DISPLAY WEEK 2016 REVIEW ISSUE

Information DISPLAY

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Display Week 2016 in the City by the Bay

Wearable, Flexible, Interactive

Plus:

Best-in-Show and I-Zone Winners

Flexible Displays Need Flexible Electronics

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ON THE COVER: Images from Display Week 2016 are, clockwise starting at upper left: Best-in-Show winner Digilens' MotoHUD demo with motorcycle (rider is Geena Dabadghav, IT Manager at MCA); Best-in-Show winning color electrophoretic displays from E Ink (photo courtesy Ken Werner); Moscone Center in San Francisco, home to Display Week 2016; Withings activity monitor with electronic-ink screen (photo courtesy Jyrki Kimmel); LG Display's 77-in. HDR OLED TV, also a Best-in-Show winner; busy show floor at Moscone; Tianma's 5.5-in. flexible OLED display (photo courtesy Ken Werner); crowds head onto the show floor as Display Week gets under way; a bus-stop demo from Best-in-Show winner Asahi Glass Co.; and crowds wait to enter the exhibit hall on opening day.

Cover Design: Jodi Buckley

In the Next Issue of *Information Display*

Emissive Technology

- Materials for EL and PL Applications
- MicroLED Displays
- Emissive Technology Landscape Overview
- An In-Depth Look at a Radical New OLED Technology
- TADF Emitters

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editorial

Mining the Vast Wealth of Display Week

by Stephen Atwood

Welcome to our annual Display Week review issue. The events at this year's show formed a rich tapestry of new and exciting technological discoveries, as you no doubt remember if you were with us in San Francisco. If you missed the show, then settle in and read all about it here. Each year, this pivotal gathering of the display industry attracts the best and brightest (pun intended) of the industry and its member companies. There is no better place to both learn from the best and contribute what you know to educate others. People come to Display Week for many reasons, including the technical presentations, the seminars, the short courses, and the business conferences, but above all, everyone comes to see the great exhibits. Our cover stories this month are the Best-in-Show and I-Zone awards, which are conveyed each year to the companies deemed by the awards committees to have created the best exhibits in all three booth-size categories and within the I-Zone. This year the field was especially great and the choices really hard, but I think the committees did an excellent job capturing the most innovative and informative exhibits. Our own Jenny Donelan has compiled the Best-in-Show results for you, and roving reporters Steve Sechrist and Ken Werner describe the I-Zone award.

In order to cover the vast array of content and happenings that is Display Week, we recruit an annual team of reporters to help us. This year, our group of talented and highly experienced reporters consisted of Achin Bhowmik and Jyrki Kimmel, as well as Steve and Ken. They spent their days combing through the vast amount of new exhibits and presentations to bring you the most important highlights of the week. I am very grateful and wish to express my heartfelt appreciation to them all for their hard work.

We lead off our Display Week review coverage with Steve's survey of TVs,"Enter the Feature-Driven Market." As you can probably guess from this title, with overall revenues in decline, set makers are desperately searching for features that will drive high-value purchasing decisions, and that desire is generating great technological advancements, especially in areas such as high dynamic range (HDR), wide color gamut (including quantum-dot enhancements), and ultra-high definition (UHD). While it is hard to know if consumers will really monetize the difference in performance these features bring, they surely will be impressed by the latest advancements. If you were at the exhibition you cannot have missed the outstanding display of the 77-in. OLED TV panel from LG and the 65-in. UHD "Black Crystal" LCD TV from Samsung. These and other worthy items are highlighted in Steve's review article for your enjoyment.

I think many attendees will remember the exciting breakthrough shown this year by E Ink using four different colors within separate microcapsules to produce an almost full-color-range electrophoretic display (EPD). This was an exciting development that I know has been many years in the making. It also can open up many new applications for EPDs. This and a number of other headlines, including advances in OLED materials, quantum dots (QDs), glass (yes glass), and light guides can be found in Ken Werner's review article appropriately titled "Four Materials Stories from Display Week 2016."

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Global Lighting Technologies Opens Fifth Fab in Taiwan

Global Lighting Technologies, a major maker of LED-based edge-lit light-guide technology, has completed construction of a fifth manufacturing facility, located within a newly built Science Park in Tongluo, Taiwan (Fig. 1). The factory was scheduled to open for production in September 2016.

Fig. 1: GLT's new fab in Taiwan will enable the manufacture of light guides up to 80 in. on the diagonal.

This facility was developed as a green building and includes new fully automatic equipment that will enable light-guide fabrication to go from "pellet to pallet" without operator involvement. These are the most efficient extrusion lines ever employed by GLT for production and are capable of manufacturing light guides up to 80 in. on the diagonal. GLT estimates that the additional capacity will enable the company to reach 15–20% market share for light guides used within edge-lit LCD TVs worldwide.

Nanoco and Merck Sign Agreement on Cadmium-Free Quantum Materials for Displays

UK-based Nanoco Group plc, a world leader in the development and manufacture of cadmium-free quantum dots and other nanomaterials, has entered into a non-exclusive license agreement with science and technology giant Merck, which will market Nanoco's material to its customer base in the display industry. Nanoco, a spinoff from the University of Manchester, already has development and manufacturing agreements in place with Osram and Dow, respectively. The license allows Merck to immediately start marketing Nanoco's cadmium-free quantum dots and to ultimately establish its own production facility to meet growing market demand. Merck will begin marketing Nanoco's technology in the near term by selling cadmium-free quantum dots manufactured at Nanoco's expanded production plant in Runcorn, UK.

"The license agreement with Nanoco will strengthen our position in quantum materials research, for which we laid the foundations by acquiring [nanocrystal materials developer] Qlight Nanotech of Israel last year," said Walter Galinat, a member of the Merck Executive Board and CEO of Performance Materials.

The financial details of the agreement have not been disclosed, but Nanoco will receive a license fee and royalties on Merck's sales of the Nanoco cadmium-free quantum dots Merck manufactures. While the environmental and performance advantages and disadvantages of cadmium-free QDs are currently a subject for discussion in the courts and in the literature (see article below), European regulations tend to favor cadmium-free QDs over those with cadmium – though perhaps not for the long term.

A Quantum Dot by Any Other Name ...

According to a recent report from authors at Germany's Öko Institute for Applied Ecology, cadmium-based quantum dots should retain a "short-term" exemption from European environmental regulations for TV applications, but not for lighting.

EU environmental regulations generally ban cadmium, but there are exceptions; for example, the cadmium-telluride (CdTe) solar panels made by First Solar, cadmium-doped optical filters, and the cadmium-selenide (CdSe) QDs used in TVs and other displays. The authors conclude that CdSe-based QDs provide wider color gamut and lower energy consumption in displays compared with alternative QDs, although that finding has already been disputed by cadmium-free QD-developer Nanoco Group (see main article). Regulations are paticularly difficult to establish, note the reports's authors, because the pace of commercial product introduction outstrips that of the related investigation and testing.[1]

[1]http//optics.org/news/7/6/8

Gamma Scientific Releases New Glass Measurement Tool

A new reflectometer system from Gamma Scientific delivers high-speed automated reflectance measurements of glass for display and architectural uses and is designed for use in a production setting. The Dual Angle Reflectance Measurement System provides ±0.05% accuracy and includes built-in second-surface reflection suppression that can eliminate measurement errors on glass as thin as 0.3 mm. Built-in self-calibration is designed to enable the system to consistently produce high accuracy data, even when being used by untrained personnel in harsh environments.

The Dual Angle Reflectance Measurement System comprises two optical heads and spectrometers, all housed in a dark enclosure that enables measurements in high-ambient-light production environments (Fig. 2).

The measurement head uses motorized positioners to rapidly acquire any number of desired data points on substrates as large 0.4 m × 0.4 m and automatically acquires correct focus at the glass surface through the use of a laser-based height sensor. All instrument control and data acquisition hardware and software are included with the system.

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president's corner

Serving the Society in an Ever-Changing Landscape

by Yong-Seog Kim
President, Society for Information Display

It is my great honor and pleasure to serve the Society for Information Display in the capacity of President for the next 2 years. As an incoming president, I found Display Week 2016 at San Francisco completely different from a personal perspective. I felt the sheer responsibility of running the SID successfully, and, in addition, I enjoyed the privilege of meeting and getting to know many volunteers and members of the society. Without their unselfish contributions and participation, DW16 would not have been as successful. To that end, I would like to thank all the SID volunteers for the countless hours of personal and professional sacrifice they have made to help SID become a better society.

Display Week 2016 in the beautiful city of San Francisco was a great success. The number of attendees exceeded 7,000 for the first time in a decade. Our exhibit remained strong even during the severe economic downturn our industry is facing. Display Week continues to offer many must-see and must-attend events for everyone in the display-industry community.

For the last 2 decades, our society has witnessed a near-explosive expansion of display technologies, including TFT-LCD, PDP, OLED, FED, projection display, laser display, and various reflective displays including electrophoretic e-Paper, to only name a few. These displays have been in competition with each other for market share over the last decade. Among those technologies, TFT-LCD has outgrown the others to rule the industry. Other technologies, for example PDP, have disappeared completely from the landscape. During this painful consolidation period, many of our close friends left the industry and the society, but others adapted and reinvented themselves for the ever-changing display-industry environment. I was one of the latter group. I transformed myself from a PDP expert to a researcher of the flexible display, which took a while.

At Display Week 2016, I believe we might have again seen a harbinger of tectonic change in the display industry. Approximately 80% of media attention was directed toward OLED flexible displays and related technologies. This indicates that the demand for differentiation from maturing and commoditized TFT-LCDs is strongly driving the evolution of our society. In an associated observation, technical sessions on vehicular displays and AR/VR displays captured a large audience at Display Week 2016. This has resulted in a significant increase in new membership in those technology areas – where traditionally SID has not been as strong.

As technology transfer occurs at light speed in the current era, a swift rise and quick replacement of one technology with another is becoming the new normal, including within the display industry. Our current flat-panel-display technology will not enjoy the 60-year run of CRTs. I am sure that we are also going to witness the rapid adaptation of new display technologies in the coming years. This change could be a relatively modest transition from TFT-LCD to OLED or a revolutionary transition from hardware display imaging technologies to direct communications with our brains, eliminating the display panel altogether. Those of us at SID should embrace and lead the way through this changing landscape of information-display technology.

With this background, I have set some goals for the next 2 years of my presidency. First, I would like to expand the society's conference scope and related membership and exhibits to new technology areas, while maintaining strong leadership in the

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Best-in-Show Winners

The Society for Information Display honored five exhibiting companies at Display Week 2016 in San Francisco last May. These companies were LG Display, Asahi Glass Co., E Ink Corp., DigiLens, and MY Polymers.

Compiled by Jenny Donelan

BEST-IN-SHOW is the most "holistic" award that SID bestows. The Display Industry Awards honor great products that have hit the marketplace; the Best Prototype award is for the most exciting, cutting-edge prototype in the Innovation Zone. Best-in-Show winners are chosen for exciting technology, whether pre- or post-market, and also for the company's ability to showcase that technology. For example, this year the awards panel chose to honor Asahi Glass Co. not for a particular product, but for the way it showcased a range of products in its booth on the show floor. Great exhibitions help anchor the other exciting events at Display Week, and these awards recognize the effort that companies invest in making the exhibition such a success This year's five winners were selected from more than 200 exhibitors at Display Week 2016 in San Francisco.

The Best-in-Show awards are presented in three categories of exhibit size: large, medium, and small.

Large Exhibit: LG Display won in the large-exhibit category for its high-dynamic-range 77-in. UHD OLED TV (Fig. 1). This display was stationed at the front of the exhibit hall this year and stopped showgoers in their tracks as they entered the hall. This was OLED at its best and biggest.

According to LG, high-dynamic-range (HDR) technology boosts the TV's picture performance with near-perfect black and improved brightness. LG adds that OLED technology is well suited to HDR because it is self-emitting. It can show deep blacks and peak luminance at the same time because each self-emitting pixel can turn on and off independently. This capability also offers superior HDR video performance, says LG.

Medium Exhibit: Asahi Glass Co. (AGC) won an award in the medium-exhibit category for its unique booth presentation showcasing integrated display technologies. Asahi is well known as one of the major players when it comes to display glass. Its booth this year at Display Week showed to great advantage the

Fig. 1: Among the admirers of LG's 77-in. HDR OLED TV at Display Week were Catherine Getz, Director of Design and Development for Elotouch Systems (left), and ID *magazine's executive editor Steve Atwood (right) and his wife Linda Atwood (middle). Photo courtesy LG Display.*

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many ways the company's products could be used.

According to Asahi, it designed its presentation to showcase its expertise in glass, advanced chemicals, ceramics, and liquid-crystal-related technologies, as well as in combining these elements to create new types of information displays. Among these are a bus-stop kiosk using AGC's infoverre, an information display directly attached to a glass wall (this appears on the cover of this issue), a programmable window shade, and the potentially interactive Glascene technology shown in Fig. 2.

AGC says that one of its goals is to convert glass areas all around us into information signage "because glass is used in every automobile or architecture." The company looks forward to promising new markets based on the fusion of glass and displays.

Also winning in the medium-exhibit category was E Ink Corp., for its breakthrough color e-Paper display. E Ink, a company that is more or less synonymous with electronic-ink technology, announced its Advanced Color ePaper (ACeP) at Display Week 2016. This is a reflective display that can produce full color at every pixel without the use of a color-filter array (Fig. 3). (For more about this product, see the Materials Review from Display Week 2016 in this issue.) The initial target application for ACeP, according to E Ink, is digital signage.

Small Exhibit: DigiLens won in the small-exhibit category for its unique presentation of highly efficient holographic head-up-display technology. Although DigiLens' Color MotoHUD display is an exciting head-up application in its own right, it did not hurt that the company's booth presentation at Display Week offered attendees a chance to sample the MotoHUD onboard a (stationary) BMW motorcycle (Fig. 4). This was a very popular exhibit during the show.

DigiLens notes that inquiries for automotive HUDs and wearable displays like the MotoHUD continue to grow. On the automotive side, it claims that the integrated nature of its optical platform enables the light

Fig. 2: *This interactive virtual concierge robot is an example of Asahi Glass Co.'s Glascene technology, in which an image projected onto a transparent glass screen becomes an interactive presentation through motion sensing.*

Fig. 3: *E Ink's new color electrophoretic technology produces color without the use of filters.*

Fig. 4: *DigiLens' Color MotoHUD display has been developed for BMW. Pictured aboard the motorcycle is Geena Dabadghav, IT Manager for MCA.*

transmission ratio for a wide-FOV windscreen AR HUD projector to be reduced from 30+ today down to under 2. On the wearable side, the company says it is committed to full production of the MotoHUD and is now finalizing designs for AR eyeglass displays.

Also winning in the small-exhibit category was MY Polymers for its low-refractive-index liquid optically clear adhesive with high bonding strength. The company's LOCA-133 (Fig. 5) is distinguished by its unique combination of low refractive index and high bond strength.

Previously, according to MY Polymers, it was not possible to produce low-index adhesives with strong adhesion, and this limitation prevented their use in the display industry.

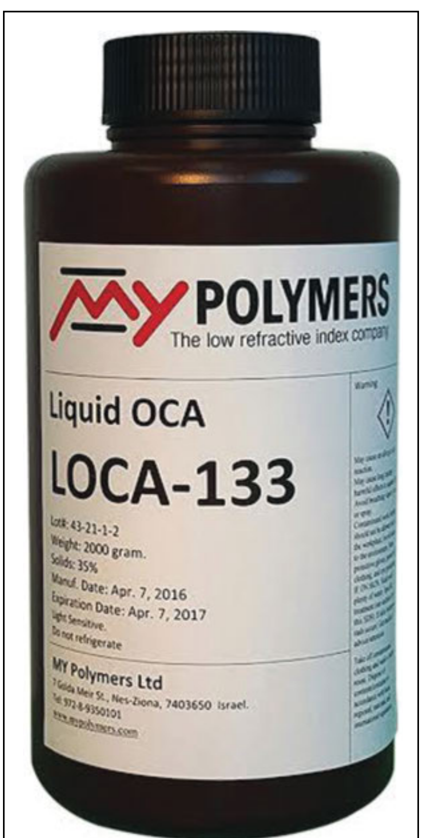

Fig. 5: While the bottle may not look all that exciting, it's what's inside that counts. The LOCA-133 adhesive from MY Polymers impressed the Best-in-Show committee because it's a low-index adhesive with strong bonding capabilities, making it useful for a wide range of display technologies.

Now, due to LOCA-133's low index, the light remains contained in the light-guiding medium. This property enables improvements in various applications, including thinner high-efficiency backlight units, a minimization of light leakage in curved and flexible LCDs, improved light-based touch screens, improved autostereoscopic 3D displays (due to enhanced disparity between the two images), improved VR and AR headsets, higher transparency in nanotech-based transparent conductors, and improved light extraction from OLEDs. ■

THE DISPLAY INDUSTRY'S SOURCE FOR NEWS AND TECHNICAL INFORMATION

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**

nVerpix Takes Best Prototype Honors in the I-Zone

Display Week's Innovation Zone continues to provide an inside look at up-and-coming display technology.

by Steve Sechrist

THE Innovation Zone (I-Zone) has become a top destination for Display Week showgoers. SID's I-Zone is celebrating its 5th year, with the same sponsor – E Ink – backing the new and emerging technology showcase. The I-Zone features both cutting-edge demos and prototypes fresh out of the labs. This is where you will see some of the most innovative display-related work anywhere.

There were 24 I-Zone participants this year. This article describes a few of the highlights, but the showstopper, and the winner of the 2016 Best Prototype award, was nVerpix. The company received the award, which is bestowed on just one I-Zone exhibitor per year, for its Carbon-Nanotube Vertical Organic Light-Emitting Transistor (CN-VOLET). This 3D design for OLED pixels creates a new architecture by pivoting the traditional horizontal structure and re-orienting the transistor channel to a vertical position. For more about this year's winner, see the sidebar, "OLEDs Get Reoriented."

Elsewhere in the I-Zone, China-based Halation Photonics was showing its new multi-stable liquid-crystal (MSLC) technology that retains its crystal alignment even after the power is off. Power is only needed to make changes to the display, so like electrophoretic EPH and other bistable technologies, MSLC is very efficient.

Halation's first applications seem to be in the shelf-label market. For this, the company developed Whiteon, a black-and-white e-Paper technology. Other applications include a smart dynamic privacy function, which operates much like 3M's privacy film for displays. MSLC technology is dynamic, however, in that the privacy can be turned off and the panel returned to a fully functional

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Fig. 1: Maradin demonstrated a new imaging system based on laser scanning and detection with MEMS technology.

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display with its conventional viewing angle for collaboration and image sharing.

Lumii is an MIT spin-off company that was showing its light-field engine that accepts 3D models and computes a set of unique patterns that can be printed and stacked, then illuminated by a backlight. This gives off a multi-view light field that, according to Lumii, can be of any size or dimension. The technology offers high resolution, large size, high luminance, full parallax, and ease of production.

Maradin showed a full laser-scanning solution based on a 2D MEMS mirror device powered by an RGB laser diode and optics. This is a laser imaging system/laser scanning and detection device. It includes a 2D single mirror that uses a small optic (to increase optical efficiency) and combines electrostatic (in the horizontal plane) with electromagnetic (in the vertical plane) sensing, which serve to improve system robustness and performance. It also offers a rather wide optical field of view (FOV) of 45° (H) × 30° (V), which is a fairly large image/scan area for this small device (Fig. 1).

***Fig. 2:** Synaptics demoed a steering wheel (left) and a fingerprint-sensing application, both using its haptic technology.*

OLEDs Get Reoriented

nVerpix's award-winning Carbon-Nanotube Vertical Organic Light-Emitting Transistor (CN-VOLET) has roots in an earlier architecture developed by Andrew Rinzler and his colleagues at the University of Florida. The university spun off nVerpix in 2010 to commercialize the CN-VOLET technology. The company is now a subsidiary of Nanoholdings.

The earlier architecture was a carbon-nanotube-based vertical field-effect transistor (CN-VFET) that could drive OLED pixels at low operating voltages, according to Rinzler. The new architecture incorporates the OLED layers in the transistor stack, creating what can be viewed as a light-emitting transistor.

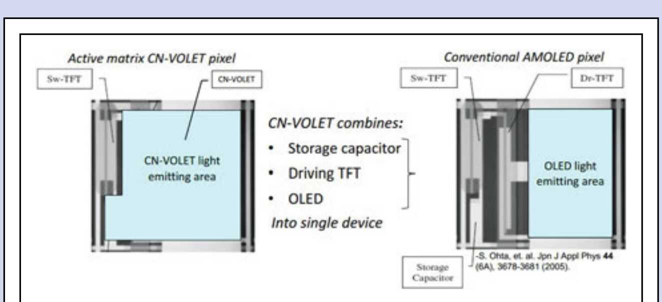

***Fig. 3:** nVerpix's carbon-nanotube-vertical OLED light-emitting transistor (left) can deliver a much larger aperture ratio than a conventional AMOLED (right).*

In the conventional TFT architecture, current flows in the plane of substrate. The CN-VFET configuration conducts the current under the channel layer, at which point it flows vertically to the drain electrode. This architecture permits the incorporation of OLED layers in the transistor stack. A top-down look (Fig. 3) shows that the new architecture can deliver an aperture ratio of up to 70%.

If you are not a specialist, it may not be immediately evident that the vertical transistor is the current-control transistor. The switching transistor is still a conventional TFT, and a simple single-transistor a-Si switch serves to drive the CN-VOLET, said R&D head David Cheney.

In its I-Zone booth, the company showed a small monochrome QVGA display. Although the technology is still a long way from being usable for TV-sized panels with their requirements for very long lifetimes and minimal color shift, it is somewhat closer for cell-phone displays, where the very compact CN-VOLET structure would be especially appealing.

– Ken Werner

Components included an advanced photodiode sensor (APD) that receives the image (it uses the MAR1100 2D MEMS scanner) mirror device that floods the object with IR laser light. Then data from the image is sent from the sensor to a special processor to crunch it for processing and displays it onto a desktop monitor. The company also includes a MEMS controller and standard digital video interface.

Last but not least, we discovered at the I-Zone a new technology from Synaptics – founded in 1985 – almost ancient in digital years. The company was showing off its latest concept device, which it calls "Torch." This is a prototype steering-wheel application, which gives force feedback via a haptic-enabled technology called ClearForce.

The group claims its haptic-enabled immersion offers the advantage of gesture validation, improved "no-look" operation, and the ability to avoid accidental activation, all while motoring down the highway. It was pretty cool to use this concept demo, but my guess is that any pure driving enthusiast would say they would much rather feel the real road than an augmented version of some other kind of human interface device not related to driving.

Synaptics also had another prototype, an ID fingerprint sensor technology it modified for cars. Its fingerprint sensor can be used for a host of biometric authentication purposes. This, according to the company, includes online navigation. The concept included finger navigation capabilities, including, remarkably, a wallet mode for on-line shopping (while you drive??) plus some features to personalize the vehicle and systems, all aimed at "reducing driver distraction," while at the same time grossly enabling it. The sweet spot between available in-auto technology and usable in-auto technology remains elusive (Fig. 2).

Each year, the crowds at the I-Zone get larger. It's exciting to see so many new technologies. Many seem far off, but at least a few will no doubt form the basis of future products as yet unimagined. ■

Enter the Feature-Driven Market

Faced with a consumer market that is reasonably content with current-sized panels and accustomed to ever-lowering prices, TV manufacturers are looking toward specialized features to drive sales – and profits – upward.

by Steve Sechrist

As ALWAYS, TV panels were prominent on the show floor at Display Week this year. The TV market has become increasingly complicated, and for that reason a good way to commence discussion of it is with some background data from the IHS/SID Business Conference, which also took place at Display Week 2016.

Speaker Paul Gagnon, analyst and Director of TV Sets Research at market research firm IHS, reported on the outlook of TV sales, noting that the global TV market will continue to grow in unit volume though the current decade (at about the same level as the decade ending in 2010), reaching 250 million units by 2020. However, said Gagnon, "Revenues are not expected to improve, which is weighing on profits for many TV brands." That revenue number peaked in 2010 at $118 billion and will decline to just over $80 billion by the end of 2016, remaining flat through the decade and ending 2020 at just over the $80 billion mark (Fig. 1).

According to Gagnon, set makers looking to increase profits can do so by targeting features that customers are willing to pay for. Such features include UHD, full color gamut, and HDR, despite the lack of available content or even standards in display quality to help drive this feature set forward. He also explained that although there has been a steady average size increase in the TV space over the last several years, this growth is slowing, which is also creating more focus on successful feature introductions. "Picture quality ranked No. 1 in [customer] decision criteria in all 14 countries surveyed," he said, "across all types of regional demographics, with high resolution a "close second."

While the "picture-quality" category seems rather nebulous, in his presentation Gagnon identified several consumer benefits such as HD, smart TV, and LED backlighting, as well as full-HD/1080p resolution, considered table stakes in today's worldwide TV market (see below). Going forward, we can expect to see UHD/4K, plus wide color gamut, HDR compatibility, and even 3D and curved sets as other options in the category. (Remember when a wireless remote was considered the sole upgrade to a color TV set?)

The survey also found that average TV price is a function of both product-specific and country-specific factors that include screen size, product features, brand, retail environment, and margins, tariffs, taxes (VAT), inflation, and exchange rates. The good news for manufacturers: higher efficiencies are helping reduce panel price per inch (ppi), moving that number down from $15 (in 2016) to an anticipated figure below half of that (for base models anyway) within the survey period that reaches the end of this decade.

Another featured conference speaker, Robert O'Brien of RJO Options LLC, also reported that new product features for improved picture quality represent an increasing share of revenue for all major brands. (O'Brien based his presentation on his company's recent brand report, which is based on point-of-sale data across hundreds of product categories in more than 90 countries.)

His company's findings were slightly different from IHS's: RJO's research indicated that smart TVs currently dominate the premium options, representing more than half of all TVs sold. But 4K resolution has almost become a *de facto* standard in most markets. "It is on the path to mainstream adoption," said O'Brien. He noted that other factors such as curved sets, color saturation, and OLED TVs were still emerging, yet likely to become increasingly important in terms of value. Figure 2 shows the relative success of some of these features to date, including 3D, high frame rate, and HDR.

O'Brien also noted that while major features such as 4K and smart-TV capability are global in their appeal, local country markets do exhibit huge variations in preferences regarding pricing, brand dynamics, and specific features. For example, "high prices are not necessarily found in high-income countries" he said, comparing the G20[1] average selling price (ASP) of $503 to Argentina's $817 and $436 for the U.S." Low prices can be a result of a competitive environment among brands and retailers," he explains.

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[1]The G20 includes Argentina, Australia, Brazil, Canada, China, France, Germany, India, Indonesia, Italy, Japan, Republic of Korea, Mexico, Russia, Saudi Arabia, South Africa, Turkey, the United Kingdom, the United States, and the European Union.

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Brand Dynamics

According to O'Brien, the TV market breaks down into three groups that represent >85% of the market: This includes four top global brands (Samsung, LG, Sony, and Panasonic) with a global presence. These typically lead major industry innovation and usually have an ASP above the industry norm. Brands including Sharp, Philips, Vizio, and Toshiba have regional strengths, and in some cases are market leaders in their territories, with average sakes prices (ASPs) at or near the industry

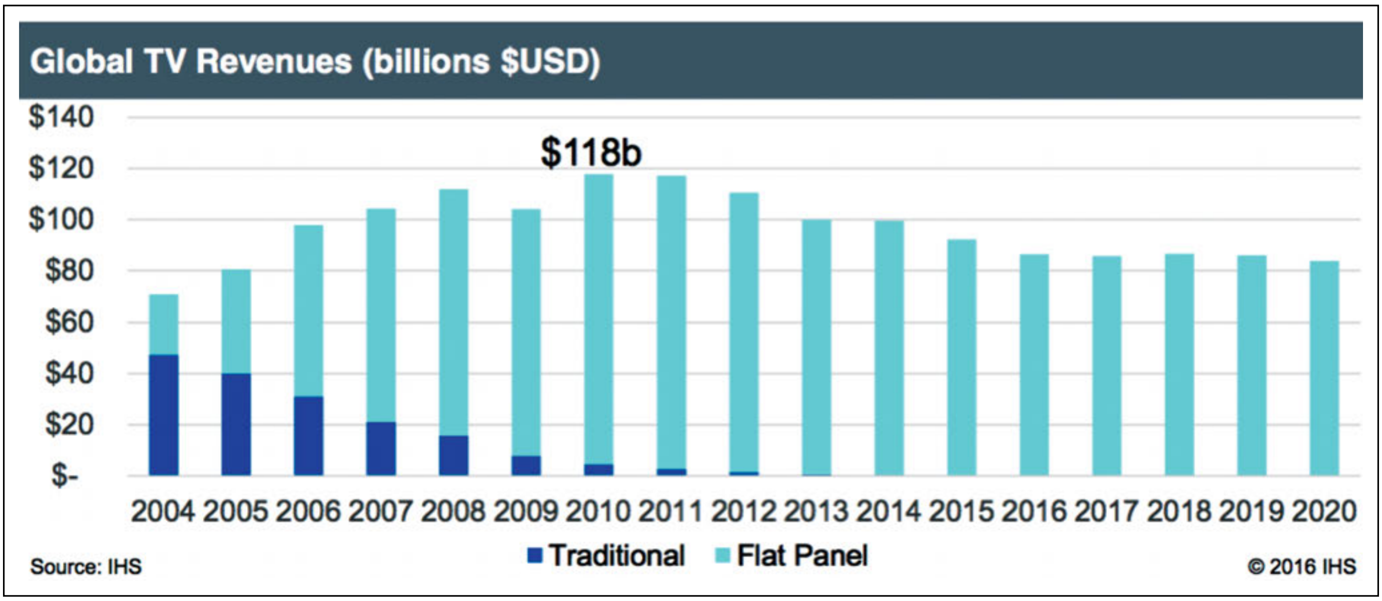

Fig. 1: The best days of flat-panel revenues are already well behind us, according to IHS market data that shows the peak occurring in 2010.

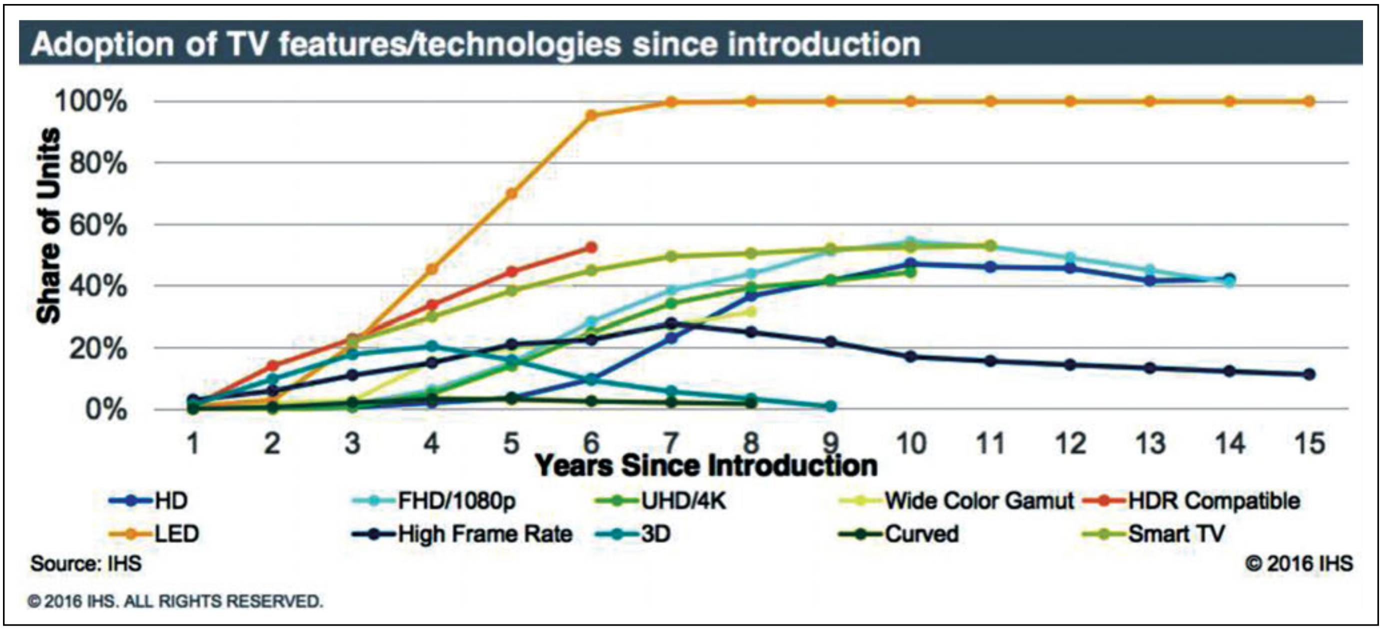

Fig. 2: Features such as LED backlighting have fared well since its introduction, whereas the curved form factor has done little to spike unit shares thus far.

Fig. 3: LG Display's 77-in. OLED panel with HDR was the first thing visitors saw when they entered the show floor, and many of them stopped to gaze for a while.

Fig. 4: The future of TV is here and "It's OLED, not LCD" proclaimed LG Display on the side of its booth at Display Week 2016. Photo courtesy Steve Sechrist.

average. The third group is represented by brands from China ("the Big 6"), which include TCL, Skyworth, Changhong, Konka, Haier, and Hisense. These companies' products typically have ASPs below the industry average, O'Brien said.

LG Display OLED TVs Light Up the Show Floor

To make the case for features driving the future of TVs, one had to look no further than the exhibition floor at Display Week. First and foremost was LG Display, which demonstrated an impressive 77-in. OLED TV with HDR that drew crowds throughout the entire 3 days of the show (Fig. 3).

This set (with a rumored price of $37K), helped the company win the large-booth Best-in-Show award, taking it away from BOE, which had won the award in the previous 2 years for its innovative TVs.

LG Display went on record at Display Week to say that the future of TVs is the OLED TV (Fig. 4). To back up its claim, the company showed an impressive range of OLED-based TV prototypes, including a concave 65-in. UHD OLED, an OLED dual-view flat-display TV and an OLED transparent display, all representing plans for future products from the Korea-based TV maker.

My favorite LG TV panel in the group was the dual-view 55-in. OLED in full HD, with a thickness of just 7.9 mm and a tiny 6.6 mm (left, right) bezel, that showed a unique OLED image on both sides. This will be quite useful in the digital out-of-home (DooH) market and other commercial B2B options. Another B2B TV candidate was a 55-in. OLED transparent display that LG said had 40% transparency. The TV operated in full HD (1920 × 1080) running at 120 Hz and 200-nit luminance. Finally, the UHD OLED concave display was 65 in.on the diagonal with 3840 × 2160 pixels and a 500-mm curvature radius.

LG Display also showed an LCD-based curved panel with WQHD resolution (that's 3440 × 1440 pixels) with a whopping 109 ppi. The display was mounted on a wall in a three-panel landscape configuration (Fig. 5). The radius of the curvature was 1900 mm, and LG said it was using an a-Si backplane. This LCD is currently in mass production, according to the company.

LG Display made the case that the best way to produce HDR images is by using OLEDs. LG said "OLEDs = The Best Solution for

HDR." And while the company may be right in the long term, as reported above in the Business Conference sessions, price and yields have yet to push OLED display technology anywhere near the volume (or low cost) of rival LCDs that still dominate mainstream TVs. So, for now, LG will continue to differentiate the high end of its TV product line with its stunning display-quality WOLED panels in sexy razor-thin form factors, albeit at higher prices and presumably lower profit margins due to yield and production-cost issues.

Samsung Sticks with LCD TVs (at least at Display Week)

Samsung Display was also exhibiting at Display Week, showing off its high-contrast-ratio low-reflectance LCD technology. The company had a 65-in. UHD "Black Crystal" display that used global dimming to achieve the high contrast ratio and low reflectance for its panels in the booth on the exhibition floor. By using its SDC VA mode, the company achieved a 6000:1 contrast with just 2.3% reflectance.

Samsung said it will use this technology to help differentiate its product line and include its Slim D-LED local-dimming feature in the step-up models that will be selling at a higher price. The company said the typical living room is at 131 lux and at that luminance level; its UHD display achieves a contrast ratio (CR) of 6K:1 (up from 1,500:1) with a remarkably low 2.3% reflectance (conventionally around 7-8%). That CR number boosts to 8K:1 in low-light levels (meaning dark or less than 1-lux rooms). Samsung will offer this panel with an edge-lit or local direct-dimming option to help support its good–better–best pricing model. On the curved side of LCDs, Samsung showed a 65-in. slim unit with UHD resolution.

Samsung's TV-panel presence this year was rather muted, with very limited material, printed or on display, in the booth considering it leadership position in worldwide markets. When we inquired about press meetings, they said none were planned at the show. One has to imagine that the company is working on something that cannot be revealed yet (see "Four Materials Stories from Display Week 2016" in this issue for some informed speculation on the company's OLED-TV strategy).

Big Displays from BOE

BOE showed an 82-in. 10K (10240 × 4320) curved display, the same technology that helped the company take a SID Best-in-Show

Fig. 5: *LG Display did show some LCD-based panels as well as OLED ones, including this WQHD-resolution curved display, shown here in a three-panel landscape configuration. Photo courtesy Steve Sechrist.*

large booth award at Display Week last year. Specs for this newest 10K curved set include 136 ppi with a luminance at 360 cd/m^2. The curved set offered a radius of 6,500 mm. Also impressive in the BOE booth was its massive 98-in.-diagonal 8K-resolution panel with HDR.

BOE claimed it could achieve black levels as low as 0.001 cd/m^2 with a peak brightness at 1000 cd/m^2 of luminance (a whopping six orders of magnitude higher). The company said its 98-in. behemoth was available now, but no pricing was included with that statement. A second 8K panel was nearby, this one a 65-in. model that was thin and sexy at 3.8 mm.

QD Vision's TV-Panel Exhibit

One interesting show-floor exhibit from QD Vision featured the "Product Wall of Fame," tracing the history of quantum-dot-enhanced LCD TV sets that have shipped since their first introduction in 2013. The world's first ever title goes to the Sony KD-65X9000A, which was shown at CES in January 2013. At the time, Sony introduced its QD-based (edge-lit LED) "triluminous panel technology" that worked together with a powerful processor to boost RGB color.

Other notable sets included examples from Thomson and TCL that both achieved the widest color gamut (90% of Rec.2020) available in a commercial TV back in 2015. In that same year, Philips gained the prize for the most energy-efficient commercial 55-in. QD set. China brand Hisense also made the QD Vision "Wall of Fame" with its K7100 model, the first ever curved QD-based LCD TV. This shipped in 2015.

A Challenging Market

So again, faced with a maturing consumer market that is reasonably content with current TV offerings, as long as they are selling for ever-lower prices, today's TV makers are facing challenges. Each TV maker must look toward specialized features (curved, HDR, and OLED panels, to name a few) to help drive the next wave of sales – and profits – forward, lest it be relegated to the razor-thin margins at the bottom of the TV commodity space.

Intense competition from low-cost China brands continues to persist, as these relatively new panel manufacturers look to shift from a position as white-box sellers to establishing their own worldwide brands that push the price/feature and display-quality boundaries ever forward. As this happens, we also expect to see continued consolidation in the space as some established TV brands decide the cost to play in the consumer-TV space simply does not justify the return on investment. In the meantime, consumers at least will continue to benefit from the increased market competition. ■

Four Materials Stories from Display Week 2016

The show in San Francisco highlighted intriguing advances in the areas of electrophoretic displays, OLED materials and processing, quantum dots, and glass.

by Ken Werner

I could begin this article by saying for the hundredth time that the most significant display developments depend on advances in materials. But you already know that. As the narrator used to say at the beginning of an old TV show, "There are 8 million stories in the Naked City…." Four of the most interesting materials (and processing and device-architecture) stories that came out of Display Week 2016 in San Francisco deal with electrophoretic displays, OLED materials and processing, quantum dots, and glass. We will start with electrophoretic displays:

E Ink's Color Display Almost Steals the Show

E Ink's Carta reflective electrophoretic display (EPD) is a near-perfect device for reading black text on a white background. But there are applications, such as many types of signage, which demand vibrant color. Until now, the only way to get "full" color from an EPD — at least the only way that E Ink has shown us — is by placing a matrix color filter in front of the monochrome display.

The problem with this approach for a reflective display is that the 40% of light reflected from a good EPD is brought down to 10–15% by the filter. This results in a limited gamut of rather dark, muddy colors. E Ink showed the way forward a few years ago with a black, white, and red display, which managed to control particles of three different colors using differences in mobility and a cleverly designed controlling waveform.

At Display Week, E Ink introduced an impressive expansion of this approach, in which particles of four different colors are included within each microcapsule, given different mobilities through different sizing, and driven with a pulsed controlling waveform that permits the creation of thousands of colors, said E Ink's Giovanni Mancini (Fig. 1).

The resulting display showed impressively bright and saturated colors and drew crowds. When a new image was written, the display would flash several times. It took about 10 sec for a new image to build to its final colors. One possible application Mancini mentioned is a color E Ink sign powered by photocells, as shown at the far right of Fig. 1. This is an important development that will significantly expand the range of applications EPDs can address.

In any other year, E Ink's new electrophoretic display, which creates full color without the cost and light loss of a matrix color filter, would have had no competition as the most exciting and significant electrophoretic story coming out of Display Week. But this year, E Ink had competition.

First, some background: Good, very-low-power monochrome reflective displays with slow redraw times exist, and with the introduction of E Ink's color display, a good low-power color reflective display with very slow redraw times now exists. What we have not had is a reflective video-rate display, and for good reasons. The only reflective technology that has proved to have both broad application and business feasibility has been electrophoretic (think E Ink), and electrophoretic displays operate by moving charged particles slowly through a significant fluid layer. The redraw time cannot be fast. (Well, it can be faster, but then the charged particles collide violently and tear each other apart, with unfortunate results.)

A development-stage company called CLEARink, which has an extremely impressive technical team, has turned the conventional electrophoretic model on its head. The CLEARink display has a thin optical plate with lenslets on the inner surface. In the white state, incoming light experiences total internal reflection (TIR) and returns to the viewer. Reflectivity is an impressive 60%.

Lurking behind the optical plate is an "ink" containing black particles that are moved toward or away from the plate. When the particles touch the plate (actually, when they get close enough to interfere with the evanescent light wave), the TIR is defeated and light at that point is absorbed.

That's clever, but it's still electrophoresis, with a particle being moved through a fluid. How can that produce video rate? Because, in CLEARink's architecture, the particle only has to move through 0. 5 microns to interrupt the evanescent wave, and that a very small distance can be traversed rapidly (Fig. 2).

The technology was announced several weeks prior to Display Week, but at the conference the company showed technology demonstrations in a suite. To demonstrate the monochrome video-rate display, CLEARview engineers had purchased a Kobo eReader and simply replaced the E Ink imaging film with

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Fig. 1: E Ink's new color technology uses particles of four different colors within each microcapsule (left) that are controlled in such a way as to create thousands of colors for an unusually vibrant electrophoretic display (right).

its own. With the application of a video signal, the display showed very clean, 30-fps video with subjectively good contrast and that bright 60% reflectivity. CEO Frank Christiaens noted that the technology is compatible with pretty much any backplane and requires no precision alignment.

As impressive as the monochrome display is, Christiaens did not want my colleague Bob Raikes and me to forget that color via matrix color filter (MCF) is part of the company's mid-term road-map, and his demos were effective. Using an MCF with an otherwise monochrome EPD has not been a satisfying approach in the past because too much of the reflective light was absorbed. The difference here is that CLEARink starts out with 60% reflectivity rather than 40%.

So, said Christiaens, CLEARink will soon be providing something that has never before been available: a reflective, color, video-rate display. In either a color or monochrome version, CLEARink's fast EPD will enable new applications that cannot be realized by existing display technologies.

OLED Materials and Processes Make Large Steps Forward

A good blue OLED phosphor must do three things well: It must have the proper color coordinates (that is, the right shade of blue) to create a wide color gamut; it must be energy-efficient; and it must have a long lifetime. Currently, OLED panel makers use phosphorescent OLED phosphors for red and

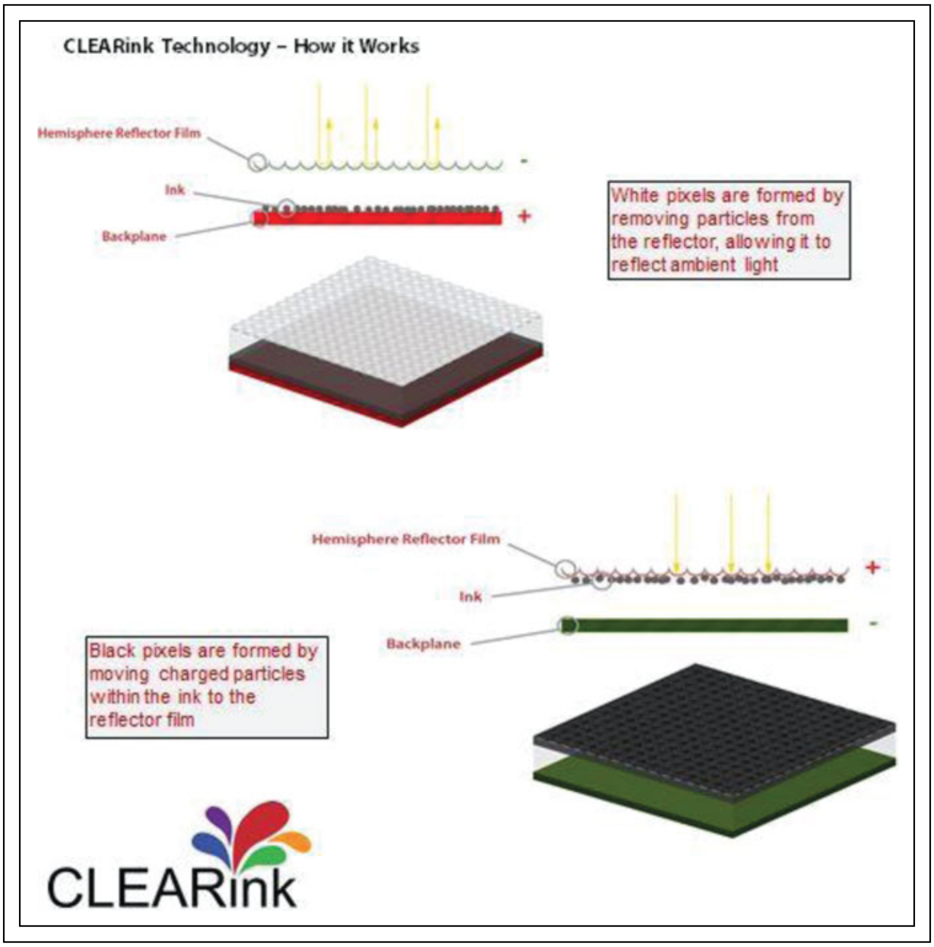

Fig. 2: CLEARink's innovative electrophoretic architecture enables a much faster response time – even supporting video imagery.

green, which do a good job of balancing all three requirements, and fluorescent phosphor for blue, which provides good color coordinates, poor efficiency, and just acceptable (or, depending on who you talk to, not-quite-acceptable) lifetime for television.

Incidentally, "lifetime" does not mean time until death; it means time until the initial luminance drops to a particular percentage. For instance, T95 is the time it takes for display luminance to drop to 95% of its original value. At T50, the display has dropped to 50% of its original output. (When companies talk about lifetime, it is prudent to make sure which "lifetime" they are specifying.)

The chemistry of blue OLED phosphors has made it impossible until now to optimize the three characteristics simultaneously. However, at Display Week we saw two companies – KyuLux and Cynora – that are exploring a quantum-mechanical mechanism called thermally activated delayed fluorescence (TADF), which is perhaps a way of combining for blue the benefits of fluorescence (good color coordinates and better lifetime) with phosphorescence (efficiency).

As explained by Cynora's Thomas Baumann, in TADF the singlet and triplet states are energetically very close to each other, which permits thermal energy to cause the triplet states to migrate to the singlet state. After a delay of a few picoseconds, fluorescent emission occurs from the singlet state with an internal quantum efficiency of 100%, since the (originally) triplet state and the singlet state are both captured. Color coordinates and efficiency are good, said Baumann, but material lifetime still needs work. Baumann anticipates customer qualification in 2017, and the first commercial panel incorporating the material in late 2018 or early 2019. But that assumes the lifetime issues are resolved in the next year. Baumann tried to sound optimistic about that, but this is the kind of material development issue that has not always yielded to optimism.

My colleague Bob Raikes reports that in the Business Conference, Junji Adachi, CTO of year-old Kyulux, described his company's version of TADF, which Adachi called "hyperfluorescent" technology. The light output of normal TADF has a fairly wide spectrum, Adachi said, which limits color saturation. Kyulux claims to have solved this problem, hence the name "hyperfluorescence." The technology is based on fluorescent materials that have a narrower spectrum, with 4 times the light output. Using evaporation, it is a simple matter to combine the TADF and host materials, Adachi said.

At an investor's meeting, Kyulux CEO Christopher Savoie showed data indicating a lifetime (unspecified in this presentation) of 1600 hours at an initial output of 1000 cd for TADF green. The company will announce blue lifetimes in September, said Savoie, but he claimed the latest blue materials have 20% external quantum efficiency (EQE) and long life.

According to the company, its materials have long life, high brightness, and low cost, and Kyulux wants to work with other companies that make materials. Kyulux believes its materials can help panel makers move back from Pentile structures to RGB. (There was no comment about why this might be a good thing.) Kyulux is working with Kyushu University, which has a research cluster in Fukuoka, Japan. Companies involved in the latest investment round include Samsung Display, LG Display, Japan Display, and JOLED, said Savoie. This could be an impressive endorsement of the Kyulux approach or it might be an example of placing stakes in the ground just in case.

Given that neither Kyulux nor Cynora has yet to demonstrate long life for blue, it is unclear whether we should be optimistic that a commercially suitable TADF blue will come to market before a phosphorescent blue does. Since UDC has been working on the phosphorescent-blue problem for years, and to date has not suggested it is making significant progress, perhaps TADF can win this horse race after all. Kyulux's strong technical team of ex-Sony, Samsung, Sharp, and Fuji Film personnel is presumably trying hard.

Other than OLED front-plane materials, a huge challenge has been a manufacturable pixel-switch backplane that can drive OLED pixels with economy, stability, and long life. Samsung, and now others, solved that problem with low-temperature polysilicon (LTPS) for small- and medium-sized displays. However, the LTPS process is difficult to scale to large sizes, in addition to having issues of material waste and acceptable but less-than-ideal uniformity. LG uses an amorphous metal-oxide backplane, which has had yield and stability problems when used with OLEDs. The ideal would be using single-crystal silicon for the backplane, if anybody can figure out (1) how to do it technically and (2) how to do it economically.

Now, a Canadian team from the University of Waterloo, Christie Digital Systems, and DifTek Lasers is reporting "single-crystal device mobility >300 cm²/V-sec in a scalable process suitable for electronic backplanes for large-area OLED displays." This report was made in a Display Week late-news poster paper entitled "Device Mobility >300 cm²/V-sec Using Planarized Single-Crystal-Silicon Spheres for Large-Area-Display Backplanes," by R. S. Tarighat and colleagues. The authors embedded single-crystal-silicon spheres in a ceramic substrate and planarized the surface, and they suggest this approach can be used to make large-area substrates with high mobility (Fig. 3).

The authors developed a method for fabricating transistors on their backplane, and the performance results look very good indeed; just what you would expect from single-crystal silicon. However, the backplane fabrication process requires grinding and etching. The authors performed these steps on a silicon-wafer-sized substrate because grinding and etching equipment for such sizes is readily available. However, it remains to be seen whether a panel maker could implement a grind and etch process on a Gen 8 or Gen 10 substrate uniformly. If that can be done, and the process can be scaled up economically, this could be an important development.

A more comprehensive approach to the backplane and phosphor problems was put forth by nVerpix in its Innovation-Zone booth, an approach that won the company SID's Best Prototype Award. nVerpix is developing what it calls CN-VOLET technology, a new architecture that incorporates the OLED layers in the transistor stack, creating what can be viewed as a light-emitting transistor. (For more about nVerpix, see the I-Zone review article in this issue.)

Samsung Display introduced a display with the industry's highest OLED pixel density yet: 806 pixels per inch (ppi) in a 5.5-in. panel targeted at virtual-reality applications. Samsung claimed 306 nits and 97% color gamut (the gamut was not referenced) for this 3840 × 2160-pixel panel.

The company also waded into the "unhealthy blue display light" discussion by demonstrating its "Bio Blue" display, which adds a light-blue phosphor to the existing RG(darkB) pixel structure. Samsung's explanation was not entirely clear, but I assume the light blue is used as a primary for those colors that can be made

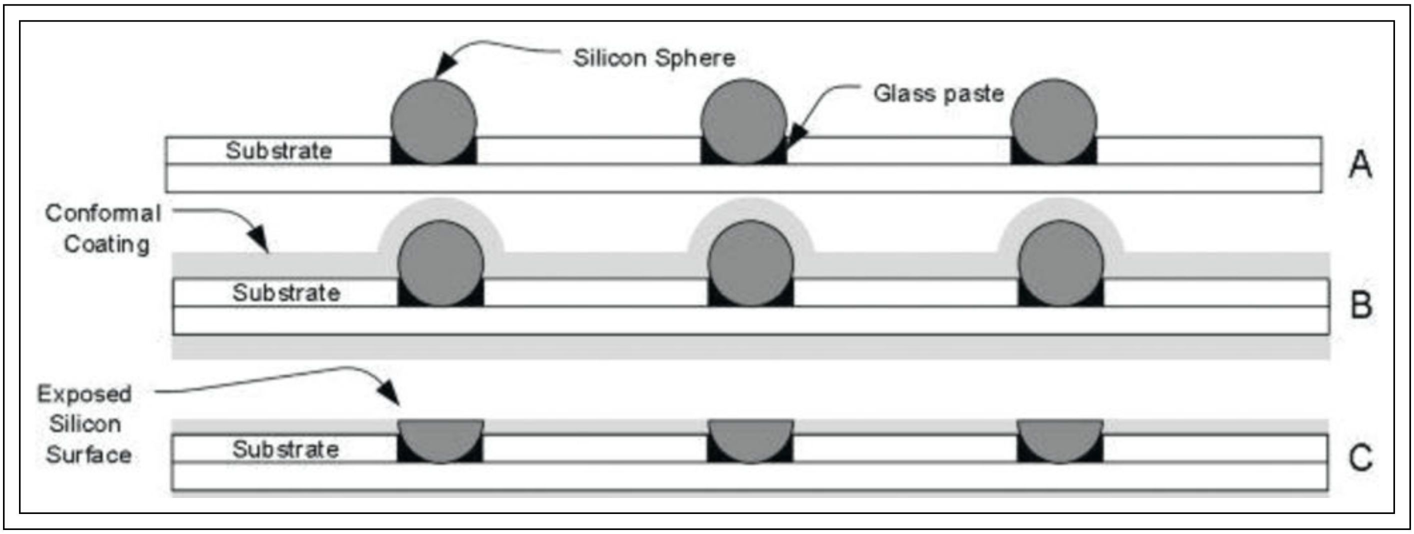

Fig. 3: Single-crystal-silicon spheres are embedded in a ceramic substrate that is then planarized at the surface in an approach that could be used to make large-area substrates with high mobility. Source: R. S. Tarighat et. al.

with a light blue, and that this blue light has an increased percentage of its spectral output outside of the biologically problematic range.

A company statement said, "Of the total blue spectrum, the proportion of blue light harmful to the human eye is 66% for LCDs and 32% for AMOLED displays." Samsung added that AMOLED displays will be able to reduce this figure to 6% in the future. I suppose it is understandable that Samsung did not discuss the fact that LCD designers can select their blue LEDs and quantum dots such that their blue light, too, is largely outside the biologically sensitive range. Samsung also showed a 5.7-in. rollable OLED display. (Tianma showed a 5.5-in. flexible display.) Other than bend-once applications such as the Samsung Galaxy S7 Edge, I am still waiting for a convincing usage case for 5-in. rollable displays.

Finally, there was a lot of discussion of Samsung's pre-SID announcement that it was discontinuing its plans for developing commercial OLED TV. There were lots of rumors and lots of competing interpretations. For now, let's just say it will be interesting to see what TV technology the company promotes in 2017. (For about TVs, see the review article by Steve Sechrist in this issue.)

Quantum Dots – Startling Progress on Major Issues

In addition to the major introduction (Hyperion quantum dots, discussed below) Nanosys planned to make at Display Week, it added another when CEO Jason Hartlove apparently went "off the script" at the Business Conference and announced the development of quantum dots that are stable in air thanks to individual encapsulation.

Quantum dots are sensitive to oxygen and moisture, and commercially available quantum-dot products, such as QD Vision's thin glass tube and Nanosys/3M's QDEF film, have elements that protect the dots from air and moisture. To prove that the company's air-stable QDs are indeed stable in air, Nanosys Corporate Communications Manager Jeff Yurek provided a lab-bench-style technical demo behind closed doors. With each dot snug and cozy in its individual encapsulation, significant new uses become possible: electrical, instead of just optical, excitation; ink-jet printing; and even gravure printing, according to Hartlove.

Think of making a color "filter" by ink-jetting patterns of red- and green-converting quantum dots on a film that sits in front of a blue direct-addressed backlight. Instead of inefficiently blocking light with a conventional color filter, you would be converting the blue light to red and green where you wanted it to make full-color pixels. Yurek suggested a possible efficiency improvement of 2–3 times.

Yurek said there is a "huge pull" from a customer who would like to go to market with an air-stable-based product in 2018, but Nanosys thinks 2019 is more likely.

Nanosys's scheduled announcements and booth demonstrations were also exciting. The company's Hyperion quantum-dot system matches the performance of cadmium-selenide quantum dots while being officially "cadmium free" under RoHS regulations, said Yurek. The Hyperion approach combines a completely cadmium-free red quantum dot with a green dot that contains very little cadmium. A QDEF sheet using the new formulation has a cadmium level less than the 100 parts-per-million limit set by the European RoHS Directive, so no exemption is required.

In a paper delivered at the SID symposium, Nanosys R&D VP Charlie Hotz said an Hyperion QDEF sheet provided over 90% of the BT.2020 color gamut, just as conventional cadmium-selenide (CdSe) quantum-dot sheets do. This was supported by a side-by-side demonstration in the Nanosys booth. So, if there are no unforeseen difficulties, panel makers and TV manufacturers (such as Samsung) will not have to choose between high-performing and more efficient CdSe dots and the less effective but RoHS exemption-free indium-phosphide (InP) dots. Nanosys says QDEF manufacturing partners will be evaluating the new materials in Q3' 16, with volume production of Hyperion QDEF expected in early 2017. Hartlove said there is no cost differential between Hyperion and CdSe dots, and that the manufacturing costs of Hyperion are actually lower.

The attentive reader may have noticed the use of the plural word partners in the preceding paragraph, and that was the subject of another Nanosys announcement. Nanosys has now added Hitachi Chemical as a partner for developing QDEF films for display applications, in addition to 3M. In a press release issued in May 2016, Hiroyuki Morishima, the GM of Hitachi Chemical's R&D Headquarters, was quoted as saying "We plan to begin shipping product in mass-production volumes during the second half of 2016." During a booth tour for institutional investors sponsored by Sanford C. Bernstein (Hong Kong) Limited, Hartlove said "[Total market size] should hit 200 million square meters over the next couple of years; this year we expect [QD market penetration] to be roughly 5% of that."

Finally, Nanosys was promoting President Obama's award of the National Medal of Science to company co-founder Paul Alivisatos for his work on quantum dots.

Given the transition from edge lighting to direct backlighting in TVs, it came as no surprise that QD Vision is working on a film-based approach with a partner, but the company's emphasis at Display Week was how cost-effective the company's ColorIQ thin-tube quantum-dot optic can be in smaller displays. (For additional coverage of QD-enhanced TVs, again see Steve Sechrist's TV report in this issue.)

In its booth, QD Vision was introducing the Philips 276E7 27-in. 1920 × 1080 monitor to the U.S. market. The monitor displays images with 250-nits luminance and 99% of the Adobe RGB gamut. The Philips monitor brand, which is controlled by TPV, has been sold primarily in Europe and Asia, but TPV plans to make a marketing push in North America, too.

Also announced was a 27-in. monitor from TPV-owned AOC, which has specs similar to the Philips 27 in. It will be available in North America Q3 at a price that will probably be close to $300 (Fig. 4).

The LEDs, and the ColorIQ optic, are on the bottom edge in these monitors. QD Vision executives stressed that ColorIQ can be very cost-effective for consumer monitors and smaller TVs.

Other ColorIQ monitors and small TVs being introduced in the booth were a 24-in. AOC monitor, a 24-in. Philips monitor, and 32-in. Philips and AOC monitors currently available in China.

QD Vision execs said the company continues to work on QLED (a structure in which the quantum-dot material is electrically rather than optically excited and is therefore suitable for an emissive display that could compete directly with OLED). The company believes that QLED is the ultimate display, and it expects to be making product in 2 years. The company continues to develop the demanding dot-on-chip, "if not for LCD then for lighting." Quantum dots for mobile-phone displays will have to be dot-on-chip, an executive said, since there is no room for anything else.

QD Vision had a side-by-side comparison (using the outdated NTSC color gamut, but still providing a helpful comparison) of four TVs: QD Vision CdSe film (105%), InP film (91%), OLED (82%), and standard white-LED-lit LCD (72%). It is no longer a surprise to anyone that CdSe quantum dots outperform InP dots, and the difference is easy to see. The very poor showing of the OLED TV was more surprising. In a recent Display Daily, OLED Association Managing Director Barry Young suggested that an older model OLED TV was being used for the comparison.

Roughly spherical dots are not the only form in which quantum particles come. The directional characteristics of quantum rods open new applications in color filters and other products, said Bob Miller of Merck affiliate EMD. In an invited paper entitled "Quantum-Rod-Containing Film Development for Display Applications," Merck Japan's Masayoshi Suzuki discussed some of the details. Among them is that Q-Rods have a smaller overlap between the absorption and emission spectra than Q-Dots, which means there is less quenching of the output when the Q-structures become more concentrated. There is also a higher out-coupling efficiency because the distribution of emitted light is directed more toward the normal to the film plane.

As influential as quantum dots have already been, we saw dramatic technical developments at Display Week that herald further significant market growth. One somewhat surprising takeaway is that cost-effective quantum-dot consumer monitors are here, and with TPV supplying about half of the world's monitors, we are likely to see a lot more of them.

Glass and Films: More Interesting than You May Think

Glass is essential to the display and lighting worlds, but it is hard to make it as exciting as, for example, a big bright TV. Still, makers of glass and associated materials were doing their best to stir the crowds.

Corning was showing LCD modules with its Iris Glass, which won a Display Component

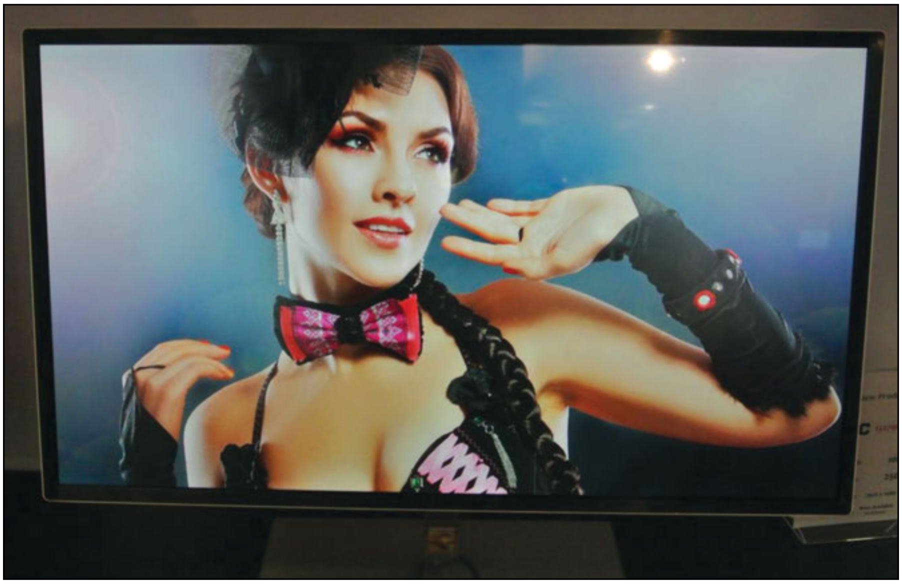

Fig. 4: AOC has introduced a quantum-dot-enhanced 27-in. monitor that should sell for approximately $300.

of the Year Award from SID. (AGC won the same award for its similar technology). Iris glass was designed to replace acrylic and other polymers as the light-guide plate (LGP) in edge-lit LCDs. Using glass instead of polymer provides greater dimensional stability and a thinner LGP without sacrificing performance, a Corning representative said. Although transmissivity was a problem, Corning says it has now been overcome. Iris Glass is being used in edge-lit TVs that are available today, and more seem to be under development in China and elsewhere.

Sets were being shown in Corning's booth that measured only about 5 mm thick, and thicknesses less than 4 mm are possible, a Corning rep said. That is not too much more than the 2.57-mm thickness of LG's top-of-the-line OLED TV. Not far from the Corning booth, BOE was showing a 65-in. 8K × 4K 10-bit-per-channel module using Iris glass and measuring only 3.8 mm thick.

Corning was also promoting both its Lotus and Eagle high-stability NXT glasses. There is significant interest in NXT glass for the coming generation of 8K LCDs, Corning said, because display drivers get hot enough for the stability of normal glass to be an issue. But that issue is not limited to TV-sized displays. Since last August, Samsung Display has been using Lotus NXT for the LTPS OLED display in the Samsung Galaxy Note 5, which packs Quad-HD pixel content into a 5.7-in. display.

Particularly for automotive applications, Corning was showing anti-glare Gorilla Glass with different amounts of haze. Samples with 3%, 10%, and 20% haze were shown.

AGC was showing its award-winning XCV extremely transparent glass for LGPs. Asahi was demonstrating the improved inner transmittance of XCV compared to conventional extra-clear glass, showing a significant difference, especially at longer wavelengths. Asahi also compared the properties of XCV with those of poly(methyl methacrylate), better known as PMMA, acrylic, or Lucite, which is a very common material for LGPs. The thermal conductivity of XCV glass is five times that of PMMA, its water absorption is 0.0% versus 0.3% for PMMA, and its thermal expansion coefficient is $84 \times 10^{-7} \times K^{-1}$ compared to PMMA's 700. AGC will supply XCV with a light-extracting dot pattern but did not say when it would be available to panel makers or what the maximum available size will be. (Corning has Iris Glass available up to Gen 10.)

AGC also showed its Glascene glass projection screen that retains its transparency during image projection. The company also showed its Infoverre smart glass windows that change from transparent to highly diffusive.

Merck/EMD was also demonstrating smart windows using the company's guest-host liquid crystal, which it calls Licrivision. The window can turn from clear to diffuse and can also change from clear to a color with the appropriate guest material (Fig. 5).

The technology is well-developed, said Merck/EMD, and the company is now working with architectural glass makers on high-volume production. Interest from architects and builders is high, said EMD's Bob Miller.

3M showed its Advanced Light Control Film (ALCF) family. The polycarbonate films contain internal optical louvers for controlling the direction of light. 3M sees the primary application as reducing windshield reflections in automotive displays. The film can be included in the LCD's optical stack. A hard-coated version can be the top film over the front polarizer.

Luminit was showing its well-known light-control films. New are products based on computer-generated holograms. One customer is using the technology to create an automobile welcome application, which projects the brand's logo on the ground to welcome the owner to his car. Luminit would not reveal its customer, but Lincoln is known to offer such a feature.

Global Lighting Technologies (GLT) has been a master of precision light guides and light-guide-based lamps for years. An unusual addition to GLT's technological portfolio this year was an extremely thin and flexible light guide that can be sewn into clothing. In the photo in Fig. 6, a GLT rep wears a flat lamp based on the light guide behind the cut-out Los Angeles logo on the front of his baseball cap. (The lamp is not lit in this photo.)

Fig. 5: *Merck demonstrated smart windows that could turn from clear (left) to diffuse (right), courtesy of the company's liquid-crystal-material Licrivision.*

Fig. 6: Logowear outfitted with GLT's lightguide lamps has been a big seller for the company, according to its representatives.

Finally, a company called Redux was showing a glass panel with transducers that created a very sophisticated, adjustable, and localized haptic experience. Virtual controls – such as sliders, knobs, and pushbuttons – could be established anywhere on the panel, and they felt much like the mechanical controls they mimicked. Adjustments could be made for button resistance, button edge sensation, friction, and clicks in a rotary control, *etc*. The same transducers can make the panel, which can be a separate panel or the front glass of a display, act like a loudspeaker (or a stereo pair). If the audio part of the Redux technology sounds a lot like that of the defunct company NXT, it's because Redux acquired NXT's IP and hired some of its former employees. There was nothing wrong with NXT's technology, said Redux Chief Commercial Officer John Kavanagh, just its product strategy. But Redux is adding its very sophisticated haptics to NXT's audio-on-panel approach. These Display Week exhibitors have not been sitting on their glasses.

In materials and devices, this was an unusually exciting Display Week. It will be interesting to see what structures the companies build on the foundations laid in San Francisco this year. ■

Better Form, Lower Power

Display Week 2016 offered an inside look at the state of the art for mobile and wearable displays.

by Jyrki Kimmel

THE mobile and wearable display technologies showcased at the booths of the major display makers at Display Week 2016 exhibited clear improvements that will serve end users well over the coming few years. While there were no radical departures from the steady path of innovation, the improvements in form factor and advances toward low-power dissipation in wearable designs were among the highlights of the show. These improvements, described below, were also emphasized in the symposium keynotes as well as in the Market Focus Conference presentations.

Edge-to-Edge Mobile Displays Incorporate a Plethora of Sensors

Even before Display Week opened, the symposium keynotes provided some insight into what the exhibitors on the show floor had in store for attendees. Hiroyuki Oshima from Japan Display Inc. (JDI) gave a keynote on mobile displays, highlighting JDI's strategy of concentrating on core technologies. One of these is its in-cell touch-based user interface. Other core technologies, LTPS and IPS, support touch functionality in the display itself that may take on new capabilities in more generalized input devices.

As the mobile-phone market saturates, JDI sees the future growth for the display business in new applications that will be enabled by advanced sensor technologies such as edge and hover touch, fingerprint sensors, and physiological sensors that will be incorporated in display modules. As a result of new sensing technologies, the mobile-phone display will become the main input device as well as the main output device for the phone, as these new sensor technologies can be leveraged in light-based sensing and imaging in addition to finger-based touch applications.

And with the increasing pixel density in mobile screens, stylus-based input becomes meaningful once again, allowing for higher definition in character input as well as in artistic applications. The increased pixel density, in turn, will be enabled by higher-pixel-density LTPS processes as well as by the IPS LC mode applied as the electro-optical modulation medium in these displays.

The new touch-technology landscape was also broadly outlined by Calvin Hsieh from

Fig. 1: The inactive space at the edges of JDI's super-narrow-border display module (right) is only 0.5 mm wide. The difference from the conventional example (left) is noticeable. Photo courtesy Jyrki Kimmel.

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IHS, who gave the lead presentation in the Market Focus Conference on Touch. In IHS's forecast, in-cell touch for AMLCDs and on-cell touch for AMOLED displays play a large role, as shown in strong projected growth for these technologies. For touch in general, as well as for mobile-display technologies, new applications drive the growth of the business. Many of these rely on sensors that are being integrated into the module itself. These sensors give the mobile display capabilities for multimodal user interaction, from fingerprint and proximity sensing to hover touch. These interaction modalities can then be leveraged over a wide range of application areas, even for automotive use.

JDI's strategy was demonstrated by its exhibit lineup of mobile AMLCDs. One IPS-based product family, for instance, sported WQHD screens from 5.2 to 5.7 in., all at a luminance level of 500 nits. This makes it possible to pick and choose a display based on product form factor. One concept helpful in improving mobile-device integration was JDI's 5.2-in. super-narrow-border 0.5-mm-bezel screen in FHD resolution. This development will become a necessity for high-end design, once the resolution can be brought on par with mainstream display modules (see Fig. 1).

There were many examples of innovative integration in mobile displays on the show floor. The LG Display booth, for example, was featuring an interesting concept with dual display drivers. This product had a low-power information screen at the top of the 6-in. dual 513-dpi display, with a normal-looking smartphone display at the bottom (see Fig. 2). This concept enables the idle screen to operate on a transmissive LCD, a feature seen only on AMOLED display screens today.

Another interesting mobile display from LG had an 806-ppi 5.5-in. screen. This same pixel density was achieved by JDI on its 5.46-in. 4K × 2K display. The "ppi race" was trumped by Sharp, however, which showed extremely high-pixel-density examples from its collaboration with Semiconductor Energy Laboratory (SEL). One Sharp IGZO-based panel was optimized for use with VR goggles, and the display was in fact shown under magnifying optics. The 2.5-in. panel had a pixel density of 1210 ppi, with a resolution of 2560 × 1600 pixels.

In the AMOLED technology space, Samsung had an interesting showcase lineup of its development in this area (not including TVs this year), starting with small-form-factor screens from 2007 and culminating with the most recent curved-edge Samsung Galaxy S7 Edge phone. This lineup showed the developments in AMOLED technology thus far in a very concrete and understandable way. According to the AMOLED development timeline Samsung was displaying in its booth, 1-billion AMOLED screens had been sold by February 2016.

One surprising innovation – again from JDI – involved power savings. A 10.2-in. panel in JDI's booth had an RGBW matrix with local dimming. The increased white transmission combined with the local-dimming scheme improved the power characteristics by 15–20%, which is a significant improvement for an LCD module. The local-dimming feature was the first demonstrated on a mobile-sized tablet display, and JDI claimed it increased the perceived contrast 100-fold, over a conventional globally dimmed RGB module (see Fig. 3).

Curves Ahead

Another trend in the mobile space is the proliferation of organic form factors. Sharp comes into this area from another direction, taking the form language from its automotive

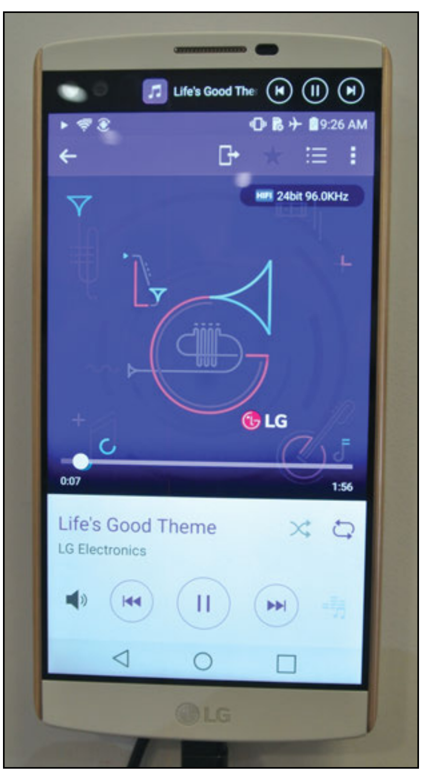


Fig. 2: LG Display's 6.0-in. dual-driver QHD+ mobile display had a 160-pixel extra screen strip at the top, leaving the bottom as the "normal" smartphone screen. Photo courtesy Jyrki Kimmel.

Fig. 3: JDI's local-dimmed 10.2-in. tablet display module had a CR of 110,000:1 or above, according to the company. Photo courtesy Jyrki Kimmel.

show review: mobile and wearable displays

Fig. 4: Samsung showed a 5.7-in. curved demonstration display. Photo courtesy Jyrki Kimmel.

curve-edged displays and transforming mobile-sized displays from rectangular-shaped objects to round- and oval-shaped objects. These affordances to form factor, combined with curved-display integration, led by Samsung, open a way for totally new device classes, beyond the mobile phone and rectangular passive information screens in automobiles.

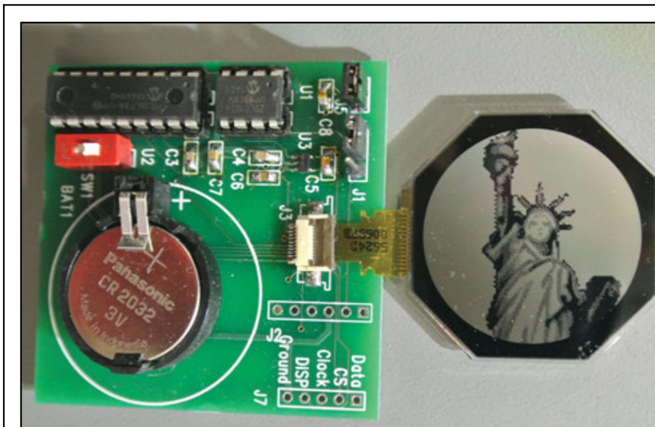
Despite this evident progress, judging from the presentations in the conferences and the modules shown in the exhibition booths, it seems that the predicted curved and flexible displays are still as far in the future as roadmaps depicted a few years ago. Many companies, including new entrants such as JDI, showed very similar curved AMOLED screens, and also similar dynamically foldable or rollable demonstration prototypes.

Samsung seems to be leading the development toward mass-producible flexible-display technology, with its Galaxy Edge displays already on the market. At Display Week, Samsung showed a 5.7-in. 518-ppi curved display in a demonstrator mockup (see Fig. 4). Sensor and system integration as well as touch user-interface evolution will play a major role as constituent technologies in this development.

Until we get to see mass-produced flexible display modules, there will be many advancements in "classic" mobile-display technologies that are extremely useful, if not as exciting as foldable and rollable. These advancements can, in turn, propagate to other application areas, making developments in mobile displays the vanguard of evolution in display technology.

Wearable Displays Sport Classic Designs

In the last couple of years, "connected watches" or "smartwatches" have become a wearable part of the mobile ecosystem, and their design has approached that of classic wristwatches. The intuitively designed



Figs. 5 and 6: At left, JDI's demonstrator was a 1.2-in. round MIP display. At right, Sharp's round 128 x 128 pixel display featured ultra-low power. Photo courtesy Jyrki Kimmel.

round-face interface has pulled through once again, creating a new customer demand for design-driven smartwatches that can do much more than the single-purpose timepieces of the 20th century. Health and fitness applications, in particular, are being integrated into the smartwatch oyster shell, as well as the ability to interface with the user's smartphone to receive alerts and messages conveyed to the watch by the mobile terminal.

Even more than in mobile displays, power dissipation in wearable devices is a critical factor in user adoption. As is customary in watch form-factor devices, the user preference is not to have to charge the battery every day or, as has been the case in some early smartwatches, even a couple of times a day. The demand for low-power LCDs in wearable form factor is already being served by JDI's round 1.2-in. 218 × 218 and 0.99-in. 180 × 186 and rectangular 1.39-in. 205 × 148 reflective color displays with memory-in-pixel (MIP) function, all at 182 ppi (see Fig. 5).

There were other small-form-factor low-power displays at the show, including some in black and white with dithered gray scales from Sharp (see Fig. 6). Kyocera also showed a round 128 × 128-pixel display.

Fig. 7: *The Withings activity monitor device uses an electronic-ink screen. Photo courtesy Jyrki Kimmel.*

Fig. 8: *The Wove wrist device prototype features an electronic-ink screen integrated with Canatu's carbon-nanobud touch screen. Photo courtesy Jyrki Kimmel.*

Another approach toward low power is with bistable e-paper displays, as shown in the E Ink booth. One such product on the market, the Withings activity monitor, was featured. It sported a reflective e-paper display in a round design (see Fig. 7). Sony's wrist-band form-factor activity monitors also had e-ink screens, as did the Wove wrist-band device shown at the Canatu booth (see Fig. 8).

The Wove/Canatu carbon-nanobud touch panel was assembled in an "on-screen" touch fashion to make a complete integral structure without any separate outside encapsulation. The entire module thickness is only 0.162 mm.

Assuming that customer demand drives the adoption of consumer devices, once the technology to realize these is available, we can infer from the exhibits shown that there is a demand to minimize the bezel and dead space in a round watch form-factor display. Companies are striving to provide a bezelless design similar to those that have become possible in mobile-phone displays. This is a much more difficult feat using a round shape. AU Optronics (AUO) showed in two symposium presentations how this can be done using a plastic-substrate display. Instead of placing the driver chip on the face of the display, in a ledge, or using a TAB lead, AUO bends the flexible substrate itself to place the driver at the back side of the display. In this way, a bezel of 2.2 mm can be achieved, with clever gate-driver placement and bringing the power lines into the active area from the opposite side of the display face.

The Way Forward

Based on the mobile- and wearable-display offerings at Display Week, as well as the presentations given by display manufacturers and analysts, it seems that the small-form-factor displays are leading the advances in many display technology areas. Whereas before, the development cycle in flat-panel displays entered the mobile-display space with a few years' delay, now mobile- and wearable-display manufacturers are leading the way in innovation, as is demonstrated by the advances in pixel density, substrate materials, narrow bezel designs, decreasing power dissipation, sensor integration, and organic form factors. In the coming few years, these innovations enabled by new mobile- and wearable-display technologies will benefit the users of smartphones, connected watches, and other devices yet to be designed. ■

Advances in Augmented- and Virtual-Reality Technologies and Applications

The first wave of AR and VR devices has reached the marketplace, but much work needs to be done in order to provide immersive and life-like experiences to mainstream users.

by Achintya K. Bhowmik

IN recent years, virtual-reality (VR) and augmented -reality (AR) technologies have moved from the realms of science fiction and imagination to advanced research in academic laboratories, to product development in the industry, and, finally, into the hands of consumers in the real world. A number of marquee VR devices have been launched, along with compelling immersive applications. A few AR devices and developer kits have been released as well. The pace of progress in both VR and AR technologies has been rapid.

So, in line with this fast-emerging trend in the ecosystem, the Society for Information Display (SID) decided to create a special track on AR and VR for Display Week 2016. The rich lineup at Display Week in San Francisco included a short course, a seminar, and a number of invited and contributed presentations in the technical symposium, and demonstrations on the exhibit floor.

It is clear that the display industry is on the verge of another exciting phase of rejuvenation. Displays are the face of some of the most used electronic devices in our daily lives – such as the smartphone, tablet, laptop, monitor, and TV, among numerous examples. As such, the health of the display industry rises and falls with the growth and saturation of these devices. Take the exciting phase of innovation in LCD-TV technologies as an example. Screen sizes went from 24 to 32 in., to 40 in., to 55 in., to 80 in., and above. The pixel resolution went from 720p to full-HD and then to 4K, and frame rates went from 60 to 120 frames per second (fps). There were many more advances – contrast, brightness, color, *etc.* However, it gets to a point where further advances in display technology provides only small incremental benefits to the consumer. This often leads to a reduced demand for new features and a slowdown in development.

Let us now turn to virtual reality. It is a completely different story at the moment. The displays on the best state-of-the-art VR devices today fall way short of the specifications required for truly immersive and responsive experiences, despite the dizzying pace of development. The pixel density needs to increase significantly and latencies must be reduced drastically, along with many other improvements such as increased field of view, lower screen-door effects with reduced non-emitting spaces between active pixels,

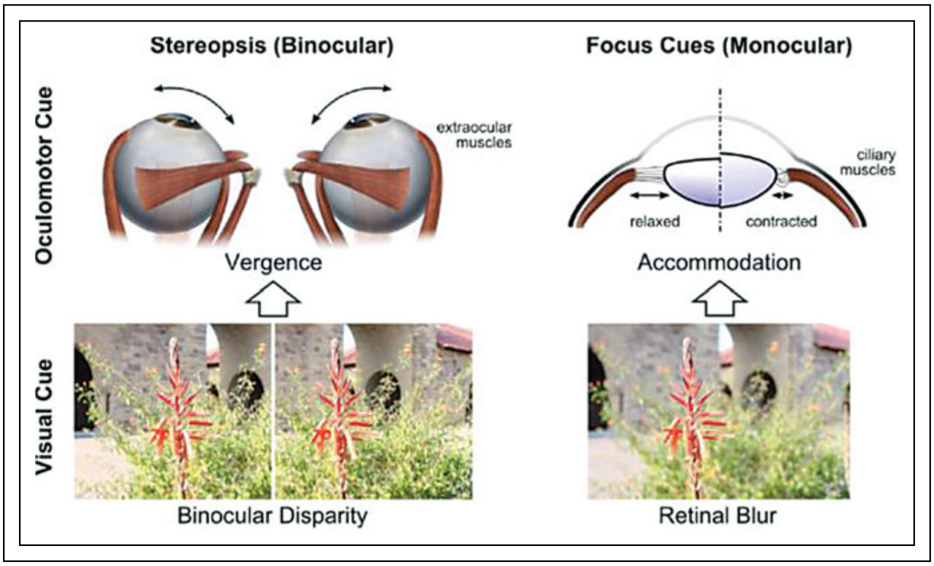


Fig. 1: Humans use both oculomotor cues (vergence and accommodation) and visual cues (binocular disparity and retinal blur).[3]

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reduced pixel persistence, higher frame rates, *etc.* Besides the display, the systems also require integration of accurate and real-time sensing and tracking technologies as well as enhanced computation and processing power. AR devices impose additional requirements relating to see-through head-worn display technologies.

So, all this is exciting for the researchers and engineers in the industry. We are back to solving some difficult challenges, with a potential for big returns. Judging by the excellent quality of the papers, presentations, and exhibits at Display Week, it is obvious the display ecosystem is all geared up.

In this article, we present a summary of some of the advanced developments reported in the fields of VR and AR at Display Week 2016. For the sake of brevity, it is not a comprehensive coverage of all the work presented at the conference, and readers are encouraged to reference the symposium digest for all the relevant papers.

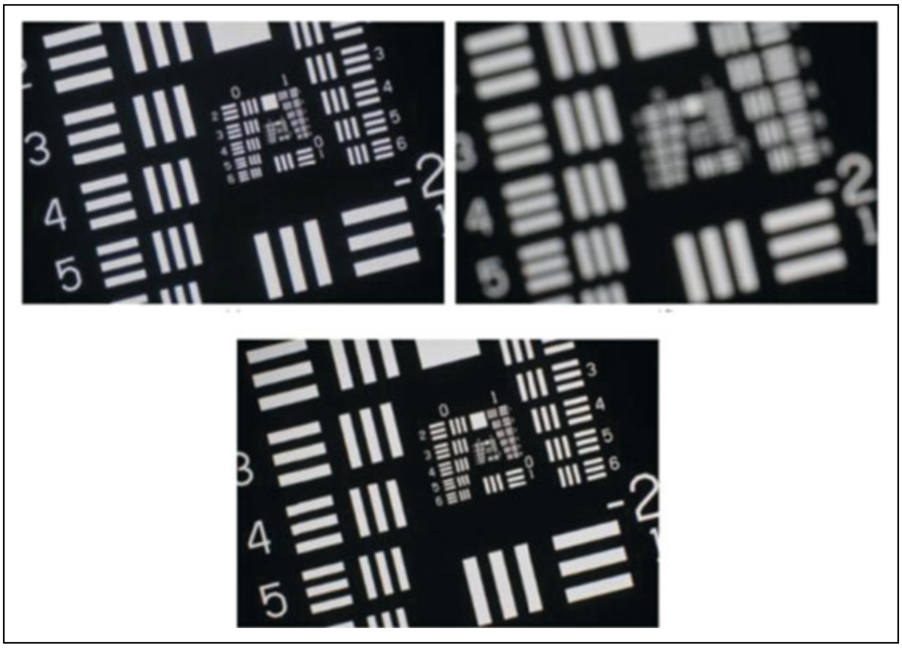

Fig. 3: Results from an adjustable liquid-crystal lens include a lens image taken with voltage applied to provide a 400-mm focal length to focus the image (top left), an LC lens image with 0 V applied (right), and a glass lens image with a 400-mm focal length for reference (bottom).[5]

An Immersive Technical Program

The Sunday short course "Augmented and Virtual Reality: Towards Life-Like Immersive and Interactive Experiences"[1] and the Monday seminar "Fundamentals of Head-Mounted Displays for Augmented and Virtual Reality"[2] provided a comprehensive tutorial on the system-level requirements of VR and AR devices. Topics covered included fundamental human-factor considerations; a review of the advances in sensing, computing, and display technologies; and a description of the need for an end-to-end system architecture for seamless immersive and interactive experiences. Besides the comprehensive reviews of the technologies and systems, the seminar

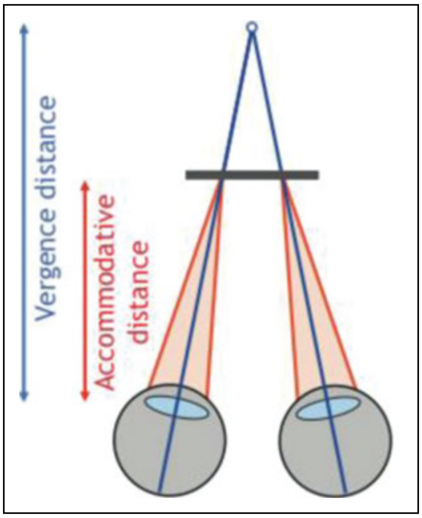

Fig. 2: The vergence–accommodation conflict arises from the difference between the point where the two eyes converge and the points to which the eyes focus or accommodate for traditional stereoscopic 3D displays.[4]

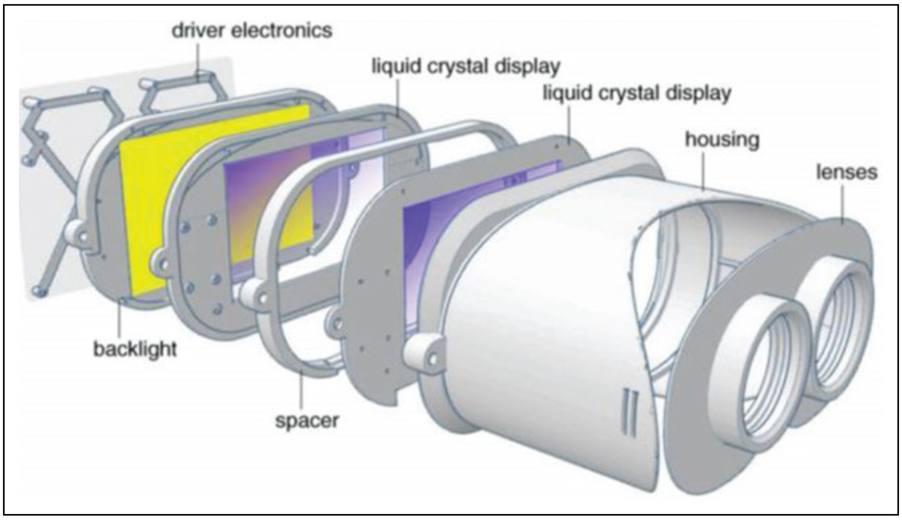

Fig. 4: A prototype light-field stereoscope comprising two stacked LCD panels.[3]

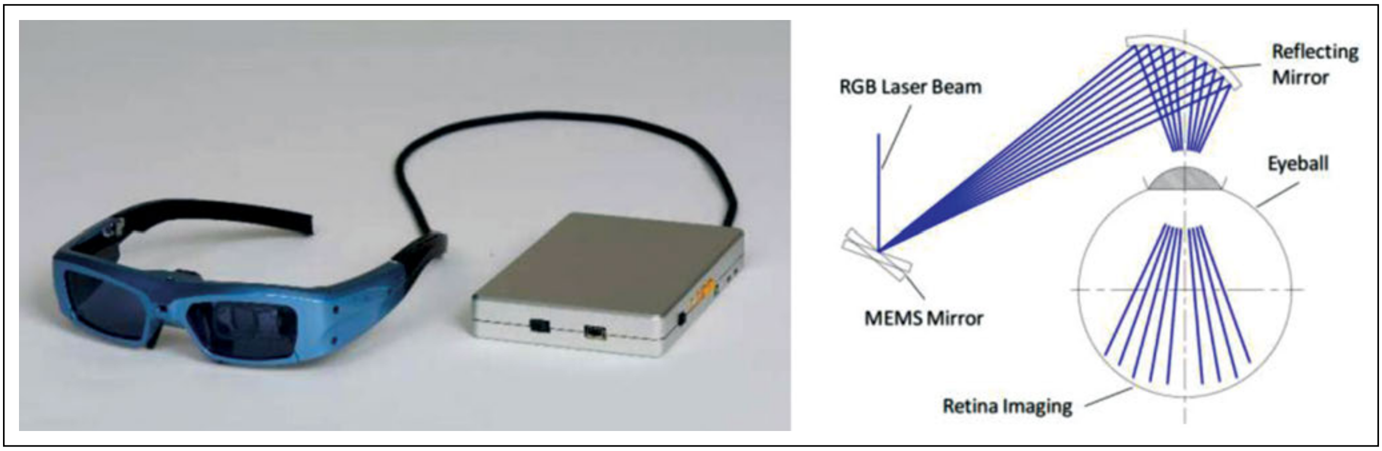

***Fig. 5:** This retinal imaging laser eyewear incorporates an asymmetric free-surface mirror.*[8]

also reviewed historical perspectives and definitions.

A VR device places the user in a virtual environment, generating sensory stimuli such as visual, vestibular, auditory, haptic, *etc.*, that provide the sensation of presence and immersion. An AR device places virtual objects in the real world while providing sensory cues to the user that are consistent between the physical and augmented elements. A new and emerging class of merged and mixed-reality devices blends real-world elements within the virtual environment with consistent perceptual cues. Subsequently, the various presentations reported developments in display technologies, sensing modules, systems, and applications-level innovations.

A key challenge for the display subsystem in VR and AR devices is to provide the user with an immersive and life-like 3D visual experience. While the devices that are currently commercially available provide stereopsis cues by presenting a pair of stereoscopic images to the left and right eyes, they are not able to provide a number of other important 3D cues that are salient to how we perceive the real world. In Fig. 1 (from a symposium paper titled "Light Fields and Computational Optics for Near-to-Eye Displays"), Gordon Wetzstein depicted a number of depth cues that we use in 3D visual perception, including the oculomotor and visual cues.

Further, in his paper, "Why Focus Cues Matter," Martin Banks described the vergence–accommodation conflict experienced in the stereoscopic 3D displays that causes visual discomfort, which is illustrated in Fig. 2. By using an experimental display, Banks *et al*. investigated how incorrect focus cues affect visual perception and comfort. The results show that the ability to perceive correct depth ordering is significantly improved when focus cues are correct, the ability to binocularly fuse stimuli is improved when the vergence–accommodation conflict is minimized, and visual comfort is significantly increased when the conflict is eliminated.

After establishing the importance of producing the correct focus cues, Philip Bos (in the paper "A Simple Method to Reduce Accommodation Fatigue in Virtal- and Augmented-Reality Displays"), Banks, and Wetzstein presented various methods to address this issue. Bos *et al.* reported a simple approach that allows the eyes to accommodate at the distance to which they are converging, through using eye-tracking and a variable lens built using liquid crystals. Figure 3 shows the variable focus capabilities of the liquid-crystal lens. Wetzstein presented a prototype display that employs two LCD panels separated by a small distance (Fig. 4), which is able to present distinct light fields onto each eye, thereby creating a parallax effect spanning the eye-box areas.

***Fig. 6:** The DAQRI augmented-reality smart helmet*[9] *is designed for industrial applications.*

In some of the other developments, Shuxin Liu *et al*. presented a multi-plane volumetric optical see-through head-mounted 3D display using a stack of fast-switching polymer-stabilized liquid-crystal scattering shutters and implemented a proof-of-concept two-plane prototype.[6] Jian Han *et al.* presented a prototype of a near-to-eye waveguide display with volume holograms and optical collimator.[7] Mitsuru Sugawara *et al.* described a retinal imaging laser eyewear incorporating a miniature laser projector that provides the digital image information through the pupil of the user using the retina as a screen,[8] as shown in Fig. 5. The authors described the benefits of focus-free image presentation independent of the wearer's visual acuity and point of focus, and the laser safety analyses based on guidelines and standards.

Beyond the advances in display technologies for VR and AR applications, presentations at Display Week also covered system-level innovations towards immersive and interactive usages. As an example, Philip Greenhalgh *et al.* presented the DAQRI smart helmet with AR capabilities (Fig. 6) designed to enable its deployment into an industrial environment. Greenhalgh's study showed that overlaying contextually filtered data in relevant physical spaces with AR technology yielded significant benefits. The authors also demonstrated how Intel RealSense embedded camera technology can further refine the context of data and enable advanced applications such as decluttering the background for object recognition, real-time sizing and measurements, hands-free human–machine interface controls, content access, *etc.*

As another example, at Display Week the author of this article described Intel's project for integrating RealSense technology into merged-reality headsets. As shown in Fig. 7, this system adds real-time 3D-sensing capability to VR and AR devices with RGB-D imaging and visual-inertial motion-tracking technologies. As a result, the devices are able to blend real-world elements into the virtual world and vice versa, enabling new applications such as natural interactions, multi-room scale mobility with integrated six-degrees-of-freedom positional tracking, real-time 3D scanning, and visual understanding. Additionally, Fig. 8 shows an application where virtually rendered 3D objects are seamlessly embedded into the real-world view with correct physical effects such as collision, occlusion, shadows, *etc.*

In summary, the special track on AR and VR at Display Week 2016 prominently featured some of the significant advances in these fields. While the rapid pace of development in recent years has brought the first wave of devices to market to enthusiastic reception, much work remains to improve the technologies to where they can provide immersive and life-like experiences to mainstream users. As the papers, presentations, and the discussions at Display Week indicate, researchers and developers in both the industry and academia are diligently continuing to enhance the key technologies, including sensors, processors, displays, and system integration and applications.

The future will blur the border between the real and the virtual worlds, and we are nearing that future!

Fig. 7: *The "merged reality "capability of a device is shown here with integrated Intel RealSense technology.[10] The 3D images of the user's hands as well as a person standing in front of the user are brought into the virtual world. This capability is also used to allow multi-room scale mobility with integrated six degrees-of-freedom positional tracking to help the user avoid colliding with physical objects.*

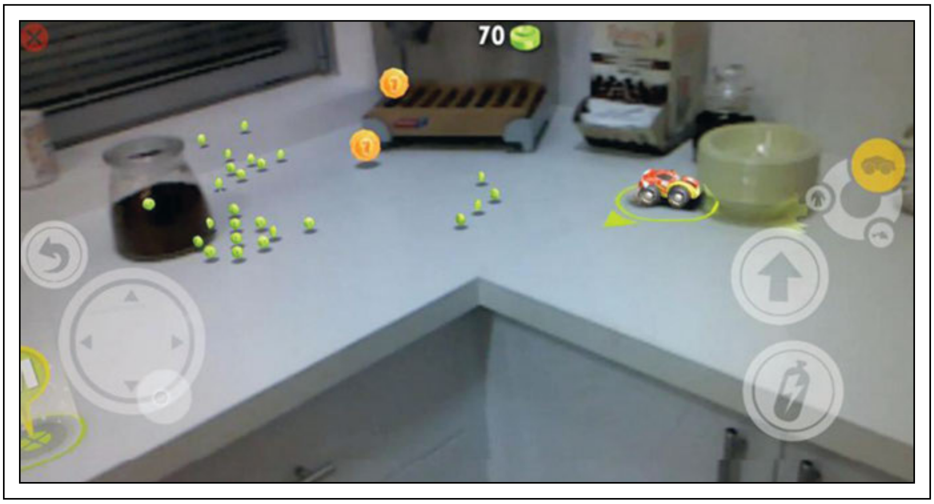

Fig. 8: *The real physical world is augmented with virtually rendered 3D objects using a device with an embedded Intel RealSense module.[10] Here, a digitally rendered car is shown racing on a real table, with realistic physical effects such as collisions with real objects, correct occlusion and shadows, etc.*

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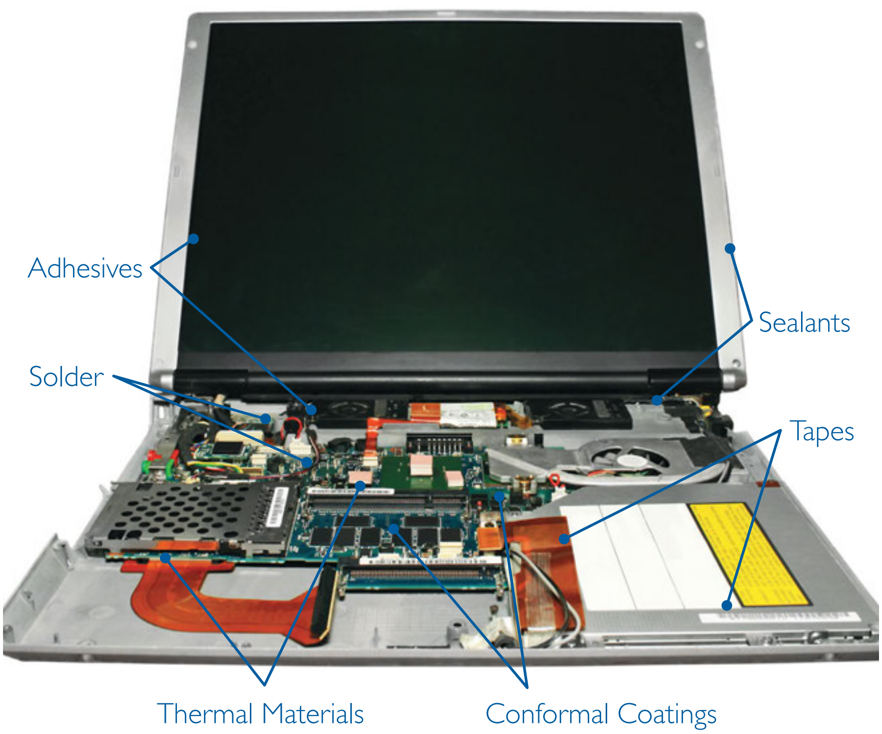

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[10]A. K. Bhowmik, "Real-Time 3D-Sensing Technologies and Applications in Interactive and Immersive Devices," Paper 35.1, SID Display Week 2016. ■

Flexible Displays Require Flexible Electronics

Display Week 2016 provided numerous examples of advancements in flexible-display technologies. But even though flexible displays are now in production, they are used in fixed formats encased in rigid packaging, so users have not experienced the actual physical flexibility. In order for truly flexible displays to emerge, flexibility of the electronics is required, beyond the backplane and display driver electronics. Clues to such developments could be found in many presentations at the annual event.

by Paul Semenza

WITH continued progress in the production of active-matrix backplanes on flexible substrates and the packaging (in particular, thin-film encapsulation) of flexible displays, the era of volume manufacturing of large full-color flexible flat-panel displays has finally arrived. OLED displays are in the lead, and there is continued development of LCDs and EPDs, among others. However, for the most part, such "flexible" displays have been used in rigid formats, such as in smart watches (which take advantage of the fact that flexible displays can be thin and light) and smartphones (which take advantage of curved or angled displays). These form factors do not allow the display to be bent, folded, or stretched in any way.

In part, such rigidity reflects the need to utilize plastic and metal casings, as well as strengthened cover glass, to protect the flexible displays from damage. In addition, a freely flexible display can in theory be bent, rolled, or folded an unknown number of times and in unpredictable ways, making it difficult to characterize failure mechanisms or predict mean time to failure. However, with volume production, it is likely that the ruggedness and lifetime of flexible displays will improve, reducing the need for such protection.

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Another reason that products with "flexible" displays are not able to take full advantage of their flexibility is that such displays are packaged with electronic systems that use metals, hard plastics, and rigid ceramics in component packaging, circuit boards, and connectors. Thus, even though it may be possible to produce fully flexible display modules, these modules would need to be physically and electrically coupled to a rigid electronics package. Early concept demonstrations of flexible displays in the mid-2000s, including Universal Display's "roll-out" OLED display, in which the display rolled out of a tube that housed at least some of the electronics, and Polymer Vision's fold-up reading device, in which a flexible EPD unfolded from a rigid housing, reflected this reality. While neither of these concepts made it into production, similar configurations would be needed to house the circuitry were a product with a fully flexible display to come to market today.

Breaking Out of the Rigid Box

In order to unleash the full potential of flexible-display technology, electronics will also need to become flexible. This could potentially include logic, memory, power, sensing, and communications functions, as well as circuit boards and batteries. Broadly speaking, there are two ways to accomplish this – either replace devices that are currently made in bulk form (semiconductors and passive components) with devices manufactured through printing or other additive manufacturing processes onto flexible substrates or integrate thinned chips or other bulk devices with printed devices on flexible substrates.

Printing or other solution-processing deposition techniques are critical for flexible electronics, due to their ability to deposit electronic materials at low temperatures over large areas of flexible substrates such as plastic and polymer. In the near term, replacing large-scale logic, memory, and processor semiconductors with printed versions is not feasible because printing techniques are not capable of depositing millions of transistors in an integrated device. Thus, a combination of printed and semiconductor devices – referred to as flexible hybrid electronics – is the most likely path. While such systems are not yet in production, presentations at Display Week 2016 indicated a breadth of research around creating flexible electronic devices using a variety of deposition techniques and materials.

State of the Art

Much of the effort on flexible electronics has been motivated by the desire to create active-

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matrix backplanes for flexible displays, particularly OLED displays and EPDs, as well as for thin-film PV and sensor arrays, using printing, coating, or other deposition methods for solution-based semiconductor materials. Historically, the focus has been on organic semiconductor materials because they are suitable for low-temperature deposition and perform well under bending conditions.

As demonstrated by papers presented at Display Week, materials suppliers continue to develop organic semiconductors suitable for TFT-backplane fabrication through spin coating. Merck reported on materials suitable for integration of spin-coating and photo-lithography in a paper titled "Photolithographic Integration of High-Performance Polymer TFTs" and has been working with flexible-electronics company FlexEnable to demonstrate full-color flexible LCDs, while BASF presented on the direct patterning of organic transistors through spin coating, but without the use of photoresist. NHK described the fabrication of organic TFTs using coating and self-assembly, including the use of TFTs on thin paper substrates. As an indication of additional applications for organic TFTs, researchers at the University of Tokyo and JST/ERATO reported on their use as flexible sensors in wearable and human-monitoring applications, in a variety of digital and analog circuit designs.

The application of alternative deposition techniques in conjunction with developments in soluble organic and inorganic semiconductor materials has expanded the potential production space for flexible electronics. At Display Week, UC Berkeley presented results of work using gravure printing to create organic and transparent oxide-semiconductor TFTs as well as MEMS devices (Fig. 1), and NHK discussed using sputtering to deposit oxide transistors using tungsten and tin instead of gallium on a cured polyimide substrate.

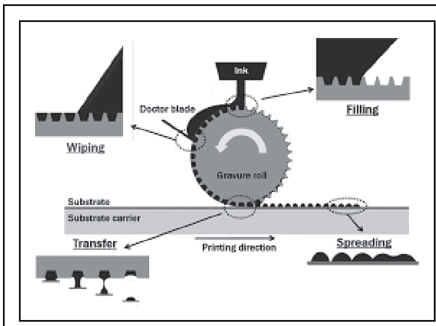

Fig. 1: *In this conceptual view of gravure printing, ink is dispensed to fill wells in the gravure cylinder. Excess ink is wiped using a doctor blade. Ink is transferred to a passing substrate; the ink subsequently spreads and dries. Source: UC Berkeley; 2016 SID Digest of Technical Papers.*

In addition to organic and oxide semiconductors, single-walled carbon nanotubes (SWCNTs) have also shown promise for flexible-display applications. Researchers from Seoul National University presented progress in ink-jet printing of SWCNT TFTs on polyester substrates with good performance under conditions of bending and illumination.

Flexibility Beyond the Display

Presentations at Display Week also included developments in flexible and stretchable electrodes, as well as integration of printed and bulk devices. Work done at PARC with UC San Diego demonstrates the capability to combine silicon ICs (microcontroller and NFC) with printed components (photo and temperature sensors) with extrusion-printed interconnects. Meanwhile, advances in the development of stretchable electrodes, which can connect to rigid devices, continues. IMEC, Ghent University, Holst/TNO, and Panasonic reported in a joint paper on combining stretchable metallic electrodes with rigid LEDs (Fig. 2), and X-Celeprint, spun off from work done at the University of Illinois, presented a seminar on transferring micro-LEDs to flexible substrates using an elastometric stamp.

Other research points to using some of these techniques to create new electronic systems. Corning and ITRI reported using gravure printing to fabricate metal-mesh grids on thin glass for antennas. Finally, researchers at the Swiss research lab EPFL showed the use of stretchable metallization to create electronic skin.

Getting to Flexible

The momentum in flexible-display technology suggests that there will be growing production of such displays, if for no other reason than that they offer thin, light, and rugged form factors. However, in order to realize the full potential of the flexible display – the ability to bend, roll, stretch, and, in general, conform

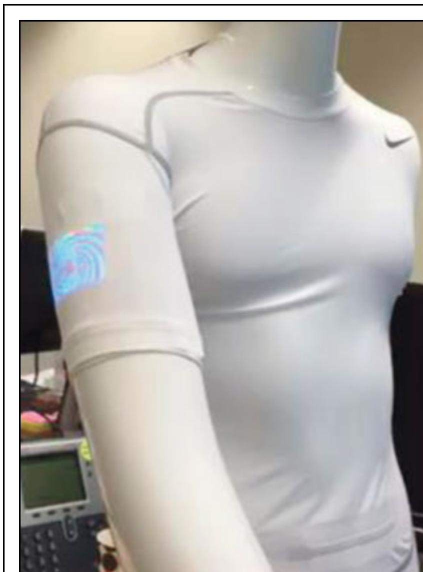

Fig. 2: *This conformable 64 × 45 RGB LED matrix is integrated into the sleeve of a t-shirt that is mounted on a mannequin. Source: IMEC, Ghent University, Holst/TNO, and Panasonic; 2016 SID Digest of Technical Papers.*

to a wide variety of use cases, there is a need for flexibility in the associated electronics, whether it be in a wearable device, a smartphone, or a variety of devices envisaged as part of the Internet of Things. It is likely that we will see increasing adoption of flexible electronics close to the display – driver electronics, communications, and graphics – and also in sensors designed for human or industrial monitoring. Fully flexible electronics systems allowing the flexible display to escape the rigid packaging of the present will likely require hybrid approaches combining high-performance silicon devices with flexible displays and other components. ■

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

In the second of a two-part series on a new backplane technology for flexible and rollable AMOLED displays, the author describes a system built on a bulk-accumulation (BA) amorphous indium-gallium-zinc-oxide (a-IGZO) TFT.

by Jin Jang

IN the first of our two-part series on a new backplane technology for flexible and rollable AMOLED displays, we reviewed 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.

The TFT backplane necessary for flexible OLEDs can be realized with low-temperature polycrystalline silicon (LTPS) or oxide semiconductors because of the high performance of these materials. Currently, all AMOLED products manufactured on polyimide 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 been working on amorphous-oxide-semiconductor (AOS) TFTs both on glass and plastic substrates. The first AOS TFT product was introduced in 2003, and since then many LCD and AMOLED-display products with a-IGZO TFT backplanes have been launched.

However, a-IGZO TFTs also have challenges. The low yield, non-uniformity, and bias instability of oxide TFTs limit their wide applications to commercial products. In part one of this article, we explained how our university's research teams have made significant progress in overcoming some of those limitations by developing a bulk-accumulation TFT, which employs an n-type a-IGZO as its active material, a silicon-dioxide layer as both gate-insulator and passivation layer, and molybdenum as its metal electrodes. In the remainder of this article, part two, 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.

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Flexible AMOLED Display with BA Oxide-TFT Backplanes with CNT/GO Buffer via Non-Laser Detach Technology

Carrier glass is usually used for plastic AMOLED displays where the plastic polyimide (PI) is

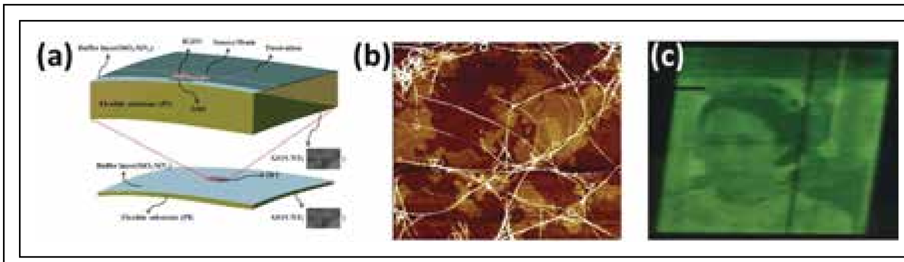

Fig. 1: A plastic AMOLED display with gate-driver–in–panel (GIP) is depicted in several views: (a) cross-sectional view, (b) CNT/GO TEM image at the back side of PI substrate, and (c) green AMOLED image on PI substrate with pixel size of 30 um x 30 um and integrated gate driver using BA a-IGZO TFTs. An AMOLED display driven by a 30-µm-pitch integrated gate driver is shown.[1,2]

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coated first and then cured before the TFT process is carried out. The schematic view of the plastic TFT backplane is shown in Fig. 1(a), where the CNT/GO buffer layer is coated first before the PI. After the whole AMOLED process, the carrier glass is separated from the AMOLED display by a detach process. The CNT/GO image can be seen in Fig. 1(b), which was taken at the back surface of the PI substrate.

The conventional method for the detach process uses excimer-laser exposure, which breaks the bonds of the PI to the carrier glass. The cost of excimer-laser exposure is high, and a non-laser detach technology offers a lower-cost alternative. We have developed a new technology that uses carbon nanotube (CNT) and graphene oxide (GO), which is coated on the carrier glass first. Then the PI process is carried out.[1] The green AMOLED with an integrated gate driver is depicted using the CNT/GO buffer in Fig. 1(c).

A very thin solution-processed CNT/GO backbone is first spin-coated on the glass to decrease adhesion of the PI to the glass; the peel strength of the PI from the glass then decreases, which eases the process of detachment after device fabrication. Given that the CNT/GO remains embedded under the PI after detachment, it minimizes wrinkling and decreases the substrate's tensile elongation. Device performance is also stable under electrostatic-discharge exposures of up to 10 kV, as electrostatic charge can be released via the conducting CNTs.[1]

The TFT transfer characteristics are measured with tensile bending down to 2 mm,

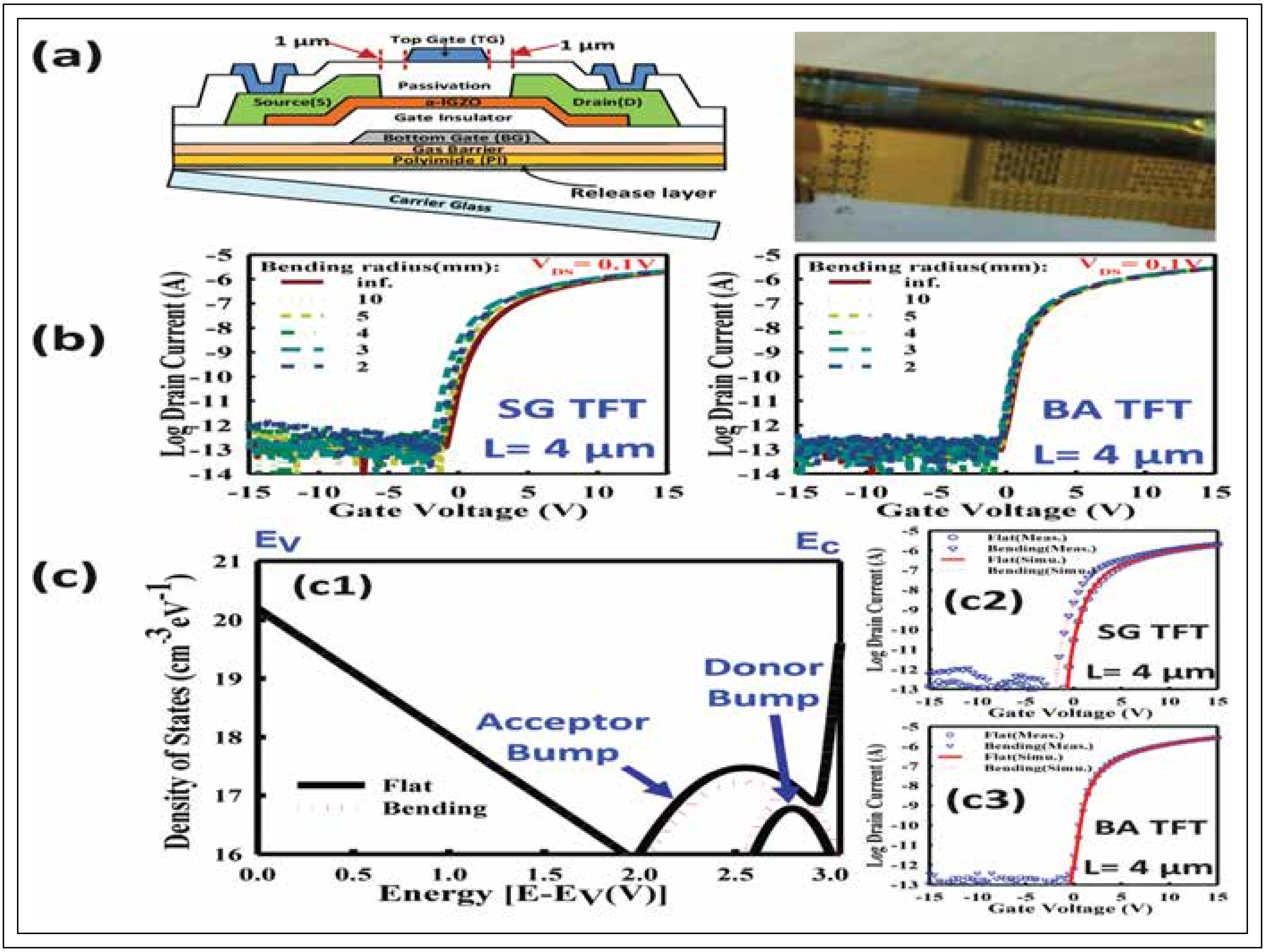

Fig. 2: The robustness of the SG and BA a-IGZO TFTs under mechanical strain are demonstrated. In 2(a), left, a schematic cross section of BA TFTs with top-gate offsets of 1 μm on each side is shown. In 2(a), right, an image of the flexible sample being rolled to a cylinder while bent to a radius of 2 mm is shown. 2(b) shows the evolution of the transfer characteristics as a function of bending radius for SG (left) and BA (right) TFTs with channel lengths of 4 μm. 2(c) shows a simulation using TCAD: (c1) a-IGZO density-of-states (DOS) model used in simulation. Simulated transfer curves (solid lines) in flat condition and under a mechanical bending radius of 2 mm for (c2) SG and (c3) BA a-IGZO TFTs. The experimental data (symbols) is also shown.[3]

demonstrating that a BA TFT is robust against strain. This is due to the fast filling of the defects generated in the gap by the strain and by the induced charges in the gap by bulk accumulation. This was confirmed by technology computer-aided design (TCAD) simulation for the transfer characteristics with the same amount of generated defects by strain.

Figure 2(a) left depicts a flexible a-IGZO TFT with an inverted staggered structure fabricated with a BCE process. The samples were first fabricated on polyimide (PI) on glass substrates, then mechanically detached to yield standing-free flexible devices. The performance of the TFTs is initially checked in the flat state, and then while the TFTs are being wound around rods of varying radius (from 10 to 2 mm) to induce tensile strain in the direction parallel to the TFT channel [Fig. 2(a) right]. Figure 2(b) shows the variations in the characteristics of SG (left) and BA (right) TFTs with decreasing bending radii. The SG TFT shows an obvious negative shift of V_{ON}, increased off-state leakage currents (I_{OFF}), and on-state currents, while no significant change in performance occurs in any of the bending radii investigated in the case of the BA TFTs. Mechanical strain is reported to result in a change in the value of the Fermi function of the semiconductor, causing an increase in the channel conductivity.[4] BA devices are less affected by these small changes in carrier concentration than SG devices, due to the strong gate drive (bulk accumulation/depletion).

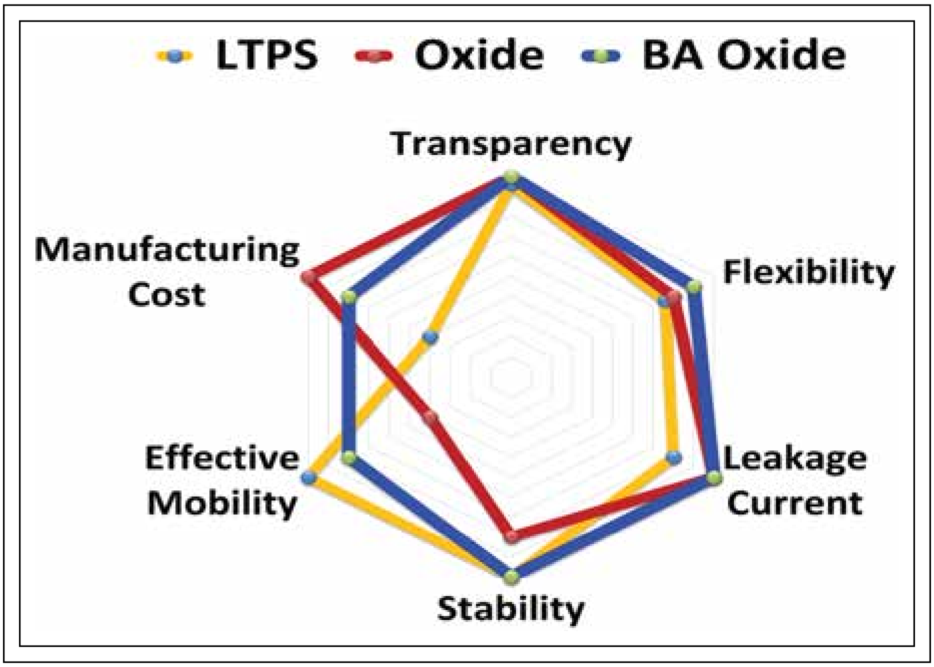

Fig. 3: The schematic illustrates a comparison among LTPS, oxide, and BA-oxide TFTs for flexible-display applications. The BA-TFT backplane has the advantages of manufacturing cost, flexibility, leakage current, and transparency compared to that of LTPS TFTs.

Figures 2(c1) through to 2(c3) show that the simulation results using TCAD (solid lines) fit well with the experimental results (symbols).[3] A density-of-states model is extracted from the numerical fitting to the electrical performance of the a-IGZO TFTs. An increase in carrier concentration, which is represented herein by the increase in the donor bump, is more representative of the effect of tensile strain. The increase in ionized oxygen vacancies and, as a result, the decrease in deep neutral oxygen vacancies (acceptors) is presented by decreasing NGA. It is interesting to note that although the same density of states (DOS) profile was adopted for single-grain (SG) and BA TFTs, both in the flat and bending states, the simulated transfer characteristics of the SG TFTs shift significantly to the negative V_{GS} direction, whereas those of BA TFTs barely shift. This confirms that BA TFTs are immune to slight changes in the DOS, whereas SG TFTs undergo substantial shift. Given the close matching between simulation and experimental results [Fig. 2 (c3)], it is reasonable to conclude that the high gate drive of BA TFTs indeed makes them immune to slight variations in the density of states that may be caused by application of tensile strain in flexible devices.

A comparison between poly-Si and IGZO TFTs for AMOLED displays is shown in Table 1. The effective mobility of a BA TFT can be 90 cm^2/V-sec because the drain current of a BA TFT can be 3–5 times that of an SG TFT. Therefore, a BA-TFT backplane can be

Table 1: The above comparison of poly-Si and IGZO TFTs for flexible AMOLED displays shows that the BA-TFT backplane is essentially the same as IGZO-TFT backplane, with bottom and top gates connected via holes. The top gate has an offset with source/drain electrodes to reduce the overlap capacitance.

	Poly-Si (ELA)	**Oxide TFT (Single Gate)**	**Oxide TFT (Bulk Accumulation)**
Materials	Poly-Si	IGZO	IGZO
Channel Mobility (cm^2/V-sec)	>100	10–30	30–90*
TFT Type	CMOS	NMOS	NMOS
TFT Photo-Mask	5–11	4–5	5–6
Cost/Yield	High/High	Low/Low	Low/High
Process	G6	G8	G8

*Effective Mobility.

used for high-resolution AMOLED displays for mobile applications because the display-driving ability can be similar to that of an LTPS TFT. A flexible 4-in. AMOLED display with an integrated gate driver has been demonstrated.[5]

The comparisons among poly-Si, IGZO, and BA IZGO TFTs are also shown in Fig. 3. In summary, BA-TFT backplanes have the advantages of manufacturing cost, flexibility, leakage current, and transparency compared with that of LTPS-TFT backplanes for display applications. These capabilities make the technology ideal for supporting future generations of flexible and rollable AMOLED displays.

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continued from page 2

Our next offering, "Better Form, Lower Power" by Jyrki Kimmel, covers the world of mobile and flexible displays. I can remember the days when we thought this category was more about novelty than substance, but we all know how much a part of our lives mobile displays have become. And it isn't just about displays but rather how they are being developed to integrate optical and electrical sensing for a wide range of expanded interaction paradigms. Low power, enhanced optics, unique form factors, and enhanced durability were all hallmarks of this year's demonstrations. However, what continues to elude us are the truly foldable and rollable displays of our imagination. There were good examples of these to be seen, but they were still not ready to go beyond the world of prototypes. Someday, yes, it will happen, but what form and function they will take is yet to be seen.

Achin Bhowmik is not just an enthusiast of augmented and virtual reality (AR/VR); he's an active participant in its creation through his leadership role at Intel and as special-topic program chair for the SID Symposium. So, he was uniquely qualified to provide us with a comprehensive survey in his contribution titled "Advances in Augmented- and Virtual-Reality Technologies and Applications." Achin starts off by explaining, "In recent years, virtual-reality (VR) and augmented-reality (AR) technologies have moved from the realms of science fiction and imagination to advanced research in academic laboratories, to product development in the industry, and, finally, into the hands of consumers in the real world." And so true it is with both concept products already on the market and a wealth of new building blocks rapidly coming available. These include development platforms such as Intel's RealSense and several commercially available head-worn displays. I have not yet found someone to take my deposit on a Holodeck for my house, but I do expect to be seeing some really cool helmet and eyeglass systems coming to market real soon.

Within the DW exhibition, there was no shortage of cool demos in the I-Zone and that included a completely new concept for something called a "Carbon-Nanotube Vertical Organic Light-Emitting Transistor" (CN-VOLET). Maybe you do not know what that is? Neither did I until I saw it. Steve Sechrist and Ken Werner explain it in the I-Zone review "nVerpix Takes Best Prototype Honors in the I-Zone." The headline is in the title but the story includes Steve's take on many additional worthwhile I-Zone demos.

Also at the show this year was frequent contributor and market expert Paul Semenza, who gives us this month's Display Marketplace feature, "Flexible Displays Require Flexible Electronics." As the title suggests, Paul expands on my earlier comment about the lack of truly flexible display products by discussing the role flexible electronics will need to play to make these products a reality. We have covered a number of different aspects of flexible electronics in *ID* in recent years, and, clearly, exciting progress is being made. But as Paul explains, there is much more work to do in the areas of materials and process. Meanwhile, he shows us some great examples from DW 2016 of how these concepts are coming to fruition.

One very important aspect of flexible electronics is the actual materials chosen to fabricate the semiconductors, and there has been no shortage of research in this area in recent years. We have published several articles on oxide TFTs and their role in rigid glass displays, but earlier this year we brought you a story from Dr. Jin Jang at Kyung Hee University in Seoul, South Korea, about a new flexible backplane technology using bulk-accumulation (BA) amorphous indium-gallium-zinc-oxide (a-IGZO) TFTs. The first part covered the details of how this backplane could be fabricated, and its associated performance advantages. In the second part, appearing this month and titled "Bulk Accumulation Oxide-TFT Backplane Technology for Flexible and Rollable AMOLED Displays," he describes how this technology was used to build a working flexible AMOLED display, its performance as a semiconductor material compared with poly-Si and single-gate oxide TFTs, and its future potential to help achieve the goal of truly flexible AMOLED displays.

Before I close, I want to take a moment to acknowledge the truly exceptional executive and program committees that made Display Week 2016 such a success. Under the leadership of General Chair Hoi-Sing Kwok and Program Chair Cheng Chen, the event met every expectation we could have imagined, and the numbers prove it. Attendance overall was up 5%, with more than 7,000 individual registrations, and Symposium registrations topped 1900. The great lineup of speakers and topics delivered on its promises, and next year in Los Angeles will surely be another great event.

And so, with those comments I wish everyone a prosperous and peaceful fall season. ■

president's corner

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traditional display technology areas. SID will continue to develop a strong conference and exhibition based on flexible displays, vehicular displays, and AR/VR displays and related technologies. In addition, SID will develop special tracks for new technologies including printed electronics and next-generation input/output devices in our technical conferences. In order to achieve this goal, SID needs many volunteers to invite new people for the special tracks and to organize the events. I would like to welcome all our members to participate and help expand the scope of SID.

Secondly, the *Journal of the SID* is our key archival journal, and for many years SID leadership has been trying to improve and expand its quality and quantity. Especially, we have tried hard to achieve SCI status for the journal, but with only limited success. It is imperative to improve the citation of the journal to achieve SCI status. To that end, we will establish a procedure to publish the distinguished papers from the Technical Symposium in *JSID* instead of the Display Week Technical Digest, for increased citations of the papers.

Lastly, the society's new governance structure approved in this spring's ballot will be implemented to streamline the administration structure of our society. This will speed up the decision-making process and help the society adapt to a rapidly changing world.

I would like to take this opportunity to thank outgoing President Amal Ghosh and the entire SID leadership team for doing an outstanding job of improving the society in various aspects. The financial health of our society has been vastly improved under Amal's leadership, membership in China has increased under his China initiatives, and improved programs and events at Display Week are attracting more people. During Amal's presidency, the society has stabilized and set the foundation for growth in future years.

Finally, I hope you had an enjoyable summer vacationing with family and friends. I look forward to serving you in the coming years. ■

industry news

continued from page 3

Fig. 2: *Gamma Scientific's Dual Angle Reflectance Measurement System is designed for high-speed automated reflectance measurements of glass for display and architectural uses.*

In addition to pure colorimetric binning, measurements can be analyzed relative to other substrate positions for uniformity and color-difference judgement criteria. By utilizing these reflectance measurements results – together with the system's integrated film thickness analysis tool – directly into the production-line feedback control, higher yields and more consistent coating uniformity on the glass or other substrates can be achieved. ■

SID 2017 honors and awards nominations

On behalf of the SID Honors and Awards Committee (H&AC), I am appealing for your active participation in the nomination of deserving individuals for the various SID honors and awards. The SID Board of Directors, based on recommendations made by the H&AC, grants all the awards. These awards include five major prizes awarded to individuals, not necessarily members of SID, based upon their outstanding achievements. The **Karl Ferdinand Braun prize** is awarded for ***"Outstanding Technical Achievement in, or Contribution to, Display Technology."*** The prize is named in honor of the German physicist and Nobel Laureate Karl Ferdinand Braun who, in 1897, invented the cathode-ray tube (CRT). Scientific and technical achievements that cover either a wide range of display technologies or the fundamental principles of a specific technology are the prime reasons for awarding this prize to a nominee. The **Jan Rajchman prize** is awarded for ***"Outstanding Scientific and Technical Achievement or Research in the Field of Flat-Panel Displays."*** This prize is specifically dedicated to those individuals who have made major contributions to one of the flat-panel-display technologies or, through their research activities, have advanced the state of understanding of one of those technologies. The **Otto Schade prize** is awarded for ***"Outstanding Scientific or Technical Achievement in the Advancement of Functional Performance and/or Image Quality of Information Displays."*** This prize is named in honor of the pioneering RCA engineer Otto Schade, who invented the concept of the Modulation Transfer Function (MTF) and who used it to characterize the entire display system, including the human observer. The advancement for this prize may be achieved in any display technology or display system or may be of a more general or theoretical nature. The scope of eligible advancement is broadly envisioned to encompass the areas of display systems, display electronics, applied vision and display human factors, image processing, and display metrology. The nature of eligible advancements may be in the form of theoretical or mathematical models, algorithms, software, hardware, or innovative methods of display-performance measurement and image-quality characterization. Each of these above-mentioned prizes carries a $2000

SID honors and awards nominations

Nominations are now being solicited from SID members for candidates who qualify for SID Honors and Awards.

- KARL FERDINAND BRAUN PRIZE. Awarded for an outstanding *technical* achievement in, or contribution to, display technology.
- JAN RAJCHMAN PRIZE. Awarded for an outstanding *scientific* or *technical* achievement in, or contribution to, research on flat-panel displays.
- OTTO SCHADE PRIZE. Awarded for an outstanding *scientific* or *technical* achievement in, or contribution to, the advancement of functional performance and/or image quality of information displays.
- SLOTTOW–OWAKI PRIZE. Awarded for outstanding contributions to the education and training of students and professionals in the field of information display.
- LEWIS & BEATRICE WINNER AWARD. Awarded for exceptional and sustained service to SID.
- FELLOW. The membership grade of Fellow is one of unusual professional distinction and is conferred annually upon a SID member of outstanding qualifications and experience as a scientist or engineer in the field of information display who has made widely recognized and significant contribution to the advancement of the display field.
- 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. These awards may be made for contributions in one or more of the following categories: (a) outstanding technical accomplishments; (b) outstanding contributions to the literature; (c) outstanding service to the Society; (d) outstanding entrepreneurial accomplishments; and (e) outstanding achievements in education.

Nominations for SID Honors and Awards must include the following information, preferably in the order given below. Nomination Templates and Samples are provided at *www.sid.org/awards/nomination.html*.

1. Name, Present Occupation, Business and Home Address, Phone and Fax Numbers, and SID Grade (Member or Fellow) of Nominee.

2. Award being recommended:
   Jan Rajchman Prize
   Karl Ferdinand Braun Prize
   Otto Schade Prize
   Slottow–Owaki Prize
   Lewis & Beatrice Winner Award
   Fellow*
   Special Recognition Award

*Nominations for election to the Grade of Fellow must be supported in writing by at least five SID members.

3. Proposed Citation. This should not exceed 30 words.

4. Name, Address, Telephone Number, and SID Membership Grade of Nominator.

5. Education and Professional History of Candidate. Include college and/or university degrees, positions and responsibilities of each professional employment.

6. Professional Awards and Other Professional Society Affiliations and Grades of Membership.

7. Specific statement by the nominator concerning the most significant achievement or achievements or outstanding technical leadership that qualifies the candidate for the award. This is the most important consideration for the Honors and Awards committee, and it should be specific (citing references when necessary) and concise.

8. Supportive material. Cite evidence of technical achievements and creativity, such as patents and publications, or other evidence of success and peer recognition. Cite material that specifically supports the citation and statement in (7) above. (Note: the nominee may be asked by the nominator to supply information for his candidacy where this may be useful to establish or complete the list of qualifications).

9. Endorsements. Fellow nominations must be supported by the endorsements indicated in (2) above. Supportive letters of endorser will strengthen the nominations for any award.

E-mail the complete nomination – including all the above material by **October 15, 2016** – to swu@ucf.edu with cc to office@sid.org or by regular mail to:
Shin-Tson Wu, Honors and Awards Chair, Society for Information Display,
1475 S. Bascom Ave., Ste. 114, Campbell, CA 95008, U.S.A.

stipend sponsored by AU Optronics Corp., Sharp Corporation, and Samsung Display, respectively.

The **Slottow–Owaki prize** is awarded for ***"Outstanding Contributions to the Education and Training of Students and Professionals in the Field of Information Display."*** This prize is named in honor of Professor H. Gene Slottow, University of Illinois, an inventor of the plasma display and Professor Kenichi Owaki from the Hiroshima Institute of Technology and an early leader of the pioneering Fujitsu Plasma Display program. The oustanding education and training contributions recognized by this prize is not limited to those of a professor in a formal university, but may also include training given by researchers, engineers, and managers in industry who have done an outstanding job developing information-display professionals. The Slottow–Owaki prize carries a $2000 stipend made possible by a generous gift from Fujitsu, Ltd., and Professor Tsutae Shinoda.

The fifth major SID award, the **Lewis and Beatrice Winner Award,** is awarded for ***"Exceptional and Sustained Service to the Society."*** This award is granted exclusively to those who have worked hard over many years to further the goals of the Society.

The membership grade of **SID Fellow** is one of unusual professional distinction. Each year the SID Board of Directors elects a limited number (up to 0.1% of the membership in that year) of **SID members** in good standing to the grade of **Fellow.** To be eligible, candidates must have been members at the time of nomination for at least 5 years, with the last 3 years consecutive. A candidate for election to Fellow is a member with ***"Outstanding Qualifications and Experience as a Scientist or Engineer in the Field of Information Display who has made Widely Recognized and Significant Contributions to the Advancement of the Display Field"*** over a sustained period of time. SID members practicing in the field recognize the nominee's work as providing significant technical contributions to knowledge in their area(s) of expertise. For this reason, five endorsements from SID members are required to accompany each Fellow nomination. Each Fellow nomination is evaluated by the H&AC, based on a weighted set of five criteria. These criteria and their assigned weights are creativity and patents, 30%; technical accomplishments and publications, 30%; technical leadership, 20%; service to SID, 15%; and other accomplishments, 5%. When submitting a Fellow award nomination, please keep these criteria with their weights in mind.

The **Special Recognition Award** is given annually to a number of individuals (membership in the SID is not required) of the scientific and business community for distinguished and valued contribution in the information-display field. These awards are given for contributions in one or more of the following categories: (a) ***Outstanding Technical Accomplishments,*** (b) ***Outstanding Contributions to the Literature,*** (c) ***Outstanding Service to the Society,*** (d) ***Outstanding Entrepreneurial Accomplishments,*** and (e) ***Outstanding Achievements in Education.*** When evaluating the Special Recognition Award nominations, the H&AC uses a five-level rating scale in each of the above-listed five categories, and these categories have equal weight. Nominators should indicate the category in which a Special Recognition Award nomination is to be considered by the H&AC. More than one category may be indicated. The nomination should, of course, stress accomplishments in the category or categories selected by the nominator.

While an individual nominated for an award or election to Fellow may not submit his/her own nomination, nominators may, if necessary, ask a nominee for information that will be useful in preparing the nomination. The nomination process is relatively simple, but requires that the nominator and perhaps some colleagues devote a little time to preparation of the supporting material that the H&AC needs in order to evaluate each nomination for its merit. It is not necessary to submit a complete publication record with a nomination. Just list the titles of the most significant half a dozen or less papers and patents authored by the nominee, and list the total number of papers and patents he/she has authored.

Determination of the winners for SID honors and awards is a highly selective process. On average, less than 30% of the nominations are selected to receive awards. Some of the major prizes are not awarded every year due to the lack of sufficiently qualified nominees. On the other hand, once a nomination is submitted, it will stay active for three consecutive years and will be considered three times by the H&AC. The nominator of such a nomination may improve the chances of the nomination by submitting additional material for the second or third year that it is considered, but such changes are not required.

Descriptions of each award and the lists of previous award winners can be found at *www.sid.org/Awards/IndividualHonorsandAwards.aspx*. Nomination forms can be downloaded by clicking on "click here" at the bottom of the text box on the above site where you will find Nomination Templates in both MS Word (preferred) and Text formats. Please use the links to find the Sample Nominations, which are useful for composing your nomination since these are the actual successful nominations for some previous SID awards. Nominations should preferably be submitted by e-mail. However, you can also submit nominations by ordinary mail if necessary.

Please note that with each Fellow nomination, only five written endorsements by five SID members are required. These brief endorsements – *a minimum of 2–3 sentences* to a maximum of one-half page in length – *must state why clearly and succinctly, in the opinion of the endorser, the nominee deserves to be elected to a Fellow of the Society. Identical endorsements by two or more endorsers will be automatically rejected* (no form letters, please). Please send these endorsements to me either by e-mail (preferred) or by hardcopy to the address stated in the accompanying text box. Only the Fellow nominations are required to have these endorsements. However, I encourage you to submit at least a few endorsements for all nominations since they will frequently add further support to your nomination.

All 2017 award nominations are to be submitted by October 15, 2016. E-mail your nominations directly to swu@ucf.edu with cc to office@sid.org. If that is not possible, then please send your hardcopy nomination by regular mail.

As I state each year: "In our professional lives, there are few greater rewards than recognition by our peers. For an individual in the field of displays, an award or prize from the SID, which represents his or her peers worldwide, is a most significant, happy, and satisfying experience. In addition, the overall reputation of the society depends on the individuals who are in its 'Hall of Fame.'

When you nominate someone for an award or prize, you are bringing happiness to an individual and his or her family and friends, and you are also benefiting the society as a whole."

Thank you for your nomination in advance.

— Shin-Tson Wu
Chair, SID Honors & Awards Committee

IDW and Asia Display Join Forces

The 23rd Annual International Display Workshops (IDW), held for the first time in conjunction with Asia Display, will take place December 7–9, 2016, in Fukuoka, Japan. The workshops, sponsored by the Institute of Image Information and Television Engineers and the Society for Information Display, feature specialized content that plays an important role in information-display activities.

This year's special topics include oxide-semiconductor TFTs, AR/VR and hyper reality, lighting, quantum-dot technologies, printed electronics, and automotive displays. Keynote addresses will include "Future Trends of Display Technology" by Chung-Chun Lee, BOE, China, and "Breaking the Barriers to True Augmented Reality" by Christian Sandor, NAIST, Japan. The event will include an exhibition and invited talks as well as scheduled technical sessions.

The city of Fukuoka is located in the northern part of Kyushu Island and is Western Japan's most active city in terms of business, culture, and industry (Fig. 1). It is known as a particularly livable and affordable city.

The Fukuoka International Congress Center, where IDW and Asia Display will be held, is located only 1.5 km from the center of Fukuoka city. Ferries and jetfoils at the adjacent international terminal of Hakata Port run routes to Pusan, Korea.

Visit www.idw.or.jp to register and obtain more information.

Fig. 1: *A bridge at Tenmangu Shrine in Dazaifu is just one of the many attractive sites to be enjoyed in Fukuoka. Dazaifu is among the most important of Japan's shrines associated with the legendary Sugawara Michizane, a ninth-century scholar and politician.*

Display Week Adds Two New Programs

Display Week 2016 in San Francisco introduced two new programs this year that were created to enhance the conference experience – the CMO Forum and the New Product Showcase. The CMO Forum, a 1-hour panel discussion moderated by SID head of marketing Sri Peruvemba, was designed to give marketing, sales, and supply-chain professionals at Display Week an opportunity to explore what Peruvemba describes as "the non-technical aspects of what we do."

The five panelists were Paul Apen, Chief Strategy Officer, E Ink Corp.; Jennifer Davis, Chief Marketing Officer, Planar/Leyard International; Albert Green, Chief Executive Officer, Kent Displays; Greg McNeil, Vice-President of the Innovation Labs, Flex; and Stephen Squires, Chief Executive Officer, Quantum Materials. The panelists fielded questions such as "What are some of the things you have done that led to your success in business?" and "How will you make money in the display industry two to three years from now?" Most of the panelists agreed that the latter is a difficult question, but some offered interesting takes. "We need to consider not only traditional ROI but user experience. It might be interesting technology, but it also must answer customers' needs," said Davis. "One thing I see happening," said McNeil, "is that products and ideas are coming from companies you would not have thought of in the past – manufacturers of windows and doors, for example. We are now opening up markets with companies who have not been 'embedded in the electronics life.' "

The New Product Showcase was a special exhibit-floor program that allowed exhibitors to show one exciting new product or technology from their booths in a designated area on the show floor. The purpose behind the showcase was to make it easy for attendees, including members of the press, to see what was "hot" at the show, and also to encourage them to visit individual booths to learn more. This year's showcase featured about 50 products. Many more exhibitors showed interest in participating next year.

Reactions to both the CMO Forum and the New Product Showcase were extremely positive, and show organizers plan to repeat both events at Display Week 2017 in Los Angeles. ■

Networking Events

May 21–26, 2017

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 22.

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 24. 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 23:
Follows the Tuesday Market Focus Conference, please note conference attendance is required for admission.

www.displayweek.org

SID International Symposium, Seminar & Exhibition

May 21–26, 2017

Los Angeles Convention Center
Los Angeles, 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 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 $1000 prize.

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