education and training of students and professionals in LCD science and technology.”



Shunsuke Kobayashi

Although he is a researcher with 270 published papers and a co-inventor with 50 patents, one of Dr. Shunsuke Kobayashi's most notable achievements, which qualifies him for the Slottow-Owaki Prize, is the training of a large number of outstanding scientists and engineers who have participated in Japan's display industry. In addition, his book, *Liquid Crystals – Their Properties and Applications*, in Japanese (1970), has enjoyed a wide circulation in Asia and provided inspiration for numerous display engineers.

“It can be said,” says H. S. Kwok, Director for the Center of Display Research at the Hong Kong University of Science and Technology, “that Professor Kobayashi helped tremendously to create an entire display industry in Japan by educating many key engineers in many large Japanese companies. He is probably the best-known professor in Japan in the display field.”

Kobayashi has won numerous awards within the SID community and from the Liquid Crystal Society for his pioneering work on, to name only a few of the technologies, defect-free TN (twisted nematic) LCD, STN (super twisted nematic) LCD, photoalignment of liquid crystals, and human factors. He embarked on his field of research after receiving his Ph.D. degree from the University of Tokyo in 1964. “A professor asked us, ‘What will you do as new doctors of engineering?’” Kobayashi's answer involved an idea that did not even have a name yet in the mid-1960s. – “In my mind, I thought, ‘computers with photons,’” says Kobayashi – a field that became photonics.

2016 SID Special Recognition Awards

Presented to members of the technical, scientific, and business community (not necessarily SID members) for distinguished and valued contributions to the information-display field.



Jongseo Lee “for his advancements in display image-quality enhancement and assessment technologies; his devotion to international standardization activities in ICDM, ISO, IEC, and SEMI; and his pioneering work on transparent AMLCDs.”

Dr. Lee is a principal engineer with Samsung Display Co. He earned his Ph.D. degree in electrical engineering at Texas A&M University.



Tetsuo Urabe “for his outstanding contributions to the research and development of OLED display technology for TV applications and for his pioneering contributions to the commercialization of OLED TVs.”

Mr. Urabe is an invited senior researcher at the National Institute of Advanced Industrial Science and Technology in Tsukuba, Japan. He earned his M.S. degree in physical chemistry from Tohoku University.



Chang Ho Oh “for his research and product development of IPS-LCD devices and for his product development of OLED displays for TV applications.”

Dr. Oh is a senior vice-president at LG Display Co. He received his Ph.D. degree in physical electronics from the Tokyo Institute of Technology.



Robert J. Visser “for his pioneering research and commercialization of new display technologies related to OLEDs, LCD materials, and barrier films, including encapsulation technologies for OLED and flexible displays.”

Dr. Visser is Senior Director of the Advanced Technology Group for Applied Materials. He earned his Ph.D. degree in physical and organic chemistry from Leiden University.



Emi Yamamoto “for her contributions to the development of microstructured film which drastically improves the viewing-angle characteristics of TN-LCDs by simply laminating the film to the surface of a panel.”

Dr. Yamamoto is a Chief Research Chemist with Nissan Chemical Industries, Ltd. She received her Ph.D. degree in engineering (chemistry) from Kyushu University.

Some years later, working at the Institute of Physical and Chemical Research (RIKEN) in Wako City, Japan, he became interested in the idea of calculators based on LC technology. "In the 1950s, portable calculators were very heavy mechanical devices," he says. "In 1970, I wrote that portable calculators would soon be enabled with LCDs because their power consumption is very low." In 1973, Sharp started to sell portable calculators with displays based on the dynamic-scattering mode developed at RCA. Meanwhile, TN-LCD had been invented by M. Schadt and W. Helfrich in 1971. "It demonstrated very low power consumption," explains Kobayashi, "but nobody knew how to make optical defect-free TN-LCDs in mass production." Doing so was his achievement, with Mr. Fumio Takeuchi, at RIKEN in 1972. Later, when solar battery-powered TN calculators became available, "it was like a dream come true for me," says Kobayashi.

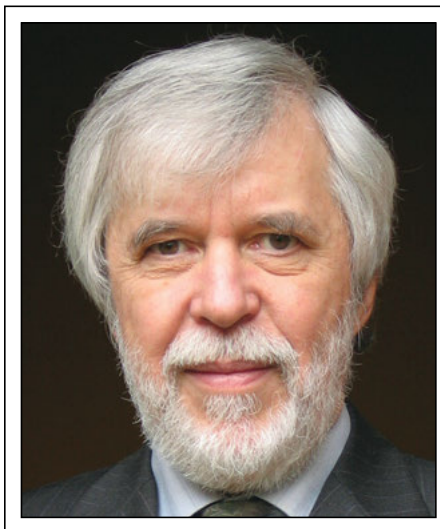
Kobayashi has always enjoyed doing real research with his students, instilling in them the same curiosity and excitement he felt back in the early days of creating commercial-ready LCD technology. Not to be ignored, according to Kent State University professor Phil Bos, was the help Kobayashi gave students from Japan who presented papers at the SID conferences. "For many years, he has been a mentor to them, helping them to provide excellent talks and to feel comfortable at our meetings. I have always admired how generous and kind he was in this role," says Bos.

According to Kobayashi, the most important thing for young scientists entering the field of displays to know is that to confront the ongoing and important issues, including high optical quality, lack of defects, low operating voltages, *etc.*, requires a knowledge of chemistry, physics, electrical engineering, mechanical engineering, computers, and more. "But nobody can cover all of these areas, so everyone needs to ask questions and listen to the answers of specialists," he says.

2016 Lewis and Beatrice Winner Award

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

Anthony C. Lowe, SID Fellow, "for his outstanding and sustained contributions to the leadership and governance of the Society and the exceptional benefit provided to SID's members throughout his editorship of the Wiley/SID book series."



Anthony C. Lowe

Anthony "Tony" Lowe has served SID for many years in many capacities, including President (the first non-U.S. citizen to assume this responsibility). He joined the society in the late 1970s, and in 1991, became Director of the UK & Ireland chapter, which was at the time the only chapter outside the U.S. besides Japan. He was ultimately responsible for the formation of the France, Mid-Europe, Belarus, and Beijing chapters, and initiated chapter formation in Russia and Ukraine. Lowe became the first Regional VP for Europe in 1992, then SID President in 1998.

In 1995, he co-organized the first SID Europe Regional Display Conference. The proceedings of this event became the first volume in the Wiley/SID series of Display Technology, through which 21 books have been published to date. Lowe has been the series editor since its beginning, though he is now in the process of handing over his responsibilities to a successor. Most recently, as Chair of the Bylaws Committee, he worked with every chapter in the Society to ensure their bylaws complied with those of the Society.

Though the list of Lowe's accomplishments is long, what do not show up on paper are his skills in negotiation and diplomacy, as well as organization and perseverance. Many of his colleagues have described the finesse with which some years ago he engineered the merger of the pre-existing display organization in France, Le Club Visu, with a new SID France chapter. "From my perspective," says

Poopathy Kathirgamanathan, a professor with Brunel University and current SID European Vice-President, "Tony was extremely successful in working around the difficulties encountered in different countries, and in finding a workable solution to the particular issues that result when the working area of a chapter crosses national boundaries."

Lowe's more recent major task was the drafting and implementation of new sets of chapter constitutions and bylaws. "This has really been a huge undertaking and its successful conclusion is a tribute to Tony's attention to detail and perseverance," says Kathirgamanathan. Lowe himself did not know the scope of the job when he started. "I agreed to become bylaws chair, thinking it was a sinecure," he said. The SID president at the time had approached the subject by saying there were some irregularities in chapter and student-chapter bylaws, which was true but perhaps an understatement. "Once I got started," says Lowe, "I decided I would do a complete job. It was not really difficult, more irksome. Most chapters were incredibly cooperative. A couple were a bit more difficult and some were just slow to respond."

Lowe's most visible role at SID for many years has been as the editor of the SID/Wiley book series. This responsibility in a certain way brought him back to earlier days. Although his career was as a scientist – he worked for IBM for 30 years and his Ph.D. degree from the University of Southampton was in Interfacial Thermodynamics – there was a point, before he entered the university, at which at least one person saw a different path for him. "I had an inspirational English teacher," he explains. "When he found out that I was intending to follow science, he came to my house one evening and spent the whole time trying to persuade me and my parents that I should study English." Though Lowe stuck to science, and has not regretted it, his skill with words did come in handy at SID, where he merged the two disciplines in his role as a book editor for the last 18 years. ■

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Ten Intriguing Display Discoveries from CES 2016

As expected, big beautiful screens were on hand at this year's show, but other less obvious examples of display technology helped complete the picture.

by Ken Werner

THE 2016 International Consumer Electronics Show – held at the Las Vegas Convention Center (LVCC) and other venues around Las Vegas on January 6–9 – reached a record size of 170,000 attendees, 3800 exhibitors, and 2.5 million square feet of exhibit space, according to the Consumer Technology Association (CTA), the show's producer. (CTA is the new name for the former Consumer Electronics Association or CEA).

Although a lot of consumer electronics can still be found at CES, the show has a steadily increasing proportion of industrial and business-to-business content. CTA promotes this, and many participants (Panasonic is a notable example) trumpet the increasing B2B component in their business mix. "Participants" is a more accurate term here than "exhibitors" because many companies do business from suites in the Westgate and Venetian Hotels, with their suites lining the corridors and stacked above each other floor over floor.

Many companies are soliciting sales or support for products that do not incorporate displays in a central or innovative way (for a look at a few examples, see the [sidebar](#),

"More Exciting Things at CES"), but even a small minority out of 3800 exhibitors provides a number of exciting, or at least interesting, display developments. Here are 10 of them:

1. LG Display's 18-in. Rollable OLED Display

In its large private suite in the convention center's North Hall, LG Display showed visitors the holy grail of display fabrication: a reasonably large-sized rollable display ([Fig. 1](#)). It was not in a vacuum chamber or inside a Lucite box, but in the open air for VIPs, customers, analysts, and even journalists to see. The 18-in.-diagonal panel has 1200 × 810 pixels and can be rolled up to a radius of 3 cm without affecting image quality, LG Display said. The company suggested that rollable TVs of 50-in. on the diagonal or more

could come to market in the foreseeable future.

It is worth noting that LG Display does not generally exhibit blue-sky demonstrations at its CES suite. In general, these are displays that are in volume manufacturing or reasonably close to it, assuming customers come forward.

2. The Best-Looking TVs in the World

The LG UHD Premium OLED TV has a high dynamic range that is superb, with blacks that are not there because they are really black (at least when the LVCC's ceiling lights were not shining on them). The Dolby Vision HDR makes the pictures snap, with an increased beauty and drama from the image itself, quite apart from any dramatic context. LG is apparently trying to capture this idea with its tag line, "The art of essence."

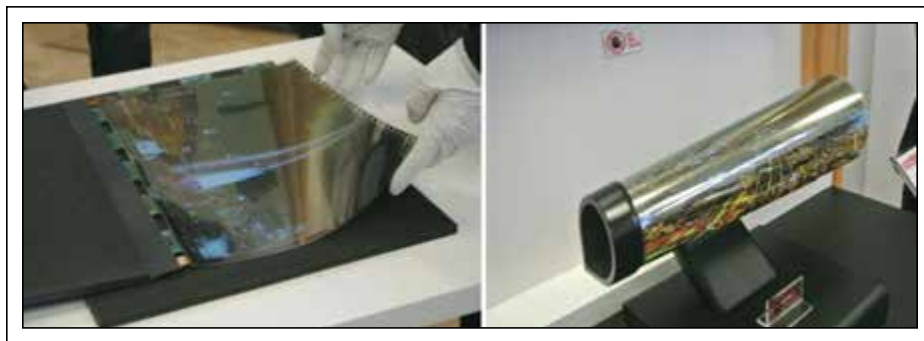


Fig. 1: LG Display's rollable 18-in. OLED display was shown and touched in an open-air demonstration – not in a case or other enclosure. Photo courtesy Ken Werner.

Ken Werner is Principal of Nutmeg Consultants, specializing in the display industry, manufacturing, technology, and applications, including mobile devices and television. He consults for attorneys, investment analysts, and companies using displays in their products. You can reach him at kwerner@nutmegconsultants.com.

The top-of-the-line “ultra-premium” OLED Signature G6 TV is built on an all-glass structure 2.57-mm thick, which LG calls “picture on glass” (Fig. 2). The image is visible on the back-side of the TV, although with less image quality than the front. The G6 has a gamut of 99% of the DCI color space (used in digital movie theaters), but will accept a Rec. 2020 signal.

On the show floor, Ted Maass, representing LG, said that in 2015 LG started making OLED TVs in a range of products instead of one super-premium model. In 2016, there will be four OLED-TV series with eight models. One, the Signature G6, will be 77 in.; all others will be 55 or 65 in. The G6 is also available in 65 in. Since the G6 has a glass chassis, all of the electronics are built into the base. All OLED sets will meet the UHD Premium spec for HDR, and all 2016 OLED sets will be 4K.

The sets all include both Dolby Vision and HDR 10. All the OLED sets have 10-bit panels, but only the UH9500 series uses 10-bit processing throughout the signal chain. The lesser series models utilize 8-bit processing. Similarly, except for the G6, only the UH9500 series has a gamut of 90% DCI. The UH8500 and UH7700 have 84%.

Once you have a 2.57-mm-thick OLED panel, you can do things other than making a gorgeous TV set. In its suite, LG showed two such panels bonded back to back to make a two-sided display that showed different programming on each side and was still very thin at about 5 mm. The next step was to tile a bunch of these OLEDs and bend them to make an S-curved two-sided display, which should appeal to high-end retailers (Fig. 3).

Other OLED TVs on the floor were from Panasonic, Changhong (available only from

Newegg in the U.S., said a rep), and Konka, with each using an LG panel (to the best of my knowledge). The great curved “small” – that is, 65 in. and less – TV fad seems to have peaked in 2015, as predicted. LG has

no curved LCD TVs in its 2016 line-up and only two curved OLED TVs.

Samsung LCD TVs

Samsung had lots of HDR sets on the show



Fig. 2: The OLED Signature G6 TV is built on an all-glass structure 2.57-mm thick. Photo courtesy Ken Werner.



Fig. 3: Curved OLED panels from LG Display were tiled and mounted back to back to create an impressive display in LG's suite. Photo courtesy Ken Werner.

show review

floor, all of them the same curved SUHD 65-in. 4K 1000-nit HDR LCD model. The set presented impressive images, and if LG's OLED model hadn't been on the floor, this one might well have been best in show. Samsung's Joe Stinziano said his company has 50% of the 4K TV market and that the Ultra HD Premium logo will soon be on every Samsung 4K set.

According to Samsung's literature: "Peak Illuminator dazzles with a brilliance three times brighter than previous peak white," and there is "35% improved contrast over conventional TV displays with Ultra Black, Samsung's proprietary reflection-suppressing technology." Samsung vigorously promoted its use of quantum dots. The company has opted for indium-phosphide dots, which provide a gamut that is less impressive than that achieved with cadmium selenide, at least for now.

Qualcomm's HDR Chip

HD affordability in the near term was a common theme among set and chip makers. At Qualcomm's press conference, Director of Product Marketing Chris Porter said, "We will make HDR affordable" and noted that Qualcomm's chip for achieving this was in 22 new TV models.



Fig. 4: The Jazz Seat from Panasonic features a 13-in. FHD display for economy airline seats. Photo courtesy Ken Werner.

3. An Organic Quantum-Dot Substitute

At its suite at the Westgate Hotel, executives of StoreDot (Herzeliya, Israel) showed me their MolecuLED – an organic color-

conversion layer that StoreDot says is an alternative to quantum dots. Although VP of R&D Daniel Aronov and Director of Product Marketing and IP Guy Paradis would not talk about molecular or structural details, they were very happy to talk about MolecuLED's performance, comparing it to the QD solutions in a prior model of the Kindle HD and an unidentified Samsung solution of (sources claim) 2 or 3 years ago.

StoreDot's organic film has peaks at wavelengths close to that of the aforementioned Kindle and Samsung solutions, and with generally similar sharpness of the emission peaks. Lifetime will be equivalent by the middle of this year, Aronov said.

Aronov said that MolecuLED can be made with a simple high-yield manufacturing process at a cost approximately 30% lower than QD films. Predictably, he also pointed out that the product is free of heavy metals.

The company was using CES to initiate an aggressive partner engagement process. It was meeting potential partners at CES, with plans to invite potential partners to test MolecuLED during Q1 and Q2, and to sign commercial agreements with from one to three partners in Q3–Q4.



Fig. 5: Samsung's transparent OLEDs were used at the show as signage for other products as well as a demonstration on their own. Photo courtesy Ken Werner.

More Exciting Things at CES

It is widely understood that cars rather than TVs take the limelight at CES these days. A few of these vehicles, as well as some other products and technologies not containing displays, are still worth noting, starting with the all-battery-powered Chevrolet Bolt.

Chevrolet chose CES for the not-quite-official introduction of its Bolt all-battery-powered electric vehicle (Fig. a). (The official reveal was at the North American International Auto Show in Detroit a few days later.) The built-from-the-ground-up-to-be-electric Bolt will have a range in excess of 200 miles and cost about \$30,000 after the federal tax credit. This is the first long-range pure-battery-powered car at a reasonably affordable price; Chevrolet considers it a very big deal. The Bolt will be available late this year as a 2017 model.

The Bolt incorporates some interesting display technology, including a 10.2-in. center-stack display that is the window to the soul of the Chevrolet MyLink system. Optional Surround Vision uses four cameras to create a bird's-eye view of the vehicle and its surroundings. The four camera views are merged on the 10.2-in. screen to provide awareness of what's going on behind and beside you in a single image. Also, optional is the "rear camera mirror" described in the main article.



Fig. a: The Bolt will be the first long-range all-battery-powered car available at an affordable price. A unique tail light design (inset) makes the vehicle's identity clear to any drivers following it.

One sign in the Chevrolet booth identified the Bolt as "Chevrolet's Commitment to Electrification."

2017 Mercedes E-Class Plus Real "Transformer" Technology

Mercedes-Benz introduced its 2017 E-Class as the first standard-production vehicle to obtain an autonomous license plate from Nevada (this indicates vehicles approved for autonomous driving tests). In addition, the company showed its Intelligent Aerodynamic Automobile (IAA) in the North Hall. The IAA changes its aerodynamics at speeds over 50 mph by extending flaps in the front bumper and eight segments at the car's rear to improve airflow. The dish wheels can change their cupping from 50 mm to zero, which also improves the aerodynamics. The system is powered by the NVIDIA DRIVE platform.

CES's Largest Drone

The eHang 184 had all of the obvious characteristics of the dozens of other drones – large and small – shown in the LVCC's South Hall, except that the 184 is large enough to carry a human passenger (Fig. b). It's still a drone because the passenger is not a pilot. He or she is simply payload. The drone flies autonomously to the destination entered on its control panel. eHang did not fly the 184 indoors, but a video showed the drone flying with a passenger.



Fig. b: The eHang 184 drone is designed to carry a passenger – not a pilot.

Route Planning Is so 2010

NVIDIA partner fka demonstrated its generic trajectory planner for highly automated vehicles (Fig. c). Trajectory planning goes beyond route selection in that once the route is selected, the vehicle must decide how to behave in detail: yield right of way, follow specific lanes when turning, overtake slower vehicles, etc., all while respecting the specific vehicle's maximum steering angle, maximum tire forces, and actuator limits. fsk built its system



Fig. c: Four Velodyne LiDAR sensors on a Ford Fusion Hybrid provided this 360° situational awareness map, important for trajectory planning and accident avoidance.

on an NVIDIA's Drive PX platform, which combines a CPU and GPU in one chip. A Ford Fusion Hybrid vehicle was equipped with four Velodyne LiDAR sensors to provide 360° situational awareness – important for trajectory planning and accident avoidance.

A Li-Ion Battery with Twice the Energy Density

During CES, Kopin announced it had entered into an agreement with Hitachi Maxell to produce and market a new kind of

(continued on next page)

More Exciting Things at CES

(continued from previous page)

Li-ion battery that uses silicon oxide with carbon in the anode. Kopin will market the batteries, which are intended for use in head-worn products, under the name SiMax. Production will start in Q2 '16, and the batteries will be used initially in Kopin's Solos cycling eyewear. Hitachi Maxell CTO Masao Okafuji suggested the new battery has twice the energy density of conventional Li-ion cells, which use graphite anodes. The batteries were shown at Kopin's suite at the Venetian hotel.

Victrola Returns

Vinyl has returned with a vengeance, with reports that vinyl records outsold CDs in 2015. There also seems to be an appreciation of vintage-looking audio equipment (Fig. d). Crosley has made a successful business of that over the last few years, and this year in Central Hall, the old Victrola brand reappeared. I would have thought that this classic brand would have been controlled by Technicolor, which owns and licenses RCA and other brands once in the RCA/Thomson pantheon. But Innovative Technologies found the Victrola brand in the hands of a private individual and bought it. The Victrola line consists of many models with styles ranging from the early 20th Century to the 1960s. The Innovative Technologies brand appears on turntables and other audio products with contemporary designs.

— Ken Werner

Fig. d: Innovative Technologies has brought back some retro-style audio equipment under the Victrola brand name.



4. 13 in. and All that Jazz

Panasonic, the world's largest supplier of airline seatback infotainment systems, showed its new "Jazz" economy seatback system with a 13-in. FHD display, the largest it could fit onto the back of an economy airline seat (Fig. 4). The Jazz Seat, which has integrated lighting and induction charging, is currently being deployed with a "middle eastern carrier." The seat is based on the Google development platform. The user's cell phone pairs with the seat via Bluetooth. Special flyer data (meals and media preferences, for instance) are communicated to the seat, and this can be pre-set before the passenger reaches his or her seat. Transmitters automatically turn off over restricted areas.

5. The Most Transparent Transparent Display

Samsung showed a prototype transparent 55-in. OLED FHD display with a remarkable 46% transmissivity (Fig. 5.). Information was in short supply, but the RGB pixels provided colors with good subjective saturation. Despite the message that appears in the photo, the transparent panels were not curved. Samsung was also using the transparent panels to post descriptions of the various products it was exhibiting.

6. Displays for the Connected Cockpit

The automotive infotainment system as we have known it is now being absorbed into something much more interesting: the connected car cockpit, which integrates data from the engine control unit, conventional cockpit instrumentation data, various vehicle-mounted sensors, conventional and non-conventional driver inputs, GPS data, and wireless network uploads and downloads, and vehicle-based and cell-phone-based infotainment.

All of this is being integrated in increasingly more sophisticated ways, culminating in semi-autonomous and fully autonomous vehicles that will regularly receive over-the-air (OTA) system updates, much as cell phones do now. But these automotive OTA updates have the potential for changing essen-



Fig. 6: The Hyundai Mobis demonstration cockpit incorporated augmented reality and a hologram-based I/O interface, anticipating multi-gigabit connectivity.

tial characteristics, not to mention the vehicle's insurance or regulatory status. As an example, last summer, Tesla made available a voluntary extra-cost OTA update that made Type-S vehicles semi-autonomous.

Vehicle-to-vehicle communication will be both point to point and network-mediated, and vehicle lighting will begin to serve communication, as well as visibility and decorative functions. The sensorized, integrated, and connected cockpit must be supported by appropriate displays and human-machine interfaces that must handle increased data loads while not distracting the driver from essential tasks. And displays will also serve decorative and brand-identity functions.

On the show floor, Panasonic showed a demonstration cockpit that included touchless HMI, multimedia input with eye tracking and gestures, large dual head-up displays, multiple high-resolution displays (flat, curved, and shaped), and an electronic rear mirror.

Figures 6, 7, and 8 show three of the many automotive-display examples that could be found on the show floor.

7. Most Concave Large Display

The claims of viewer immersion and constant viewing angle for curved 55–77-in. TVs are mostly fantasy because the curvature is so small and the viewer sits so far inside the center of curvature. But what if you curved the screen enough to make those claims meaningful? LG Display showed such a screen – an OLED technology demonstration – in its suite at the LVCC (Fig. 9). The effect was immersive, disorienting, and distinctly unpleasant, and the LG personnel seemed to enjoy watching viewer reactions. It is only fair to note that the content was not created with the extreme curvature in mind.

8. Sharp the Invisible

When Hisense purchased Sharp's North American TV business in 2015, it was widely assumed that Hisense was as much interested in Sharp's still-respected name (despite the company's financial crisis) as in its technology and sales infrastructure. So, analysts and media were surprised to see absolutely no evidence of Sharp TVs on the show floor, either in its own booth or in Hisense's. Apparently, there was a conference room buried deep in the structure of the Hisense booth where Sharp products were discussed with buyers. I was politely but firmly told by



Fig. 7: This Panasonic demonstration cockpit showed displays using a lot of dashboard real estate.

a booth rep that entrance to this room was by appointment only and that I wasn't going to get one. None of the other analysts and media I spoke with were admitted either.

9. The Last of the CRTs

An affordable karaoke machine stood out in the GPX booth in Central Hall because of its 5-in. monochrome CRT (Fig. 10). The CRT



Fig. 8: An extra-cost option in the new Chevrolet Bolt – the new relatively affordable all-battery electric vehicle that has a range of over 200 miles and was introduced at CES – is a “rear camera mirror” in which the mirror can act as a display that presents a wide-angle view of the area behind the car “without the obstruction of rear head restraints or rear-seat passengers.” Photo courtesy General Motors.

show review

will soon be replaced with an LCD because GPX can no longer find a source for the CRTs.

10. Pioneer Transparent OLED CHMSL

Pioneer showed an OLED Center High Mounted Stop Lamp (CHMSL) that is transparent and can thus be mounted in the rear window within the driver's line of sight (Fig. 11). When viewed from the vehicle's interior, it is more-or-less transparent when lit (not shown), as well as highly transparent when not lit.

So there you have it: 10 intriguing display discoveries from CES 2016, including the new, the strange, and the missing. The growing emphasis on industrial and B2B products at CES makes the event more, not less, interesting from both the industry and technical perspectives.

Can I make any predictions based on what I saw at CES? Of course, and so can you, but I won't shy away from stating the obvious. You will be able to buy OLED and LCD TVs this year that are the best consumer sets you have ever seen. OLED sets will get less expensive this year and almost affordable next year. UHD and wide color gamut will be commonplace, and HDR will work its way from high-end through mid-range sets. Flexible OLEDs will appear in a broader range of products, and increasing resources and creativity will be devoted to automotive displays to support advanced infotainment systems and the connected cockpit.

Amidst the several hundred varieties of cell-phone cases, there are always lots of intriguing discoveries to be made at CES. The hunt is very much worthwhile. ■



Fig. 10: A 5-in. monochrome CRT in a karaoke machine from GPX could well be the last CRT seen at CES. Photo courtesy Ken Werner.



Fig. 9: LG Display showed a very curved OLED in its suite – to mixed reactions. Photo courtesy Ken Werner.

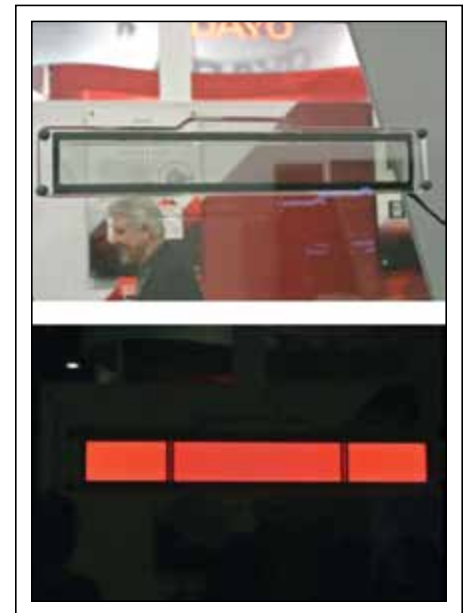


Fig. 11: Pioneer's transparent OLED lamp is transparent when not lit (see top), somewhat transparent when lit (not shown), and looks like a stop lamp from the outside (bottom). Photo courtesy Ken Werner.



Networking Events

May 22-27, 2016

Looking to meet up with your colleagues in the display industry to discuss technology, business, or just socialize? The events below present just that type of opportunity:

Annual Awards Dinner, Monday:

Each year, SID recognizes individuals that have played a critical role in improving the display industry. This year's winners will be honored at an awards banquet taking place the evening of May 23.

Business Conference Reception, Monday:

Follows the Business Conference, please note conference attendance is required for admission.

Annual Award Luncheon, Wednesday:

The annual Best in Show and Display Industry Awards Luncheon will take place at noon on Wednesday, May 25. Both awards are peer-reviewed, such that the luncheon is well-attended by captains of industry for high-level networking and recognition of the best in the industry over the last year.

Investors Conference:

The IC will feature presentations from leading public and private companies in the display technology supply chain and encourage questions and discussion between presenters and participants. Concludes with Drinks & Displays: Networking Reception with Presenters and Investors.

Market Focus Conference Reception, Tuesday, May 24:

Follows the Tuesday Market Focus Conference, please note conference attendance is required for admission.

www.displayweek.org



SID International Symposium, Seminar & Exhibition

May 22-27, 2016

Moscone Convention Center
San Francisco, California, USA

Rolling Out the Red Carpet



I-Zone

Competition of live demonstrations regarding emerging information-display technologies, such as not-yet-commercialized prototypes and proof of concepts. *Sponsored by E Ink.*

Individual Honors and Awards

The SID Board of Directors, based on recommendations made by the Honors & Awards Committee, grants several annual awards based upon outstanding achievements and significant contributions.

Display Industry Awards

Each year, the SID awards Gold and Silver Display of the Year Awards in three categories: Display of the Year, Display Application of the Year, and Display Component of the Year.

Best-in-Show Awards

The Society for Information Display highlights the most significant new products and technologies shown on the exhibit floor during Display Week.

Journal of the Society for Information Display (JSID) Outstanding Student Paper of the Year Award

Each year a sub-committee of the Editorial Board of JSID selects one paper for this award which consists of a plaque and a \$2000 prize.

Emergence and Convergence Highlight This Year's Technical Symposium

This year's technical program at Display Week features almost 500 papers on topics including microdisplays, holograms, quantum dots, QLEDs, OLETs, flexible/wearable devices, vehicle displays, augmented and virtual reality, and much, much more.

by Jenny Donelan

PUTTING TOGETHER this year's preview article on the annual SID International Symposium at Display Week was more difficult than usual for two reasons. First, there are so many highlights – new technologies, new solutions to old problems, new materials – that it was hard to choose among them. An emerging technology – the quantum-dot LED or QLED, for example – with the power to disrupt future generations of displays, is obviously worthy of notice. But so is a new manufacturing technique that promises to shift OLED TVs from the luxury to the mainstream category.

Second, so many of these papers fall under multiple subject headings. It was tough to describe where some of them fit in. Is a new type of OLED stack that enables a flexible display an OLED story, a flexible technology story, or a manufacturing story? Of course, it's all three. And although such overlaps are not new to the symposium, the degree of convergence was quite striking this year. It just underscores how developments in one area are spurring further development in others. There are some great synergies at work in our industry.

It's also worth noting a major demographic trend in paper submissions this year. "We are having a boom in papers from China," says

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technical program chair Cheng Chen. In fact, while papers from many top contributors such as Korea, Japan, and the U.S. were slightly up or holding steady, the number of submitted papers from China nearly tripled this year. It's encouraging to see so much R&D emerging from this manufacturing powerhouse.

This year, the technical symposium features 81 sessions and close to 500 papers. Obviously, that's many more papers than any one person can take in during the four days (May 24–27) of the program, but you can focus on the ones that are most important to you if you plan ahead by accessing the preliminary program online at <http://displayweek.org/2016/Program/Symposium.aspx> and also by reading this article, in which we point out some of the highlights. Last, but not least, don't forget to bring friends and colleagues along to cover what you cannot!

Each year, the papers presented are organized by their major technical focus – Active-Matrix Devices, Applications, Applied Vision/Human Factors, Display Electronics, Display Manufacturing, Display Measurement, Display Systems, Emissive Displays, e-Paper and Flexible Displays, Lighting, Liquid-Crystal Technology, OLEDs, Projection, Touch and Interactivity, and Vehicle Displays and HMI Technologies – then assigned to sessions designated by topic, such as Advances in Automotive Display Measurements. Each session consists of 3–5 20-minute paper presentations. This year, six

special topic areas have been included: Augmented and Virtual Reality, Digital-Signage Solutions, Lighting, TFTs and Display Circuits on Plastic Substrates, Vehicle Displays and User Interface Technology, and Wearable Displays.

The peer-reviewed papers chosen for presentation at Display Week represent the best work being done in display technology. Here are a few of the highlights from this year's sessions. While it is not possible to mention every exciting development or worthwhile presentation in this space, we hope this list will serve to whet your appetite for what's in store at the symposium.

Quantum Dots: Once More, with QLEDs

Quantum dots were a very big topic at Display Week last year, and they are big again, according to Qun "Frank" Yan, chair of the emissive displays subcommittee. Last year, quantum dots were just beginning to be used to enhance commercial LCD products. This year, says Yan, quantum-dot solutions for backlighting are becoming a mature application. And QLEDs are getting a lot of attention now as well. A QLED is a quantum-dot LED (with a structure similar to an OLED) that can be used to create an emissive display on its own, similar to an OLED. "QLEDs potentially have better luminous efficacy, purer color, and longer lifetimes than OLEDs," says Yan, "and their efficiency is also better." He compares the relative stage of development

Display Week 2016 Symposium at a Glance

2016 SID Display Week Symposium at a Glance – Moscone Convention Center										
Times		Room 102	Room 103	Room 104	Room 130			Room 131	Room 132	Room 133
		SID Business Meeting and Keynote Session (Rooms 103/104)								
Tuesday, May 24	8:00 – 10:20 am									
	11:10 am – 12:30 pm		3 AR / VR Display Systems I (Joint with Systems)	4 Flexible and Curved LCDs I	5 MEMS Projection Displays	6 Advancement in Solid-State-Lighting Sources	7 AMOLED Driving			
	2:00 – 3:20 pm		8 AR / VR Display Systems II (Joint with Systems)	9 Flexible and Curved LCDs II	10 Laser Speckle (Joint with Vehicular)	11 Convergence of Lighting and Displays	12 Driving Circuits		13 Digital-Signage Displays (Joint with Digital Signage)	
	3:40 – 5:00 pm		14 Wearable AR / VR Applications (Joint with Applications)	15 Color-Sequential Displays	16 Liquid-Crystal Protection Devices (Joint with Liquid Crystal)	17 Lumiance and Lighting System Design	18 Advanced Displays		19 Holographic and Lighting Display Systems	
	5:00 – 6:00 pm									
Author Interviews (Room 134)										
Wednesday, May 25	9:00 – 10:20 am	20 Quantum Dots / Rods (Joint with Emisive)	21 Mixed Reality Applications (Joint with Applications)	22 Future of Vehicular Display Technologies	23 High-Image Quality	24 OLED Devices I	25 Touch Materials I		26 Oxide-TFT Manufacturing	
	10:40 am – 12:00 pm	27 Applications and Issues for Quantum Dot/Rods (Joint with Systems)	28 Augmented Reality and Virtual Reality Additional Session I	29 Automotive Display-System Optimization	30 LC Beyond Displays	31 OLED Devices II	32 Touch Materials II		33 Flexible Display Manufacturing and Test	
	2:00 – 3:30 pm									
Designated Exhibit Time (Exhibit Hall)										
	3:30 – 4:50 pm	34 Quantum-Dot Materials	35 Augmented Reality and Virtual Reality Additional Session II	36 Automotive Materials: Optical Performance and Impact Resistance	37 High-Resolution LCDs	38 OLED Printing	39 Capacitive Touch		40 Optical Materials and Component Manufacturing	
	5:00 – 6:00 pm									
Author Interviews (Room 134)										
Thursday, May 26	9:00 – 10:20 am	41 Photoluminescent Quantum Dots	42 Wearable Devices and Displays	43 Advances in Automotive Human-Machine Interaction	44 Photoalignment	45 OLED Displays I	46 Force Sensing and Emerging Technologies		47 TFTs on Flexible Substrates (Joint with Active-Matrix)	
	10:40 am – 12:00 pm	48 Electroluminescent Quantum Dots	49 Wearable / Stretchable Displays / Quantum Dots (Joint with e-Paper)	50 Automotive Applied Vision: Challenges and High Temperature (Joint with Applied Vision and Lighting)	51 Reflective LC Devices	52 OLED Displays II	53 Display Imaging and Color Vision		54 Novel Active-Matrix Applications	
	1:30 – 2:50 pm	55 Emisive Devices		56 Advances in Automotive Display Measurements (Joint with Measurement)	57 e-Paper / Reflective Displays	58 OLED Materials	59 High-Dynamic-Range and Field-Sequential-Color Displays		60 New TFTs (Joint with Liquid Crystal)	
	3:10 – 4:30 pm	61 Backlight Systems	62 OLED Wearing Displays (Joint with OLEDs)	63 Automotive Head-Up Displays: Technology and Challenges	64 Flexible / Printed TFTs (Joint with Active-Matrix Devices and TFTs on Flexible Substrates)	65 Advanced Measuring and Modeling Techniques	66 Curved and 3D Displays		67 Low-Temperature-Polysilicon TFTs	
	4:30 – 5:30 pm									
	5:00 – 8:00 pm									
Author Interviews (Room 134)										
Poster Session (City View Room - Metreon)										
Friday, May 27	9:00 – 10:20 am	68 Applications Beyond Displays	69 Oxide TFTs	70 Automotive LCDs I: Wide Color Gamut and High Temperature (Joint with Liquid-Crystal)	71 Printed Electronics	72 Measurement Methods and Equipment	73 Autostereoscopic Displays I		74 OLED Manufacturing (Joint with OLEDs)	
	10:40 am – 12:00 pm	76 Emerging Technologies	76 Oxide TFTs II	77 Automotive LCDs II: Fast Response and High Temperature (Joint with Liquid-Crystal)	78 Flexible AMOLED Displays	79 Measurements for AR / VR Displays	80 Autostereoscopic Displays II		81 Advanced LCD Manufacturing (Joint with Liquid-Crystal)	
	12:00 – 1:00 pm									
Author Interviews (Room 134)										

TECHNOLOGY TRACKS KEY						
Active-Matrix Devices	Applications	Applied Vision		Augmented Reality and Virtual Reality		Display Electronics
	Display Systems	Digital Signage	Emissive Displays	e-Paper/Flexible	Lighting	
	Display Measurement					
OLEDs	Projection	TFTs on Flexible Substrates		Touch and Interactivity		Vehicular
						Liquid-Crystal Technology
						Wearable Displays

for QLEDs today to where QD materials for backlighting were several years ago. The technology is showing promise, but the means of commercializing it has not yet arrived. Whatever the solution is, it will be solution-based, he says – the QLEDs will be sprayed or printed. Accordingly, there are a number of papers on solution-based QLEDs this year.

A good overview for both quantum dots and QLEDs is the paper “Quantum Dots for Displays: From Photoluminescence to Electroluminescence” by Xiaogang Peng of Zhejiang University, which discusses the material’s “reality as down-conversion phosphors in backlighting units” and “near-reality as a new type of LEDs.” Other QLED papers of interest include “Quantum-Dot Electroluminescence: Towards Achieving the Rec 2020 Color Coordinates” by Poopathy Kathirgamanathan of Brunel University, “High Efficiency and Ultra-Wide-Color-Gamut Colloidal Hybrid Quantum-Dot LEDs” by Jesse Manders of NanoPhotonica, and “N- and P-Type Metal Oxides for Quantum-Dot LEDs” by Jin Jang of Kyung Hee University. (Jang is also the author of a symposium paper on Bulk-Accumulation Oxide TFTs and a related article on that subject in this issue).

Although QLEDs may be the new material in town, there is still a lot going on with QDs, as made is clear by the paper, “The Quantum-Dot Revolution,” in which Luminix’s Seth Coe-Sullivan not only reviews the major technical innovations that enabled QDs to enter the LCD market, but the material and integration options available to display system designers and the technology’s future both for LCDs and emissive displays. Yan also recommends a paper that describes how researchers used a combination of cadmium-free and low-cadmium quantum dots to achieve >90% Rec.2020 in a RoHS (Restriction of Hazardous Substances) compliant package: “‘Greener’ Quantum-Dot-Enabled LCDs with Rec. 2020 Color Gamut” by Charlie Hotz of Nanosys.

Microdisplays, Holographs, and Other Emerging Technologies

Microdisplays are another emerging technology with potential. Yan recommends that symposium attendees check out “GaN-Based Emissive Microdisplays: A Very Promising Technology for Compact Ultra-High-Brightness Display Systems” by Francois Tempier of CEA-LETI. In this paper, Tempier describes how high-

brightness GaN-based emissive microdisplays can be fabricated using a variety of approaches and how display prototypes have shown luminance as high as 1×10^7 and 1×10^8 cd/m² for blue and green arrays, respectively. This technology is a good candidate for augmented-reality systems or head-up displays.

A paper that Ian Underwood, subcommittee chair for applications, says will be very exciting, is “Realizing Holographic Head-Up Displays” by Jamieson Christmas of Two Trees Photonics. “This technology puts a holographic display on your windshield,” says Underwood. The invited paper covers the principles and benefits of using phase-only holography for HUD applications and also describes the successful implementation of the world’s first automotive head-up-display system to use this technique.

Force-sensing, an interaction modality recently popularized by the Apple Watch and iPhone 6s, is another emerging technology – one so popular, in fact, that it has its own session this year, with papers including, “Touch and Display Integration with Force Measurement,” by Kurth Reynolds of Synaptics. Reynolds describes a mobile touch interface with sensing electrodes integrated onto a TFT display with a single display IC, explaining that it enables new interfaces such as force input to be integrated into a device without additional components. According to touch and interactivity subcommittee chair Jeff Han, force-sensing is, broadly speaking, one of three major themes in touch this year, along with the continued confinement of projected-capacitive technology and fundamental utilization of new material improvements, such as IGZO.

OLEDs: TVs, Lighting, and Flexible Technology

This year’s OLED topics cover three main areas: TVs, lighting, and flexible technology. “OLED TVs in general are a big deal,” says OLED subcommittee chair Mike Weaver. While these TVs are no longer new, he notes, they continue to gain market acceptance. From a technical standpoint, the OLED TV products are being improved to address increased color gamut, brightness, and lifetime requirements. This is being tackled with OLED material improvements along with system-level advances. And there are some really interesting papers addressing new designs, such as “A 3-Stacked Top-Emitting

White OLED for High-Resolution OLED TV” by Chang Wook Han of LG Display which describes the novel approach of adopting a 3-stack top-emission white OLED so as to improve efficiency, operating voltage, and viewing angle – properties that will enable resolutions such as 4K × 8K in the future.

“Lighting papers at Display Week are traditionally pretty OLED centric,” says lighting chair Mike Lu. “We do strive to get more LEDs. And some of the papers are light-source agnostic – they have to do with system design.” That said, some of this year’s most exciting papers do involve OLEDs. The trend that many people are working on is a light source with a high degree of control, explains Lu, whether that be color, orientation, or direction of the beam. Highlighting this idea is a session called Convergence of Lighting and Displays, with three invited papers: “Spatial and Beam Control in Solid-State-Lighting Applications” by Rodrigo Pereyra of OSRAM Sylvania; “Convergence of Lighting and Display: Opportunities, Requirements, Challenges” by Matthias Bues of the Fraunhofer Institute for Industrial Engineering; and “Daylight-Emulating LED Luminaires as Daylight Phase Indicators and Occupant Circadian-Rhythm Entrainment” by Jonathan Mapel of Arborlight.

Lastly, flexible OLEDs are probably the biggest news in flexible technology, according to Ray Ma, subcommittee chair for wearable displays. Many of the wearable papers this year are OLED-based. “For high-end wearables it seems like everybody is using OLED technology, and AUO and Huawei explain why,” he says. The invited papers he refers to are “A True Circular 1.39-in. AMOLED for Wearable Applications” by Tsang-Hong Wang of AUO, which describes the processes that enabled much sought-after circular shape for watches, and “Display Technologies for Wearable Devices” by Gang Xu of Huawei, which compares the relative suitability of LCDs and OLEDs for high-end wearables such as watches, and comes out in favor of OLEDs. A related late-news paper on plastic-based circular AMOLEDs that Ma recommends is “A Circular Flexible AMOLED Display with a 1-mm Slim Border” by Li-Fong Lin of AU Optonics. One very intriguing flexible/wearable paper that is based on electrophoretic technology is “Advances in New Electrophoretic Display Technology and Wearable Applications” by Michael McCreary of E Ink Corp., which



Display Week 2016 Overview

Moscone Convention Center, San Francisco, California, USA

May 22 – 25, 2016

TIMES	Sunday May 22	Monday May 23	Tuesday May 24			Wednesday May 25		Thursday May 26		Friday May 27
	Short Courses	Seminars	Business Conf.	Symposium	Market Focus Conference	Exhibitors Forum Sessions / I-Zone	Investors Conf.	Symposium	Exhibitors Forum Sessions	Symposium
8:00 AM				Session 1: SID Business Meeting						
8:30 AM				Session 2: Welcome / Keynote Addresses						
9:00 AM		Seminars M1 - M3	Business Conference		Ribbon Cutting Ceremony		Exhibitors / Exhibitors Forum / I-Zone		Exhibitors / Exhibitors Forum / I-Zone	
9:30 AM										
10:00 AM										
10:30 AM	Short Courses S-1 & S-2		Seminars M4 - M6			Oral Sessions 20-26	CMO Panel (9:00-10:00) / Exhibitors / Exhibitors Forum / I-Zone		Oral Sessions 41-47	Oral Sessions 68-74
11:00 AM						Oral Sessions 27-33			Oral Sessions 48-54	Oral Sessions 75-81
11:30 AM						DIA & Best-in-Show Awards Luncheon	Market Focus Conference: Wearables - Flexible		Lunch	Author Interviews
12:00 PM						Designated Exhibit Time			Oral Sessions 55-60	
12:30 PM			Bus. Conf. Lunch			Oral Sessions 34-40	Special Networking Event California Academy of Sciences		Oral Sessions 61-67	
1:00 PM						Author Interviews			Author Interviews	
1:30 PM		Seminars M7 - M9	Business Conference						Poster Session	
2:00 PM										
2:30 PM										
3:00 PM	Short Courses S-3 & S-4		Seminars M10 - M12							
3:30 PM										
4:00 PM										
4:30 PM										
5:00 PM		Seminars M13 - M15	Bus. Conf. Recept.							
5:30 PM										
6:00 PM										
6:30 PM										
7:00 PM										
7:30 PM										
8:00 PM										
8:30 PM										
9:00 PM										
9:30 PM			Honors and Awards Banquet							

symposium preview

describes flexible all-plastic TFT displays with both a-Si TFT as well as OTFT backplanes. McCreary also describes advanced color EPD platforms, which should be very interesting, says Ma.

Automotive Displays

Most people in the display industry are well aware that vehicles are an important new market. "What is also important," notes Rashmi Rao, co-chair of the Vehicle Displays and User Interface special topic, "is reaching out to the automotive community to let them know that the display experts at Display Week can help them solve all kinds of problems with displays in automobiles." Those key trends or challenges include high-ambient-light conditions, wide color gamut, and wide-temperature-range requirements, as well as combining optical performance with meeting safety requirements such as a display's ability to withstand head impact in an accident. This year's symposium features seven sessions that deal with vehicular displays or automotive interface technology. Many of these are joint sessions with other subcommittee topics, such as LCDs and Projection. Among the many notable papers in these sessions are "Automotive Biometric Automatic Luminance Control System" by Paul Weindorf of Visteon Corp., which describes the use of an eye-gaze tracking camera to measure the driver's pupil size to provide automatic luminance control for comfortable display visibility.

Other Papers of Note

The Past and Future of DLP: One paper that will no doubt be very popular, according to projection subcommittee chair Dave Eccles, is "Steering Light with TI's Digital Micromirror Device: Past, Present, and Future" by Patrick Oden, a Texas Instruments Fellow. Oden's paper describes how since 1996, DLP products have powered tens of millions of projection systems for a variety of applications ranging from ultra-bright cinema systems capable of handling >100k lumens down to small-form-factor ('pico') projection with dimensions on the order of a thumb-nail and light outputs of ~30–300 lm. In addition to this historical journey, he will chart some future directions.

OLETs: A description of an organic light-emitting transistor (OLET) is offered in "Flexible Active-Matrix OLET Display on a Plastic Substrate" by Hsing-Hung Hsieh, Polyera Taiwan Corp. The organic light-

emitting transistors (OLETs) are built on a novel architecture of tri-layered organic semiconducting heterostructure and feature good performance, including record-high EQE. The author also describes an active-matrix display based on OLETs without driving TFTs.

Field-Sequential-Color LCDs: "Liquid-Crystal Technologies towards Realizing a Field-Sequential-Color Display" by Simoin Siemianowski of Merck KGaA describes how modern liquid-crystal displays' use of RGB color filters significantly reduces the maximum possible light efficiency. He describes how Merck is actively working on a number of technologies that would enable field-sequential driving to be realized and outlines the ways in which such a backlight system would increase efficiency and reduce power consumption.

As always, there is so much to learn at the Display Week Symposium. The examples mentioned here are just the start. We haven't even touched on laser-speckle measurement, mobile displays on Gen 8, thin form factors, and oxide TFTs. There's so much to see. So get started now. Download the preliminary program and create your plan. See you in San Francisco! ■

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Display Week 2016

Innovation Zone (I-Zone)

May 24–26, 2016

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The prototypes on display in the Innovation Zone at Display Week 2016 will be among the most exciting things you see at this year's show. These exhibits were chosen by the Society for Information Display's I-Zone Committee for their novelty, quality, and potential to enhance and even transform the display industry. Programmable shoes, interactive holograms, the latest head-up displays, and much more will not only fire your imagination, but provide an advance look at many of the commercial products you'll be using a few years from now.

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**I-Zone 2015 Best
Prototype Award Winner:
Ubiquitous Energy**

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Event Date	Event Description	Closing Date
January/February	Digital Signage, Materials Special Features: Digital Signage Technology Overview, Digital Signage Market Trends, Oxide TFT Progress Report, Alternate Display Materials, Top 10 Display Trends from CES, Chinese Business Environment Markets: Large-area digital signage, in-store electronic labeling, advertising and entertainment, market research, consumer products, deposition equipment manufacturers, fabs	December 28
March/April	Display Week Preview, Flexible Technology Special Features: SID Honors and Awards, Symposium Preview, Display Week at a Glance, Flexible Technology Overview, Wearables Update Markets: Research and academic institutions, OLED process and materials manufacturers, consumer products (electronic watches, exercise monitors, biosensors), medical equipment manufacturers	February 29
May/June	Display Week Special, Automotive Displays Special Features: Display Industry Awards, Products on Display, Key Trends in Automotive Displays, Insider's Guide to the Automotive Display Industry Markets: Consumer products (TV makers, mobile phone companies), OEMs, research institutes, auto makers, display module manufacturers, marine and aeronautical companies	April 21
July/August	Light Fields and Advanced Displays Special Features: Overview of Light-field Display Technology, Next-generation Displays, Market Outlook for Commercial Light-field Applications Markets: Research institutions, market analysts, game developers, camera manufacturers, software developers	June 20
September/October	Display Week Wrap-up, Emissive Technologies Special Features: Display Week Technology Reviews, Best in Show and Innovation Awards, Quantum Dot Update, A Look Forward at Micro-LEDs Markets: OEMs, panel makers, component makers, TV and mobile phone companies	August 25
November/December	Applied Vision Special Features: Advanced Imaging Technology Overview, Current Key Issues in Applied Vision, Real-World Applied Vision Applications Markets: Medical equipment manufacturers, game developers, research institutions, OEMs, software developers	October 24

ID Interviews Mustafa Ozgen, CEO of QD Vision

Mustafa Ozgen recently took the reins as CEO of QD Vision, a leading quantum-dot (QD) company based in Lexington, Massachusetts. QD Vision was the first company to supply QDs for televisions (by Sony). Ozgen's work history includes 20 years in Silicon Valley, mainly in the software and semiconductor space, where he focused on consumer electronics. Prior to joining QD Vision, he was Senior Vice-President of Sigma Designs, where he oversaw the Home Multimedia business.

Conducted by Jenny Donelan

ID: You have a long history in TVs.

MO: Yes, I've been involved in many different technology lifecycles, from basic TVs to smart TVs and from lower resolutions to 1080p or 4K, and from NTSC color technology to today's wide color gamut and high dynamic range. I've been through a lot of transitions in the display market, but particularly in the TV and monitor space.

ID: So there are some good synergies here, as QD-enhanced LCD TVs are so important to the industry right now.

MO: Exactly. That's why QD Vision approached me for this role.

ID: QD Vision was founded in 2004, and it was the first company to commercialize quantum dots, yes?

MO: Yes, but the founders spent their first 5 years or so working on electroluminescent applications for quantum dots. The original goal was to displace OLED and LCD and build displays based completely on quantum dots. That was the vision, and they developed the technology and built the prototypes. As a result, they actually own some of the more fundamental patents and IP in this area. But, like a lot of startups, they were just a little

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ahead of their time. The whole infrastructure wasn't ready. The company also



Mustafa Ozgen

started out pursuing some lighting applications, which were ahead of their time as well. Finally, they entered the backlighting domain for LC TVs. I would say for the last 5 years or so we've been focused on LC TVs and on commercializing the use of quantum dots in the TV backlights.

ID: Lately, there is interest in quantum-dot LEDs (QLEDs). Isn't this going back to the original company vision in some ways, using the QDs with the LEDs to create the display without LCs? Are you working on that?

MO: It is an interest. It's becoming more feasible to manufacture quantum-dot-based displays, as OLED printing and other machines are becoming more available.

ID: Would QLEDs be most feasible as a printed technology?

MO: Well, at the moment this looks most likely as a technology for smaller displays. For much larger displays it would require a much larger investment.

ID: Then would you say that QLED-based TVs aren't something we're going to be seeing in the short-term?

MO: Not in the next 3 years. There are definitely developments happening, in research labs. The key point is we own the fundamental IP in this space, so we would like people to go and build something that would use it!

ID: How do you differentiate yourselves from other companies that make quantum dots?

MO: We are more commercially focused in terms of actual deployment of technology than other QD companies. We have been shipping our quantum dots in large volumes since 2013 and have been in commercial production since 2013, starting with Sony. Our Color IQ edge-lit technology is now in millions of TVs around the world. And we have the largest number of QD customers in the industry. TCL is a partner, as is Hisense and TP Vision, under its globally recognized Philips display brand.

ID: And your implementation is unique. You have the Color IQ technology. Can you explain that?

MO: Sure. Color IQ is the most efficient and therefore the most widely adopted quantum-dot solution in the world today. One of the advantages of QD Vision's quantum-dot technology is that it can perform under higher heat and flux conditions, very close to the LED. Because of this, we are able to use a tiny amount of QD material [cadmium selenide] encased in a slim glass tube located just behind the bezel to achieve the same performance as our competitors' quantum-dot enhanced film. With a film, you have to use much more material because you're covering the whole display screen with a film that contains the QD material. Color IQ requires fewer QDs and less protective material. This helps our OEM customers put quantum dots in lower-priced higher-volume SKUs. It's good for them, and good for consumers.

ID: Where does the tube go in the LCD TV? Is it part of the edge-lighting system?

MO: The current version goes into the edge-lit displays, yes. We work with customers to mount our Color IQ optic tube just above the LED bar behind the bezel. Precisely tuned quantum dots convert high-energy blue light from the LED to both green and red light. The result is perfect white light – and a capacity to show any color inside the display's much wider color gamut. In addition to today's edge-lit solution, we are working closely with partners to produce film using our quantum dots – these will be announced soon.

ID: There's a perception that QDs, in particular those based on cadmium, are dangerous. This is especially the case in Europe. How have things been going there?

MO: It's important to know that cadmium-based products are approved for this application and are selling well in Europe and

around the world. But, there are some people who are looking at the situation over-simplistically and we are working to correct some misperceptions there – it's going well. Very simply, there's a desire to remove cadmium from products where legitimate alternatives exist. As a sustainable technology company, we support that goal and are actively pursuing it ourselves. However, the simple facts are that cadmium selenide – a much less toxic compound than free cadmium – gives you the benefits of the widest color gamut while also delivering the most energy savings. Other wide-color-gamut technologies waste energy – sometimes lots of energy. And, since energy production is one of the leading causes of free or environmental cadmium, a cadmium selenide-based solution results in a smaller cadmium footprint than other alternatives in the market.

ID: Alternatives like indium phosphide?

MO: Yes. As a side note, QD Vision developed indium phosphide for several years. QD Vision has worked with indium phosphide since our inception. We also own some fundamental IP in that area. I would also add that although cadmium is a toxic material, cadmium selenide is safe. It's less soluble, so not absorbed into the body. When our customers today build the TVs using our optics, there is no incremental risk and no special handling requirements. It's the same for consumers. And the recycling infrastructure for cadmium is much more mature – so we can reuse and recycle safely and efficiently.

ID: What are QD Vision's immediate plans for the future?

MO: Our plan is to be a "one-stop quantum-dot shop" for our global OEM customers. Based on our quantum-dot and packaging innovations, customers are asking for us to create more ways to deploy our QD solutions, so we are responding. As I mentioned earlier, we are working to deliver a Color IQ film solution and plan to announce availability later this year. We recently announced a collaboration with Sigma Designs, one of the leading chipset providers for TVs. Together, we created a Dolby Vision HDR system using Color IQ in an edge-lit display. It's perfect for mainstream HDR solutions and for thin format displays.

ID: So what kinds of TV do you own?

MO: I have a 70-in. LCD by Vizio and a 55-in. LCD from Hisense that uses Color IQ quantum dots. And a 50-in. Roku TV from TCL. They're all based on the key technologies of the companies I've worked for. ■

“ Our plan is to be a ‘one-stop quantum-dot shop’ for our global OEM customers. ”

continued from page 2

and his team gave us so much important information about their work, we asked Dr. Jang to help us make this a two-part article. This first part talks about the underlying device physics and the achievements on test devices so far. The second part, coming in a few months, will describe work on process engineering and the creation of demonstration flexible OLED displays.

Our third feature, appropriately titled “Flexible AMOLED Displays Make Progress,” by Annie Tzuyu Huang and her colleagues at AU Optonics, addresses some of the critical challenges to encapsulating OLED materials in a flexible construction and hence achieving rollable and bendable active-matrix OLED (AMOLED) displays. She also includes a discussion of key optical considerations such as flexible circular polarizers for contrast enhancement and then describes some of the recent achievements of AUO to achieve high-contrast full-color bendable displays.

Given what we read this month, and adding in some of our flexible and touch coverage from the January and July 2015 issues (remember the robot at the Golden Gate Bridge?), you can start to build a vision for how this all ties together into a new paradigm of truly wearable electronics with displays in every form factor imaginable. I would encourage you to look back at those issues in our on-line archives, and imagine for yourself where this can rapidly start to go. By the way, now that we have many issues in our archives stretching all the way back to 1964, you can literally research the evolution of flexible displays or any other similar aspect of display technology from inception to the present day. One of the reasons the archiving process is taking so long is that I am slowly reading through much of what we are scanning, and it is fascinating. Where we have come from and how much has been achieved in our industry is just as important as what we now have in front of us to work with.

This, by no accident, brings me to the next important topic for this issue – the announcement of the annual SID Honors and Awards, which encompass several very prestigious prizes and categories of recognition. Each year, the Society for Information Display honors those individuals who have made outstanding contributions to the field of displays. Each one of our honorees has dedicated a long period of professional work to achieving unique and innovative milestones. In many

cases, the outcome of their efforts has been woven into prominent products we use and enjoy every day without directly realizing the contributions of these key innovators. If you look closely at our archives, you will see their work appears in articles describing technological advances step by step, year by year. At least three of this year’s honorees have been contributing authors and/or recent guest editors for *Information Display* as well. We are all extremely grateful for their contributions to the industry and extend to them a hearty congratulations. Read “SID’s Best and Brightest” for 2016, by Jenny Donelan, and you will see these are people who lead by example and continue to give so much back to help fuel our industry not only today but for future generations to come.

I mentioned CES in the beginning of the editorial, referring to the annual Consumer Electronics show that has become an important first-look at what many new displays and display-centric products will look like in the year ahead. This year we asked frequent contributor Ken Werner to report back for us on what was noteworthy. Ken gave us a great Show Review article titled “Ten Intriguing Display Discoveries from CES 2016,” which included several flexible and curved examples, including the headline-making LG rollable 18-in. OLED prototype. As Ken explains, this was not a carefully preserved protected laboratory specimen but instead a fully functioning open-air demonstration of a 1200 × 810-pixel AMOLED display that could be repeatedly rolled to a radius of as small as 3 cm and still survive. This and many other equally important items made up Ken’s top ten list, which I’m sure you will find as interesting as I did.

Another story that came out of CES, for at least the second year, is the growing importance of automotive “technology,” including many new themes for incorporating displays into cabins. This is an exciting trend for me because I know how long the hard-core automotive-display folks have been working on ways to get digital dashboards into cars. It is felt like a strange tug of war in which automobile manufacturers have wanted to incorporate new display concepts, but at the same time have shied away from things more radical than the center console backup camera and navigation screens commonly incorporated today. But the wind is definitely, finally (sigh), blowing harder in favor of more

comprehensive ideas for digital dashboards and head-up displays – supported at last by a wider variety of form factors and technologies available to car manufacturers, including flexible displays.

This important display trend has been recognized and nurtured not only at CES but also by SID at Display Week. SID’s involvement with vehicle displays goes back many years. The SID Detroit Metro chapter has been holding a regional Vehicle Displays Conference for 24 years. Last year, in our show issue of *Information Display*, we provided significant coverage of the current state of the art and hot topics in vehicle displays. Once again, this year, the special focus topics at Display Week include vehicle displays, along with augmented and virtual reality, digital-signage display solutions, lighting, TFTs and display circuits on flexible substrates, vehicle displays and user-interface technology trends, and wearable displays. These key topics are represented not only in the exhibit hall but also in the incredible array of technical papers being presented at the SID Symposium portion of the program.

To create our Symposium Preview titled “Emergence and Convergence Highlight This Year’s Technical Symposium,” Jenny Donelan interviewed the Symposium program subcommittee chairs and asked them to highlight the most significant trends in their subject areas. What she reports is one of the best lineups I think I have ever seen for the Symposium. In short, when people say something is a “don’t-miss” event, you generally expect it is an exaggeration. In this case, the term almost feels like an understatement. While the Symposium is just one part of the full (some would say too full) program of Display Week, I think it is an undeniable barometer for the future trends of the industry. Whether your focus is technical, marketing, or management, you cannot be a leader in our industry without looking closely at what’s inside the Symposium papers and who is represented in the presentations. So, I would strongly urge you to block off the time and make your plans to attend all of Display Week, not just the exhibits and not just for a single day. You will not be disappointed.

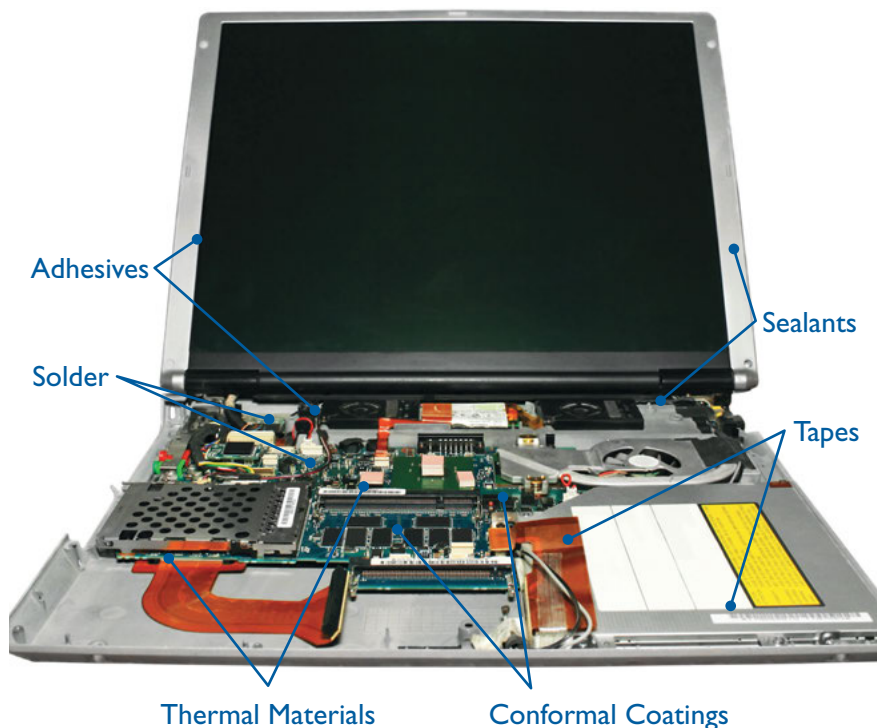
One of the companies that has had a significant presence in SID through the years is quantum-dot (QD) innovator QD Vision. QD Vision is based in Massachusetts (as I am) and I have had the privilege to hear them present

their technology several times at New England chapter meetings, where they have always been a generous supporter of our local events. Recently, QD Vision has been part of the exciting emergence of QD-enhanced backlights for LCDs, and the company has become a leading player in that application. To get an inside look on their progress, *Information Display* contacted QD Vision's new CEO Mustafa Ozgen and persuaded him to sit down for a Q&A session. We learned some interesting things about the company's history, current activities, and future plans. We also got Mustafa to comment on the debate over indium phosphide vs. cadmium QDs and explain how its backlight enhancement implementation differs from that of its competitors. This is a burgeoning field, and personally I think we have only begun to explore what QDs can do for displays and lighting products.

I hope everyone enjoys what we have assembled this month, and I'm very thankful to all the efforts of our authors, our guest editor, and the hard-working staff that assembles *Information Display* each month. Next time I write, it will be for the show issue to be released during Display Week and featuring the winners of SID's highly coveted Display Industry Awards. Having just submitted my ballot as a member of the awards committee, I can tell you it was a tough choice among many very worthy nominees. The committee will have some outstanding winners to announce in May. In that month, we will also feature another round of vehicle-displays coverage and continue with some more stories about digital signage. Don't forget to pick up your next issue of *Information Display* when you get to San Francisco. Safe travels! ■

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Dr. Huang and her colleagues provide an overview of AU Optronics' advancements in flexible AMOLED technology, from fixed curve to bendable, and now working toward a foldable display. A bendable phone with bending and touch sensors provides more intuitive operation and control, which is an excellent example of the advantages of flexible displays. You will also find a detailed discussion on key enabling technologies for foldable displays.

These three articles cover a wide range of topics in flexible displays. In terms of back-planes, three technologies – LTPS, oxide TFT, and organic TFT – are being explored for flexible displays. In terms of applications, researchers are working on bendable and wearable bands, bendable smartphones with bending as a sensor/control, and foldable devices. These are all truly flexible applications. Although rollable technology is not discussed in the articles, it is not necessarily more challenging than foldable technology, when bending-radius requirements are considered.

Reflecting back on my roadmap slide from 7 years ago, here are three things I have learned while preparing for this special issue. First, the “rugged,” or “flat unbreakable,” phase I predicted is not happening, at least not for mainstream applications. Second, researchers are actively working on all the following forms of flexible displays: rigid, bendable, foldable, and rollable. Third, in order to develop products using flexible displays, designers have to consider all the practical limitations such as the rigidity of electronic components. These limitations are unique to each specific application. As a result, for each form of flexible display, a variety of new forms will also be generated at the product level – flexible displays will come in many forms.

What's the ultimate flexible display? Seven years ago, I gave my answer as the 5th phase of flexible-display development – “free form” – the display is extremely flexible in all directions, or simply put, paper-like. Have fun with that. ■

Ruiqing (Ray) Ma is Director of Flexible PHOLED Lighting R&D at Universal Display Corp. He can be reached at RMA@udcoled.com.

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of the Board in January 2016. Lawrence Tannas, founder of the company, will remain a member of the new board of directors and a consultant. The company has been renamed Pixel Scientific and has moved headquarters from Orange, California, to Scotts Valley, California. Pixel Scientific will maintain and expand on the product line based on custom sizing of LCDs and continue licensing of the patents covering resizing LCDs to the industry worldwide.

Sigma Designs and QD Vision Partner to Enable Rec. 2020 HDR Quantum-Dot TVs

Sigma Designs, a leading provider of intelligent system-on-chip (SoC) solutions, and QD Vision, a global leader in quantum-dot display technology, recently announced a strategic partnership to develop a cost-effective UHD TV platform with high dynamic range (HDR) and Rec. 2020 performance. The platform will be based on Sigma's TV SoC and frame-rate conversion (FRC) chips and QD Vision's Color IQ quantum-dot (QD) technology.

According to the companies, the next wave of UHD TVs will offer a combination of HDR and Rec. 2020, but thus far these capabilities can only be found in the extreme high end of the TV market. Achieving mainstream adoption without sacrificing image quality requires tighter integration between the TV's firmware (e.g., the SoC) and its hardware (e.g., backlight, panel, etc.), which has spurred the strategic partnership between Sigma Designs and QD Vision.

Power Technology Unveils the Illumina Light Farm

Power Technology, a laser specialist in the photonics industry for 45 years, recently released what it claims is the world's only multi-projector laser light source. Unlike traditional projectors with lamps or lasers inside single projectors, the Illumina Light Farm allows a single source of light to be delivered via fiber optics to multiple new or retrofitted projectors. This extends the life of already purchased technology while spreading the laser upgrade investment across multiple projectors.

Initially targeted to retrofit cinema projectors, the Illumina Light Farm should prove valuable to amusement parks, virtual reality, and flight-simulator applications, according to Power Technology.

“We are laser experts, not projector manufacturers, so we did not come into the market with the pre-conception that the light source had to be inside the projector. We aren't just replacing a bulb with a laser. We are replacing all your bulbs with one maintenance-free light source that lasts for years,” says Walter Burgess, Vice-President of Engineering and Sales with Power Technology. ■

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Turn to page 43 for a list of 2016 editorial themes, with approximate dates for submitting article proposals.



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How to Stand Out for SID's Best in Show Awards

The deadline for participating in Display Week 2016's Best in Show awards is fast approaching – nominations for these exhibitor-only awards are due no later than May 1. Each year, three to five Best in Show winners are chosen by an independent panel of display experts who review the products, prototypes, and processes nominated for the awards on the show floor. Winners are selected for their ability to excite display experts and members of the general public and press.

A Best in Show win can really open doors for a company, as it did for Cima NanoTech, 2013 winner in the small Exhibit Category for its self-assembling silver nanoparticle mesh technology. That exhibit, and winning the award, says Cima NanoTech founder Jon Brodd, got the attention of a current major partner – Foxconn. On the display show floor, Cima NanoTech showed its technology in as many formats as possible, including EMI shielding, transparent heating, thermo-formed 3D devices, and a 21.5-in. projected-capacitive touch panel on which visitors could play Fruit Ninja. “We tried to demonstrate the breadth of Cima NanoTech’s SANTE nanoparticle technology as a platform that enables a range of the products,” says Brodd. “We showed the people who really knew p-cap [projected-capacitive touch technology] that we understood what was needed.”

Last year’s exhibit by Nanosys, a Best in Show winner for its quantum-dot TVs, is another example of effective booth presentation. Nanosys showed three 65-in. UHD TVs side by side, identical except for the method used to create the white light in the backlight. The materials used were conventional white LEDs. One set used the LEDs only, another included Nanosys’s QDEF quantum-dot technology and another, Nanosys’ cadmium-free QDEF quantum-dot technology. With the sets side by side, viewers could make a clear determination of the differences – not much further explanation needed. As *Information Display* reporter Ken Werner wrote: “These demos made it very clear that cadmium quantum dots deliver a much greater color gamut than indium-phosphide dots [or conventional white LEDs.]”

Best in Show is open to all exhibitors on the show floor during Display Week 2016, and prizes will be awarded regardless of exhibit size. Self-nominations are encouraged! For details and to download a nomination form, visit <http://www.sid.org/About/Awards/BestinShowAwards.aspx>.



KOREA COMES ON STRONG AT DISPLAY WEEK

Last year, we wrote about how Chinese display companies created major impact in the exhibit hall at Display Week. Companies such as BOE and Central China Display Laboratories had very large, very beautiful displays to show. We don't see any signs of China pulling back, but this year looks to be an exciting one from the display powerhouses out of Korea – LG Display and Samsung. We don't know yet what either company will be showing, but we hope to see more of LG's flexible OLED technology (see this issue's CES review for pictures and descriptions of the company's 18-in. rollable OLED). And with Samsung returning to the show after a year's hiatus, we can only suspect that it has something big to show. Will it be OLED or quantum-dot-enhanced LCD based, or both? We'll just have to hit the show floor and see.

Displays, Electronics Evolve for Connected Car

The average American spends 20 hours a week commuting in their car, and automakers are doing what they can to ensure that these hours are seamlessly connected to the commuter's work and personal life. How this incentive plays out, and how it involves display makers, was the subject of a recent Bay Area SID Chapter presentation, “The Evolution of Displays and Electronics for the Connected Car,” by Rashmi Rao, Director of Advanced Engineering for Harman International.

Among the highlights from her presentation:

- J. D. Power and Associates reports that automakers are investing billions into technologies that more than 40% of consumers are not using.
- The connected car is forecasted to be the most disruptive force in the technology industry since the smart phone.
- The connected car is slated to be a \$270 billion industry by 2020.

This connectivity, Rao explained, will dramatically change our relationship with our vehicles. As these relationships evolve, it's vital that automakers focus on relevant technologies that provide intuitive, contextual information. Autonomous driving, smart displays, and active and passive safety are all subjects of aggressive and ongoing R&D. Rao points out that display makers already have many answers to car-maker's current challenges.

You can read more about specific display-related solutions in Rao's feature article, written with Stefan Marti, on “Advances to In-Car Human-Machine Interface Systems,” in our next issue. This issue will focus on vehicle displays and will also include articles from Daimler and Continental.



Harman International's Rashmi Rao (left) recently presented a talk on the connected car to members of the Bay Area Chapter. Shown at right is Bay Area Director Sri Peruvemba.

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