DISPLAY WEEK 2018 REVIEW ISSUE

Information DISPLAY

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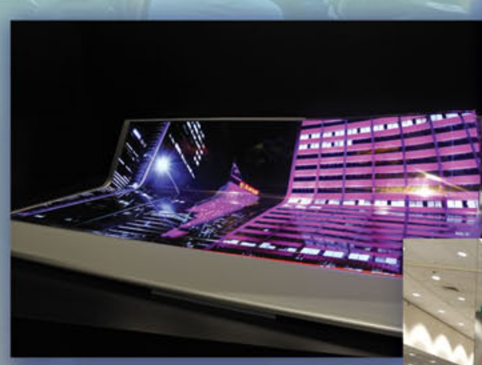
Exciting Emissive Technology at Display Week 2018



Plus

Best in Show and I-Zone Winners
Q&A with Fieldscale

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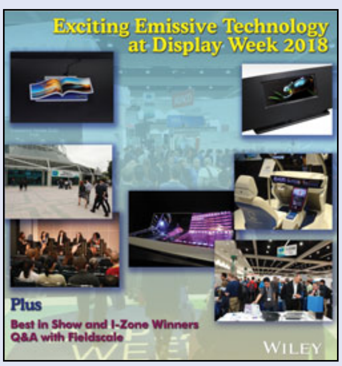
ON THE COVER: *Scenes from Display Week 2018 in Los Angeles include (center and then clockwise starting at upper right): the exhibit hall floor; AUO's 8-in. microLED display (Photo: AUO); JDI's cockpit demo, with dashboard and center-console displays (Photo: Karlheinz Blankenbach); the 2018 I-Zone; LG Display's flexible OLED screen (Photo: Ken Werner); Women in Tech second annual conference, with moderator and panelists; the entrance to the conference center at Display Week 2018; foldable AMOLED e-Book (Photo: Visionox).*



Cover Design: Jodi Buckley

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- Color Concerns

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editorial

Looking Back at Display Week and Summer, Looking Ahead to Fall

by Stephen P. Atwood

Hello and welcome to our annual Display Week review issue. I hope you all enjoyed your summer as much as I enjoyed mine. It's the time of year when we get a chance to test that work-life balance theory people keep talking about. Business moves ever forward, but the outdoors and recreation opportunities beckon with a full-throated plea for us to engage in them! As the summer comes to an end, many of us find ourselves involved in strategic planning and product road-mapping activities. These activities frequently require inspiration and hence it's a great time to look back at all the innovation and new ideas we saw just a few months ago at Display Week in LA.

Our issue this month includes eight articles reviewing various topical areas of the show. This could be a record for *ID,* and it was made possible by the very energetic work of our roving reporters, each of whom possesses subject-matter expertise in a specific area. I'll comment on some of the key topics as we move along, but let me acknowledge all of our reporters and their beats right up front and thank them very sincerely for their contributions: Achin Bhowmik (Augmented and Virtual Reality), Karlheinz Blankenbach (Automotive Displays), Gary Feather (Emissive Materials for Digital Signage), Tom Fiske (Metrology and Image Quality), Steve Sechrist (I-Zone Exhibits), and Ken Werner (Glass and Polymers and Emissive Materials). Also, a special thanks to Jenny Donelan, who authored our story recognizing the winners of the prestigious SID Best in Show awards. This year's four Best in Show winners were selected from more than 200 outstanding exhibitors, both large and small. Their winning displays and exhibits are summarized in Jenny's article.

MicroLEDs, AR/VR, Foldable OLEDs, and a Super-Fast LCD

There were several significant technology trends and meaningful breakthroughs at this year's show to talk about. The first was a surge of presentations and demonstrations on microLED technology. Driven by significant improvements in performance, packaging, and manufacturing costs, µLEDs are showing promise as the building blocks for very high-performance displays in both small and large formats, as well as potential projection imagers. As the luminous output of LED technology advances to remarkable levels, the concept of making a matrix display by simply laying out an array of extremely small discrete or modularly packaged RGB LEDs becomes all the more viable. While it's somewhat straightforward to fabricate many thousands of discrete LEDs per inch on a wafer, it's not practical to make a tablet-size display this way for multiple reasons. The challenge hence is transferring the individual devices from wafer-scale fabrication spacing to tablet or TV-size substrates in an economical way. Using the technology that is available commercially now, it could take days or weeks to assemble a single, reasonably sized display this way. That is the next hurdle, and it received a lot of attention this year – though it did not stop some companies from showing 7- and even 8-in. panels, proving the concept has great promise.

Another topic that was very well represented, at least in the technical symposium, was augmented reality/virtual reality (AR/VR) and all manner of tangential research areas such as dynamic focus techniques, foveated rendering schemes, advances in position tracking for head-worn systems, and a variety of ways to increase resolution

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president's corner

Goals for a Sustainable Society

by Helge Seetzen

Dear members of the Society for Information Display community:

A few months ago, at a record-breaking Display Week conference in Los Angeles, I assumed the role of president of this great society. I would like to share with you my goals for my two-year term. When I joined the board of SID nearly a decade ago, our society was in dire straits. The devastating financial impact of the 2009 San Antonio conference, coupled with a global recession, had brought us to the brink of insolvency. Since then, the executive board and my predecessors have worked hard to restore, repair, and restructure our society. Today, we are in great financial health and our conference is experiencing peak attendance. This strong foundation encourages me to set out three goals for my presidential term that are designed to bring SID to the next level.

Openness. A society is only as strong as its members, and we have great strength indeed. But communication and interaction among our members are still limited. To improve member interaction —with headquarters, the board, and one another — we will be rolling out a number of communication features in the coming months. First, we will launch a new online membership tool that allows opt-in and follows the latest in privacy solutions. This tool will streamline interaction among members as well as communication with SID's leadership. One such communication will be regular updates from me on the state of our society and opportunities for members to contribute. Complementing this tool will be a restructuring of *Information Display* magazine to better leverage online distribution. In partnership with the publishing company Wiley, we will bring the full range of 21st-century interaction to our readers. Other communication features will follow in later months to bring our members together for the best possible society.

Inclusion. Bringing our members closer together is wonderful, but we also need to ensure that we include anybody and everybody in our society. Our industry is diverse, and our membership should be as well. Inclusion is a topic close to my heart, and I am very pleased that we have already made strides in this direction. Our second Women-in-Tech event at Display Week 2018 was again well attended, and similar events are now taking root in other SID-supported conferences. Meanwhile, our inaugural student fair opened doors to another underrepresented demographic. Beyond outreach, we need role models. It thus gives me great pleasure that for the first time in our history, five women now serve in leadership roles in the governance organization — including Rashmi Rao as general chair of Display Week 2019. This is great progress from a leadership table that last year was entirely male. However, much more work still lies ahead of us, and I hope to have all of your support in making our society welcoming and open to everybody from everywhere.

Expansion. Last, but most definitely not least, we need to continue our push to expand SID in emerging regions. Our new governance structure ensures that regions are now fairly and proportionally represented in the society, but we also need representation in those regions. Nothing beats boots on the ground, and with that in mind, we have recently opened our first international headquarters branch in China. Led by Qun (Frank) Yan, this new facility in Shenzhen will provide regional support for our

president's corner

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members and will organize local events such as the recent very successful International Conference on Display Technology in Guangzhou. We are exploring similar regional support in other countries to expand our society and reach members who cannot attend our signature events in North America.

As you can see, we are well on our way to delivering on all three of these ambitious goals. Much of this is because of the efforts made by my esteemed predecessors and the society's leadership team over the past few years. These individuals — volunteers all — move mountains to bring SID forward, and it will be a privilege to serve with them for the next two years. But progress can't just come from a small group at the top. All of you can make a difference. In my next editorial I will describe some of the volunteer opportunities in more detail, but please reach out to me now if you would like to contribute to growing and opening our society. I look forward to working with many of you over the next two years to make SID the best it can be for all of you.

Helge Seetzen *is president of the Society for Information Display. He can be reached at helge.seetzen@tandemlaunch.com.* ■

industry news

by Jenny Donelan

Metrology Company Takes Aim at Digital Billboards

As the use of roadside digital signage has increased, so have the number of studies and articles about whether the technology causes light pollution and traffic accidents. The former is somewhat in the eye of the beholder, as in New Haven, CT, last spring, when public objection to a new, 230-square-foot LED-based billboard, described by the *Connecticut Mirror* as "blinding,"[1] led to proposed new legislation for digital signage regulation. The latter, traffic accidents, have been studied at some length, with a 2015 National Institutes of Health Study concluding that while billboard-related driver distraction appeared to be minor, further study was required.[2]

Industry and governmental uncertainty over digital signage is a possible windfall for display metrology manufacturers such as Konica Minolta Sensing, which recently released a white paper about how instruments such as its CS-150 Luminance and Color Meter could help ensure that luminance guidelines for roadside digital signage are met. Konica Minolta suggested that its products be used to calibrate billboards for optimal luminance both day and night – hitting the sweet spot of getting people's attention without distracting them to the point of danger or discomfort.

It may take some time before the public and the government decide on acceptable parameters for roadside digital signage. In the meantime, automotive technology itself could make the call. The sequential Burma-Shave signs that proliferated from the 1920s to the 1960s disappeared as people began driving at speeds too fast to read them. It is possible that by the time digital signage has been optimized, autonomous driving may be taking off and driver distraction will be less of an issue.

[1]https://ctmirror.org/2018/05/04/house-passes-billboard-brightness-bill/
[2]www.ncbi.nlm.nih.gov/pmc/articles/PMC4411179/

OLED NEWS

LG Display to Build OLED Plant in Guangzhou

LG Display recently announced that its OLED production joint venture in Guangzhou, China, has been approved by the Chinese government. The new plant (Fig. 1) will be an 8.5-Gen (2,200 × 2,500 mm) production facility, established with 2.6 trillion Korean won in capital, of which LG Display will control a 70 percent share. The remaining 30 percent will be owned by Guangzhou Economic and Technological Development District.

The Guangzhou OLED plant will mainly produce large-size OLED panels for TVs. LG Display will start producing 60,000 input sheets per month and will gradually ramp up to a maximum of 90,000 sheets per month. Adding that to the production capacity of 70,000 input sheets per month from LG's plants in Paju, the company's total production capacity of large-size OLED panels will reach 130,000 sheets per month by the second half of 2019. This capacity will enable the company to ship up to 10 million 55-in. OLED TV panels on a yearly basis. The start of mass production in Guangzhou is planned for the second half of 2019.

Fig. 1: A conceptual drawing shows LG Display's future OLED panel production facility in Guangzhou, China. Source: LG Display

OLED Displays with Pins

Electronic Assembly has developed what it describes as the world's first OLED display family with connector pins for easy plug-in mounting (Fig. 2). These high-contrast OLED displays can be soldered directly or plugged into socket strips, eliminating the need for gluing procedures or special mounting devices.

These OLED displays feature a flat design (typically 2.4 mm), wide viewing angles (up to 170°), high contrast (2,000:1), fast response times (typically 10 μs), and a high overall luminance (100 cd/m^2). The company says that these features, together with an extended temperature range (–40 to +80°C) and a long service life (at least 50,000 hours), make the displays particularly suitable for mounting in mobile handheld devices for robust outdoor use.

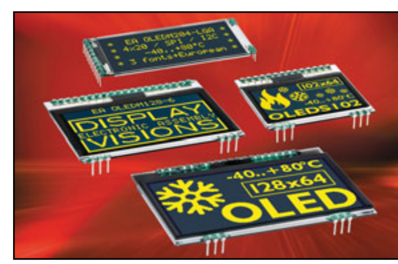

Fig 2: Electronic Assembly offers OLED displays in a variety of sizes (as above) that include pins for easy assembly. Source: Electronic Assembly

Innolux Demos Flexible OLED Smartwatch

At Touch Taiwan 2018, Innolux showed what it claims is the first smartwatch to feature a flexible OLED display. The 1.39-in. flexible OLED display has a resolution of 400 × 400 pixels, and is built using a low-temperature polysilicon (LTPS) process at Innolux. Company representatives say Innolux is working on numerous OLED-based flexible, wearable devices.

MicroLED Summit to Take Place in China

There may be no surer sign of a technology's arrival than having conferences designed around it. This year, the 2nd International MicroLED Summit will take place in Shenzhen, China, on November 12, 2018. Due to the success of last year's event and the ongoing interest in microLEDs in China, organizers say they expect more than 1,000 attendees. On November 13, a related business conference will be held for companies and investors looking into microLED. For more information on either event, visit: www.sidicme.com.

New Holographic Display Is in Development

Still in Kickstarter campaign mode but due to start shipping product soon (according to its maker) is The Looking Glass from Looking Glass Factory (Fig. 3). Its inventor describes it as "A Holographic Display for 3D Creaters"

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and it is designed to be used by people working in 3D content creation programs such as Maya, ZBrush, and SolidWorks. The display involves a patent-pending combination of lightfield and volumetric display technologies in one three-dimensional display system. It is designed to provide 45 unique simultaneous views of a virtual scene, as captured at 60 frames per second.

According to a recent article in *The Verge*,[3] The Looking Glass will be available at $600 for an 8.9-in. model and $3,000 for a 15.9-in. model. The first 100 units are supposed to ship in the third quarter of 2018. ■

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[3]www.theverge.com/circuitbreaker/2018/7/24/17607136/the-looking-glass-holographic-display-hologram-3d-image-kickstarter

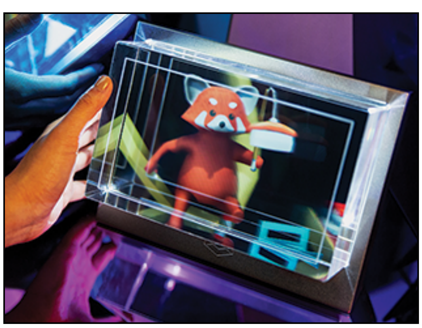

Fig. 3: *As pictured on its Kickstarter campaign page, The Looking Glass is a glasses-free holographic-type device. Source: The Looking Glass Factory*

editorial

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and fields of view. In particular, emerging technology for motion tracking with high speed and resolution is extremely important if we expect to achieve user experiences equivalent to real life at an affordable cost any time soon. This could be critical to making AR/VR systems practical for long periods of productive use in industrial applications. It's not just the displays that are getting a lot of attention but also the systems that those displays enable. I counted a total of 12 AR/VR paper sessions over the three days, and the ones I attended had big audiences. Clearly there is a lot of good work going on in this area all over the world and it will create a surge of new products and applications very soon.

In the category of "Gee Whiz," I would put the numerous demonstrations of flexible displays, including LG Display's 77-in. flexible OLED screen shown in the very front of the exhibit hall, where it was continuously folded and unfolded during the show. Also notable was the Visionox demonstration of multiple foldable AMOLED formats, including a 7.2-in. panel that could achieve a 1.6-mm folding radius. Visionox rightly won a Best in Show award for its innovative and creative application demonstrations. Of course, there was also a wide array of great technical papers on OLED technology, many of them with flexible substrates, and lots of new work reported on substrate materials and fabrication techniques as well.

I think this year's Innovation Zone (I-Zone) exhibit was the best ever, and I applaud the committee for expanding the format and including close to 50 demonstrations. Several I-Zone exhibitors were also recognized with their own version of Best in Show awards, including a team from Hong Kong University of Science and Technology that also received a best student paper award. Their development was a 60-Hz frame-rate 250-ppi active-matrix field-sequential color LCD – yes, you read that right – an LCD with a 10-µs response time!

The field of display metrology was also well represented this year, with a nice suite of papers in the symposium and exhibits on the show floor. The ability to employ substantial numerical processing power at low cost has enabled an exciting new generation of instruments that not only collect data but in at least one case can generate simulations and predict performance under variable ambient conditions. The ability to embed advanced data analysis and predictive simulation directly into instrumentation could be a real paradigm shift for the display metrology industry.

There were many other great things at Display Week, too many in fact to enumerate in this short space, but I think the best part was getting to see colleagues and friends I know well along with meeting many new people who share a common passion for this industry.

SID's New President

One important milestone this year was the handoff of the gavel to incoming SID President Helge Seetzen. Helge has been a great supporter of the Society and I have come to respect him a great deal through our work together on the SID publications. Helge took the time to lay out his vision for the next two years in his President's Corner column, "Goals for a Sustainable Society." I especially like his ideas about fostering a greater number of women in SID leadership, which I hope will translate to a greater representation of women in the display industry as well.

The Entrepreneurial Adventure

In addition to all the time Jenny Donelan invested in assembling this issue, she also interviewed Yiorgos Bontzios, CEO of Fieldscale, a company based in Thessaloniki, Greece, that makes simulation software for touch-panel developers. In our Business of Displays feature, Yiorgos shares the experience of developing his company's flagship product, SENSE, which is the first-ever full-simulation tool for capacitive touch sensors. Like most entrepreneurs, he and his team underwent the highs and lows of having a vision, realizing how hard it was to commercialize that vision, then seeing their work evolve into something meaningful and valuable. That, along with SID News and Industry News, is a quick summary of what you will find in this issue.

Work-Life Balance

But before I end this column, I want to come back to that seed I planted in the opening remarks when I mentioned work-life balance. If you are in a fast-paced work environment, you probably feel the pressure to keep advancing your work and not stray too far from the email and the cell phone – I know I feel the pressure constantly. But despite that, I've taken several weeks of vacation so far this year and made them most effective by almost completely disconnecting from work and on-line activities. I've spent quality time with my family, most of it in outdoor settings – camping, hiking, and boating. I've taken both a long stretch of two weeks and some short stretches of long weekends. Even short stretches of time off seem to reduce my stress and improve my sense of well-being. I'm sharing this with you because as you read this, there is probably still some warm fall weather left and some time for you to get out there and enjoy it. So take my advice: take some time off for yourself and take along this issue of *ID* for some easy reading on the way. ■

Best in Show Winners

The Society for Information Display honored four exhibiting companies with Best in Show awards at Display Week 2018 in Los Angeles: Ares Materials, AU Optronics, Tianma, and Visionox.

by Jenny Donelan

SMALL displays and small materials were big news at Display Week this year. There were, of course, big, beautiful panels on the 2018 show floor, but it was the smaller mobile displays and microLEDs (µLEDs) and miniLEDs that really captured the attention of the SID awards committee. Each of the four 2018 Best in Show winners was honored for a technology related to mobile devices.

At 8 inches diagonal, AUO's winning panel made of µLEDs 30 micrometers "big" was the largest at the show to feature the new and promising emissive µLED technology. Tianma won for an LCD less than 7 inches that was backlit with microLEDs. Visionox earned its Best in Show award for a 7.2-in. flexible, bendable OLED panel *and* the way the company showed off what you might be able to do with the technology – bendable e-books as well as cups, speakers, and other items. In the humble-but-essential category of adhesives, Ares Materials won a Best in Show award for its new mechanical lift-off technology that promises to improve yields for the OLED smartphone industry.

Jenny Donelan *is the editor in chief of* Information Display *magazine. She can be reached at jdonelan@pcm411.com.*

This year's four Best in Show winners were selected from more than 200 exhibitors. Awards, determined by the awards committee the evening after the first day of the exhibition, were presented in three categories by exhibit size: small, medium, and large. We salute these winners and hope you enjoy reading about them.

Small Exhibit Winner

Ares Materials received a Best in Show award in the small exhibit category for its mechanical lift-off technology. Ares, an optoelectronic materials design company based in Texas, launched the new material used in the lift-off process under the name of Easybond (Fig. 1). This material is designed to temporarily bond a flexible substrate to a carrier to enable microfabrication on the substrate. The substrate can then be released from the carrier using a simple, mechanical peel process. Easybond is designed specifically for attaching a polymer substrate to a carrier in order to build on thin film transistors (TFTs) to create color filters and touch panels for displays. The major target market is flexible OLED panels used for major smartphone brands. The material provides a high surface energy for improved wettability and is compatible with high-temperature processing in excess of 500°C. Mechanical peel of the display module can be done with forces below < 5 cN/cm.

A major benefit of the Ares process is that it enables manufacturers to use their current microfabrication processes for flexible substrates. They can, for example, continue to use polyimide or Pylux (a polysulfide thermoset film also made by Ares), eliminating the need to purchase additional equipment or to implement new micropatterns and setups.

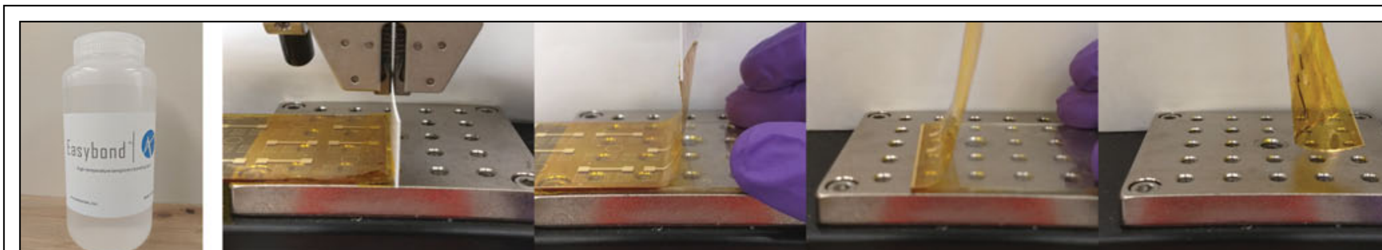

Fig. 1: *Easybond (far left) is an adhesive material that bonds a substrate to a carrier for fabrication, then allows the substrate to be easily peeled from the carrier, as shown from left to right. Photos: Ares Materials*

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Medium Exhibit Winner

AU Optronics received a Best in Show award in the medium exhibit category for its multiple advanced display technologies, including µLEDs. The latter product category was represented by a full-color, TFT-driven, high-dynamic range (HDR) 8-in. µLED display, which debuted on the exhibit floor at Display Week 2018 (Fig. 2). AUO's µLED technology employs a LTPS-TFT backplane, which allows each pixel to be lit independently to realize more refined images with high dynamic range and power saving. AUO achieved a 169-ppi density with µLEDs that were less than 30 micrometers in size.

AUO also demonstrated a suite of new miniLED-backlit LCD panels with high luminance and high dynamic range that are designed for gaming monitors and notebooks as well as virtual reality headset applications. And it highlighted its LTPS technology with several displays for mobile devices, including a 13.3-in. ultra-high definition (UHD) 4K narrow-border LTPS LCD that supported the use of a stylus. Exhibition highlights also included a 13.2-in. freeform car display with gate circuit-in-active (CIA) area and a 13-in. transparent AMOLED display.

Large Exhibit Winners

Tianma received a Best in Show award in the large exhibit category for its HDR LCD for mobile applications. Tianma's 6.46-in. panel, based on LTPS technology, is a WQHD full-screen display for smartphones, with a resolution of 498 ppi (Fig. 3). The display uses miniLED backlight technology to achieve multi-zone local dimming. The display offers excellent performance for smartphones, with peak luminance above 1,000 nits and maximum local contrast greater than 3,000,000:1. The display also features 10-bit gray-code signal input and output with DCI-P3 color gamut. The company says that the prototype performs competitively with AMOLED displays in terms of contrast ratio, response time, resolution, and luminance. The display is scheduled for production by the end of 2019.

Fig. 2: *AUO's 8-in. microLED display featured 169-ppi resolution. Photo: AUO*

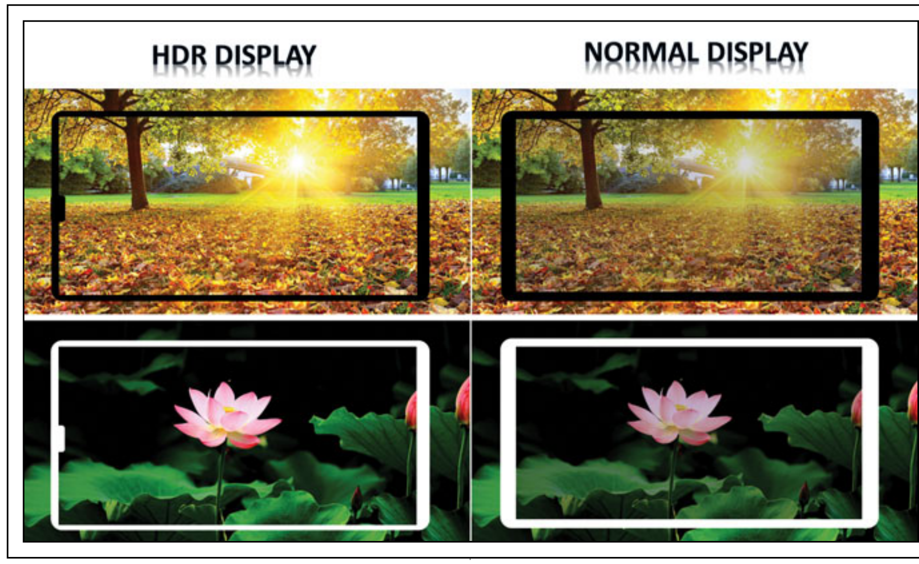

Fig. 3: *Tianma's 1,440 × 2,880 resolution HDR LCD for mobile applications (left) is compared side by side to a "normal" LCD of comparable size with 1,080 × 2,160 resolution. Photos: Tianma*

Fig. 4: *In its booth at Display Week, Visionox showed examples of different applications for its flexible AMOLED panels, including a speaker. Photo: Visionox*

Visionox received a Best in Show award in the large exhibit category for its multiple innovative applications using flexible OLED displays. At Display Week, Visionox was showing its flexible and foldable AMOLED technology in a number of formats, including a 7.2-in. panel that can achieve a 1.6-mm folding radius. Visionox's flexible AMOLED display panels also offer high contrast ratio, wide color gamut, and wide viewing angles. In its booth at Display Week, Visionox was also showing new display application concepts for flexible AMOLEDs, such as a smart cup, a smart speaker, and an e-Book (Fig. 4). Visionox says it created these novel display application demonstrations in part to validate its own technology, but also to bolster the display industry ecosystem by suggesting new kinds of applications. ■

Emissive Materials Generate Excitement at the Show

MicroLEDs created the most buzz at Display Week 2018, but quantum dots and OLEDs sparked a lot of interest too.

by Ken Werner

THE emissive materials that matter to displays are micro light-emitting diodes (µLEDs), organic light-emitting diodes (OLEDs), quantum dots (QDs), and phosphors. While phosphors remain a very mature technology with little new innovation, the other three material types are evolving rapidly and there were many new developments available to see on the show floor at Display Week 2018 in Los Angeles.

MicroLED displays – displays consisting of micron-scale inorganic LED chips that are not individually packaged – have been much discussed but seldom seen. At Display Week, though, several µLED technology demonstrations could be seen on the show floor, and at least two others were shown behind closed doors. And there was extensive coverage in the technical symposium.

In his Monday seminar, "MicroLEDs: Recent Advances and Applications," Jongseung Yoon of University of Southern California observed that some of microLED's advantages are infinite contrast ratio (similar to OLED's), a response time in the nanoseconds (compared with microseconds for OLED and milliseconds for LCD), long lifetime, low energy consumption, high viewing angle, and extremely high pixel density.

The Canadian company VueReal, which did not appear to be represented at Display Week this year (the company presented an invited paper in 2017), reported 6,000 ppi with microLEDs last year. That's impressive and useful for microdisplays and projection, but for direct-view applications such as TV sets, this level of pixel density isn't needed and cannot easily be supported by the rest of the system. So, technologies for selectively picking up microLEDs from the wafer on which they were made and depositing them on a substrate with much greater pixel spacing to make a "sparse matrix" are crucial if µLEDs are to be a major display technology for consumer electronics.

In their paper, "Status and Prospects of microLED Displays," Eric Virey (Yole Development) and Nicolas Baron (Know-Made) wrote, "Assuming traditional pick and place equipment could manipulate such small devices, those tools typically deliver processing speeds of around 25,000 units per hour (UPH). At this pace, it would take more than 1 month to assemble a single display!" The authors continue on to say that in order to be cost-compatible with most consumer applications, microLED chip transfer must reach rates of about 50 to 100 million per hour. The authors mentioned X-Celeprint's polymer stamp transfer process, Apple/Luxvue's electromagnetic and electrostatic MEMS approaches, and eLux's fluidic assembly. Virey also commented that µLED chips are less efficient than LED chips of normal size, "but it just has to be better than OLED." (Virey wrote an article on microLED technology for the May/June 2018 issue of this magazine.)

In the invited paper, "MicroLED Displays: Key Manufacturing Challenges and Solutions," Ajit Paranjpe and colleagues from Veeco said that meeting cost targets for µLED displays will be challenging. Veeco believes: "A two-step mass transfer approach using a dense interposer substrate or cartridge provides the benefit of maintaining low overall transfer costs while increasing epitaxy wafer usage and yield through the use of smaller transfer fields." In other words, instead of using microtransfer printing (µTP) to directly transfer µLED chips from the wafer to the final large display substrate, Veeco suggests it would involve less cost and produce greater chip consistency if chips were extracted from a relatively small area of the wafer and deposited on a relatively small interposer substrate. Then the interposer substrates will be transferred onto the final display substrate. The paper makes a convincing argument for this approach.

Looking at µLED Hardware

Behind closed doors, X-Celeprint showed a technology demonstration of its 5.1-in. µLED display. Until I saw the AUO display (see

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Fig. 1), I believed this to be the largest microLED display yet constructed. The display has 70 pixels per inch, active-matrix switching using micro-ICs (not TFTs), pixel-level compensation, subjectively very high contrast, and highly saturated colors including a very red red.

X-Celeprint has accumulated an extensive IP portfolio on µTP, including the transfer of µLED chips and the transfer of microcircuits and other small objects. The company intends to spin off a new company devoted exclusively to displays within the next 12 months. (Disclosure: The author is a member of an X-Celeprint advisory committee, for which he is paid modestly – very modestly.)

In a private conversation, Optovate's Graham Woodgate and Paul May updated me on their company. Founded by former Sharp and CDT people some years ago, the company developed significant IP only to find that nobody was interested in µLED displays at the time. Now interest is high, and the company is being re-energized. Optovate's IP focuses on two areas. The first is removing the LED chips from their wafer via patterned laser lift-off (p-LLO) rather than using a sacrificial layer process that separates all the LEDs from the wafer at once, with chip selection relegated to a separate step. The second major focus is sheets of catadioptric optics for controlling the angular emission of the LEDs. One application involves thin miniLED backlights for LCDs that rival OLEDs in thinness and functionality. MiniLED backlit displays with local dimming (some using Optovate technology) appeared in several booths on the show floor, and Paul May said Optovate was receiving "lots of interest on the optics part now."

AUO won a Best in Show Award in the medium exhibit category at Display Week, in part for its 8-in., full-color µLED with 1,280 × 480 pixels (Fig. 1).

Fig. 1: *AUO's 8-in. µLED display is the largest shown publicly to date. Photo: AUO*

AUO's Norio Sugiura said each LED measured less than 30µ, and that the display was driven with an LTPS backplane. The display uses color conversion technology, which means it employs only blue µLEDs and presumably obtains red and green with phosphors or quantum dots. I asked if the display uses a mass-transfer technique (such as µTP) or whether it was assembled from relatively large sections of two or more LED wafers. (The latter approach would be expensive and totally impractical for volume production, but could be a way of getting a demo to the show floor if you had not yet mastered an appropriate mass-transfer technology.) Sugiura would only say, "That is a very good question."

Hong Kong Beida Jade Bird Display, an I-Zone honoree at Display Week this year, showed a green µLED display with 3 million – yes, million – nits (Fig. 2). This first-generation, proof-of-concept display measured 0.65 inches on the diagonal, had a pixel pitch of 20 µm, and pixel dimensions of 640 × 480. A different chip had 2,560 × 1,920 pixels. Jade Bird, which was founded in 2015, is targeting its displays for projection.

Taiwanese company PlayNitride was also an I-Zone honoree, for "utilizing its PixeLED display technology to build a transparent display with an innovative and unique process to transfer RGB microLEDs onto a pixel." The fabless company, established in 2014, focuses on gallium-nitride µLEDs, which the company says it can make at pixel densities up to 1,500 ppi. In April 2017 there were rumors that Samsung Display was interested in acquiring PlayNitride. In April 2018, several online publications reported that PlayNitride was discussing a cooperative arrangement with Apple. True or not, an Apple investment rumor tends to make investors more patient.

There was lots of µLED activity at Display Week, and lots of work remains to be done. Companies such as Jade Bird and New York start-up Lumiode, which are focusing on microdisplays and don't have to tackle microtransfer issues, have a shorter path to commercialization. But they are also leaving the largest markets on the table.

The 800-Pound Gorilla in the Quantum-Dot Room

If you buy a quantum-dot or QD-enhanced LCD TV, it will have quantum dots made by or licensed by Nanosys. There are other quantum-dot companies operating in this industry – but for some reason those dots don't appear in products any of us buy.

So what do you do if you have a virtual monopoly on the display market for quantum dots? First, because quantum dots are currently used only in premium sets, you realize you don't want to limit your customers to those whose names begin with "S." Also, you want to develop QD products and architectures that will improve TV performance

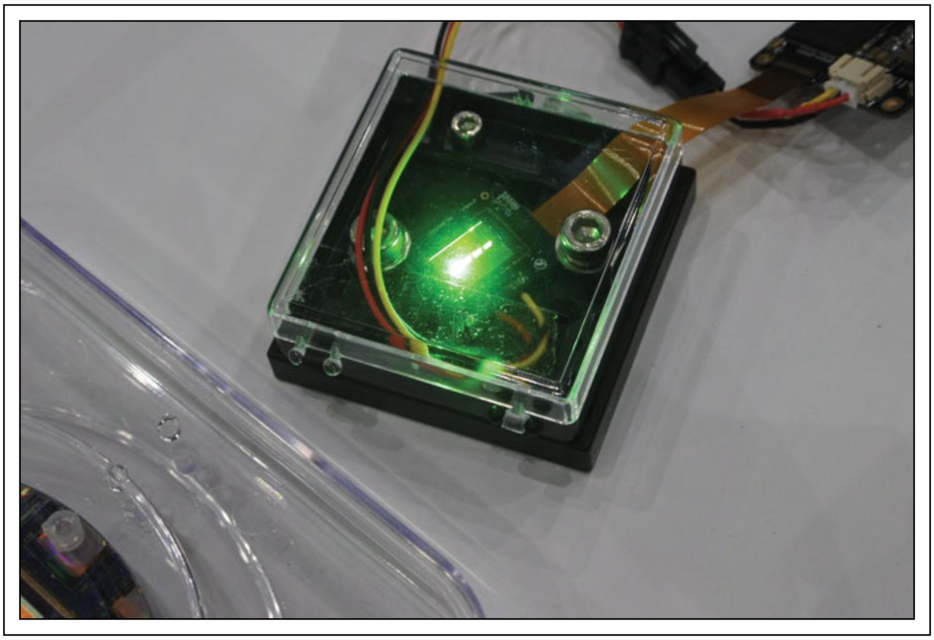

Fig. 2: Jade Bird's 0.65-in. green display has a luminance of 3 million nits! Photo: Ken Werner

and lower cost. And you don't want to limit applications only to LCDs.

At Display Week, Nanosys's Jeff Yurek said, "Quantum dots are the technology platform for all future displays. We don't care where the photons come from." In other words, the color conversion performed by QDs can be just as useful for downconverting the light from blue µLEDs as from the blue LED backlight in an LCD TV.

Yurek added later that AUO was showing "a fantastic QD gaming monitor" and that Tianma was showing a demo with 90 percent BT.2020 based on what Tianma called "less-Cd [cadmium] Dots."

In its booth, Nanosys showed technology demos that included one for ink-jetted QD matrices to replace the matrix color filters used in current LCDs. Another showed early-stage electroluminescent QDs. These demos were shown privately at CES. At Display Week they were available for all to see.

Also shown in the booth, and new to me, was the Vizio P Series Quantum 65-in. TV (Fig. 3).

The set uses Nanosys's Hyperion low-cadmium QD film and has a full-array backlight with 192 local-dimming zones. Peak brightness is greater than 2,000 nits, according to a data card next to the exhibit, with DCI-P3 coverage of greater than 98 percent and BT.2020 coverage of greater than 80 percent. This impressive-looking set was scheduled to be available in a few months at an MSRP of $2,200, according to the card. This price compares with an MSRP of $3,500 for Samsung's stunning 65-in. Q9F with 500 local dimming zones. It would be interesting to compare these sets side by side.

Also in the booth was a side-by-side comparison of the Samsung Q9 and an unidentified OLED TV. We reported on this comparison at CES, where the Q9 competed with the OLED very effectively. What was unexpected here was the serious burn-in of a logo in the OLED set (Fig. 4). Yurek said the set had only been running for about 60 hours and offered to show me the dated sales receipt. The burn-in was a complete surprise to everyone who saw it, and it's hard to believe this is typical of modern OLED TV sets.

TADF Players on the Show Floor Ranged from C to K

A blue OLED emitter with long life, high efficiency, and "deep-blue" color coordinates is the holy grail for OLED materials developers. Everybody is looking for it and nobody has found it. Thermally activated delayed fluorescence (TADF) is a clever quantum-mechanical trick that permits us to make use

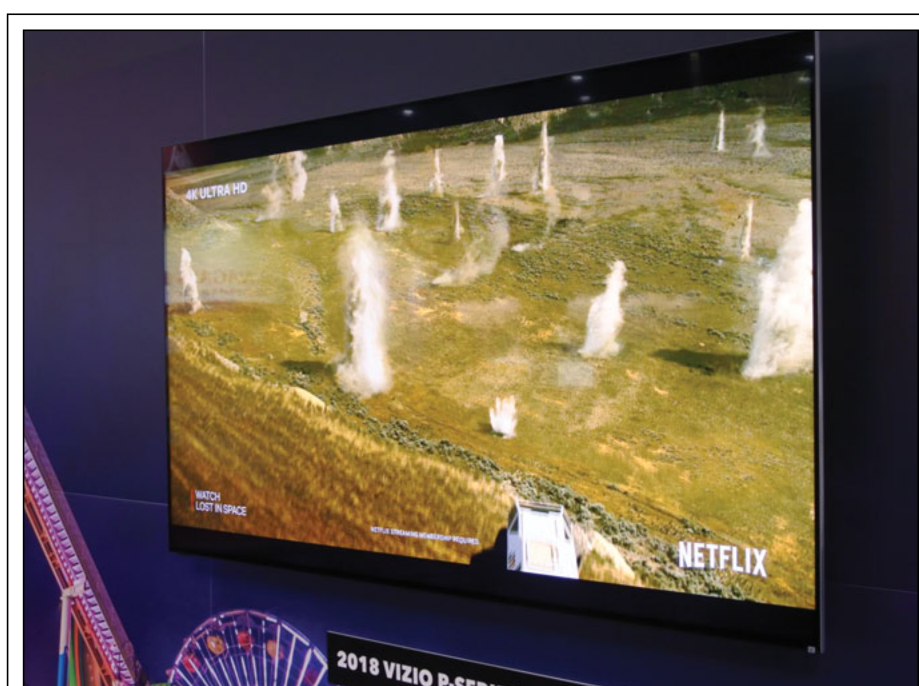

Fig. 3: The Vizio P Series Quantum TV with Nanosys's Hyperion QD film and 192 full-array local dimming zones delivered an impressive image. Photo: Ken Werner

***Fig. 4:** The Familytime logo (left) appeared almost constantly on both the OLED set and the Samsung Q9 set in the Nanosys booth. The logo burned into the OLED set (right) after about 60 hours, according to Nanosys's Jeff Yurek. There was no burn-in on the quantum-dot-enhanced LCD TV. Photos: Ken Werner*

of the three quarters of quantum states in fluorescent OLED emitters that are usually unavailable, thus increasing the internal quantum efficiency from 25 percent to 100 percent. Universal Display Corporation (UDC) already does this with phosphorescent OLED emitters, which appear in commercial OLED displays ranging from the smartphone displays made by Samsung Display to the TV displays made by LG Display.

If you are hopelessly cynical, you might say that the main reason to pursue TADF is to find a way around UDC's impressive patent portfolio. If you have a more benevolent nature, you might observe that although UDC has very nice red, green, and yellow phosphorescent materials, the company has not yet been able to develop an efficient, long-lived, deep blue that would make an all-phosphorescent OLED display possible. Current displays use UDC's phosphorescent red and green (or, in LG Display's case, yellow) and then fill out the spectrum with a less efficient fluorescent blue.

There may be uses for TADF greens, reds, and yellows, but once you have acknowledged the creative synthetic chemistry and quantum physics involved, these materials are not going to change the OLED display game in any fundamental way. What the industry wants is a "deep blue," as opposed to a "sky blue," which may have applications in lighting but not in displays, at least not in any straightforward way. (UDC has demonstrated a four-subpixel configuration that uses both sky blue and deep blue to reduce the aging of the short-lived deep-blue emitter, but this has not appeared in any commercial display as far as I know.)

In the past few years, the general attitude toward TADFs has evolved from skeptical curiosity to hopeful respect. In his Sunday seminar, "OLEDs: Recent Progress and Applications," Jian Li of Arizona State University said, "I used to be a doubter." Although he no longer doubts, Li said, "[It is] difficult to push TADF design forward." However, people are developing new device architectures in their search for "a new route to harvest triplets."

If OLED Generation 1 is fluorescence, Gen 2 is phosphorescence, and Gen 3 is TADF, then a more recent approach, TADF-assisted fluorescence (TAF), could be considered Gen 3.5. The advantage of TAF, said Li, is that it expands the molecular design possibilities beyond TADF, thus increasing the likelihood of being able to synthesize molecules with the desired color coordinates (such as "deep blue"), lifetime, and efficiency.

On the show floor, the range of TADF developers ran from C to K; that is, from Cynora to Kyulux. Kyulux, the Japanese company founded in 2015 on the basis of technology licensed from Kyushu University, showed green, yellow, and sky-blue TADF OLED emitters. Daniel Tsang told *Information Display* that the green and yellow are in customer development, while the sky blue is still at the in-house development stage (Fig. 5). A deep blue is possible, he said, but lifetime still needs improvement.

In their paper, "Progress of Highly Efficient Blue TADF Emitter Materials Toward Mass Production," Thomas Baumann and Matthias Budzinsky of the German company Cynora said that one problem with deep-blue emitters is that they have too broad an emission spectrum. However, by using molecular design principles, Cynora increased the percentage of narrow emitters from about 15 percent to nearly 50 percent over the first three quarters of 2017. The team's most recent results "of 14 percent EQE [external quantum efficiency] at a CIEy coordinate of 0.15 [deep blue] with a lifetime LT97 [lifetime measured to 97 percent of initial luminance] at 700 nits of ~10 hours show that blue TADF emitters are

(continued on page 46)

I-Zone Turns Seven

Five Innovation Zone exhibitors received recognition for their emerging, best-in-class display technology at Display Week 2018.

by Steve Sechrist

FROM its inception seven years ago, the Innovation Zone (I-Zone), the exclusive, peer-reviewed exhibition area at Display Week, was meant to augment the research/academic and commercial offerings of the event with horizon technology and "what-if" possibilities to spur imagination, nurture communications, and ultimately lead to developments that would broaden display technology. When you visit the I-Zone, you are guaranteed to see technology that has not been shown elsewhere, and early-stage technology that will form the basis for commercial products in years to come.

Just one example of such a technology is PolarScreens, founded in 2003 and making its Display Week debut in 2015. Based on eye-tracking technology, the company's "steerable backlight system" directed the LCD backlight into the eyes of the user being tracked. Its most recent iteration is in the new Kyocera autostereo 3D head-up display (HUD) prototypes that are scheduled for production by 2020.

The 2018 I-Zone was a record breaker. It has doubled in size from the first year, growing to almost 50 booths. This year also marked the first time the I-Zone has been split into two different sections on the exhibition floor, making it easier to explore all the cutting-edge technology. This was also the first year that the I-Zone Committee honored a total of five I-Zone participants for outstanding technology: Hong Kong University of Science and Technology for Best Prototype; and Dimenco, Hong Kong Jade Bird Display, PlayNitride, and XTPL SA as honorees.

Probably the most talked-about technology at Display Week 2018, microLED, was represented in the I-Zone by several exhibits, as described below. Other leading-edge technologies shown in the I-Zone included light-field displays, transparent displays, low-cost printed color displays, and chip-on-display technologies. There was even an exhibit on nano-based electrode printing for high-value device repair.

Hong Kong University of Science and Technology

This year's "Best Prototype" winner was Hong Kong University of Science and Technology, which developed a 250-pixel-per-inch (ppi) active-matrix field-sequential-color (FSC) display panel based on electrically suppressed helix ferroelectric liquid-crystal (ESHFLC) technology.

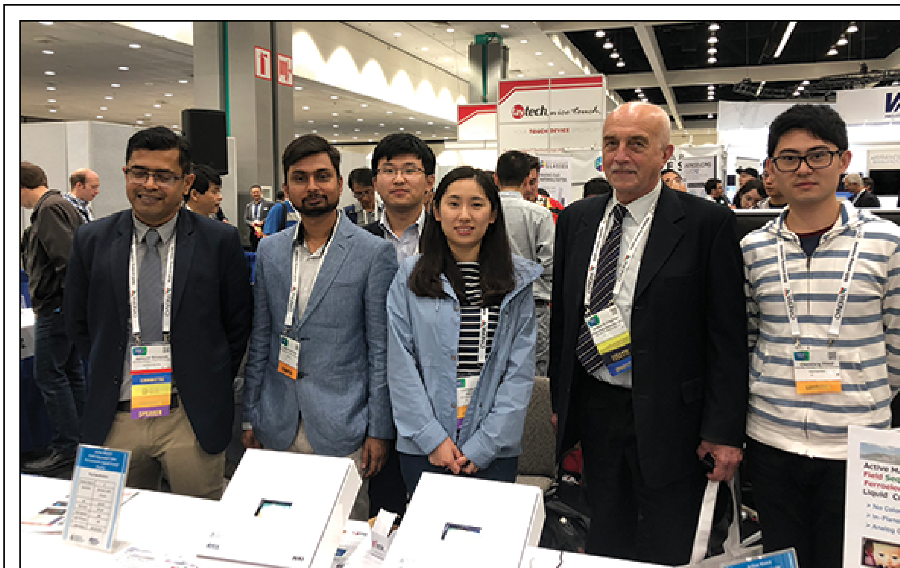

Fig. 1: The team from Hong Kong University of Science and Technology stands in the I-Zone with its award-winning display technology. Pictured from left to right: Abhishek Kumar Srivastava, Swadesh Gupta, Alex Cheung, Liangyu Shi, Vladimir Chigrinov, and Chenxiang Zhao, all of Hong Kong University. Photo: Steve Sechrist

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The significance of this new, very-fast field-sequential color display is that it that could potentially replace in-plane switching (IPS) or fringe-field switching (FFS) modulation for the portable/mobile market. The high-resolution FSC-ESHFLC might also find use in emerging virtual reality displays.

In the I-Zone, the group from the university (Fig. 1) demonstrated the 3-in. color display (Fig. 2) operating on an ultra-fast response time (~10 µs) at very low voltage (6.67V/µm) that enabled a 60-Hz frame rate with a 360-Hz FLC drive frequency.

The prototype included a 3T1C pixel circuit that was designed to convert the analog drive signal to run in a pulse-width modulation mode. This was achieved on low-temperature polysilicon (LTPS) thin-film transistor (TFT) panels, resulting in an active-matrix FSC ESHFLC integrated display system. It is important to note that this is an LCD that is capable of switching gray states fast enough to enable field sequential color imaging, with a highly improved gray-scale performance.

The research group says its "anchoring energy" is comparable to but less than the elastic energy of the helix of FLC. The team also confined the FLC to the ESHFLC mode, where it is mechanically stable and free of chevron defects. It also offers a high contrast ratio over conventional surface-stabilized FLC. When combining the FLC fast-response (around 10 µs under 6.66V/µm), low-driving voltage into a field sequential system, researchers can achieve triple the current resolution for a wide variety of applications, including emerging virtual reality and next-generation liquid-crystal displays. In a video interview with I-Zone Chair Harit Doshi, the research team said that the next step for the technology was to find some suitable applications (and interested partners.)

Fig. 2: Hong Kong University of Science and Technology's 3-in. diagonal, 250-ppi active-matrix field-sequential color display featured an ultra-fast response time of ~10 µs. Photo: Steve Sechrist

Benefits outlined by the group include:

- No color filters
- In-plane switching (IPS) with reduced color shift compared to traditional IPS LCD
- Analog gray scale
- 3X high light efficiency panel
- 3X resolution (360 gate × 640 column) without any sub-pixels (see above)
- Wide color gamut

The Hong Kong University team also authored a distinguished student paper at Display Week, "Active-Matrix Field-Sequential Color Electrically Suppressed Helix Ferroelectric Liquid Crystal for High Resolution Displays."

The four companies that received 2018 honoree designations in the I-Zone are:

Dimenco

Dimenco, founded in 2010 by former Philips engineers, showed its newest LC alignment layer for switchable lenses in the I-Zone (Fig. 3). Dimenco's glasses-free 2D-3D switchable displays are made by applying lenticular lenses on top of an LCD. The lenses are turned on and off by switching the orientation of the liquid crystals. This lenticular lens technology is not new. What is new is that Dimenco has replaced the conventional polyimide alignment layer on the lenticular lens with nanogrooves, which improves the alignment of the liquid crystals. In this way, the polyimide layer can be eliminated, which simplifies the production process and improves the optical quality of the lens, while reducing cross-talk "significantly," according to spokesperson Maartin Tobias of Dimenco.

It's reasonable to question the significance of a glasses-free 3D display in the age of VR, AR, and 8K devices, but in fact 3D continues to be a niche display area, with many commercial and medical applications.

Hong Kong Beida Jade Bird Display

Hong Kong Beida Jade Bird Display (JBD) showed an active-matrix microLED in a chip format with 5K pixels per inch and 1 million cd/m^2 of luminance (green rated at 500 lu, red rated at 300 lu, blue at 250 lu). The microLED on integrated circuit (IC) panel specs include 640 resolution, 20-µm pixel pitch, RGB single

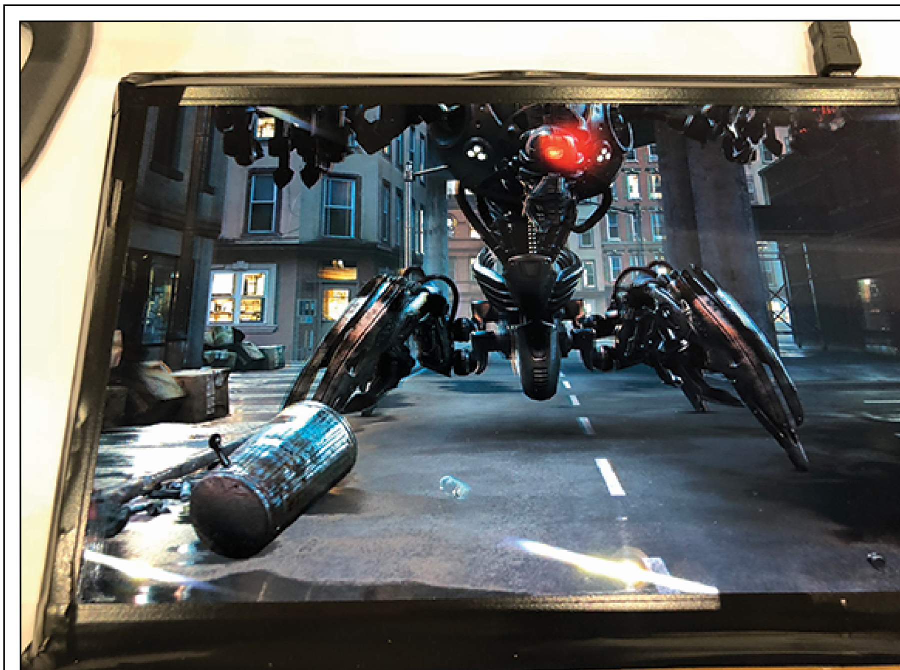

Fig. 3: Dimenco showed its newest glasses-free switchable 2D-3D panel in the I-Zone. Photo: Steve Sechrist

color, and 256 gray levels, at an operating voltage of 5.3 V with typical power consumption of 6 W at 60-Hz refresh.

This microLED was based on monochromatic red, green, and blue microdisplay panels. JBD also showed application demos using the panels (Fig. 4). These included a portable projector with ultra-high-luminance microLED microdisplays in excess of 3 million cd/m^2 (for the green color), and AR goggles using an ultra-high resolution microLED microdisplay (with a pixel density higher than 5K ppi.)

In an SID video interview conducted at Display Week, the company principals said they believed that the technology would be ready for full-color small-area projectors as early as 2019. Other possible applications include head-up displays for vehicles. Jade Bird also relayed that it was recently contacted by a potential customer interested in using its technology for a military application.

Fig. 4: JBD showed its microLED integrated into a near-to-eye device in the I-Zone. Photo: Steve Sechrist

PlayNitride, Inc.

PlayNitride, Inc., created a transparent display using a unique process to transfer its RGB microLEDs onto the backplane substrate. The group showed a 3.12-in. diagonal 256 × 256 resolution, transparent, full-color RGB microLED display with a luminance of more than 800 cd/m^2 and a wide color gamut (Fig. 5).

The pixel size was 0.219 mm, and PlayNitride claimed this represented the equivalent of a section of a 76-in. diagonal 8K display. The mass-transfer process is characterized as 8 shots per color and 24 shots per panel, with microLED quantity at 262K chips/color and 786K chips per panel.

XTPL SA

XTPL SA has developed technology that enables ultraprecise printing of nanomaterials. According to the company, the XTPL solution allows users to repair interrupted thin conductive lines in the production stage, without complicated, slow, and expensive vacuum processes. To get there, XTPL created an innovative process for printing electrodes that are several hundred times thinner than a human hair, with conductive lines thinner than 100 nm (Fig. 6).

Initial use is for corrective procedures in high-cost manufacturing of displays. XTPL created a unique printing head and dedicated nano-inks for repairing defects in electrical connections at micrometric and nanometric scale (conductive lines from 100 nm to 3 μm). There is also an optical detection system that is already in commercial use to provide a full technological solution the company can implement on production lines. Target markets include solar cells, LCD/OLED panels, PCBs, multichip modules (MCMs), and integrated circuits.

Additional I-Zone Displays of Interest

rdot AB showed a low-cost, energy-efficient, printed electrochromic color display.

The company's roots are in the National Institute of Technology at Sendai College. The group is working on developing and commercializing an ultra-low-cost and energy-efficient reflective electrochromic color display.

In the I-Zone, the group showed a single-substrate, surface-mounted chip component on a roll-to-roll display. The roll to roll enables large-volume production, with benefits that include energy efficiency (1 mj/cm^2 or millijoule 1/10,000 of a joule per sq. cm) per switch, ultra-low cost due to mature manufacturing processes, and a flexible substrate with a less-than-5-mm bend radius. The rdot technology also offers a static display memory that lasts up to 60 minutes without power.

Manufacturing goals for the printable electrochromic display include small and large formats and multiple shapes and forms. According to rdot AB, prototypes, including segmented displays, are close to market-ready – but no one there will say just how close… at least not yet.

FoVI3D showed its integral imaging type light-field display the company describes as "a glasses-free, 90 × 90-mm, full-parallax, horizontal light-field display with a 90° projection frustum."

It is important to note there were two displays – one that targeted spatial resolution and one focused on angular resolution. The latter (a smaller 3.5-in. display) boosts the field of view (FOV) and depth volume at the cost of resolution. This smaller device achieved a 90-degree FOV with a 1-mm hogel diameter. The group built a 90-squared hogel display that created a 9 cm-cubed active light-field volume with a 110 × 110 vph (views per hogel).

Alternatively, a reduced field of view resulted in a roughly 5-in. tall display with a 60-degree FOV, a 0.5-mm hogel diameter, and a 180 squared hogel display with a 50 × 50 vph. The primary difference was the

Fig. 5: PlayNitride's transparent microLED display was 3.12 inches diagonal, with a luminance of more than 800 cd/m^2. Photo: Steve Sechrist

microlens array size, which determined the size of the hogel diameter (1 mm *vs* 0.5 mm).

FoVI3D said it was going for a "natural visualization experience." Optical elements were used to project light from a spatial light modulator (SLM) toward the viewer. FoVI3D said it is critical for the optical design to be both correct and optimized, so the company is focusing on both calibration and developing its own set of agnostic APIs (application program interfaces) to enable the projections.

Information College of Nankai University, Tianjin, showed a patented technology using what the developers call "non-paraxial axis optics" to deliver a 3D experience without passive polarizing glasses, or the active LC shuttering more commonly used. This personal stereoscopic cinema device was shown earlier this year at the International Conference on Display Technology (ICDT) in Guangzhou before coming to the 2018 I-Zone. The system shown at the exhibition used a dual screen with an impressive resolution of 2,560 × 1,440.

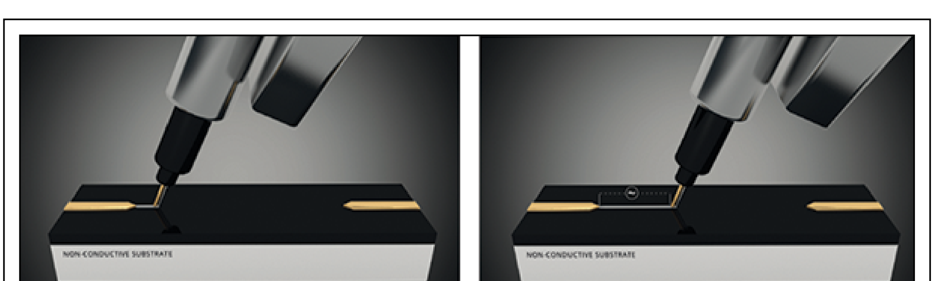

Fig. 6: XTPL's innovative process prints electrodes that are several hundred times thinner than a human hair (< 100 nm to 3 μm). Source: XTPL SA

I-Zone Exhibits Hold Promise for the Future

This year's I-Zone did not disappoint, with an extended number of new and emerging technologies on display. There were some game-changing prototypes, devices, and applications; new updates on 3D passive displays, and even an optical 3D solution. Those companies that succeed can say they started out in a humble I-Zone booth as part of SID's Display Week. So hats off to the hard working I-Zone committee and also E Ink (itself a startup not that many years ago), which has sponsored the I-Zone since its inception.

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Advances in Virtual, Augmented, and Mixed Reality Technologies

Virtual, augmented, and mixed reality (VR/AR/MR) technologies offer the promise of seamlessly blending the real and the virtual worlds, thereby enabling many exciting immersive and interactive applications and experiences. This article provides a synopsis of some of the key new developments in the field presented at Display Week 2018.

by Achintya K. Bhowmik

DISPLAY Week 2018, the annual conference organized by the Society for Information Display, featured a special track on virtual- and augmented-reality (VR/AR) technologies and applications. This was quite timely, given the rapid technology developments on this topic in recent years, as evidenced by the increasing number of companies introducing new products and universities offering specialized courses in associated technologies.

The VR/AR special track in this year's conference included a keynote speech delivered by Doug Lanman from Oculus/Facebook Research Labs, a short course taught by this author, a seminar presented by Robert Konrad from Stanford University, several talks in the market focus conference, an extensive array of technical papers in the symposium, and a number of live demonstrations in the exhibit hall.

VR/AR devices promise exciting immersive experiences in the areas of gaming and entertainment, education, tourism, and medical applications, to name a few. The state-of-the-art results presented and demonstrated at Display Week this year are bringing virtual- and augmented-reality experiences ever closer to reality.

The March Toward Increasing Resolution

In the review article following Display Week 2017,[1] we included a section on the topic of improving visual acuity for virtual-reality devices, addressing a popular question: "How many pixels are really needed for immersive visual experiences with a virtual-reality head-mounted display?" In that discussion, we referred to some facts related to the human visual system. An ideal human eye has an angular resolution of about 1/60th of a degree at central vision. Each eye has a horizontal field-of-view (FOV) of ~160° and a vertical FOV of ~175°. The two eyes work together for stereoscopic depth perception over ~120° wide and ~135° high FOV.[2] These numbers yield a whopping ~100 megapixels for each eye and ~60 megapixels for stereo vision to provide the visual acuity of 60 pixels per degree (ppd)! Packing 60 to 100 million pixels in a small near-to-eye display is clearly not feasible with today's manufacturing technology. However, some significant progress has been made over the past year, which was reported at this year's Display Week technical symposium as well as demonstrated in the exhibit hall.

Vieri *et al*. reported the design and fabrication of a 4.3-in. (diagonal) organic light-emitting diode (OLED) on glass display with over 18 million pixels in a 3,840 × 4,800 format.[3] Thus, this prototype, intended for head-mounted display (HMD) in VR applications, had a very impressive 1,443 pixels per inch (ppi) resolution with a 17.6-µm pixel pitch. The authors calculated that such a display would provide an angular resolution of ~40 ppd when integrated into an optical system with 40-mm focal length, ~120° horizontal and ~100° vertical viewing angle. Such a pixel density is well above what is available in today's commercially available virtual-reality devices, and is approaching the specification required to meet human visual acuity.

Demonstrations in the exhibit area also included a 3.5-in. miniLED display panel shown by BOE that featured 4,320 × 4,800 pixels with 1,850-ppi resolution, integrated in a headset with 100° FOV. Samsung Display showed a 2.43-in. OLED panel with 1,200-ppi resolution, and JDI demonstrated a 3.25-in. LCD module with 2,160 × 2,432 pixels and 1,001 ppi.

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Pushing the frontiers of pixel density even further, Fujii *et al*. presented a 0.5-in. microdisplay with an astonishing 4,032-ppi resolution and a 6.3-µm pixel pitch, based on OLED-on-silicon backplane technology.[4] With the relatively small size of the current display, the targeted applications are in near-to-eye systems such as electronic viewfinders.

Besides manufacturing advances to pack an increasing number of pixels onto the display panels as reported above, other research efforts include enhancing the perceived resolution with the addition of appropriate optical apparatus. For example, Zhan *et al*. described a method to double the perceived pixel density in near-to-eye displays using a fast-switching liquid-crystal phase deflector,[5] and Peng *et al*. presented a technique to enhance the resolution of light-field near-to-eye displays by using a birefringent plate.[6]

Dynamic Focus Cues

Achieving a truly immersive experience with VR, AR, and MR devices requires providing natural perceptual cues to the user. An important area of continued investigation is to understand the human visual and oculomotor cues that are vital to perceiving 3D structures in the real world, and to mimic those mechanisms with technologies implemented within virtual- and augmented-reality headsets. In a seminar titled "Computational Near-Eye Displays with Focus Cues," Konrad reviewed the fundamentals and various methods that are being explored.[7] The author explained the interplay between the convergence and accommodation mechanisms of the human visual system when viewing a natural 3D scene, as shown in Fig. 1.

Appropriately, a number of papers presented at the Display Week symposium focused on this important topic. For example, Dunn *et al*. described a prototype AR display that implements a mechanism to provide a variable focus using a deformable beam splitter and an LCD panel.[8] As shown in Fig. 2, this display system adjusts the perceived distance of the displayed image with a dynamic modification of the corresponding optical power of a reflective and adjustable membrane to match the gaze of the user. The authors report that this system is able to provide a focal range of 11 diopters, effectively between 10 cm and optical infinity. While this prototype is much bulkier than what would be acceptable for a commercially viable device, it is expected that further developments will improve the form factors.

Among several other promising approaches, Jamali *et al*. presented a continu-

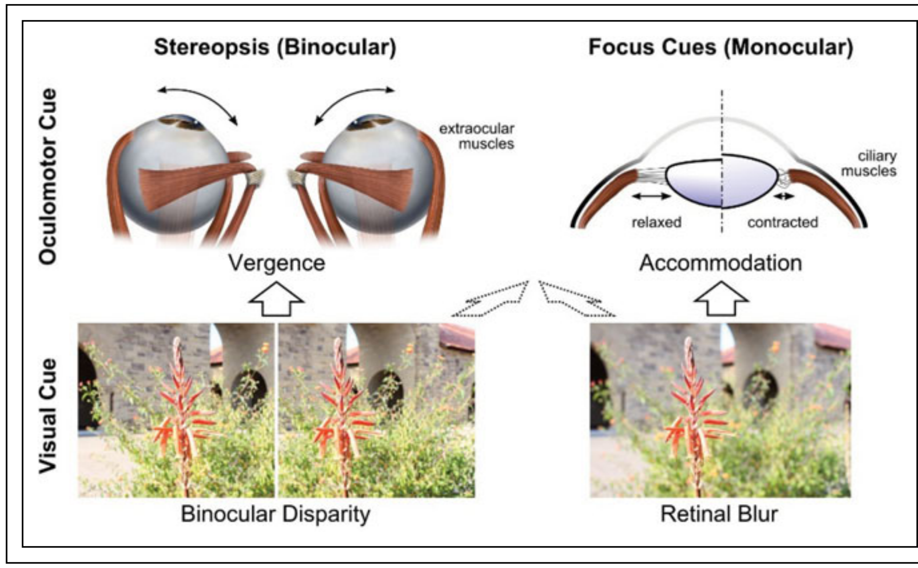

Fig. 1: *When viewing a natural scene, our eyes converge on the object of interest in the 3D space, while the lenses of our eyes adjust accordingly to bring the light reflected by the object to focus on our retinas.*[7]

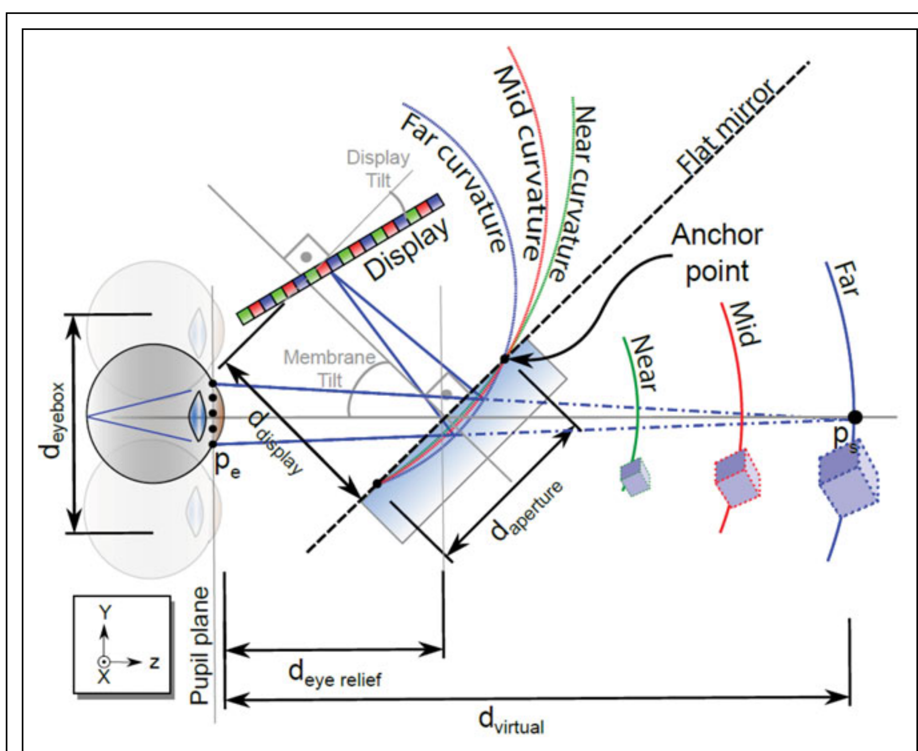

Fig. 2: *This prototype display provides variable focus using a deformable beam splitter in conjunction with an LCD panel.*[8]

ously variable lens system,[9] and Liu *et al*. presented a method involving a liquid-crystal lens and dual-layer LCD panels.[10]

Foveated Rendering and Display

In last year's review article, we also discussed the challenges involved in the computation required to render visual images corresponding to 60 to 100 million pixels per frame and the transportation of this vast amount of data into the display.[1] We also considered the human visual perceptual system to seek ways to mitigate this challenge. High human visual acuity is limited to a very small visual field – about +/– 1° around the optical axis of the eye, centered on the fovea. So if we could track the user's eye gaze in real time, we could render a high number of polygons in a small area around the viewing direction and drop the polygon density exponentially as we move away from the central vision. Graphics engineers have a term for such technologies already in exploration – "foveated" or "foveal" rendering. This would drastically reduce the graphics workload and associated power consumption problems.

The work reported by Vieri, *et al*., also included a driving scheme for foveated rendering and transport of the image data onto the display.[3] Specifically, the authors propose to decompose each high-resolution frame into a high-acuity domain and a low-acuity domain; for example, into 640 × 640 and 1,280 × 1,600 pixel formats, respectively, and pack them into a single frame as shown on the left diagram of Fig. 3 for transportation to the display panel. The foveation logic incorporated into the driver chip is shown on the right of Fig. 3.

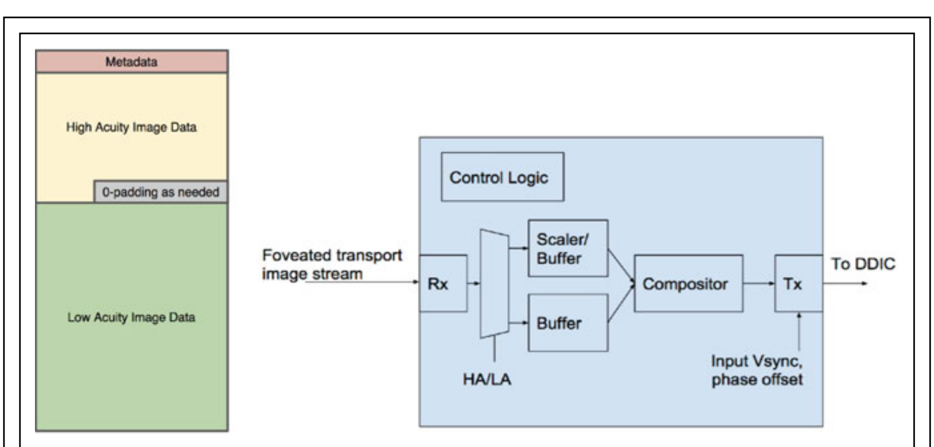

Fig. 3: *The left figure shows how the high-acuity and low-acuity image data are packed into a single frame for transporting the pixel values from the memory into the display. The right figure shows the block diagram of the foveation logic.*[3]

Advances in Computer Vision and Spatial Tracking

While the visual display is arguably the most important component in a virtual-, augmented-, and mixed-reality headset, also crucial toward providing an immersive experience are accurate and real-time spatial tracking and computer vision technologies.[11] Traditional VR platforms have largely involved headsets that are tethered to a computer or gaming console. They rely on external tracking systems, including infrared light emitters and detectors. However, it is widely accepted that future mass adoption of VR/AR/MR devices by mainstream users will require standalone headsets that incorporate the computing engines within the devices, as well as self-contained tracking systems, also referred to as inside-out tracking techniques. Life-like interactions in the 3D space also require that the devices be capable of low-latency tracking with six degrees of freedom (6DOF), whereas many standalone or smartphone-based VR headsets that are commercially available now are only capable of spatial tracking with three degrees of freedom (3DOF). Systems that can only perform positional tracking along the three Cartesian axes have 3DOF, where those that can also track the three angular rotations (yaw, roll, and pitch) have 6DOF. A state-of-the art algorithmic approach is visual-inertial odometry (VIO), based on a combination of computer vision and motion detection, using imaging and inertial sensors, termed as simultaneous localization and mapping (SLAM).

A number of papers and demonstrations addressed this topic. For example, Lieberman *et al.* presented a 6DOF SLAM technique with sub-millisecond latency based on a linear imaging sensor.[12] Other work reported in the symposium included a semantic SLAM method including both tracking and object detection,[13] and a review of tracking applications using visual-inertial odometry based on artificial intelligence, specifically deep learning techniques, as shown in Fig. 4.[14] Devices with built-in imaging and inertial sensors, and algorithms such as SLAM and VIO, are capable of inside-out 6DOF spatial tracking, rather than the traditional approach of relying on external tracking setups.

Beyond 3D spatial tracking and presentation of 3D visual information on immersive near-to-eye displays, the virtual- and augmented-reality experiences will also include semantic understanding of the environment and user interactions. Thus, there is an increasing focus on real-time visual understanding based on 3D computer vision using artificial intelligence techniques, in conjunction with the miniaturization and system integration of depth-imaging sensors.[15]

Advances in Many Areas Are Taking AR/VR/MR Toward the Mainstream

While many challenges remain in advancing the technologies to bring virtual-, augmented-, and mixed-reality devices and applications into mainstream adoption, significant results continue to be accomplished and demonstrated. Display Week 2018 featured a special track to facilitate the review and presentation of the advances made around the world, both in academia and the industry. In this article, we have highlighted some of the key results, covering the areas of immersive visual displays with enhanced visual acuity, natural visual cues for 3D perception, spatial tracking, and semantic understanding with artificial intelligence.

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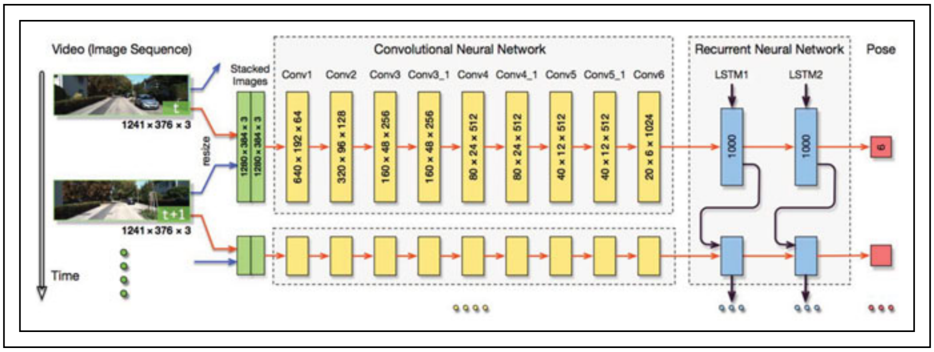

Fig. 4: Above is an example of utilizing artificial intelligence techniques based on deep learning in visual-inertial odometry and spatial tracking in virtual and augmented reality applications.[14] In this specific approach, a convolutional neural network (CNN) followed by a recurrent neural network (RNN) is deployed to derive real-time 3D pose information.

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Digital Signage and the Emissive Materials Evolution

A series of new emissive materials – miniLEDs, microLEDs, and QLEDs – seem poised to take at least a portion of digital signage market share from surface-mount device (SMD) LEDs and LCDs.

by Gary Feather

IN 2018, Display Week proved once again that it is the world's best program for all the latest updates on business, markets, information, and processing across virtually every display category. From projection display to transmissive LCD, and emissive display to reflective, each category was robustly represented.

The emissive display category, in particular, continues to deliver compounded growth in performance and features. Solutions include both the organic (OLED) and inorganic solutions, which are maturing rapidly for large-screen televisions and near-to-eye virtual reality, respectively. The emissive inorganic solutions are undergoing a revolution in increased luminance, higher efficacy, smaller size, and best color, meeting the most stringent requirements of a very large segment of the display market. With these improvements, cost per pixel is dropping rapidly, expanding product reach closer to commercial viability.

In parallel, the emissive display industry's exploitation of new quantum-dot (QD) material capabilities to reach beyond initial performance goals will grow the quantum-dot LED (QLED) market even faster. Acceleration of µLED development will feed the largest-area emissive display solutions, from signage to cinema, and soon, to prosumer displays.

Ken Werner's separate show review, "Emissive Materials Generate Excitement at the Show," outlines the vast number of improvements in emissive devices and materials. The development focus at present is coupled most closely to emerging augmented-reality/virtual-reality (AR/VR) displays and smaller display-based solutions with microLED (µLED) and now added QD material for performance.

While current display pixel-per-inch (ppi) levels > 1,000 are being reported for these applications, the alignment and placement of emissive devices for the digital signage market will be dramatically different. Large displays' most valued solutions are in the range of 10 to 20 ppi. Digital signage by definition is very large. Therefore, the useful viewing distances are usually measured in meters, not inches. A major transition for exploitation of new display materials and devices will incorporate solutions with much lower ppi. (This is also a matter of what ppi clients are willing to pay for, and what they are able to support from a content perspective.)

Manufacturing Transitions

Digital signage displays will transition from existing discrete, inorganic red, green, blue (RGB) LED surface-mount devices (SMDs) with 1 pixel per package, to 4 pixels per package, to 9 pixels per package. RGB-SMD LED packages with a single pixel in a package range from 2 mm per side down to .5 mm per side. With improvements in reliability and yield, the technology is moving to direct-board matrix solutions (chip on board or COB) with emitters and placement in an array size and methodology to exploit the new smaller LEDs and leverage new QD materials. Placing hundreds and maybe thousands of RGB LEDs directly on a single board and sealing that one large display array in an epoxy can drive manufacturing to a revolutionary change of methods and equipment, and significantly lower costs.

In his article, Werner also highlights the most important challenge facing COB implementations for larger displays (those with lower ppis) using bare-die LEDs, miniLEDs, µLEDs, and QLEDs – the need for a new manufacturing approach. Pick and place of these tiny dice must move as quickly as the pick and place for RGB-SMD LEDs. The challenge of shifting to rapid die placement over large areas from very close proximity on small wafers will trigger the need for increased ingenuity to arrive at solutions.

Spacing and placing dice farther apart is critical technology that was discussed at Display Week 2018. The display manufacturing process for µLEDs in particular will require new COB techniques supporting production of a "sparse-matrix" approach at ~10–20 ppi. These new processes were highlighted as a barrier in two presented talks; however, the solutions are already in development. A pixel contains a red, green, and blue LED. Today, the inorganic LEDs are in the LED dice with 150-µm-width edges to 220-

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µm edges. Pick and place of these dice is usually directed to a carrier for SMD packages. The packages (in sizes of 1 mm on a side in a carrier array of 50 × 25 on a side), are then scribed, separated, tested, and taped for the packaged-pixel pick and place for SMD. A typical SMD facility placing SMD LEDs on a pitch of 2.5-mm to 0.9-mm and supporting backplane/drive devices places 3 to 4 million devices per day; supports production of 1 to 2 full-HD LED displays per day. The existing RGB-SMD display industry supports about 20 billion placements per year. The current market is well supported. Over the next two to five years, new and existing LED SMD packaging will shift from being 100 percent of business to becoming part of a mix of COB modules with hundreds to thousands of pixels in a module for display system assemblers.

Seminar presentations at Display Week 2018 reinforced the momentum in emissive displays; many of these advancements directly impact advances in digital signage for indoor displays. The indoor digital signage RGB-LED display retail market is now greater than $1.5 billion annually. Digital signage has evolved over the past five years, from RGB-SMD pixel pitches of 4 to 6 mm to solutions now in production that are down to 0.7 mm; approximately equal to the spacing of the 60-in. 2K LCD TV (~ 35 ppi). It is important to remember that the metric of pixel per inch takes on a new focus in digital signage displays, with the sweet spot in the current market at 10 to 20 ppi; not 200 to 600 ppi. For a 2.5-mm pixel-pitch HD display, the ppi is ~10. The digital signage market has a focus on HD displays larger than 120-in. diagonal (~1.3 m^2 using 0.8-mm pixel pitch). Most emissive-HD LED signage displays are ~220-in. diagonal (2.5-mm pixel pitch and 10 ppi) on the average with no constraint on the maximum area of these displays (usually >50 m^2). Massive LED display systems are currently installed in multiple airports and casinos, demonstrating seamless video solutions in the 150-m^2 to 400-m^2 range, with resolutions of 10 to 15 HD displays in a single display.

Exploring the application for new LED and µLED solutions also requires understanding the luminance requirements. At Display Week 2018, there were AR/VR and display solutions with µLEDs (monochromatic) demonstrating 10,000 nits; these are dense-packed emitters. A typical LED indoor display is ~700 nits for indoor applications at 8- to 12-bit depth. Applications in e-Entertainment and e-Sports ideally require luminance more in the area of LCDs – around 300 nits. Applications for cinema are in the range of 50 to 100 nits, per the Digital Cinema Initiatives (DCI) specification. The current DCI specification was written and limited by the capabilities of the DLP projection systems using Xenon arc lamps. With the advent of LED displays in cinema, DCI members, including the studios and the creatives, are considering expanding the requirements for DCI to create more natural "real-world" displays. Future DCI requirements will expand the color space. In addition, increasing the luminance from 50 nits to 500 nits appears possible. Finally, using specular highlights at 1,000 to 4,000 nits and leveraging perceptual quantizer (PQ), as discussed in the Monday Seminar on high-dynamic range (HDR) by Dolby Laboratories, future cinema experiences will be able to emulate reality as never before.

That being said, we must also consider the emergence of the µLED. Its replacement of the currently used LED dice (with some adaptation) may be a way to lower costs dramatically at no reduction in picture quality. Consider a few examples. In a full multiplexed drive (1/32), pixel luminance for a 75-nit display for red, green, and blue requires 12 nits, 42 nits, and 7 nits respectively. With the 2.5-mm spacing, the luminance for the D6500 balanced output of the R, G, and B dice would be 5.8, 8.5, and 1.7 millicandellas (mcd), respectively. Reducing multiplexing to 1/8 (requiring more drivers) would reduce that die luminance requirement by a factor of 4, which is within the current capability of the µLED and QLED dice being discussed today. LED drives the costs of the display, so a smaller LED will drive a net lower cost.

The package-die market-valued cost for digital signage today is ~2 cents per pixel. The value of a pixel for digital signage is currently 500x that of the pixels' value for AR/VR. If leverage of the µLED/QLED solutions can be applied to digital signage, the advantages may lead to a significant market opportunity for the emitter supplier. Based on the developments and technical presentations at Display Week 2018, it is clearly now appropriate to investigate the significant potential of µLED and QLED for digital signage.

Finally, the challenge of color, color consistency, and balanced luminance seems well in hand for the current inorganic LEDs as well as the µLEDs in development. LEDs supporting REC.709 is a typical scenario, and supporting the DCI-P3 color space in production has been specified for the past year. These fast-switching emissive devices have a powerful, fast-growth market opportunity ahead.

Fig. 1: *The author attended a showing of* Avengers: Infinity War *on one of the new Samsung 4K LED "Onyx" screens at the Pacific Theatres Winnetka in Chatsworth, California. The imagery was impressive (left). At right, a business card is compared to the pixel arrays in the theater screen. All photos by Gary Feather*

Digital Signage Sessions at Display Week 2018

The emerging technology track at Display Week 2018 addressed a number of digital-signage-related developments in progress. Douglas Dykaar of DifTek Lasers presented the development of a new design for scalable active pixels for digitally driven video walls. The applications of the single-crystal silicon spheres, which are embedded in ceramic and planarized, offer the promise of high-performance (mobility) solutions in the digital-signage market.

Jon Karafin of Light Field Lab showed the scope of display implementations for the creation of holographic video. He demonstrated a clear understanding of the specifications and requirements of displays leveraged to create immersive experiences and the potential requirements for true holographic displays, as well as the appreciation of the single-viewer requirement and experience of light from each physical location of a virtual object. From that understanding, Karafin presented the challenges for creating tens or hundreds of views for a multiviewer holographic system. From a display manufacturing perspective, work toward single viewer should occur this year. Adding multiple viewers will be step two in the years to follow. Proposals for a single-viewer location-adaptive image may help build demand for these visual experiences in the future.

Jorge Perez from NanoLumens presented the first-ever paper on HDR solutions for digital signage. Perez focused on the research of specifications to create more natural images. The research provides for a proper specification of HDR for signage. The exploitation of a "dynamic drive" feature enables an LED display solution that allows for 12 bits at nominal luminance and extended dynamic range in image areas where replicating highlights is required.

Last, AGC's Kenta Kasuya demonstrated the results of a prototype system for direct-bonding a display to a glass space so as to create an integrated solution for high luminance. Test methods and test results were presented, with examples supporting solutions working in environments with 10,000 lux.

Fig. 2: CLEARink's reflective color display (left) is designed to offer video-level refresh rates. At right, E Ink was demonstrating color panels at Display Week that could be tiled and updated to provide a large, changing display.

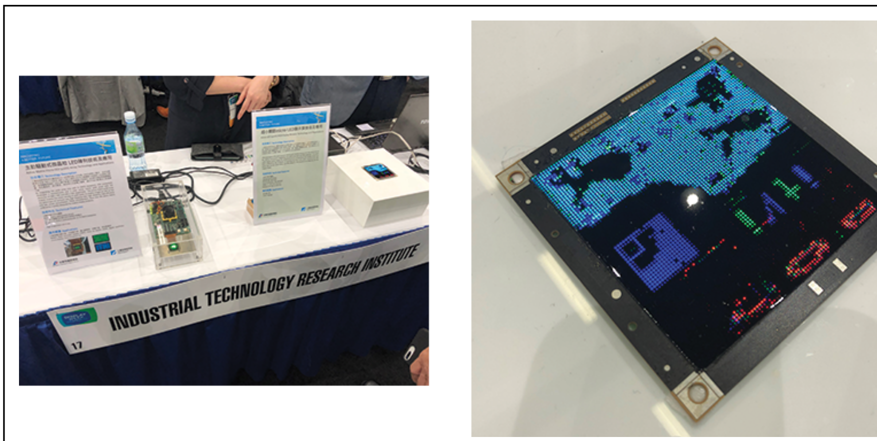

Fig. 3: In the I-Zone, ITRI was showing a µLED device with longer-range potential for the digital signage space and other markets.

Digital Signage in the Field and on the Show Floor

Because the show was in Los Angeles, attendees had the opportunity to view the first DCI-certified, US-based LED (SMD-RGB) display at a theater not far from the conference center (Fig. 1). There, visitors could see a 2.5-mm pixel-pitch theater display at a full 4K resolution (8.29 million pixels/24.88 million LEDs). The system was visually better than the DLP projection system in an adjacent theater. With 188,000 digital-projection cinema systems (many aging) deployed in the US, and over 1,000 new DLP (Xenon lamp and laser illumination) systems being purchased, the opportunity for LED displays to displace DLP is now a reality. The annual market for digital cinema display is over $250 million/year. The LED offers a clear visual advantage over the two-decade-old DLP

(continued on page 31)

Automotive Displays Proliferate at Display Week 2018

As displays in vehicles continue to increase in number and evolve in quality, they become an ever-greater focus at Display Week.

by Karlheinz Blankenbach

LARGER, higher, and more – three words that can easily be applied to the latest automotive displays. These displays are getting larger and larger; their total resolution and pixel densities are rising to new heights; and their sheer numbers are increasing as cars are being equipped with more and more displays. All of this explains the huge impact of automotive displays and related topics at SID's Display Week. Automotive displays also represent one of the most promising applications for growth – especially revenue growth – in the display industry.

This article provides a brief overview of automotive display-related activities at the show this year in Los Angeles, including the symposium, the market focus conference on automotive displays and the automotive luncheon – a first this year. Selected automotive highlights from the 2018 exhibition are presented mostly in pictures.

***Professor Dr. Karlheinz Blankenbach** has been involved with displays since 1990 and has conducted numerous projects related to displays (many with the automotive industry) at Pforzheim University, where he been a full professor since 1995. He is vice chair of the SID technical symposium subcommittee for automotive/vehicular displays and HMI technologies and a member of the International Committee for Display Metrology (ICDM). He can be reached at karlheinz.blankenbach@hs-pforzheim.de.*

Notable Automotive Presentations

The symposium provided seven sessions (including joint sessions and posters) on automotive and human-machine interface (HMI) topics, with many invited speakers and outstanding contributions. Here is a brief summary:

- A distinguished paper award was issued to a team at Visteon for "Active Polarizer Dimmable Lens System," which described significant advances in achieving the "black-panel effect" (hidden display), reducing power consumption, and raising lifetime (Fig. 1).
- Plastic-based OLCDs (LCDs with organic TFTs) enable large-area automotive LCDs without glass. FlexEnable presented successful pre-production reliability results for high temperature/humidity tests in the paper "OLCD: Manufacturing Glass-Free Vehicle Displays."
- Continental offered a summary of calibration effects on hundreds of thousands of series production units in the paper

Fig. 1: Paul Weindorf (center) and the team from Visteon receive a distinguished paper award from David Hermann of Volvo (left), a new member of the vehicle subcommittee. On the right is Rashmi Rao of Harman, chair of SID's automotive displays subcommittee. All photos by Karlheinz Blankenbach.

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Fig. 2: The first automotive luncheon was well attended and resulted in new ideas and focused networking.

Fig. 4: Continental and AGC teamed up for a curved hot-formed glass display with two 12.3-in. OLEDs and one 7-in. OLED.

"Performance Optimization for Display Solutions by Smart System Integration." Special attention must be paid to maintaining consistent and repeatable luminance and contrast ratio (CR) performance for premium displays throughout the supply chain.

- It is well known that quantum dots enlarge the color gamut of LCDs, and this is particularly beneficial for LCDs in vehicles, as pointed out in the paper "QLED Auto: Quantum Dot Based Wide Color Gamut LCD-TFT Display for Automotive Applications," from Harman and Samsung Electronics. Other presenters on QD topics included Fujifilm and Nanosys.
- Trust in autonomous cars will be enhanced by large head-up displays (HUDs) with larger fields of view (FOVs), called augmented-reality or AR HUDs, as outlined in the paper by a team from Toshiba, "Superiority of Monocular Augmented Reality when Continuous Viewing Is Required."
- A new architecture for a holographic waveguide (that is mirror-less) is described in a paper by DigiLens, "AR HUD Waveguide Technology." This approach achieves a dramatic reduction in total volume required for the HUD system.
- Luminit and Thales teamed up for "Holographic Grating to Improve the Efficiency of a Windshield HUD," in which a transparent holographic optical grating significantly improves reflectance up to 80 percent, compared to 20 percent with today's methods.
- And last, the human-machine interface (HMI) will change significantly when it comes to autonomous driving, as described in the papers "HMI Concept for the Autonomous Car" from Renault and "Human Interface Design in Transition from Automated Driving to Manual Driving" from AIST. Both authors cited the latest approaches and results.

Market Focus on Automotive Displays

Display Supply Chain Consultants (DSCC) organized a well-attended market-focus conference on automotive displays at Display Week. Speakers from Strategy Analytics and Roland Berger presented information on market growth: display units for center-console and driver information will grow to nearly 200 million units by 2025. A keynote presentation by Kristin Kolodge of JD Power illuminated

Fig. 3: JDI's immersive cockpit demo, with dashboard and center-console displays, was one of the most popular exhibits on the floor at Display Week.

Fig. 5: This demo includes examples of LG's automotive LTPS LCDs with high luminance (1,000 cd/m^2) and about 200 ppi. The center display sports an in-cell touch while the co-driver display achieves a dynamic contrast ratio of 100,000:1 by local dimming.

Fig. 6: An unbreakable plastic OLED was developed by Samsung for the steering wheel. The 6.2-in. display reaches 529 ppi and 600 cd/m^2. It withstands the impact of a 6.8-kg ball (comparable to a head) released from a height of 2.3 meters.

Fig. 8: This visualization of local direct dimming by Tianma with 240 segments (LEDs) resulted in a dynamic contrast ratio over 40 million to 1 and consumes power at reference images only about 1/3 of the electrical power of a standard panel.

the role that displays play in developing drivers' trust in the vehicle in a semi-autonomous system. Displays will be a critical piece of the human-machine interface as automobiles adopt autonomous features, and the conference included a panel discussion among industry experts about the challenges and opportunities for the display industry.

An LG Display presentation highlighted some of the technologies (such as improved lifetime and contrast) that the company is bringing to enable improvements in both LCD and OLED for automotive displays, and the conference concluded with a session on HUDs, with a joint presentation from GM and Envisics on bringing AR HUDs to vehicles, with additional presentations from Continental, Pioneer, Luminit, and Texas Instruments on unique developments that will enable advanced HUD systems.

Fig. 7: Visionox also featured a demo with OLED displays integrated into the steering wheel.

Fig. 9: This picture shows an automotive autostereoscopic 3D light-field based display with 18 views by Samsung. This 7-in. WXGA OLED enables a 3D depth of 80 mm in total.

Automotive Assembly

For the first time, the automotive displays community met for an "automotive luncheon" (Fig. 2) at Display Week for networking and discussions with peers. This event was sponsored by the German Flat Panel Forum (www.displayforum.de, DFF) and Harman. SID's Automotive Subcommittee Chair Rashmi Rao of Harman, and the author of this article welcomed the attendees with demos and outlooks for automotive displays.

Exhibition: Seeing Is Believing

While the networking, technical sessions, market focus conference, and other events at Display Week whetted our appetites for automotive display technology, there is nothing like actually seeing displays in action. Therefore, the demos on the exhibition floor were the best way to experience and judge automotive display innovations.

As in the technical symposium, automotive topics are mostly from innovations in LCDs, OLEDs, HUDs, materials and measurement, *etc*., although there are new approaches on the horizon such as microLEDs. The current de facto standard for automotive interior panels (such as in Figs. 4 and 11) is 12.3-inches with 1,920 × 720 pixels; however, many companies are presenting larger sizes or glass solutions that stretch from A-pillar to A-pillar. The following paragraphs and figures provide selected highlights from the exhibition.

AM (TFT) LCDs dominated on the show floor just as they do in today's cars. However, automotive OLEDs have improved from year to year in terms of pushing the luminance-

Fig. 10: This 13.2-in. center-stack freeform LCD from AUO has two symmetrical holes of 35-mm diameter that enable easy integration of mechanical rotary knobs. Other features are a curvature of 1,000 mm, a-Si gate driver integrated within the display area, 1,000 cd/m² and a resolution of 1,600 × 1,200.

Fig. 11: This thin (0.5 mm) flexible 12.3-in. OLED from BOE features 600 cd/m², a wide color gamut, and a power consumption of 14 W.

Fig. 12: *This electrostatic tactile touch display by Tianma improves safety for automotive use compared to standard touch. Both texture (e.g., rough surface) and click (a feeling similar to a mechanical push button) sensations are possible.*

lifetime-temperature relationship toward series requirements. OLEDs should eventually evolve from a luminance range of 500 to 600 cd/m^2 to values of LCDs in the range of 1,000 cd/m^2.

As demonstrated at other shows in prototype cars from manufacturers such as Mercedes and BYTON, full-size dashboard cover glass has become important and was exhibited by several companies at Display Week. Most of these demos consisted of three to four displays using a black-panel effect as pictured in an attention-getting demo on the show floor from JDI (Fig. 3), and in an OLED-based dashboard display from Continental and AGC in Fig. 4.

Figure 5 shows a set of automotive dashboard LCDs with different characteristics exhibited by LG.

A recent area for integrating displays is the steering wheel, as demoed by Samsung (Fig. 6) and Visionox (Fig. 7) – all these displays are OLEDs. Essential for those types of displays are head-impact characteristics and compatibility with airbags.

Automotive displays have to deliver high luminance for bright-light conditions. This typically results in high power consumption requiring sophisticated and costly heat management. Consequently, there is a noticeable trend toward local dimming in automotive LCDs, from edge lighting to direct backlighting, as exhibited by Tianma in Fig. 8 and also by LG in Fig. 5.

The challenge is to deal with the typically bright foreground and dark background of automotive HMIs. Here OLEDs have the advantage, as only pixels that are lit draw power.

Samsung presented a light-field 7-in. OLED display for an instrument cluster at the show (Fig. 9). This should speed up data gathering for the driver even for "overloaded" instrument cluster HMIs.

Another trend in automotive displays is replacing rear-view exterior mirrors with cameras and displays, as shown in Figs 4 and 7. However, there is a great deal of ongoing discussion about where to place the "mirror displays" in terms of ergonomics and safety.

A perennial demand from interior designers are curved displays, as there is basically no large, flat surface in a car. Many activities for curved displays (convex and concave) are related to the center-stack area. Tesla's 17-in. flat-touch display paved the road for other OEMs. AUO showcased an interesting approach to combine the best of two worlds – a curved touch display with two holes for mechanical rotary knobs (Fig 10).

A 12.3-in. curved OLED with large color gamut was presented by BOE (Fig. 11).

Touch control has become more and more widespread in automotive center-stack displays. But as many car functions are set or modified by the driver while driving, a haptic/tactile feedback is almost certainly more practical in terms of usability and safety. Tianma showed a significantly improved (over previous efforts) prototype (Fig. 12).

Last but not least, as an example for automotive materials improvements, Dexerials presented a reflection reduction film (Fig. 13) with very low reflectance, which is essential for bright light conditions.

These examples are just a personal selection of the huge variety of automotive products at SID's Display Week 2018 symposium and exhibition. Autonomous driving will foster even more and larger displays. The duration of a driver watching a display will jump from seconds to hours. HMIs will evolve from offering today's functional properties to providing an emotional user experience. And owned cars will become a third living space for fun, leisure and work. All of this means we will continue to see automotive display innovations at Display Week for some time. ■

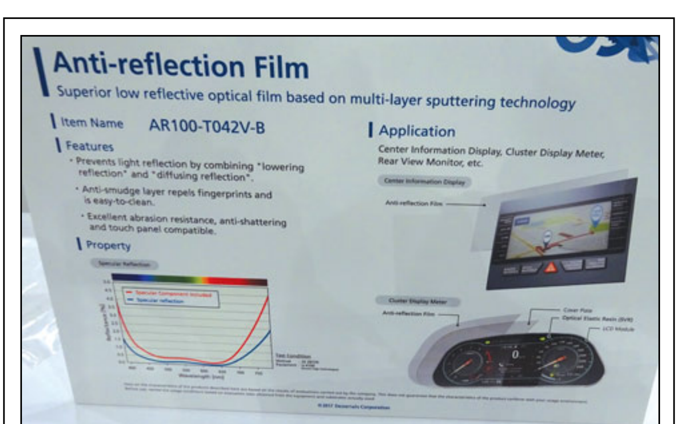

Fig. 13: *This low-reflective film from Dexerials combines anti-reflection and anti-glare characteristics for a specular reflectance below 0.2 percent.*

continued from page 24

technology for studios and creative cinematographers. This fact is evident in the new DCI specification being drafted for LED. Dramatic increases in contrast ratio, extreme requirements on the first step in black, much higher luminance for viewer experiences, and perfect "focus" are just a few of the advantages of LED over DLP.

The exhibition provided a few notable demonstrations related to digital signage. CLEARink Displays' 6-in. reflective-color display (Fig. 2, left) showed promise for video refresh rates, especially when contrasted with E Ink solutions also on the floor. Applications for e-schoolbooks and digital signage are intriguing. The current CLEARink design is for a tablet at 100 dots per inch (dpi). Extending that to a panelized lower dpi for digital signage (reflective) could be a novel addition to the market.

E Ink demonstrated large-area tiled displays (reflective) with static update capabilities as an alternative (Fig. 2, right). Non-emissive signage has yet to impact the industry; however, these solutions show promise.

Displays leveraging µLED devices are limited but emerging. In the I-Zone area was a demonstration from Industrial Technology Research Institute (ITRI) of an active-matrix µLED array with a silicon complementary metal-oxide semiconductor (Si CMOS) backplane (Fig. 3). The display was 960 × 540 and performed as a single-color and RGB solution. Leveraging these developments against various needs across the display market should allow for significant applications when performance and reliability requirements are met. There was no information at this time on the cost or requirements to manufacture.

The Industry Rises Again

Just when many felt that displays had reached a plateau, the industry reinvents itself. The specific performance improvements in LED alone provide the opening of new $1 billion markets over the next decade. The increases in visual performance are opening up new entertainment and experiences never before seen. The integration of modules in arrays with COB can drop costs dramatically. The new display configurations with content will create new markets. Certainly Display Week opened eyes to many new aspects in 2018; be prepared for a greater expansion in 2019. ■

Innovative Glass and Polymer Components Impress at Display Week

Among the oldest of flat-panel components, substrates and optical films in novel formats continue to improve display performance.

by Ken Werner

As soon as you walked into the exhibition area at Display Week 2018, you were confronted with an impressive flexible display substrate, the one used in LG Display's flexible 77-in. display (Fig. 1). In addition to having 8 million pixels and a bending radius of approximately 80 mm, the panel had a transparency of 40 percent. The transparency is obtained by placing a transparent, inactive area adjacent to each subpixel's emitting area.

This was just Display Week's first example of innovative substrates and optical films used to produce improved and/or novel display characteristics. Flexible displays are increasing their market penetration, so substrates and optical-stack components that bend were very much in evidence at the show. But it is still true that most displays don't bend, and there was no shortage of improved ways to use glass in displays.

Ken Werner is the principal of Nutmeg Consultants, specializing in the display industry, manufacturing, technology, and applications, including mobile devices, automotive, and television. He consults for attorneys, investment analysts, and companies re-positioning themselves within the display industry or using displays in their products. He is the 2017 recipient of the Society for Information Display's Lewis and Beatrice Winner Award. You can reach him at kwerner@nutmegconsultants.com.

Materials on the Floor

BenQ Materials featured its high-durability functional films, including a wide-viewing-angle polarizer that maintains color fidelity off angle (Fig. 2).

The company's True Black Functional Film reduces ambient reflection and internal light leakage, while reducing screen luminescence by only 10 percent, according to BenQ Brand Management Director WeiYin Tsou. A demonstration comparing displays with and without the film was impressive (Fig. 3).

BenQ's UHDEP – Ultra-High Definition Enhancement Polarizer – is designed to improve the off-angle color of 4K vertically aligned (VA) displays, such as Samsung's. With UHD, most LCD panels use only four VA domains instead of eight, said Chairman and CEO Z.C. Chen, which is why the film is needed. Other products currently available are a very flexible polarizer and a flexible hard coat that is foldable and stretchable.

The company was also showing a flexible smart-window film based on polymer-network

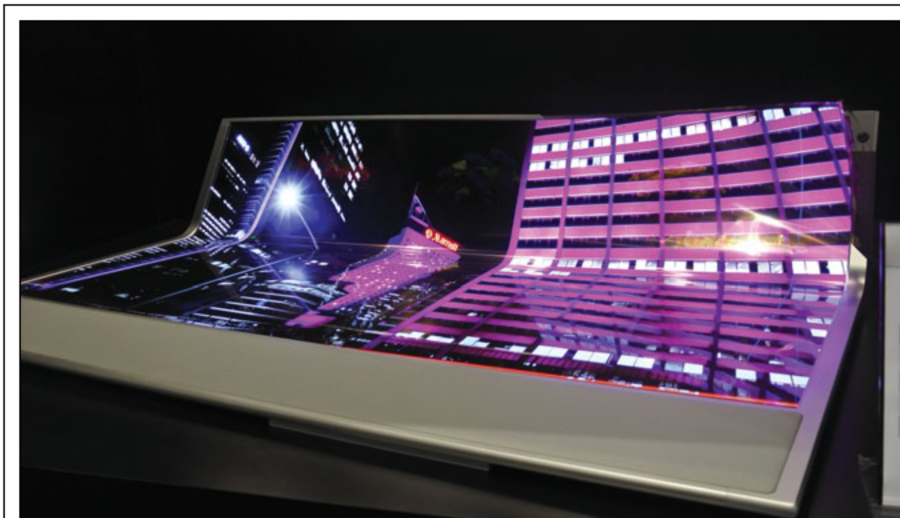

Fig. 1: *LGD's 77-in. flexible OLED screen with 8 million pixels and 40 percent transmittance greeted attendees at the Display Week exhibition. Photo: Ken Werner*

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Fig. 2: BenQ Material's wide-viewing-angle polarizer (right) maintains color fidelity at large viewing angles. Photo: Ken Werner

Fig. 3: BenQ Material's True Black Functional Film (bottom) reduces ambient reflections and internal light leakage, as compared to the top image without the film. Photo: Ken Werner

liquid crystal (PNLC) – a reverse-mode polymer-dispersed liquid-crystal (PDLC) that is clear when the power is off, a desirable characteristic for automotive smart windows after a power-disrupting accident.

Polyimide Progress

Polyimides (PIs) are thermally stable and have good chemical resistance and excellent mechanical properties, including high flex strength. They would make excellent display substrates except for their orange/yellow color.

In its booth, the Korean company Kolon Industries was featuring a colorless PI (CPI) that was scheduled to be ready for mass production near the time of this publication, according to Principal Researcher Sang-Kyun Kim. (Kolon's CPI received a 2018 Display Industry Component of the Year award from SID.) The material will be available in widths up to 1.55 meters, and its mechanical properties will allow it to directly replace glass, said Kim. Kolon's competitors are not yet ready for volume production, he claimed, and their mechanical properties are not yet as good.

Kolon will also sell a CPI varnish and a CPI hard-coat (HC) sheet. In the booth, the company showed a folding test of an OLED display with CPI HC film as a cover window (Fig. 4).

Merck showed the latest generation of its licrivision-brand guest-host liquid-crystal exterior smart windows. The material was

Fig. 4: Kolon's colorless polyimide hard-coat film served as a flexible cover glass for an OLED display. Photo: Ken Werner

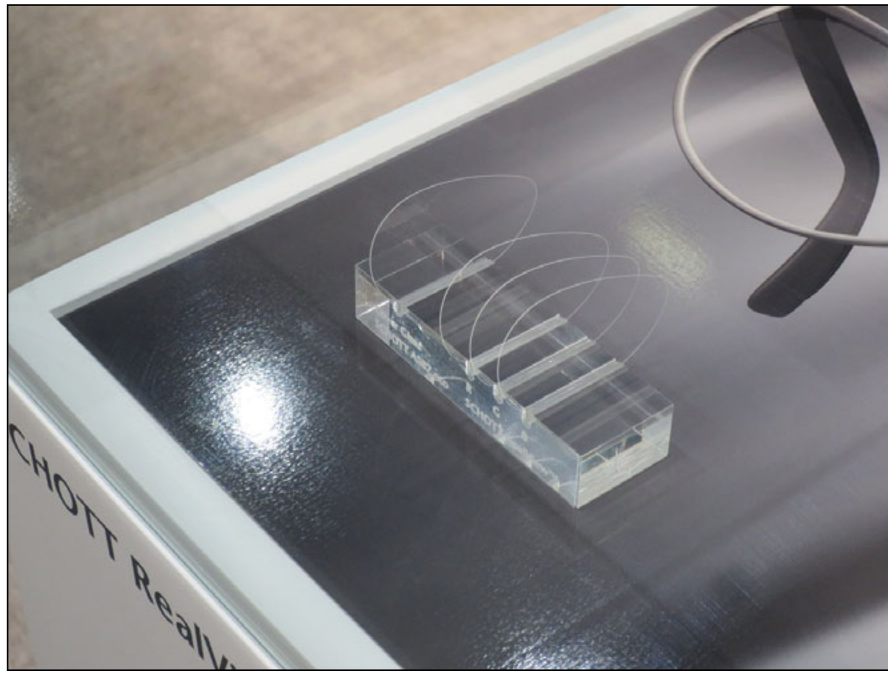

Fig. 5: Schott's RealView glass, intended for AR displays, is smooth and flat and has a high index of refraction. Photo: Matt Brennesholtz

remarkably haze free in its transparent mode and more opaque than previously in its opaque mode. The licrystal product has demonstrated an equivalent of 10 years' life in accelerated life testing, said Merck/EMD's Bob Miller.

Corning's Iris Glass for glass light-guide plates (LGPs) is now, for the first time, being used in commercially available monitors as well as TVs. Corning says Iris Glass allows product makers to reduce thickness, increase brightness, and design products with thinner bezels. Shown in the booth was a Dell 27 Ultrathin monitor with a thickness of 5.5 mm (at the thinnest point). Resolution was 2,560 × 1,440. A Lenovo 24-in. ThinkVision monitor had a thickness less than 4.0 mm. An upcoming issue of *Information Display* will include an article that further discusses this technology.

Pilkington, the UK specialty glass company that has been a subsidiary of Nippon Sheet Glass since 2006, was featuring an AR glass that does not introduce a color tint.

Schott Glass was showing its CONTURAN-brand chemically toughened, low reflectivity, and neutral-color cover glass at Display Week. In other words, this is Schott's competition for Corning's Gorilla Glass.

For augmented reality (AR) applications, Schott was aggressively promoting its RealView family of glasses (Fig. 5). RealView glass is intended for lenses in eyeglasses or goggles that will transfer AR imagery laterally to a position in front of the user's eye, where an optical structure will direct the image to the eye.

These waveguides must be planar, and they require a high refractive index for a wide field of view (FOV). The thickness must be precisely controlled, and flatness must be plus or minus one micron – 10 times the flatness required in semiconductor processing, Augmented Reality VP Rudiger Sprengard told *Information Display*. (Look for an article on this technology as well in an upcoming issue of this magazine.) Schott refers to this as Waveprint technology, and it is currently used in motorcycle glasses for AR. The company is also developing its technology for automotive AR, where it would enable a much smaller light box than is possible with conventional approaches, according to Sprengard. At the consumer level, AR technology must be miniaturized, and waveguide technology is a likely candidate, he said.

Schott Business Development Manager Brian Sjogren told my colleague Matt Brennesholtz that the glass is specially manufactured from melt to coating. This control of the entire manufacturing chain, said Sprengard, is the company's competitive advantage. Schott has been working on the technology for two years. The product has been developed and is ready for customers.

In its large booth, Asahi Glass Company (AGC) showed its XCV glass, which is AGC's answer to Corning's Iris Glass. AGC's wrinkle is that the glass contains a prism structure. Asahi also showed its curved glass in Continental's multicurved auto-

(continued on page 46)

Fig. 6: The pages of Visionox's flexible display eBook were each 5.99 inches on the diagonal with a resolution of 1,080 × 2,160 and a thickness of 0.4 mm. Only the top pages seemed to be displays, but it still made for an effective demo. Photo: Ken Werner

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Invitation to submit review papers

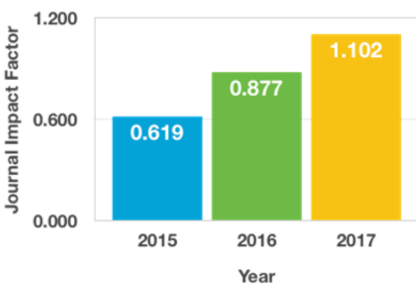
The Journal is soliciting review papers on any display-related topic. If you have a great idea for a review paper, please contact the editor at editor@sid.org.

Page charges for invited review papers will be waived.

Jiun-Haw Lee
Editor-in-Chief

Announcements

New impact factor



JSID's Journal Impact Factor has increased to 1.102 in 2017, a dramatically growing trend from 2015. This impact factor in 2017 (1.102) is also the record high for JSID. Thanks for the contribution from all authors. Thank Wiley and SID teams for the support. Thank the editorial board for the hard-working. Especially thank Prof. Herbert DeSmet, former Editor-in-Chief of JSID, for his leading in the past three years (July, 2015- June, 2018).

Herbert DeSmet
JSID Editor-in-Chief
(July, 2015- June, 2018)

Special Sections

There are several special issues related to SID sponsored conferences. '**Best of EuroDisplay 2017**' and '**Best of IDW '17**' are coming in the next issues of JSID. Besides, we have '**Best of ICDT 2018**' starting from this year. At the time of writing, '**Best of ICDT 2018**' papers are being reviewed, which are expected to appear in Q1 or Q2, 2019.

New Editor-in-Chief

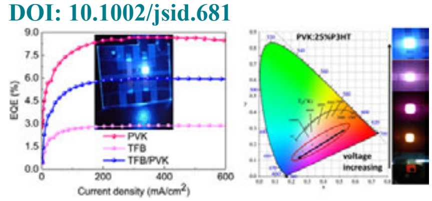
It is Jiun-Haw Lee from National Taiwan University, successor of Prof. Herbert DeSmet as the EiC of JSID. Herbert set a perfect example. Our goal is to keep the increasing trend of impact factor.

Highlighted recent papers

Limits of peripheral acuity and implications for VR system design | David Hoffman, *et al.*| **DOI: 10.1002/jsid.730**

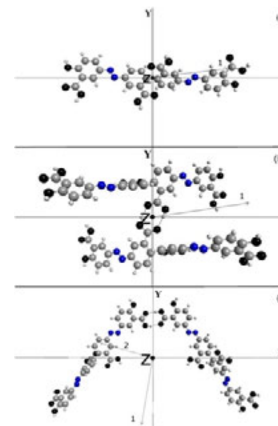
The sensitivity of the visual system to downsampling artifacts in different parts of the retina was quantified. These measurements are highly relevant to designing foveated rendering solutions for virtual reality imagery that match the ability of the visual system to detect the impairments. The types of artifacts include different levels of temporal volatility, spatial aliasing, blur, transition boundaries, chromatic aberration, and latency.

The influence of the hole transport layers on the performance of blue and color tunable quantum dot light-emitting diodes | Xiaoyu Huang, *et al.*| **DOI: 10.1002/jsid.681**



The blue QLEDs with TFB/PVK bilayered HTL simultaneously exhibit a low driving voltage of 2.6 V and a high external quantum efficiency of 5.9%. Moreover, by utilizing PVK doped with 25% P3HT as HTL, the emission color can be effectively tuned from red to blue as the driving voltage changing from 2 to 10 V.

Relation between dichroism of photoalignment azo dyes and their orientation under light wave field | Liangyu Shi, *et al.*| DOI: **10.1002/jsid.682**



The relation of azo dyes dichroism with their orientation under light wave field is considered. Values of an orientation order parameters of both molecules and dimers were obtained. The angles distribution functions for different dimers were found. Dipole electrical transition moments directed on angles close to 90° to the direction of maximal polarizability of dimers were revealed.

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Display Metrology and Image Quality Are Relevant, Vital for Development

Display Week 2018 featured a variety of exhibits, seminars, and symposia on topics related to display metrology and image quality. These topics are (or should be) of interest to anyone who's serious about developing displays or integrating displays into a system where visual performance is of paramount concern.

by Tom Fiske

THE adage "If you can't measure it, you can't improve it" certainly applies to the optical performance of front-of-screen displays. Valid and robust display characterization is crucial to the timely development of display technology and of devices that use that technology. In fact, it's a critical component of the "fail fast" methodology of product and technology development. Engineers need trusted data to succeed. Data that confirms a null result is just as valuable as data that supports an idea, if not more so. Display metrology continues to be an important component of SID's Display Week, as evidenced by the strong metrology showing in 2018 at the symposium, in seminars, in standards meetings, and on the exhibit floor. But there's a lot more to display metrology than pointing a luminance meter at the screen and pushing a button. Good data comes from understanding the idiosyncrasies of different display technologies, proper measurement techniques, and a competent analysis and understanding of the measurement result and how it relates to the purpose of the display in the system.

__Tom Fiske__ is currently a Senior Electrical Engineer at Microsoft Surface working on display technology, image quality, and optical metrology. He has been on the technical staff at Qualcomm, Rockwell Collins, Philips Electronics, dpiX LLC, and Xerox PARC. He can be reached at tom.fiske@microsoft.com.

Metrology on Display

The exhibition floor at Display Week sported many examples of display-measurement devices and systems to aid enterprising engineers in their search for measured truth.

Gamma Scientific impressed with tightly packaged GS-1160 and GS-1160B handheld and portable spectroradiometers. The GS-1160, in particular, is a marvel. It detects the spectral power distribution of a 10-mm spot via contact or proximity measurement. It also measures temporal quantities, such as flicker as specified by the Japan Electronics and Information Technology Industries Association (JEITA) and Video Electronics Standards Association (VESA) It can be operated in stand-alone, battery-operated mode or in a connected mode via USB. It comes with software to operate the device in connected mode and reports spectra, luminance, chromaticity, and temporal results. A display on the device facilitates a quick readout of the results.

In a similar vein, Konica Minolta showed its newly released CA-410 Color Analyzer. The CA-410 is the follow-up to the CA-310, a staple in many of the labs I've worked in over the years. The CA 410 is a filter colorimeter that's very fast and has a high-luminance dynamic range (0.001 to 5,000 cd/m^2, depending on the configuration). It also measures JEITA flicker and is designed to be used in a production environment. It can be purchased with a CA-DP40 data processor that can operate 10 CA 410 optical heads at once for multipoint measurements. It can also be operated from a PC or Mac using the CA-S40 software package.

TechnoTeam Bildverarbeitung GmbH (located in the German Pavilion) was showing its "LMK 5 color" imaging colorimeter with accompanying software and system components. The LMK 5 color is similar in principle to the devices offered by Radiant Vision Systems in that it's a monochrome 2D sensor combined with a color filter wheel that matches the CIE color-matching functions. The resulting data sets are color and luminance maps of whatever object is captured by the imaging system: displays (LCDs, OLEDs, augmented reality/virtual reality [AR/VR]), light sources, illuminated symbology, *etc.* TechnoTeam offers a variety of sensor resolutions and lenses for spatial measurement as well as a conoscopic lens for angular characterization. The accompanying analysis software can report parameters for uniformity, image retention, and mura artifacts, to name a few. I was personally interested in the mura analysis feature, BlackMURA, which con-

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forms to the Deutsches Flachdisplay-Forum (DFF, or German Flatpanel Display Forum) standard, "Uniformity Measurement Standard for Displays, v1.2." There are many mura analysis routines, including BlackMURA, one based on the International Display Measurements Standard (IDMS) Section 8.2.3, the proprietary TrueMura software sold by Radiant Vision Systems, and one from Konica Minolta. I'd like to see a "mura shoot-out" sometime to determine which one is most effective at finding and correctly classifying mura artifacts. Anyone game?

One of the most interesting things I saw on the floor this year was at the ELDIM booth. Start-up company United Visual Researchers uses spectral and polarization measurements from any surface at all angles and then uses the information in a powerful graphics engine to render the appearance of the surface in a wide variety of ambient lighting environments. In the context of displays, this means that you can measure the spectral emissive properties of the display in a dark room, then measure the reflective characteristics of the front surface of a display and the reflectance characteristics of the bezel and backside (at all angles). After feeding the device optical characteristics to the model (and letting the model do a few calculations), the user sees what the display will look like in a variety of scenarios: on a city street on a cloudy day, in the park on a sunny day, in the office, at home – from any angle. The model allows professionals in R&D, engineering, marketing, and management to see how design choices will affect the appearance of a proposed display device. The rendering engine will operate in real time – that is, the user can move the device around in the virtual environment and see the immediate result of a change in viewing angle, a device brightness adjustment, or some other design change. This seems to me to be a very powerful engineering and business tool for display development.

Seminars Measure Up

Seminars and Short Courses at Display Week give attendees the opportunity to broaden their knowledge of recent and prominent topics in display technology. SID brings together experts in various fields of technology and makes them available for those wishing to develop their expertise in these areas. These are marvelous opportunities for career development and not to be missed.

At the Monday Seminars this year, Michael Becker from Instrument Systems gave a wonderful overview of display-measurement foundations in his seminar, "Display Metrology: Basics, Framework, & Applications." He reviewed the basic definitions of the field; *i.e.*, display metrology is the measurement of the electro-optical properties of electronic visual displays. There are four main organizations dealing with different aspects of light and display measurement: International Commission on Illumination (CIE), International Electrotechnical Commission (IEC), International Organization for Standardization (ISO), and International Committee for Display Metrology (ICDM). One must be mindful of the intended application scenario, the type of display technology in use, the parameters to be measured, the type of measurement instrument most suited to the task, the most effective way to present the data, the ambient conditions of the test, and other factors. Becker did a great job in defining the basic types of display technology, different types of measurement instruments, perceptual limit considerations, resolution, and how to evaluate reflections. All in all, it was a great introduction to the field of display measurement and well worth attending. The notes make a good reference as well.

James Larimer of Image Metrics gave a nice seminar called "Display Color Standards and Image Quality." He provided a brief history of color imaging and talked about why we need a standard for color: standards determine the signal coding and primaries for image capture; they set rules and formats for transmitting imagery data; the image data must be decoded and the imagery reconstructed, rendered, on the display screen; and though not generally part of a standard, color management systems enable display of images in different modes to address the desires and requirements of the viewer and to differentiate display products. The seminar focused on color gamut and color space definitions and characteristics and the electro-optic transfer function – or how gray levels are rendered and black-and-white levels defined.

"High-Dynamic-Range: A Consumer Ecosystem" is the title of the seminar given by Timo Kunkel and Rob Wanat from Dolby Laboratories. Dolby does have a definite point of view regarding HDR, and it has proprietary IP for handling HDR content as part of its licensing business model. But Dolby's seminars and papers are always well presented and backed up by good research done by knowledgeable engineers. Kunkel and Wanat enriched their talk with a description of how the human visual system sees the world and responds to high-dynamic-range scenes in the real world. This informs their approach of how to best acquire, deliver, and display HDR content. They build a good case for the Dolby Perceptual Quantizer as embodied in SMPTE 2084 as a good way to encode the electro-optic transfer function (EOTF) for HDR displays. It will be interesting to see how HDR continues to evolve as displays improve and HDR standards and pipelines are developed.

Metrology Papers of Note

Papers in the Symposium part of Display Week focus on recent advances in display technology, processing, and measurement methods. They are generally presented by the scientists and engineers from industry, academia, and other institutions who created the work. This gives everyone in the industry the chance to share knowledge of exciting new advances, and this year was no exception. We summarize here two papers – one about reflective-display measurement and one about measurement of AR/VR displays. Both topics are of intense interest in display technology today.

Dirk Hertel of E Ink gave a very informative paper, "Application of the Optical Measurement Methodologies of IEC and ISO Standards to Reflective E-Paper Displays (EPDs)." He presented an extension of the method for measuring reflective displays from the International Electrotechnical Commission (IEC) and IDMS and showed that "the optical characterization methodology specified in IEC 62679 has been extended with methods from ISO 09241 to account for unwanted, disturbing reflections. This was done by adding a glare term to the ambient display luminance model." The IEC model includes emissive characteristics of the display – in this case, the light from an integrated front light unit on the EPD, light from a diffuse source, and light from a directed (or specular) source. The addition leverages the work of the International Organization for Standardization (ISO), National Institute of Standards and Technology (NIST), Becker, and others to include wavelength and ambient-lighting geometry to measure meaningful reflective characteristics of EPDs in relevant scenarios.

Another paper worth a look, "Standardizing Fundamental Criteria for Near-to-Eye Display Optical Measurements: Determining Eye Point Position," by Draper, Penczek, Varshneya, and Boynton from the Army Night Vision Lab, NIST, and University of Colorado at Boulder, gave a good take on how to establish eye position for a near-to-eye display (NED). Most developers ask users to wear the NED systems, then optimize some optical feature as a function of eye position so that the eye is placed at the design eye position within the eye box of the display. This procedure is not very repeatable, will differ between users, and may result in a less than satisfactory experience for the user (Fig. 1). The authors review four different methods for objectively determining the eye-box extent and design eye position for a NED: crosshair, center luminance, center resolution, and full field-of-view method. These methods use cameras or luminance probes of various types to determine the luminance, line width, resolution, and so on of a NED as a function of eye position and orientation. It was found that all methods give reasonable results, though some are more complicated and time-consuming than others. The authors suggest that these methods can adapted for production line use.

Supporting Standards Committees

Part of SID's mission is to encourage and support the development of display standards. As part of this mission, SID makes available meeting space and food and beverage service to standards development organizations including the IEC and the ISO. There was some robust discussion at the IEC meetings around color topics this year (judging from the request for a large meeting room and conversations with participants). Administrative matters dominated this year's meeting of the ICDM, as the committee held its biannual election of officers. SID has also offered more financial and logistical support in the next few years to help with ICDM organizational development and the publication of a follow-on version of the Information Display Measurements Standard.

The Ongoing Importance of Display Measurement

The interesting thing about display measurement and the assessment of image quality is that they touch on all display technologies – direct-view OLEDs or LCDs, reflective displays, and AR/VR systems. These devices exist to deliver photons of a certain type and spatio-temporal pattern to the human visual system. The photon patterns convey visual information in the form of human-perceivable images with the purpose to inform, warn, or entertain. This purpose can only be optimally achieved if all the subsystems in the device work together to deliver the visual image in the way the system designers intended. This means that the quality of the image has to meet certain standards. And this is where display measurement connects all things display. If display developers and manufacturers cannot guarantee that their system meets image quality standards, then why would a user buy it?

Display measurement enables display sellers and buyers across the supply chain to know that the display meets objective image-quality standards and will be able to fulfill the developer's intent and the user's expectation. Display measurement is where we connect human perception to objective physical quantities that can be evaluated against a threshold informed by our understanding of how people see the world. The way I see it, display measurement enables the entire display industry. So the next time you see a display metrologist, shake her or his hand and say thank you. ■

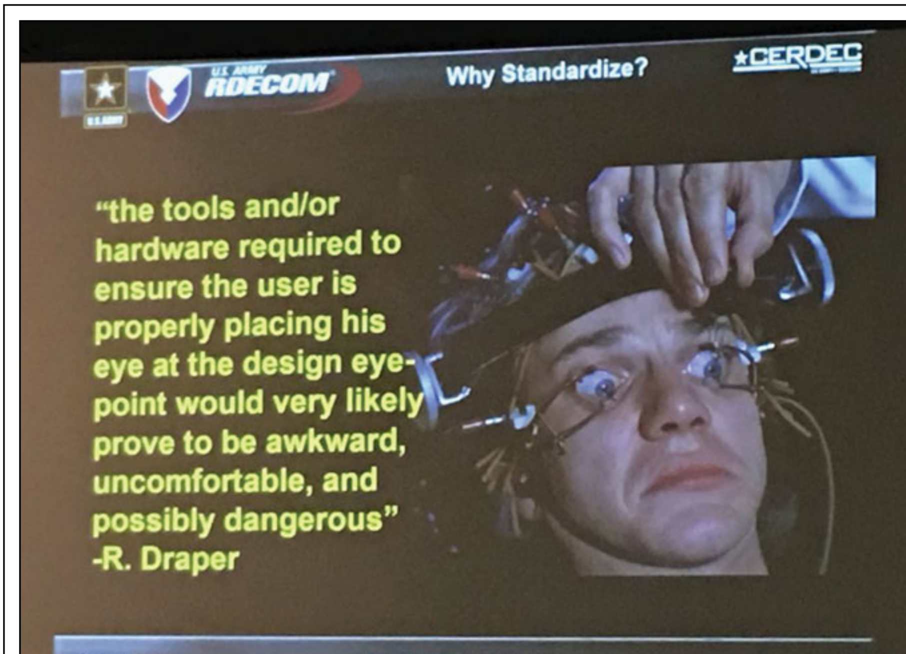

Fig. 1: This slide from a symposium presentation shows the wrong way to find the design eye point.

ID Interviews Yiorgos Bontzios, CEO of Fieldscale

Yiorgos Bontzios sets the vision and long-term targets for Fieldscale, a company based in Thessaloniki, Greece, that makes simulation software for touch-panel developers. Bontzios has a Ph.D. in electrical and computer engineering from the Aristotle University of Greece. He is the principal inventor of one patent, and has published over 20 papers and 4 books.

Conducted by Jenny Donelan

Information Display: Can you tell us a little about Fieldscale and how you got started?

Yiorgos Bontzios: My cofounder, George Bouzianas, and I met while we were working on our Ph.D.s seven years ago. We were both using simulation software for our theses, and we recognized two big problems with it: the speed – sometimes it was so slow – and the complexity. All the engineering simulation software out there at the time was so hard to use. You needed to be an expert, a scientist, to use it.

We decided to do something about that. We decided to create simulation software products from scratch that were faster and easier to use. So we founded the company in 2015, and we received our first funding from a local venture capitalist. Since then, our mission has been to democratize simulation software and make it mainstream. We are now a company of 30-plus people.

Yiorgos Bontzios

ID: How did you and your partner arrive at the idea of simulation software specifically for touch technology?

YB: We started exploring the market to find the highest growth potential. And after looking at many different market segments, we realized touch sensors was an industry where the pain was very big, and the growth opportunities were even bigger. The starting point was our background in simulation software, and then the market need led us to apply that background to touch.

The product that we introduced to the market in 2016 was called SENSE (Fig. 1). This software targets the touch-sensor industry and specifically the capacitive-sensor industry. The benefit that we give to our customers is that we can help them reduce product development cycles and, at the end of the day, ship products faster to market.

ID: So SENSE can reduce the number of physical prototypes a developer has to create?

YB: Exactly. It depends on the product, but a company might normally make five, six, seven, or even more iterations before they are sure that a product will work. These prototypes cost a tremendous amount of time and a huge amount of money – many months of work, and hundreds of thousands of dollars. In some industries, this is something that can make or break the business.

ID: Do you do a lot of customization with your partners? That is, do they ask you to make certain changes to the software?

YB: We get many requests from customers and potential customers. This is always the case with software. And it is actually the greatest feedback you can get. Our goal is to deliver the best user experience and make the lives of our customers easier. So every time we have a request, we look at it from many angles: Will the request add a new feature? Will it add value? Can we include that feature in the product without affecting the user experience?

This article is based on phone and email interviews conducted by Jenny Donelan, editor in chief of Information Display.

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ID: Do you sometimes get requests that are not that valuable to implement on a one-off basis?

YB: It definitely depends on the case. Sometimes we have to educate the customer about what works best for them. After all, we are showing new customers something they haven't seen before. Sometimes they may not realize how a feature can add value for them. At that point, we guide them. But we are always striving to do what is best for customers and what makes life easier for them.

ID: What's the tech scene like in Greece?

YB: The startup scene is growing and evolving. We are moving into phase 2.0 of the startup scene, so to speak. We have had some great successes, like the Taxibeat app that was acquired by Daimler for 43 million euros. And companies like Workable.

ID: What are some of the lessons you have learned as a startup?

YB: It's really hard. When I did my Ph.D., I said wow, this is really hard, but trust me, it's nothing like starting a new business. In a new business you are always doing three things at the same time. And you learn a different lesson – something new – every day. When we look back at how we did things one or two years ago, we laugh at our ourselves. If we project into the future, I'm pretty sure that years from now we will laugh at what we are doing now.

ID: What was your biggest challenge along the way?

YB: There were many, but the biggest challenge, if I had to name one would be translating the idea we began with into the product that it is today. I always think of an interview I saw with Larry Ellison, the CEO of Oracle. He said that everybody has good ideas but translating those good ideas into great products is unbelievably hard.

I remember clearly one day when our entire team was gathered in the meeting room. It was a little bit hot that day, when we drew the very first mockup of SENSE. We didn't know what it would look like one or two years from that point, but from the beginning our goal was to create a simulation software that followed two simple criteria: it had to be 10 times faster than anything else and 10 times easier to use than anything else out there. So we set the bar high – maybe too high – and right after that we realized how difficult it was going to be. We had to have continuous refinements and iterations of the software before we even began to get close to that goal. And there were times when that initial goal seemed unrealistic. That's the biggest challenge – when you start executing and you see how difficult it is. It's very hard to stay focused on your vision.

But you know what? If you have kids, you can appreciate this: my kids are both troublemakers and they do things that drive me crazy. But when I see the smiles on their faces, I forget everything else. It's the same with your product. The moment you hear your customers say things like, "Your software saved me from doing so much work," or, "It saved me hundreds of thousands of dollars," you forget the hard times, and the struggles. There's nothing like the smile on the face of your customer.

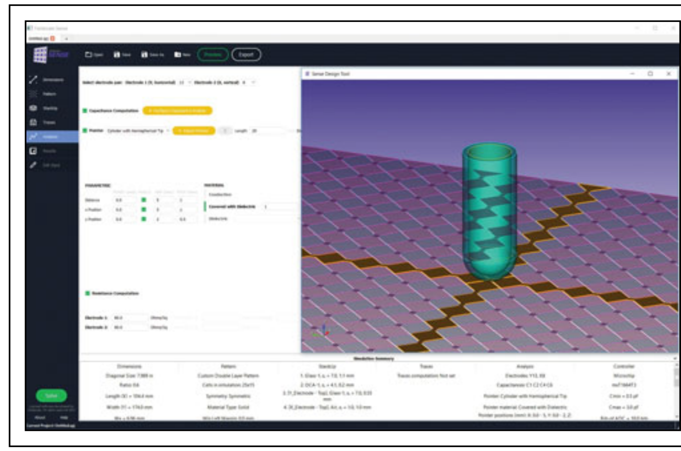


Fig. 1: This screenshot of the SENSE simulation software shows a gloved pointer placed above a central electrode node.

ID: How did you develop your simulation engine in such a short amount of time?

YB: Even though SENSE was created in less than two years, a lot of the preliminary work had been done years before [when we were in graduate school.] But in order to develop an entirely new product, with so many specs to consider, you need two things: a very strong, dedicated team and a good sense of prioritization. For the team, Fieldscale recruited professionals with diverse levels of expertise: electrical engineering, mechanical engineering, software development.

After that, we established a plan of action. We employed principles of Agile software development, forming cross-functional teams and delivering the product in small, incremental steps. Instead of adding a lot of features we were unsure about (in terms of whether they would be valuable to our target customers), we decided to create a core version of our product and throw it into the market for early feedback. That's where SENSE version 1 was launched: right in the middle of Display Week 2016. And that is how we managed to attract our first customers. Those customers became the ones that helped us shape our product to the version that it is today.

ID: How did you validate the product?

YB: Our technology was validated against existing literature (published research) as well as through confidential, under-NDA data from our customers. We are proud that we have been able to develop smart algorithms that provide accurate results for many different touch designs and applications – automotive, industrial, smartphones, *etc*.

ID: How did you achieve such a significant increase in speed?

YB: Regarding the technology, our fast and robust EM (electromagnetic field) solvers are our big advantage against the competition. Leveraging the Boundary Element Method, we combine innovative methods and algorithms that take advantage of multiple cores and parallelized simulation processes, which speeds operations. We are proud to say that our solver is currently under patent.

Apart from that, our biggest innovation is that we simplified and automated the most tedious part of the work, which is the pre-processing: setting up the geometry of a product, as well as the parameters for simulation, and – the most demanding part – the meshing process. With SENSE, the user doesn't need to do any of these operations manually. Everything is automated.

ID: Since you work with panel developers, I have to ask if you are seeing any industry trends that you can share with us.

YB: Generally speaking, we believe that in the next 5 to 10 years we will have two interfaces – touch and voice. And on our part we are committed to lead the innovation in touch. Two years ago at Display Week, the keynote speaker from Microsoft [Steven Bathiche] spoke about Surface and how the company's vision of the future is the touch screen everywhere. That is a definite trend.

Large screens are also a trend. And a very large market driver is the autonomous car of the future. Once you remove the steering wheel, you need to rethink the user interface. The car of the future, at least from what we have seen, will use touch and voice commands, and you will see touch controls everywhere. For example, you won't open your window with mechanical devices anymore. You will slide your finger along a panel in the direction you want the window to go – up or down.

A big difference between touch panels in the car and most of the touch screens we have at the moment is that a lot of them are curved to follow the form factor of the car, and this is easier said than done, because the material used for touch screens is most often indium tin oxide (ITO), which can't be curved. ITO is also not the best material for designing very large screens because of some technical limitations, so right now the touch industry needs to be working with new materials like metal mesh or nanowires *etc*. This means that all these products will need to be redesigned. Large screens, curved screens, bezel-less screens – all these trends follow different form factors and will need to be redesigned.

ID: So that's good news for you!

YB: It's actually music to my ears! We watch these trends, and move new capabilities into our products so we can fulfill customer requests, such as support of metal mesh.

ID: What is next for Fieldscale?

YB: I can say that our move toward simplification [in terms of simulation software] has been embraced. So we are planning to introduce a range of new products that follow the same concepts of simplification. As as we dig deeper into the touch-screen market and the supply chain in general, we realize that IC makers, OEMs, materials suppliers – every single player – has painful experiences related to R&D, production, *etc*. So having come up a with a pain reliever for touch-panel production, it's possible that we might be able to fix all this pain in the supply chain in a very unified way.

ID: Any last thoughts?

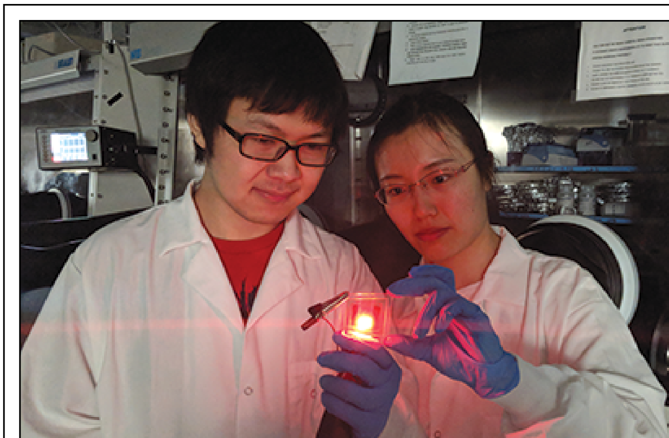
YB: I would say always, always do things that you love. I quote what Elon Musk said about how running a startup is like chewing glass and staring into the abyss. It's absolutely true. I couldn't nail it down better. So if you don't love what you do, if you don't have this drive to move forward, you won't stand a chance. ■

UCF Students Develop QLED Devices for Medical Applications

Photomedical researchers have been in search of low-cost, effective illumination devices with form factors that could facilitate widespread clinical applications of photodynamic therapy (PDT) or photobiomodulation (PBM). Student researchers from the University of Central Florida and other scientists recently discovered that ultrabright, efficient deep-red quantum-dot light-emitting devices (QLEDs) could fit nicely into this niche. Their recent paper in the Journal of the SID *(JSID) described how a photomedical approach based on these QLEDs could increase cell metabolism over control systems for PBM applications and kill cancerous cells efficiently for PDT applications.*

by Hao Chen and Juan He

At Display Week 2018, student authors Hao Chen and Juan He (both pictured below); their advisors, Yajie Dong and Shin-Tson Wu; and collaborators Raymond Lanzafame, Istvan Stadler, Hamid El Hamidi, Hui Liu, Jonathan Celli, Michael R. Hamblin, Yingying Huang, Emily Oakley, Gal Shafirstein, and Ho-Kyoon Chung received the 2017 Outstanding Student Paper Award for "Quantum-Dot Light-Emitting Devices for Photomedical Applications." Chen, He, Wu, and Dong are with the College of Optics and Photonics (CREOL) and NanoScience Technology Center (NSTC) at the University of Central Florida. Lanzafame and Stadler are affiliated with the Laser Surgical Research Laboratory at Rochester General Hospital in Rochester, NY. El Hamidi, Liu, and Celli are with the Department of Physics at the University of Massachusetts Boston. Hamblin and Huang are with the Wellman Center for Photomedicine at Harvard Medical School in Boston, MA. Oakley and Shafirstein are with the Photodynamic Therapy Center at Roswell Park Cancer Institute in Buffalo, NY. And Chung is with the ITRC AMOLED Research Center at Sungkyunkwan University in Korea. Chen and He describe their research:



Student researchers Hao Chen (left) and Juan He (right) appear with the QLED device they developed for their award-winning project and paper.

Photomedicine is an emerging medical field in which light is used either to kill cancer cells with the assistance of photosensitizers and singlet oxygen or to stimulate cellular function leading to beneficial clinical effects. Both techniques, using laser or LED arrays, have been demonstrated as minimally invasive treatment strategies.[1]

Photomedicine has not, however, received widespread clinical acceptance, mainly because of the lack of effective, low-cost illumination devices. Lasers and LED arrays are large and bulky. Organic light-emitting diodes (OLEDs), which offer a uniformly large-area light source and a thin, flexible, lightweight form, have been proposed for light-emitting bandage applications for PDT[2], but have been largely abandoned in favor of LEDs[3] because photomedical applications generally require light sources of relatively high luminance (>20,000 Cd/m^2 or ~10 mW/cm^2) at wavelengths in the deep-red region in order to have deep-tissue penetration while still maintaining sufficient energy for molecular excitation.[1] Existing OLEDs with either fluorescent or phosphorescent emitters cannot achieve such high luminance at the right wavelength windows because of significant efficiency roll-off problems at high current density[4] and the lack of efficient deep-red emitters with narrow spectra.[5]

We began our research considering a promising alternative technology – electroluminescent quantum-dot light-emitting diodes (QLEDs), which have size-controlled tunable-emission wavelength and narrow emission spectra.[6] Among QLEDs of various colors, red are currently the most advanced and have demonstrated efficiency and luminance that rival or beat state-of-the-art thermal-evaporated red OLEDs, with narrow peak linewidths in the 20- to 30-nanometer (nm) range.

As shown in Fig. 1, the devices demonstrate a peak emission wavelength of 620 nm and a narrow bandwidth of 22 nm. They can achieve

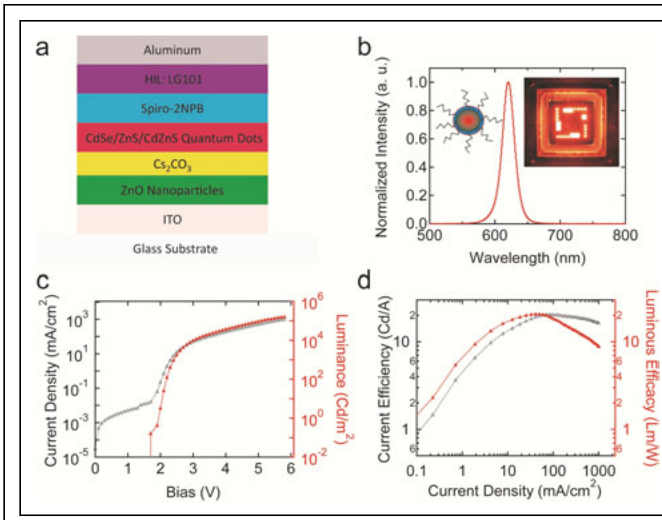


Fig. 1: *The above schematics and charts represent ultrabright, highly efficient, low roll-off inverted quantum-dot light emitting devices (QLEDs). (a) A schematic representation of the ultra-bright, high efficiency, inverted QLEDs. (b) Spectra of QLED electroluminescence. (c) Luminance and current density vs. driving voltage and (d) luminous efficacy and current efficiency vs. driving current density for typical devices. Adapted from data in reference.*[7]

high current efficiency (20.5 Cd/A at ~20,000 Cd/m^2) and small-efficiency roll-off at high-driving current density.

Although the relatively short lifetime of these ultrabright deep-red QLED devices compared to state-of-the art OLEDs has limited their immediate applications in display or lighting markets, they are promising light sources for photomedicine, in which low-cost, wearable, disposable light-emitting bandage products are highly sought-after. And the narrow emission band and wavelength tunability of QLEDs enable them to more easily fit the emission spectrum into the absorption window of photosensitizers (for PDT) or cytochrome C (for PBM). Note: For our QLEDs, the LT50 at 2,000 nits or 100 nits initial luminance is estimated to be 350 hours or 7,000 hours respectively. The failure mode of QLED is not yet fully understood.

Our paper presented preliminary PBM and PDT results using these ultrabright red QLEDs as excitation light sources, with parallel studies using inorganic LEDs as comparisons. We also discussed the possibility of tuning QLED wavelength for targeted photomedicine, the development of flexible QLEDs, and their potential impact on wound repair or cancer treatment.

Finding a Suitable Problem

For our research team at the University of Central Florida, this was a typical "solution looking for a problem" process. Our group had developed high-performance red QLEDs with ultra-high luminance, narrow emission spectra, and a tunable wavelength range, but the device lifetime was limited. These QLEDs were not yet ready for display applications.

We were looking instead for applications that could make full use of the merits of our devices without our having to solve the lifetime issue yet. The early work of Lumicure (a UK company now called Ambicare Health) caught our attention. Lumicure's researchers tried to use OLEDs as flexible light-emitting bandages for the phototherapy of skin cancers. The idea was cool, but the results were not that satisfactory, because the relatively low power density and broad spectra of OLEDs can't meet phototherapy's stringent requirements. We thought, aha, that is where we can do better and the doctors don't need a bandage that lasts forever, so our lifetime issue won't be a problem. That is how we got started.

Because of the truly interdisciplinary nature of this project, we needed many partners from both the OLED and photomedicine communities. To connect with the photomedicine doctors, we went to the annual conference of the American Society for Laser Medicine and Surgery (ASLMS) and showed our prototype QLEDs to physicians who were using red light in their practice. They were excited to see the color and brightness of our QLEDs and were happy to start some preliminary cell studies with us even if we only had small rigid QLEDs on glass at the time. The preliminary results were very promising. With these results, we then introduced the concept to the OLED community at Display Week and the OLED Summit to seek support for making flexible devices.

Preliminary PBM Results

We initially developed a 4-pixel (4 × 4-mm each.) QLED array as a photomedical light source. As shown in Fig. 2, a specialized platform/cradle was built to stabilize the QLED array, allowing proper tray positioning underneath cell cultures for in-vitro PBM and PDT experiments. The results were compared with control cell cultures that received no light treatment or parallel studies with inorganic LED treatment.

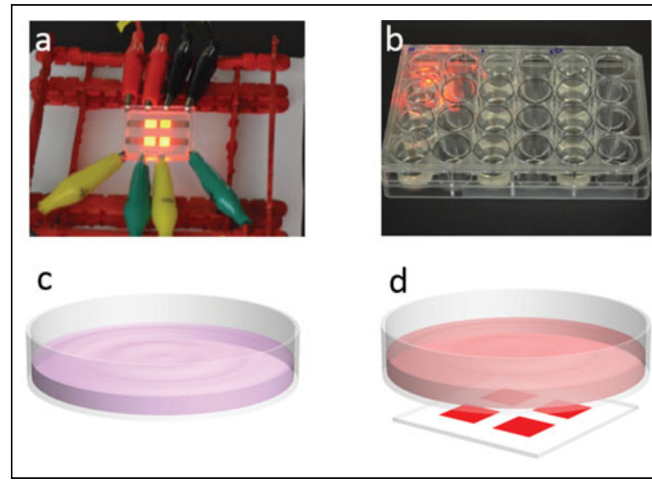


Fig. 2: *The experimental setup for photomedical testing included (a) a 2 × 2 red QLED array; (b) an experimental setup; (c) control cell cultures without light treatment; (d) cell cultures using QLED as a light source.*

For PBM testing, we used three cell lines cultured in 24-well trays. Photoradiation was performed using the ultrabright QLED to deliver 4.0 J/cm^2 to the culture wells during a 10-minute "treatment" at a power density of ~8 mW/cm^2. Control cell cultures received no light treatment. Cell metabolism was assessed using a 3-(4,5-dimethylthiazol-2yl)-2,5-diphenyltetrazolium bromide assay (Chemicon International Inc., Temecula, CA) 24 hours after treatment. (The 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide assay is a colorimetric assay and is a popular method for evaluating cell metabolic activity.)

Parallel studies were performed at 670 nm ± 20 nm using an LED device (Quantum Devices, Barneveld, WI) delivering 4.0 J/cm^2 for 10 minutes' duration for comparison with the QLED PBM. Assay results at 24 hours showed that QLED PBM increased cell metabolism in one cell line and in a similar fashion to a NASA LED source.[8] Although the peak wavelength of QLED (~620 nm) is still not up to the ideal 660 nm for PBM, the results of QLED BPM are comparable with the LED PBM. Further tuning of the emission wavelength of QLED is expected to lead to improved PBM results.

Preliminary PDT Results

To evaluate the potential of red QLEDs as a light source for PDT, we used 3D cultures of A431 cells (a human cell line frequently used in cancer-associated biomedical studies). Cultures were treated using either the QLED sources with low average irradiance (approx. 1.8 mW/cm^2) or a solid-state LED with similar spectral emission but higher irradiance (approximately 130 mW/cm^2). Dosimetry was controlled so that cultures received the same total light dose of 30 J/cm^2 over the course of either 4.75 hours (QLED) or 4 minutes (solid state LED). Treatment response was evaluated 24 hours after PDT using an imaging-based approach.[9] Both QLED and LED sources achieved photodestruction of 3D tumor nodules, while quantitative image processing of multiple replicates revealed that PDT efficacy was slightly enhanced using the QLED source, with residual tumor viabilities of 0.61 +/ 0.04 versus 0.53 +/ 0.08 for the solid state and QLED sources respectively. This result is consistent with previous reports that PDT at low dose rates may be more effective and is significant here in view of the capability of the QLED to act as a low-cost, effective, and ergonomic source for PDT light activation over extended periods. These in-vitro studies are the first to demonstrate PBM and PDT using a QLED device and should pave the way for further developments in QLED-based photomedicine.

Wavelength Tunable Red QLED for Targeted Photomedicine

It should be noted that these promising preliminary results were obtained with ultrabright red QLED with a peak wavelength of ~620 nm. While this wavelength falls into the favorite range for most photomedical applications (620 to 670 nm), highly effective phototherapy calls for better wavelength-specific spectral control to maximize the absorption for photosensitizers (for PDT) or cytochrome C (for PBM) from QLED. By tuning the synthesis conditions (QD size and composition), we can achieve ultrabright QLEDs with precisely controlled emission peaks at specific wavelengths for wound repair and cancer treatment applications. Currently, such precise wavelength control can only be realized by expensive, bulky lasers, although the laser light needs to be waveguided with optical fibers and spread out with diffusers for large-area applications. Compared to lasers, QLEDs have clear advantages as low-cost, large-area, and wearable light sources, such as shown in a rendering in Fig. 3.

Facing Challenges, Lessons Learned

The key technical challenges of this project resided in its inherently multidisciplinary nature. The work required deep understanding and close collaborative process with regard to QLED device performance, medical treatments, and regulatory approval processes. Another challenge, political in nature, lies in the public's concerns about the cadmium contained in QD materials. Such concerns may be eased by serious medical evaluation of the QLED's beneficial treatment effect and the monitoring of any possible side effects.

The biggest lesson we learned from this work was how to effectively conduct teamwork among many parties; that is, utilizing the specialty of each party and coordinating the whole team to move forward together. It was a vast communication project. Strong interest from both photomedicine and OLED communities was the key to helping us maintain great working relations with both parties.

Working Toward a Flexible Implementation

Now we are looking forward to moving this project further ahead with real flexible QLEDs. Rigid QLEDs on glass substrates have been demonstrated to be effective in wound repair and cancer treatment in in-vitro tests. We now need to fabricate flexible QLED products on plastic substrates, with technical assistance from those in the flexible OLED field, and then demonstrate the therapeutic effects of the flexible QLEDs in-vivo.

We are now working on fabrication of flexible QLED prototypes with large active area and improved stability. Using the newly developed QLED prototypes, we are also collaborating with our photomedical partners to carry out preclinical in-vitro studies for treatments of several specific medical conditions, including oral cancers and diabetic wounds.

Fig. 3. *A QLED-based bandage for photomedicine applications might look like the rendering above.*

Our preliminary PBM and PDT results should pave the way for using the bright, pure-color red QLEDs in rigid or flexible form factors to positively affect phototherapy applications in dermatology, oncology, minimally invasive surgery, stroke, and brain disease, among other fields. We believe that this QLED-based technology, initially developed out of strong interest from the information display industry, can make inroads into new medical areas and have a direct, beneficial impact on mankind by radically changing the ways we manage cancer, acute and chronic wounds, inflammation, and antimicrobial resistance, to mention only several potential uses for photomedicine. The experience and knowledge gained in this project and the successful commercialization of QLEDs in the niche photomedical lighting market could help enhance QLEDs' stability and eventually enable their applications in display and/or general lighting.

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■ March/April

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Markets: OEMs, deposition equipment manufacturers, panel fabricators, materials industry research and developers, display and electronic industry analysts, OLED process and materials manufacturers

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Fig. 5: *Kyulux's sky-blue TADF OLED emitter appeared in the company's Display Week booth. Photo: Ken Werner*

not far from mass production specifications." The specifications for volume production "are typically considered to be around 0.15 CIEy, 15 percent EQE and >100h LT97 at 700 nits. We therefore expect that our blue TADF emitters can be found in first products by 2019 after all the necessary processing tests will have been done in 2018."

In the company's booth, Cynora CEO Gildas Sorin gave *Information Display* more recent results for TADF blue: 20 to 26 percent EQE and LT97 (700 nits) of 20 hours. Early last year that lifetime was only 1 minute, Sorin said. This compares to an EQE for fluorescent-blue OLEDs of 7 percent and an LT97 of 150 hours.

Since the company has solved two of the three key problems, said Sorin, Cynora can now focus on lifetime exclusively, a much easier task than having to work on color coordinates, efficiency, and lifetime all at once, which is the challenge facing Cynora's competitors, according to Sorin. However, Sorin was more conservative than his technical colleagues in predicting commercial introduction. He said he hopes that Cynora will achieve the lifetime goal in the middle of 2019, with commercialization at the end of 2020.

There were also lots of LCDs discussed in the technical sessions and shown at the exhibition at Display Week, but the excitement seemed to be generated by emissive displays and the materials and processes that enable them. ■

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motive cockpit display, versions of which were shown in Continental's giant suite at CES in Las Vegas earlier this year.

Also on display were windows with active lighting or displays behind them. The first approach gave a convincing impression of moving foliage on the other side of a translucent window. AGC calls these Glaterrace Windows. Applications are basements, hospitals, offices, and closed spaces such as elevators. The second approach set large displays several inches behind windows. The spacing and the lake scene in the middle distance created a convincing sense of a lake really being outside the window.

AGC also demonstrated a glass speaker. The general idea here is the same as LGD's Crystal Sound, but AGC has worked for very high-quality sound and an executive-suite look. AGC says it has realized the ideal of the "glass diaphragm" by suppressing the resonance of the glass.

Finally, it seemed that every Chinese display exhibitor was showing a flexible OLED. BOE, Tianma, Visionox, and others all had flexible OLED demos (Fig. 6). One or two even claimed they were products. Whether or not that's true now, it will be.

It is easy to think of substrates and optical films as the relatively uninteresting components that simply support the high-tech processes that make displays work. That is not at all the case, as the exhibits at Display Week made clear. ■

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5, 10093 (2015) https://doi.org/10.1038/Srep10093

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Sakai Display Products
Sharp Corp.
SiOptics GmbH
Solas OLED
TDMDA
TFD, Inc.
Tianma Japan, Ltd.
TLC International
Universal Display Corp.
YUASA SYSTEM Co., Ltd.