DISPLAY WEEK 2017 PREVIEW AND DISPLAY MATERIALS

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ON THE COVER: *The winners of this year's major awards from SID are: (clockwise from top left)* ***Shui-Chih Alan Lien, Kenneth I. Werner, Martin S. Banks, Deng-Ke Yang, Yi-Pai Huang,*** *and* ***Hiroyuki Ohshima.***

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In the Next Issue of *Information Display*

Show Issue/Automotive Displays

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- Products on Display
- Interior Vehicle Lighting
- Conformable LCDs
- Vehicle Display Marketplace
- Q&A with Luminit

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editorial

Onward to Display Week

by Stephen P. Atwood

It's hard to believe we're here again, just a couple months away from Display Week 2017. This year, the big show is in sunny and warm Los Angeles beginning on May 21 and spanning the entire week with short courses, seminars, business and market focus conferences, the International Symposium, some great keynotes, and the world-class Display Week Exhibition. I'll have more to say about this later on but if you have not yet made your plans to visit, you should! I'm sure by the time you read this, the winter rains will have ended and the southern California landscape will be vivid, bold, and as welcoming as ever.

Our cover story this month celebrates the SID 2017 Honors and Awards, which are presented each year by the Society for Information Display to honor those individuals who have made outstanding contributions to the field of displays. Here at *ID* we do our best to capture the essence of their achievements in the biographies and citations thoughtfully compiled by our own Jenny Donelan. But nothing we write can come close to documenting the lifetimes' worth of ideas, challenges, setbacks, inspirations, and successes that these individuals have experienced on behalf of our industry.

As Jenny describes in this year's article, great innovation often comes from teamwork and collaboration, where new ideas are born and get distilled through a process of collaboration, either intentional or accidental. Inspiration can come from the team in your midst, or from the wider world (such as conferences like Display Week), which these days also includes the incredible on-line community that we all interact with. Inspiration can come from students, teachers, business leaders, peers, or even from a fortuitous invitation to speak at an SID meeting, as happened to one of this year's award winners some time ago. Regardless of the source, it's what people do with that inspiration that counts, and this year's award winners have all made great contributions to the world of displays, either through direct invention or through enthusiastic teaching, mentoring, and supporting of those around them! While the honors are being bestowed on these leaders of the display industry, the real honor goes to those of us who have had the privilege of knowing them, working with them, learning from them, and using their innovations to build better products that enrich people's lives.

Among those being recognized this year is one individual I have had the privilege to know personally and who is a former editor of *Information Display* magazine. Ken Werner was a caring and thoughtful steward of this publication when I first met him and through the years he has been a trusted advisor to me on many issues. Ken continues to be a strong supporter of SID and *ID* magazine, sharing his writing talents with us on numerous occasions (including this issue), frequently speaking at SID events and organizing conferences, and being a leading consultant to our great industry. His recognition, as well as that of all the others, is well deserved and we say congratulations to all the honorees!

Display Materials

Our technical theme for this month is Display Materials, and it was developed masterfully by our returning Guest Editor Ion Bita. To get a good introduction to both the latest developments in this field and the articles covering materials in this issue,

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industry news

Samsung Addresses Note 7 Incidents

In a live streaming press conference from Seoul, Korea, in late January, Samsung announced that poorly designed and manufactured batteries from two different sources were the reason that some of its Galaxy Note 7 smartphones had overheated, occasionally to the point of catching fire or exploding. Last fall, Samsung cancelled production of the Note 7 and recalled all the phones that had been sold or were in the sales channel. The company estimates that to date, approximately 96% of phones globally have been returned through its recall program. Samsung also revealed that it lost approximately $5 billion as a result of the recall and production stoppage.

In the conference, D. J. Koh, president of Samsung's mobile communications business, expressed apologies to Galaxy Note 7 customers, mobile operators, and retail and distribution partners, while also thanking them for their patience and continued support. The company indicated that its latest flagship Galaxy S smartphone could be delayed as a result of enhanced product safety measures it has put into place.[1] (The traditional forum for Galaxy S series launches is the Mobile World Congress trade show in February.)[2]

Fig. 1: Samsung's product designs going forward include better battery standards as well as shielding and software algorithms to manage charging temperature, current, and duration. Image courtesy Samsung Electronics.[1]

Several commentators have suggested that the design of the phone itself worked in conjunction with the badly made batteries to cause the problems.[2] Samsung's rather exhaustive infographics, released as part of the press conference, show that – in addition to using rigorously designed and tested batteries – it is adding increased protection within its next phone in the form of enhanced battery packaging and software algorithms to protect against over-charging and over-temperature conditions (Fig. 1).

During the press conference, Samsung also announced the formation of a battery advisory group made up of academics from the University of Cambridge, UC Berkeley, and other institutions, to ensure battery safety and proper procedures in the future.

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Manufacturers Adopt New Color Gamut Specifications

In our July/August 2016 issue, we published a Frontline Technology article by Raymond M. Soneira that discussed important aspects of modern color gamuts in use by the display industry today. One point that Soneira highlighted involved the continuing use of the National Television System Committee (NTSC) color gamut in display specifications. Soneira explained: "…the NTSC color gamut was never actually implemented for volume commercial production of color TVs. As a result, the NTSC gamut was never an actual standard color gamut, and there is essentially no consumer content based on the true NTSC color gamut. This is amusing (and annoying) because now, more than 60 years later, many manufacturers and reviewers are still quoting and referring to the NTSC gamut as if it were some sort of state-of-the-art standard, while in fact it has been obsolete and colorimetrically disjointed from most other standard gamuts for an incredibly long time."

The NTSC gamut is significantly different from all other color gamuts in use today, so NTSC is not useful as a gamut metric. In particular, the NTSC blue primary coordinate represents a very different spectral response than the blue of current standard gamuts, so current content would look rather poor on a display that actually was "100% NTSC" compliant.

In recent years, other authors have voiced concerns about NTSC on the pages of this magazine; and we established an editorial policy of only publishing NTSC gamut specifications when the authors could not provide any other more up-to-date color gamut data for their results. We are pleased to note that recently the message appears to be getting across. In the recent technical specs published for the Microsoft Surface Studio 28-in. PixelSense Display, the company clearly references the sRGB and DCI-P3 color gamuts. When Google initially published its specs for the Pixel smartphone, it referenced the NTSC gamut, but recently Google has updated its verbiage to say "95% DCI-P3 Coverage." The Apple iPhone 7 display specification also references "P3," which we take to mean DCI-P3 as well.

It's harder to find color gamut specs for TV products, but a look at some of the newest announcements shows that they too seem to be moving away from NTCS and toward DCI-P3. We say thanks and tip our hats to those of you who heard the message and are adopting these new and much more meaningful color gamut specifications for your products.

It is important that the display industry, including both display and device manufacturers, specify a product's color gamut in terms of the standards of today, such as sRGB, Rec.709, Adobe RGB, DCI-P3, and Rec.2020 (now BT.2020). This will allow consumers (including developers) to better compare the colors and color accuracy of the displays they are buying.

Now, if we could only get everyone to specify "luminance" instead of "brightness" when referring to the measured light output …

guest editorial

Advances in Materials for Display Applications

by Ion Bita

At the end of May we will once again welcome the Society for Information Display's annual Display Week meeting. Among the wide variety of technology topics included in the program, Display Materials and Processes (DMP) was selected as a special topic track for this year. I have been working with SID program committee colleagues to organize this DMP track, so I was glad to learn that the March/April 2017 issue of *Information Display* was going to include a section on materials. I'd like to take this opportunity to share with you our excitement for the work in materials that is helping to pave the way for future generations of displays.

The number and quality of the papers received in the DMP technical track clearly reaffirmed the role of materials as one of the main pillars in the development of new display technologies and applications. With collaboration across all SID program committee teams, almost 40 presentations were identified and assigned to the DMP track, including papers on emerging electronic and optoelectronic materials, flexible substrates, advanced laser processing, nanomaterials, OLED, LCD, automotive, and touch-sensing applications.

The list above offers an up-to-date perspective of the current trends shaping materials innovation and development across the display industry and in academic research labs. For readers interested in more details, we recommend reviewing the conference program already published on the Display Week website. Most importantly, we recommend attending the conference during May 21–26 at the Los Angeles Convention Center.

In this issue, we include articles on two exciting topics that are currently the subject of intense investigations in the international display community.

In the first article, a team led by Professor Yajie Dong from the Department of Materials Science & Engineering at the University of Central Florida gives an overview of emerging luminescent nanomaterials for applications in displays and lighting devices. Specifically, the authors give an introduction to metal halide perovskite materials and their potential for photoluminescence (PL) and electroluminescence (EL) based display applications. The excitement driving renewed interest in perovskite-based optoelectronics stems from recent progress for photovoltaic applications, coupled with good potential for display applications based on the materials' narrow-band emission spectra, which rivals those produced by semiconductor quantum dots.

Organic-inorganic perovskites (OIPs) of interest in displays have been metal halides of AMX_3 composition, where X is a halide (F^-, Cl^-, Br^-, I^- anions), and M is a relatively small cation (Pb^{2+}, Sn^{2+}, *etc.*) with stable octahedral coordination forming an extended network of MX_6 octahedra layers intercalated with larger A cations (organic, such as $CH_3NH_3^+$, or inorganic, such as Cs^+). This particular crystal structure leads to very well-defined optoelectronic properties due to the formation of an effective quantum well structure, as the semiconducting inorganic layer is confined between organic layers with larger band gaps. This is one of the main attractive properties of OIP, where efficient and narrow band emission (<20 nm FWHM, with PL quantum yield 70–90%) can be achieved even with low-cost processes. This is due to OIP's intrinsic tolerance for material processing variations, unlike the traditional case of semiconductor nanoparticles, which require a tight dimensional control.

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Emerging Solution-Processable Luminescent Nanomaterials in Hybrid Structures Offer New Solutions for Displays and Lighting

As the development of quantum dot and perovskite luminescent materials accelerates, it is expected that these materials will increasingly gain applications in display and lighting markets, particularly in hybrid structures with state-of-the-art phosphor or OLED systems.

by Yajie Dong, Hao Chen, Juan He, and Shin-Tson Wu

Solution-processable semiconducting nanomaterials, including cadmium-based or cadmium-free colloidal quantum dots (QDs)[1,2] and, most recently, metal-halide perovskites[3], have emerged from academic labs to become promising luminescent component materials for optics and optoelectronics in the display and lighting industries. Working as independent players in either photoluminescence (PL) or electroluminescence (EL) mode, these materials could help two competing display technologies (LCDs and organic light-emitting diodes [OLEDs]) in achieving better color quality and higher efficiencies. A recent article published in this magazine by Wang and Sun,[4] "Quantum-Dot and Quantum-Rod Displays – the Next Big Wave," provided a comprehensive overview of this technology, covering both QD-enhanced LCD products in the market and active QD LED research in the lab.

QDs and perovskites are often touted as disruptive material systems that could completely replace traditional phosphor-based LEDs for backlighting LCDs or organic material-based OLEDs. In the near future, however, these materials are more likely to complement than to replace traditional technologies for optimizing color and efficiency in display and lighting applications.

This article will provide an overview of the technology status of solution-processable luminescent QDs and metal-halide perovskite nanomaterials, as well as a report on some of the most recent developments on both PL and EL fronts, and a vision of how these materials could work with traditional technologies in hybrid structures for display and lightings in the near future.

__Yajie Dong__ and __Shin-Tson Wu__ are faculty members at the University of Central Florida. They can be reached at Yajie.Dong@ucf.edu or swu@ucf.edu, respectively. __Hao Chen__ and __Juan He__ are graduate students at the University of Central Florida.

Status Overview of Colloidal Quantum Dots and Perovskites: Merits and Challenges

As outlined in Wang and Sun's article[4], the merits of QDs and perovskites include:

- Precisely tunable emission wavelength through size and/or composition control of QDs and perovskites that can cover a wide range of wavelengths (Fig. 1)
- Highly saturated colors (narrow emission bandwidth)
- High luminescence efficiency
- The ability to be easily solution-processed into large areas with thin, flexible form factors

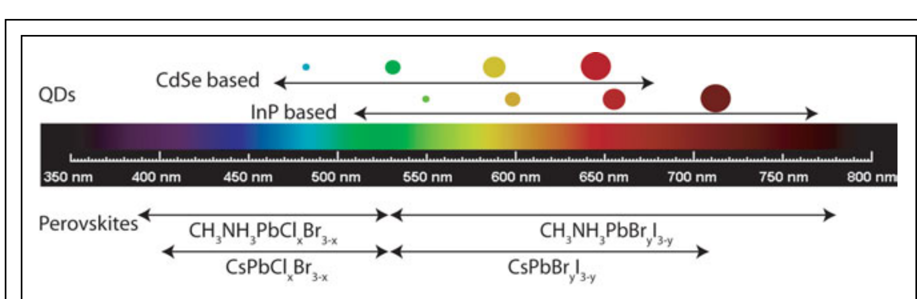

***Fig. 1:** The tunable emission spectral range of solution-processable colloidal quantum dots is shown at the top and that of perovskite materials is shown at the bottom.*

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A closer look at these specific material systems can provide a better understanding of their merits and respective remaining challenges.

Colloidal Quantum Dots: Cd-based *vs.* Cd-free

Colloidal QDs are nanometer-sized (*e.g.* 2 ~10 nm) semiconductor particles whose optical properties are mainly determined by the so-called quantum confinement effect. Simply put, the quantum confinement effect indicates that when the sizes of the semiconductor nanoparticles fall below a certain value, their effective electronic and optical properties (and hence the fluorescent light wavelength) will deviate from the value of their bulk counterpart and be dependent on the particle size. The smaller their size, the larger their electronic bandgap (and thus the shorter their emission wavelength) will be. Therefore, the emission wavelength of QDs can be tuned simply by adjusting the particle size during the synthesis process. The purity of the emission color will depend on the size distribution of the nanoparticles.

As the most developed and well-characterized QD material system, II-VI semiconductor cadmium selenide (CdSe) has a bulk bandgap value of 1.73 eV (corresponding emission is ~716 nm). As schematically illustrated in Fig. 1, the emission spectrum of CdSe-based QDs can be adjusted to cover the entire visible region by tailoring their particle size. State-of-the-art CdSe-based QDs exhibit a quite narrow full width at half maximum (FWHM) of 20 ~ 30 nm and super-high luminescent quantum efficiency (> 95%). QD materials with such high optical quality seem to be a perfect choice for display applications and have already been employed in some commercial products since the first generation QD-enhanced LCD TV (with QD components from QD Vision) was released by Sony in 2013, followed by other brands such as TCL, Haisen, *etc*. However, cadmium is considered a toxic element, and the Restriction of Hazardous Substances (RoHS) directive issued by the European Union requires that the maximum cadmium content be less than 100 parts per million (ppm) in consumer electronic products. This has been a major concern and has limited the industry's adoption of CdSe-based QDs.

The other established QD system, indium phosphide (InP), which is cadmium-free, has a smaller bulk bandgap value of 1.35 eV (corresponding emission ~918 nm). As a result, to reach the same emission wavelength, the size of InP QD particles has to be much smaller than that of CdSe QDs (Fig. 1). This restriction complicates the nanocrystal synthesis process and makes InP QDs' size distribution difficult to control. Thus, the emission of InP-based QDs generally has a broader FWHM (> 40 nm) and lower efficiency. Despite the existing performance gap, InP-based QDs have gained significant momentum, as exemplified by Samsung's recent flagship SUHD TVs, which have been rebranded as QLED TVs for 2017.[6] It should be noted that Samsung's "QLED" TVs remain PL-based LCD products and shouldn't be confused with the emissive EL QLEDs to be discussed later on.

Metal Halide Perovskites: History and Challenges

Metal halide perovskites are a group of emerging optoelectronic materials with perovskite structure AMX_3, where X is generally a halide (F, Cl, Br, I) anion, and M and A are cations of different sizes. The smaller cation M is usually a divalent metal (Pb^{2+}, Sn^{2+}, or other metal ions) with stable octahedral coordination, forming an extended network of MX_6 octahedra intercalated with larger organic or inorganic cations of A (Fig. 2). Among the many options of A cations, of particular interest to the display community could be the organic methylammonium ($CH_3NH_3^+$, MA) or cesium (Cs^+) ions, since compounds of these two (*e.g.* $MAPbX_3$ or C_sPbX_3) exhibit optical properties of similar or even better performances than QDs for certain colors (*e.g.* green).

While the recent fame of perovskite materials is mainly due to the unprecedented efficiency gains of organic-inorganic perovskite (OIP) based solar photovoltaics[7], the history of perovskite research for displays can be traced at least as far back as the 1990s, when David Mitzi at IBM systematically studied OIPs for light-emitting devices and thin-film transistors.[8,9] The OIP was regarded as a unique crystalline organic-inorganic hybrid system in which inorganic components offered the potential for a wide range of electronic and magnetic properties, substantial mechanical hardness, and desired thermal stability. In addition, organic molecules provided high fluorescence efficiency, large polarizability, plastic mechanical properties, ease of processing, and structural diversity. Being crystalline meant that their structures could be well characterized and their chemical, electrical, and optical properties fine-tuned at the molecular level. In certain cases, OIPs can be considered as natural quantum well structures with semiconducting inorganic layers confined by organic layers with large bandgaps. So the quantum confinement effect could be achieved without any physical particle size limits.[9]

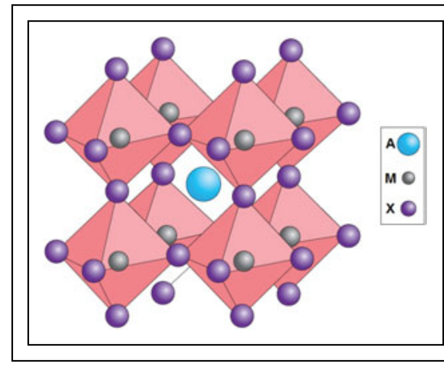

Fig. 2: This scheme represents the crystal structure of a perovskite with chemical formula AMX_3.

Recent studies on metal halide perovskites have extended the materials systems to include both OIPs [*e.g.* $MAPbX_3$ (X=Cl, Br, I)] and purely inorganic perovskites such as $CsPbX_3$ (X = Cl, Br, I) (Fig. 1). Meanwhile, the merits of most perovskites seem to resonate with those early considerations of OIPs in the 1990s: (i) these materials can be easily solution-processed into crystalline thin films; (ii) with simple tuning of the halide components, they can emit over the entire visible spectrum; (iii) the purity of their emission color seems to be relatively independent of their particle size. Particularly for $CH_3NH_3PbBr_3$ or $CsPbBr_3$, highly efficient green emission with a narrow FWHM of less than 20 nm can be achieved even with large particle size variations. This capability makes these perovskites especially promising for wide-color-gamut display applications.

It should be noted that the original challenge that hindered Dr. Mitzi from further exploration of OIPs is still relevant today[8]: Most perovskite materials have major stability issues. The instabilities of perovskites are often attributed to their low formation energy, or the energy needed to form them (~0.1–0.3 eV), which makes it easy for them to be conveniently solution processed, but also renders them vulnerable to external stresses, such as moisture, heat, light, or electrical field.[8,10] It has been observed that, in the presence of moisture and oxygen, the OIP grains grow spontaneously even at room temperature, leading to a higher density of defects and a shorter carrier lifetime.[11] While it can be envisioned that OLED encapsulation technology such as cover glass or barrier films could help protect perovskite devices as well, the intrinsic stability of perovskite materials also needs to be significantly enhanced.

Three passivation strategies have been developed to stabilize perovskites, with successes of different levels. One commonly used approach involves film formation through impregnation and pore filling of a pre-formed mesoporous inorganic matrix (such as TiO_2 or Al_2O_3) with the perovskite precursor solutions.[3,7] However, the solvent evaporation from pre-formed, and thus static, inorganic porous structures will inevitably lead to partially exposed, unprotected perovskites. In fact, it has been reported that significant decomposition already occurs during annealing of perovskites on porous TiO_2 at 85°C, even in an inert atmosphere. Further coverage of these perovskite films with carbon nano-tube/polymer composites demonstrated impressive "water-resistant" devices, but such macroscale passivation leaves perovskites vulnerable to potential degradation due to film leakage.

The second strategy, solution-based synthesis of surfactant-protected perovskite nanoparticles, employs a surfactant-assisted growth technique similar to Cd-based QD synthesis. This technique can achieve passivation of individual nanocrystal grains and lead to colloidal perovskite QDs (both OIPs[12–15] and inorganic perovskites[16,17]) with enhanced stability and photoluminescence quantum yield (PLQY). As shown in Fig. 3, by tuning halogen components, the emission spectra of both $MAPbX_3$ and $CsPbX_3$ QDs can cover the entire visible spectrum. Of the various demonstrated colors, the green emission of bromide perovskites ($MAPbBr_3$ and $CsPbBr_3$) stands out with its ultra-high color purity (FWHM <20 nm) and high PLQY (~70–90%). This green purity is particularly interesting for display applications, because the human visual system is very sensitive to green color, and slight changes in green can lead to big color gamut variation. By comparison, even the best CdSe-based green QDs normally show a broader emission, with FWHM > 25 nm. While surfactant passivation can stabilize perovskite QDs in the solution phase, when they are processed as thin films, their efficiency tends to be substantially reduced because of quenching induced by spontaneous QD aggregations.[18] In addition, the reaction yield of perovskite QDs remains low. The large overlap between absorption and emission spectra [Fig. 3(e)] also indicates that self-absorption could be an issue for PL or EL applications.

The third strategy involves deposition of composite films from mixtures of perovskite precursors with protecting media, such as organic small molecules, polymers,[19] or inorganic nanoparticles.[20] Although inherently simple, this approach often results in serious phase separation between OIPs and the protecting media, leading to large OIP grain-size variation, broad PL peaks, lower PLQY, and unsatisfactory robustness. In the most recent study, by controlling the crystallization process from precursor solutions, a green perovskite containing polymer films with very high PLQY (94%) was reported, although its thermal stability remains unsatisfactory.[21]

Stable Perovskite-Polymer Composite Films via Swelling-deswelling Microencapsulations

A microencapsulation strategy has recently been developed by the authors' team to achieve well-dispersed, intimately passivated OIP ($CH_3NH3PbX_3$, $MAPbBr_3$) nanoparticles inside polymer matrices. This formulation could lead to OIP-polymer composite films with high photoluminescence efficiency, color purity, and ultra-high stability against heat and water exposure.[22]

This strategy takes advantage of the well-known swelling-deswelling phenomenon in

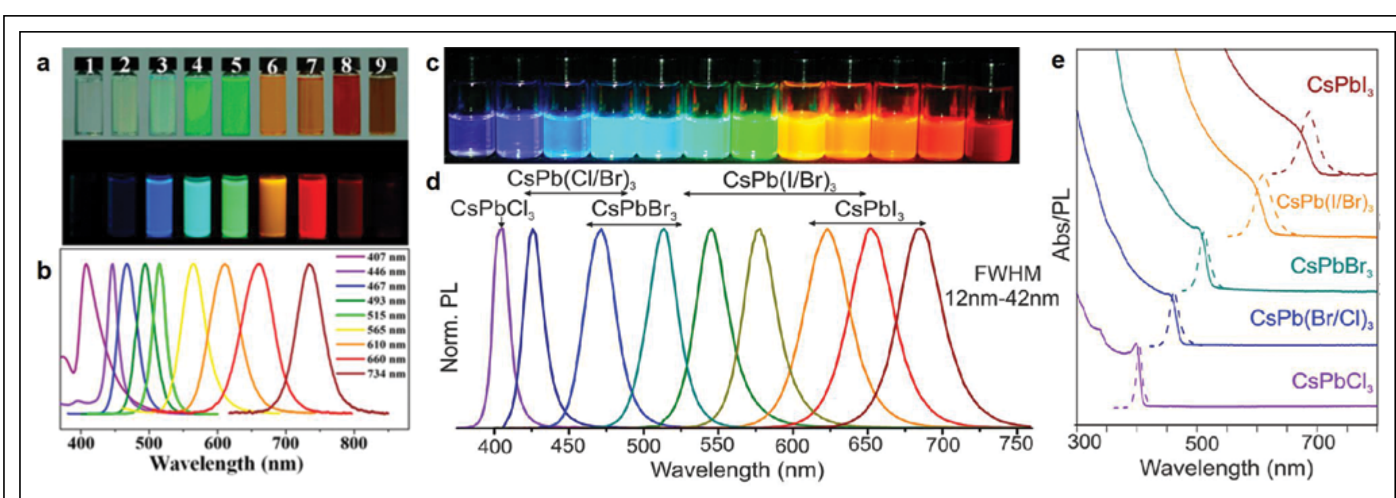

Fig. 3: *In (a), an optical photograph (top left) shows suspensions of mixed halide $MAPbX_3$ (X being I, Br, or Cl) perovskites under visible and UV light, with (b) their corresponding PL spectra.[14] In (c) (top center) an optical photograph shows suspensions of mixed halide $CsPbX_3$ (X being I, Br, or Cl) perovskites under UV light with (d) their corresponding PL spectra, and (e) typical optical absorption and PL spectra.[16]*

polymer physics. When brought into contact with good solvents, polymer chains will swell and expand, letting in solvents and solutes. Such expansion is generally reversible through a deswelling process, when the solvent is evaporated. OIP precursors can be introduced into polymer matrices as solute through the solvent-induced polymer swelling process. When the solvent is driven out of the polymer matrix (*e.g.* by heating), the OIP precursors will be left within the matrix to react and form high-quality, well-dispersed OIP nanoparticles. Meanwhile, the polymer matrix will deswell, shrink back, and form a coherent barrier layer around the OIP nanoparticles, protecting them from water, oxygen, or heat in the surrounding environment [Fig. 4(a)].

This strategy was demonstrated to be general, effective, and robust. A series of technically important polymer substrates (including polystyrene (PS), polycarbonate (PC), acrylonitrile butadiene styrene [ABS], *etc.*,) that swell in dimethylformamide solvent can be easily converted into highly luminescent OIP-polymer composite films through either cotton swab painting [Fig. 4(b)] or spin coating [Fig. 4(c)] of OIP precursor solutions. These composite films show high photoluminescence quantum yield (PLQY) of up to 48% and superior color purity owing to FWHM as small as 18 nm (narrower than even the best-performing CdSe-based green QDs).

Most importantly, these OIP-polymer composite films possess unprecedented water and heat stability. Some OIP-polymer composite films ($MAPbBr_3$-PS, $MAPbBr_3$-PC, and $MAPbBr_3$-ABS films) can be immersed directly in water for two months, and experience less than 7% reduction of PLQY, indicating significant water stability [Fig. 4(d)]. Among them, $MAPbBr_3$-PS and $MAPbBr_3$-PC composite films can survive boiling

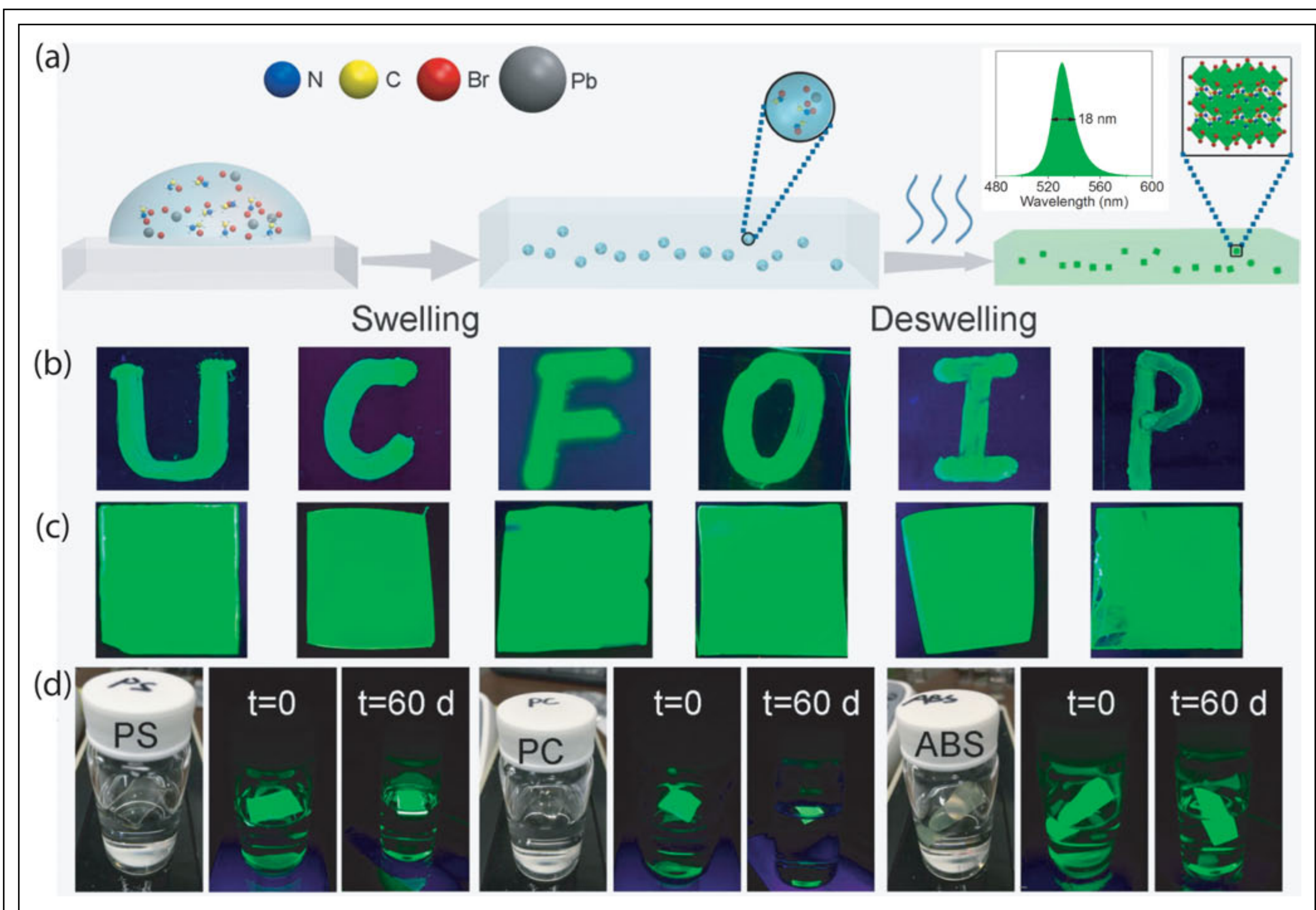

Fig. 4: *Above appears the swelling-deswelling microencapsulation strategy for OIP-polymer composite films. In (a) is a scheme of $MAPbBr_3$ – a polymer composite film formation process through swelling-deswelling (the inset shows a typical emission spectrum of as-prepared films). In (b) and (c) are images of the luminescent composite samples prepared by cotton swab painting (b) or spin coating (c) under UV excitation (365 nm). Samples from left to right are $MAPbBr_3$-PS, $MAPbBr_3$-PC, $MAPbBr_3$-ABS, $MAPbBr_3$-CA, $MAPbBr_3$-PVC and $MAPbBr_3$-PMMA respectively. In (d) are shown stability characterizations of the composite film samples ($MAPbBr_3$-PS, $MAPbBr_3$-PC and $MAPbBr_3$-ABS) immersed in water.*

water treatment for 30 minutes with PLQY degradation of less than 15% and 7%, respectively, indicating high thermal and water stabilities even without any special barrier layer protection.[22]

Compared to Cd-based QDs, these perovskite-polymer composite films show clear advantages in terms of simpler processing (thus potentially lower cost), better color purity, and lower toxicity (according to RoHS regulations, the allowable concentration limit for Pb is 1,000 ppm, one order higher than that for Cd). Further investigations of PL efficiency and long-term stability under high optical flux conditions are needed to estimate their potential as a lower-cost, yet better-performing alternative to the green QD downconverters used in today's QD-enhanced LCDs.

Photoluminescent Perovskites Work with QDs or Phosphors for LCD Backlights

While perovskite materials emitting other colors are under active development, the outstanding green perovskite-polymer composite films could work synergistically with other red downconverters in the near future. Besides CdSe- or InP-based red QDs, various narrowband red phosphors could also be their good partners. Specifically, a $K_2SiF_6:Mn^{4+}$ (KSF/PFS) phosphor has been demonstrated to be a red downconverter with narrow emission peaks centered at 631 nm, with high conversion efficiency and high stability that could enable on-chip LED integrations. Recently, KSF/PFS phosphors have been commercialized by GE under RadiantRed and TriGain trademarks and have started to be adopted by major customers in the display and lighting industries.[23,24] Another narrowband red phosphor ($Sr[LiAl_3N_4]:Eu^{2+}$, SLA) with longer emission wavelength also exhibits an exceptional stability.[25] In the following section, we will discuss two configuration options in which these red downconverters could work with green perovskite-polymer composite films for LCD backlight unit (BLU) applications, and analyze the potential color gamut performance gains in these configurations.

Three commonly used downconverter backlight geometries are "on-chip," "on-edge," and "on-surface".[26] With simple, large-area processability and low cost, perovskite-polymer composite films are ideally suited for "on-surface" configuration. With high thermal stability, KSF/PFS or SLA phosphors can be applied in an "on-chip" configuration. For

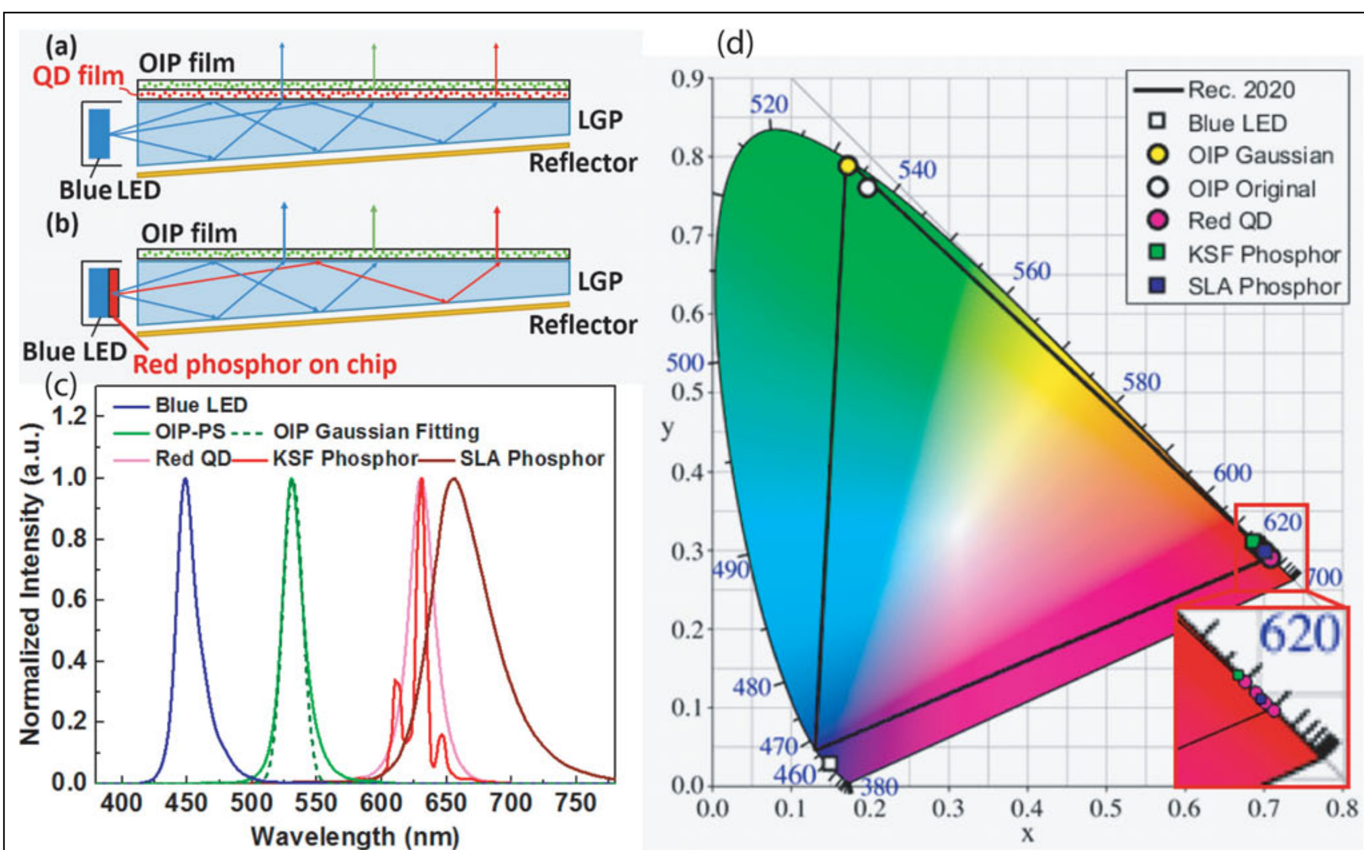

Fig. 5: The integration of perovskite-polymer composite films is shown with various red downconverters. Above are backlight system configuration for: (a) blue LED + green OIP + red QDs; (b) blue LED + green OIP + red phosphor (or red QDs in future); (c) the spectra of primary colors used for calculation; and (d) RGB color primaries in CIE 1931. Rec.2020 is plotted for reference. Insets on the right show relative positions of different red emitters.

QDs, while all three configurations have been reported, the currently commercialized products use "on-surface" configuration, and are called quantum dot enhancement films (QDEFs). Thus, the combination of green perovskite-polymer composite films and QD or phosphor can be carried out in the following two geometries:

(1) Blue LED with on-surface green OIP above red QDs. Fig. 5(a) shows the configuration of "back-to-back" green OIP/red QDs film pumped by blue LED. In terms of reducing reabsorption and enhancing the photoluminescence, the layered structure with green emitters on top of red emitters was found to be more effective. Considering their wavelength tunability, QD spectra with a series of peak wavelengths (630, 635, 640 nm) have been analyzed.

(2) Blue LED with on-chip red KSF/PFS phosphor/red SLA phosphor and on-surface green OIP [Fig. 5(b)].

Fig. 5(c) shows the spectra of high-power blue LED, green OIP-polymer composite film, and red QDs or phosphors. Their respective positions in the CIE 1931 have been marked in Fig. 5(d).

Table 1 lists the analysis results of color gamut coverage and total light efficiencies (TLEs) when a commercial color filter and liquid-crystal system are taken into consideration.[26] Clearly, in order to gain wide color gamut while maintaining a moderate TLE, BLUs with green OIP-polymer composite films and 630-nm QDs or KSF phosphor are ideal choices, with nearly 90% Rec.2020 and around 20 lumens-per-watt efficiency. Among these, the combination of on-chip KSF phosphor and on-surface perovskite-polymer film are particularly promising for low-cost, efficient, color-vivid, and cadmium-free BLUs for LCDs.

Table 1. Below are the Rec.2020 color gamut coverages in CIE 1931 and total light efficiencies (TLEs) of several proposed configurations.

BLU Red Emitter Choice		No LC/CF	With CF	
		Rec.2020	Rec.2020	TLE (lm/W)
QDs	630nm	88.7%	89.6%	19.5
	635nm	89.5%	90.5%	18.5
	640nm	90.0%	91.2%	17.2
KSF Phosphor		88.2%	81.7%	20.2
SLA Phosphor		89.7%	85.2%	11.4

Electroluminescent Colloidal Quantum Dot and Perovskites for Displays and Lighting

When using QDs or perovskites as the emitting layer in an OLED-like EL device structure, quantum dot LEDs (QLEDs) or perovskite LEDs (PeLEDs) can be achieved. Because of the unique material merits discussed in previous sections, QLEDs and PeLEDs promise to enable solution-processable, highly efficient light-emitting devices with tunable colors of high purity. At the same time, the challenges introduced earlier (such as stability issues and color variations) remain potential obstacles for these materials' EL applications in displays or lighting.

PeLEDs and QLEDs: Development Status Varies for Different Colors

With the upsurge of perovskite solar cell research, PeLEDs have been revisited in the past several years in either forward[28] or inverted[29,30] OLED structures, and even in single-layer, light-emitting electrochemical cell structures.[31] For PeLEDs with colors in display-relevant regions, green devices are the most developed, with demonstrated efficiencies of 42.9Cd/A[28]. However, it should be noted that very few papers have reported lifetime data for PeLED devices, suggesting that reliability remains one big challenge for PeLEDs that needs to be addressed before the

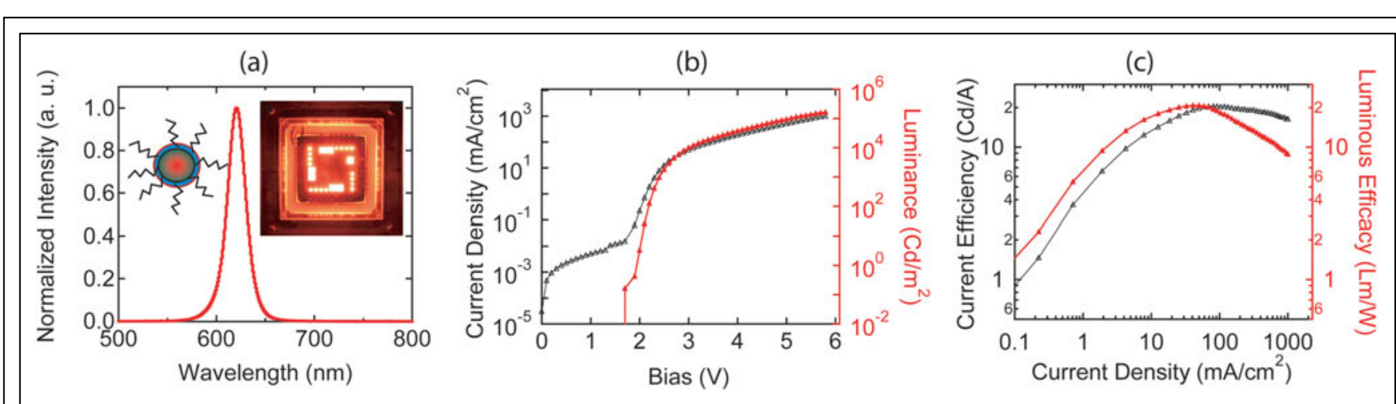

Fig. 6: Ultra-bright, highly efficient, low roll-off quantum-dot light-emitting devices (QLEDs) are demonstrated as follows: (a) spectra of QLED electroluminescence (inset: scheme of core/shell/ligand based quantum dots and photograph of a typical test chip); (b) luminance and current density vs. driving voltage; and (c) luminous efficacy and current efficiency vs. *driving current density for a typical device.*

technology can be developed into something of broader industrial interest. For further details on PeLED developments, interested readers can turn to several recent review papers.[32–34]

QLEDs are widely regarded as the next generation of self-emissive displays after OLEDs. Samsung's recent acquisition of QD Vision has been taken as a signal of the company's dedication to QDs and strong interest in QLEDs.[35] Among QLEDs with visible colors,[36–40] red QDs are currently the most developed in EL devices. Solution-processed CdSe-based red QLEDs 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-nm range.[36,37,40] In contrast, green and blue QLEDs remain inferior to their OLED counterparts.[38,39] This is partly because of the size-dependent quantum confinement effect; *i.e.,* red QDs usually have the biggest size among QDs of all visible colors and can tolerate relatively large absolute size variation while still maintaining a tight percentage distribution, thus high color quality and efficiency.

In particular, the authors recently developed ultra-bright and efficient deep red CdSe-based quantum dot light-emitting devices (QLEDs).[40] The device EL spectrum shows an FWHM of only 22 nm at CIE coordinates of (0.69, 0.31). More importantly, these devices achieved high peak current efficiency (20.5 Cd/A at ~20,000 Cd/m^2 with a driving voltage of only 3.5 V), high luminous power efficiency (with a peak level of 20.8 Lm/W) and small efficiency roll-off at high driving current density (Fig. 6). Ultra-high luminance of 165,000 Cd/m^2 was achieved at a current density of 1000 mA/cm^2 with a driving voltage as low as 5.8 V, which sets a new luminance record for existing organic-related, red, light-emitting devices.

Hybrid White OLED with Narrow Red QD Emitters for Lighting

Considering the demonstrated merits and existing challenges of QLEDs and PeLEDs, it will be difficult for them to displace OLEDs completely in the near future. Instead, a hybrid device that could integrate the advantageous QD or perovskite components with existing OLEDs will probably be a viable

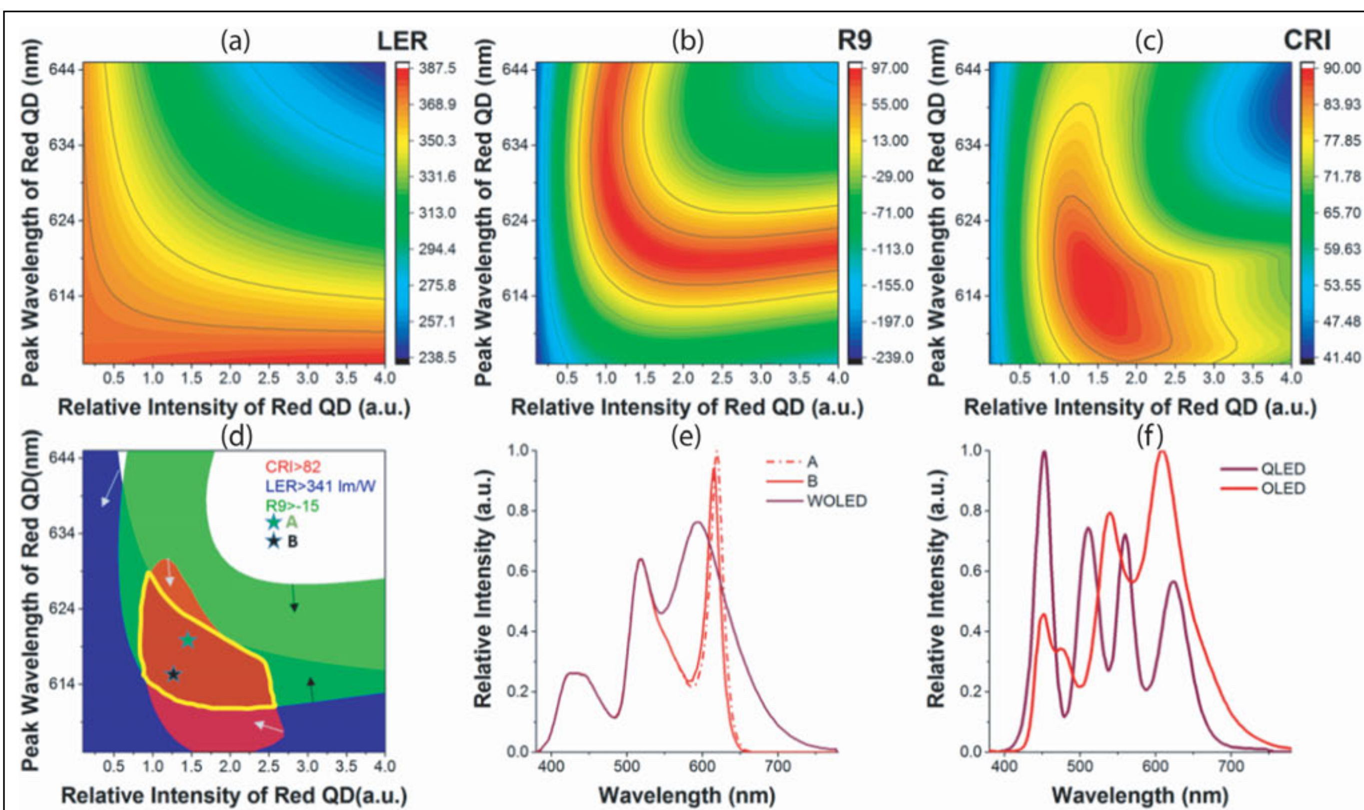

Fig. 7: This spectra analysis of the advantages of hybrid WOLED incorporating narrow red QD emitters includes: the contour plot of (a) LER, (b) R9 and (c) CRI for hybrid WOLED spectra when replacing the red organic emitter peak with red QDs' narrow spectra; (d) overlap improvement area for wavelength and intensity (surrounded by yellow line) when CRI > 82, LER > 341 lm/W, and $R_9 > -15$, which are better than all the performance metrics of the original WOLED; (e) spectra of WOLED and two typical spots A and B (as denoted in d) obtained by replacing the red organic emitter peak of the WOLED with red QD spectra at different wavelengths and relative intensities; and f) spectra of all-organic emitter WOLED from LG Display and all-QD WOLEDs.[40]

entry point for these materials to enter the display or lighting industry.

State-of-the-art white OLEDs (WOLEDs) use organic emitters for all colors and cannot achieve simultaneously high luminous efficacy and good color quality primarily due to the absence of organic emitters with narrow red emission peaks.[41] Integrating narrow red-emitting QDs with organic blue and green emitters will help solve this problem. The integration could be based on tandem multi-stack structures (as in the all-organic WOLEDs from LG Display) or on a single-stack device structure in which emitters of different colors share the same electron/hole injection or transport layers. Figure 5 analyzes the potential benefit of replacing an existing red organic emitter in a single-stack WOLED device[42] with red QDs' narrow spectra of different intensity or peak wavelength choices. The resultant spectra have been analyzed for the enhancement of three key solid-state lighting performance metrics: the Color Rendering Index (CRI), R_9, and luminous efficacy of radiation (LER), and then compared to the original OLED's performance.

As shown separately in Fig. 7 (a)–(c), each of these metrics can reach a very high value (with LER_{peak} = 387.5 lm/W, CRI_{peak} = 91, and $R_{9\ peak}$ = 97) by simply tuning the peak wavelength and intensity of the red QD emitter. When comparing Fig. 7(a), (b), and (c), the overlapped region highlighted within the yellow boundary line indicates the parameter improvement zone where the color performance (CRI and R_9) and efficacy (LER and efficacy without extraction enhancement) can be improved simultaneously. This overlap area is large enough and provides sufficient design freedom to allow researchers to tune and optimize the three parameters. The authors have selected two representative points and listed their corresponding LER, CRI, and R_9 in Table 2. In either case, all three parameters have been significantly improved compared to the original white OLED. Case A can achieve ~18% improvement in LER with comparable color performance to an all quantum-dot white LED,[43] while Case B can get ~9.5% improvement in LER with much better color than an all-organic WOLED from LG Display.

These initial results show that narrowband red QD emitters can significantly improve both color rendering and optical efficiency over state-of-the-art WOLEDs, where the ability to tune the peak wavelength and relative intensity of red QDs gives the resulting hybrid WOLED system the flexibility to achieve different color or efficiency targets with the same organic emitter materials.[44] So as long as their respective emission properties can be well reserved in the hybrid system, integrating red QDs into WOLED emitters will bring breakthroughs to the efficiency and color performances of OLED-based solid-state lighting.

In addition, it should be noted that this hybrid WOLED concept will provide a hybrid device platform for future developments. Novel materials, such as long-lifetime, high-efficiency, thermally activated, delayed-fluorescence (TADF) blue organic emitters, as discussed in another article in this issue,[45] could be integrated into this platform in the future, leading to further performance improvements.

Table 2. Performance improvements can be realized by replacing the existing red organic emitter with the narrow-band red spectra of QDs [A and B as marked in spectra of Fig. 7 (d) and (e)].

	LER [lm/W]	CRI	R_9
WOLED	341	82	–15
A	349	90	81
B	359	91	32
All organic WOLED by LG Display[41]	328	89	31
All QD WOLED[43]	296	93	75

A Hybrid Future

As emerging solution-processable luminescent nanomaterials, QDs and perovskites have outstanding merits of tunable color with high purity and high efficiency, but still suffer from stability issues for certain colors. Hybridization of these exciting new components with state-of-the-art phosphor or organic materials in PL or EL modes could accelerate their adoption in the near term and favorably impact the display and lighting markets.

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Thermally Activated Delayed Fluorescence Is a Key New Technology for OLED Displays

TADF emitters are poised to contribute to the next material-driven advancement of the OLED industry, making OLEDs ideal for even more applications.

by Daniel Volz

In the last few years, the development of new materials has had a significant impact on the advancement of organic light-emitting diodes (OLEDs). Thanks to these advanced materials, OLED displays are now being used in smartwatches, smartphones, and TVs. However, there is still room for improvement in areas like display resolution and energy efficiency. Thermally activated delayed fluorescence (TADF) is a relatively new technology that has been developed to tackle these issues. This article describes the crucial role of emitter materials in OLED technology, and introduces the TADF concept.

OLEDs were first developed in the 1990s,[1] but began to be used in commercial products just several years ago. Inside an OLED, the main properties are dictated by the so-called emitter, a molecule that can make direct use of the energy provided by the electric current to generate visible light. A simplified diagram of an OLED appears in Fig. 1.

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Role of the Emitter in OLEDs

Three main principles are used to convert electrical energy into light: fluorescence, phosphorescence, and thermally activated

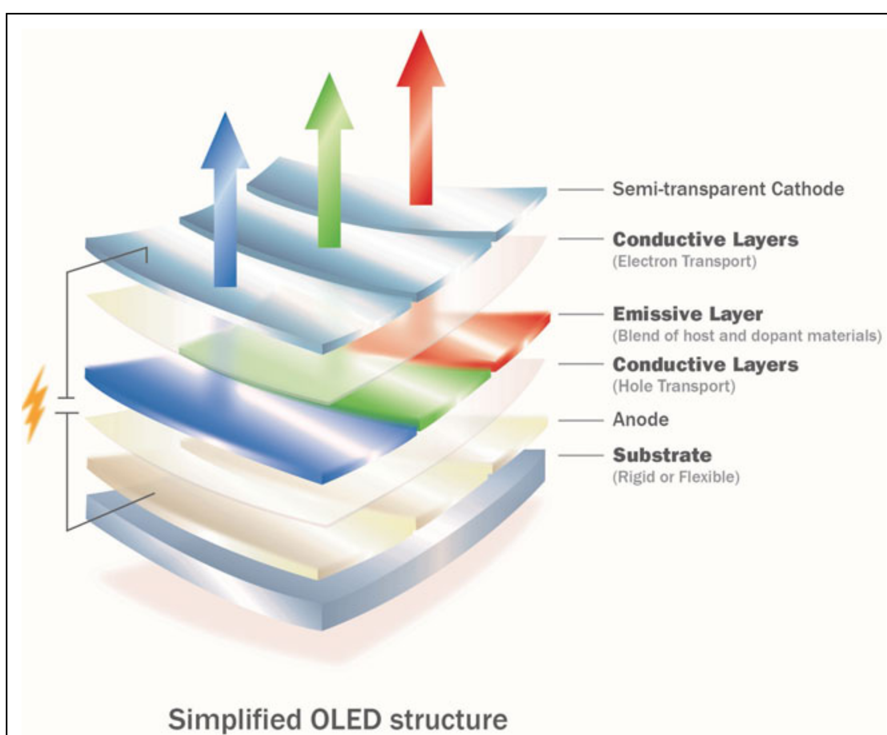

Fig. 1: OLEDs consist of multiple thin, organic layers. While this simplified structure shows a total of six layers including the substrate, commercial OLEDs sometimes consist of many more layers – as many as 15 or more. The emitter or dopant materials are in the emissive layer.

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delayed fluorescence (TADF). In the earliest OLEDs, fluorescent materials (FLUO) were used.[3] Around 1998, it was found that phosphorescent materials (PHOS) could also be used in OLEDs, which led to a significant increase in efficiency.[4,5] Recently, TADF materials have also been found to be suitable for very efficient OLED devices.[6–8] TADF can be as efficient as phosphorescence, with up to 100% internal quantum efficiency.

The impact of using different emitter materials in commercial products can be seen in Fig. 2, where selected key performance indicators are plotted for various generations of Samsung's Galaxy smartphones. The initial commercialization of OLED displays was possible only after the development of phosphorescent red emitters with suitable stability and efficiency.[4]

Consequently, the first-generation Samsung phone, the S1, featured fluorescent materials for green and blue pixels, while red pixels contained phosphorescent materials. After the introduction of green phosphorescent materials, average power consumption dropped from 2.5 to well below 1 watt. The display's resolution was also doubled to roughly 400 pixels per inch. Using the more efficient phosphorescent green materials allowed display manufacturers to significantly decrease the size of green pixels, which allowed for an increase in resolution.

The main differences between fluorescence, phosphorescence, and TADF are summarized in Table 1 and Fig. 3. For fundamental physical reasons, FLUO is less efficient than PHOS or TADF. The differences are caused by quantum-mechanical effects that lead to the formation of two different kinds of excited states when the electrical energy is being transferred to the emitter molecule: so-called singlet and triplet excitons. Because of quantum statistics, singlets and triplets are formed in a ratio of 1:3 upon recombination of electrically injected electrons and holes.[7–9] FLUO is only capable of using singlet excitons, meaning that only 25% of the formed excitons will generate light, while 75% of the electric energy going into the OLED device is essentially lost.

PHOS and TADF employ two different strategies to generate photons from both singlet and triplet excitons. These strategies enable 100% efficiency:

- PHOS emitter materials employ rare heavy metals such as platinum and iridium to enable a quantum-mechanical phenomenon called spin-orbit coupling, which increases the radiative rate of triplet excitons. The main downside of this approach is the availability (and price) of such elements. Even elements such as uranium or rare earth elements (such as lanthanum and gadolinium) are more abundant than iridium.[2]
- TADF emitters, on the other hand, are metal-free molecules. A special molecular design principle evens out the ener-

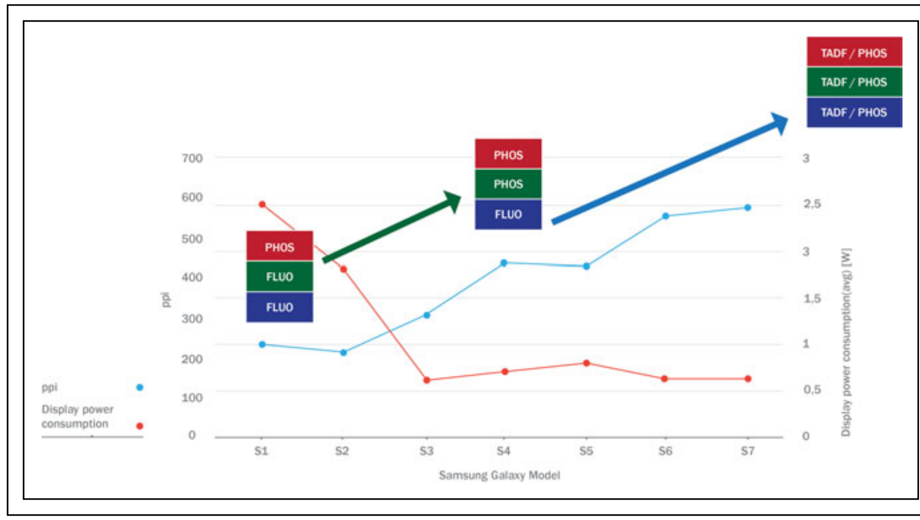

Fig. 2: *The display resolution (in pixels per in. or ppi) and average power consumption (in watts) of several generations of Samsung Galaxy smartphones featuring OLED displays shows that significant improvement correlates to the use of new generations of materials. (Credit: Display power management data and ppi are from the DisplayMate article series on the Samsung Galaxy smartphones. Displaymate.com/mobile.html.)*

Table 1. The major differences among the main emission principles (FLUO, PHOS, and TADF) used in OLEDs are shown in terms of performance and features.

	Performance	Key feature
FLUO	25% of the energy can be used for light generation	Generally used for blue and often green pixels. Focus on efficient emission from the S1 to S0 level to use singlet exciton emission.
PHOS	100% of the energy can be used for light generation	Generally used for red pixels and in some cases also in green pixels. Blue phosphorescent emitters do not show enough stability. Heavy-metal-based materials that feature large spin-orbit coupling to harvest both singlet and triplet excitons. Metals can be iridium, platinum, or osmium, for example.
TADF	100% of the energy can be used for light generation	Comparable efficiencies to PHOS but a higher stability is expected. Materials feature carefully adjusted energy levels S1 and T1, to allow for a small ΔE(S-T) to harvest both singlet and triplet excitons.

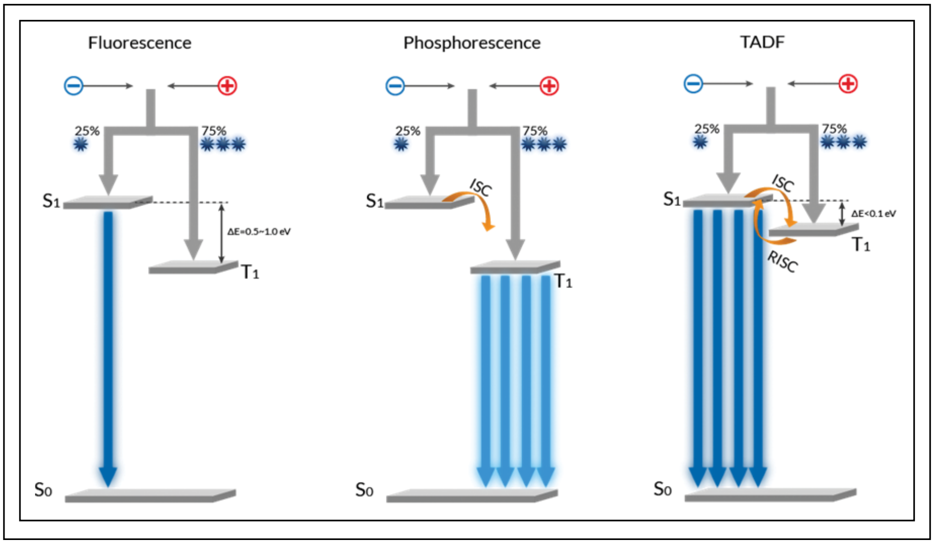

Fig. 3: Emission principles used in OLEDs include: fluorescence (FLUO), which often relates to the first emitter material generation; phosphorescence (PHOS), which is the second material generation; and TADF, which marks the latest conceptual development.

getic differences that normally are found between singlets and triplets. In fact, the energetic differences are so small that the thermal energy at normal environmental temperatures is enough to help excitons move from the triplet to the singlet state, where they can then be transformed to visible light. Using this process, every exciton in the device can be used to emit light, which corresponds to 100% internal quantum efficiency and is comparable to phosphorescent emitters.

Electroluminescence mechanisms aside, FLUO, PHOS, and TADF emitters are synthesized using well-established chemical techniques similar to those employed for the large-scale production of pharmaceuticals such as aspirin, as well as for fertilizers and plastics.

Closing the Blue Gap in Displays

Aside from sustainability concerns, which stem from the fact that extremely rare elements such as iridium are required to make PHOS materials, there is also a technical issue that favors TADF over PHOS materials: the blue gap, which denotes the current trade-off between the efficiency and the stability of blue emitters. Figure 2 indicates that as of today, blue pixels of commercial products contain FLUO materials, even though they are less efficient. The reason for this is that – even after almost 20 years of industrial and academic research in the field of PHOS emitters – science has failed to produce a blue PHOS material that combines efficiency, stability, and a proper color point. If a blue emitter were to show high efficiency and long lifetime, as TADF is promising to do, this would create great opportunities to develop better products with even lower power consumption and better resolution. To date, it has been demonstrated that TADF emitters can deliver an excellent blue color point, while methods to achieve improved efficiency and stability are still being developed.

Figures 4 and 5 indicate the impact of the blue gap in existing blue fluorescent emitters. All OLED displays currently require relatively large blue pixel areas to reach enough brightness in the display. In smartphones, with red, green, and blue pixels, the blue pixel makes up 52% of the total area. Having TADF or PHOS pixels with a much higher efficiency would enable the display manufacturers to make smaller blue pixels to yield the same amount of light, which would pave the way again to increased resolution. Apart from a better display, customers would also benefit from a longer battery life for their mobile device. Battery life is closely connected to the power consumption of the display.

OLED TVs have a complex stack architecture, essentially making white light from red, green, and blue emitting layers and then using color filters to separate the colors again for the

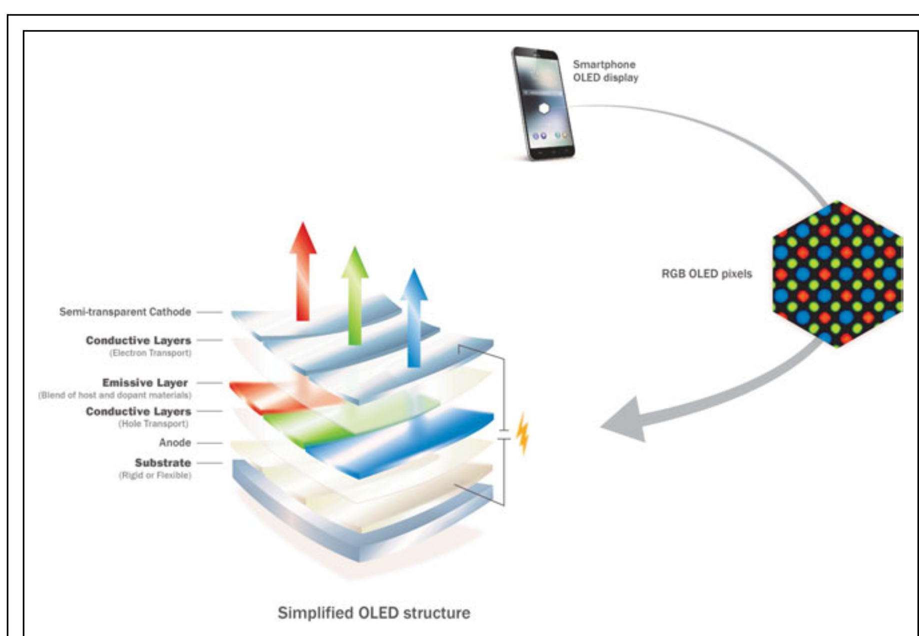

Fig. 4: This simplified OLED structure is the type generally used in smartphone displays. The light emitted by the blue, red, and green pixels directly generates the displayed image. Currently, the blue pixel area is on the order of 52% of the total display area.

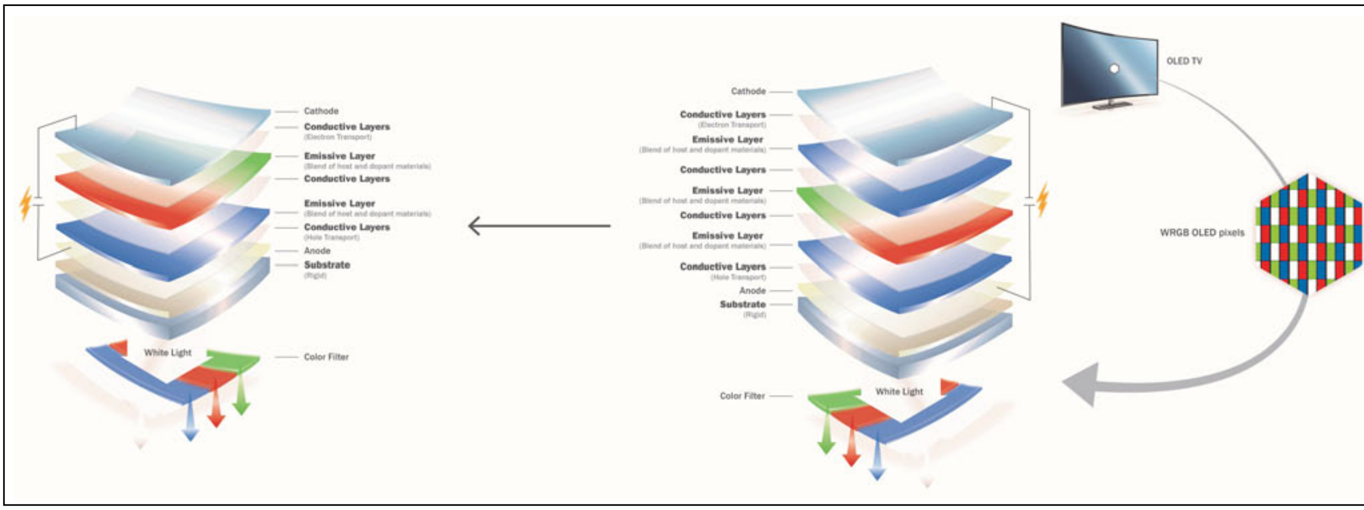

Fig. 5: This simplified OLED structure is the type commonly used in TV displays. For such applications, complex architectures are used to create white light, including color filters to create the image. Currently, the surface area of blue pixels is on the order of more than 50%.

different pixels. Having a more efficient blue, which again makes up about 50% of the display area, would effectively reduce the power consumption of the TV by switching to a less complex stack design (such as in Fig. 4), which could potentially reduce manufacturing costs.

TADF Is Catching Up Quickly

Conceptually, donor and acceptor groups such as the ones shown in Fig. 6 can be connected in many different ways, as is illustrated in Fig. 7, which provides several recent examples for actual TADF molecules.

During the last two years we have witnessed major improvements in TADF materials, which now can surpass (blue) or reach similar performance (red and green) as conventional PHOS materials in terms of color point, efficiency, and stability. A main driving force behind this progress was the development of suitable screening algorithms for molecular design, which make use of density functional theory (DFT) calculations (Fig. 6). These computational tools drastically increased the efficiency of material development by allowing only promising, highly efficient TADF materials to be synthesized. This leads to extremely short material development cycles with a very steep learning curve per cycle.

Results based on this development approach were recently published by our team at CYNORA. We reported several blue materials, among them a blue emitter reaching 14% external quantum efficiency (EQE) at 500 nits and a lifetime to 80% of the initial luminance

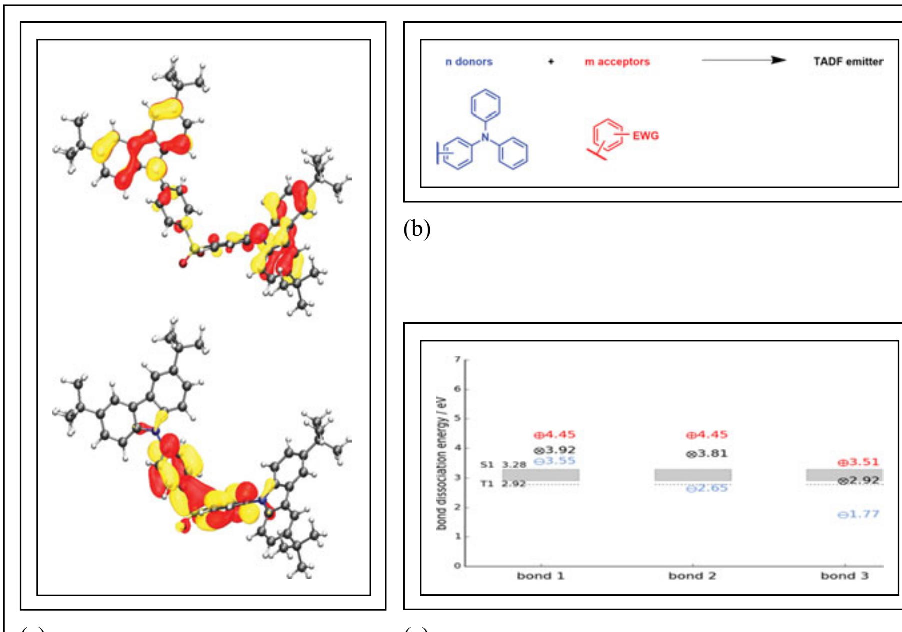

Fig. 6: Density functional theory (DFT) calculations are one cornerstone of the development of TADF materials (a). It is possible to use the computational prognosis, based on empirical results, as a pre-screening tool to avoid bad TADF emitters. This methodology drastically accelerates material development. Conceptually, TADF molecules consist of donors and acceptors covalently bonded (b). Apart from the prediction of TADF properties, molecular issues can also be seen in DFT calculations. Weak bonds, for example, can be identified by calculating the bond dissociation energy (c).

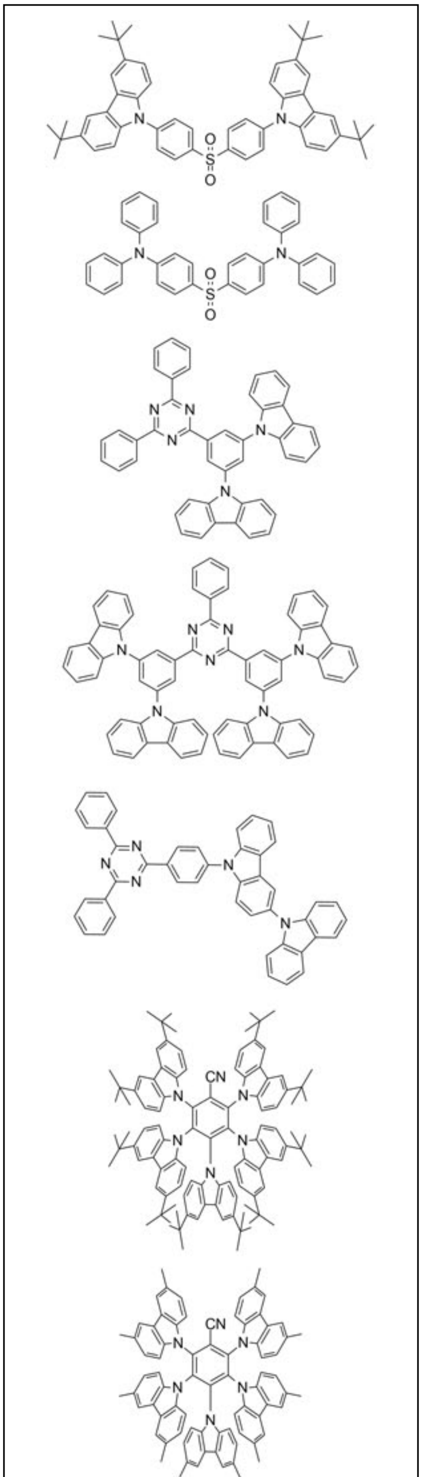

Fig. 7: These selected blue TADF emitters were recently published by researchers Lian Duan, Chihaya Adachi, and Jun Yeob Lee.[10-12]

(LT 80) of 420 h at 500 nits starting luminance.[13] This material featured an emission maximum below 480 nm. Properties of a recently developed material are shown in Table 2 and Figs. 8 and 9. The electro-optic JVL characteristics of this material in a simple device architecture, using the literature-known host mCBP[14] (short for 4,40-bis(3-methylcarbazol-9- yl)-2,20-biphenyl), demonstrate about 4.2 volts at 500 nits. The so-called blue index, which can be calculated by dividing the current efficiency in cd A^{-1} and the CIE_y color coordinate (for CIE coordinates, see Fig. 10), approaches 80 at 500 nits in a bottom-emitting device.

Ir(dmp)3, short for iridium (III) tris[3-(2,6-dimethylphenyl)-7-methylimidazo[1,2-f] phenanthridine], currently represents (in the literature) the most stable blue iridium emitter with a relatively blue color point (CIE 0.15 / 0.31, see Fig. 10 for definition) and decent efficiency of 8% EQE at 1,000-nits luminance in a conventional OLED architecture. In a recent study by Forrest and co-workers,[15] the basic performance was reported in the same host used to obtain the data shown in Table 2.

Table 2. This table shows the device performance of the CYNORA material (TADF) vs. $Ir(dmp)_3$, currently the most stable and efficient blue phosphorescent emitter,[15] in 13 w-% mCBP (PHOS).

	CIE (1000 nits)	EQE (1000 nits)	LT80 (500 nits)
TADF	(0.17, 0.27)	12%	94
PHOS	(0.16, 0.31)	8%	ca. 100

The LT80 at 500 nits was estimated from the values given in the publication. Even using a simple, non-optimized screening architecture and normal R&D-grade purity, the stability LT80 at this starting luminance is on the order of 100 hours, which is in the range of the best phosphorescent materials when also considering the better color and the higher efficiency[15] (Table 2). Considering that phosphorescent materials have been under investigation since 1997,[4] while TADF has been studied only

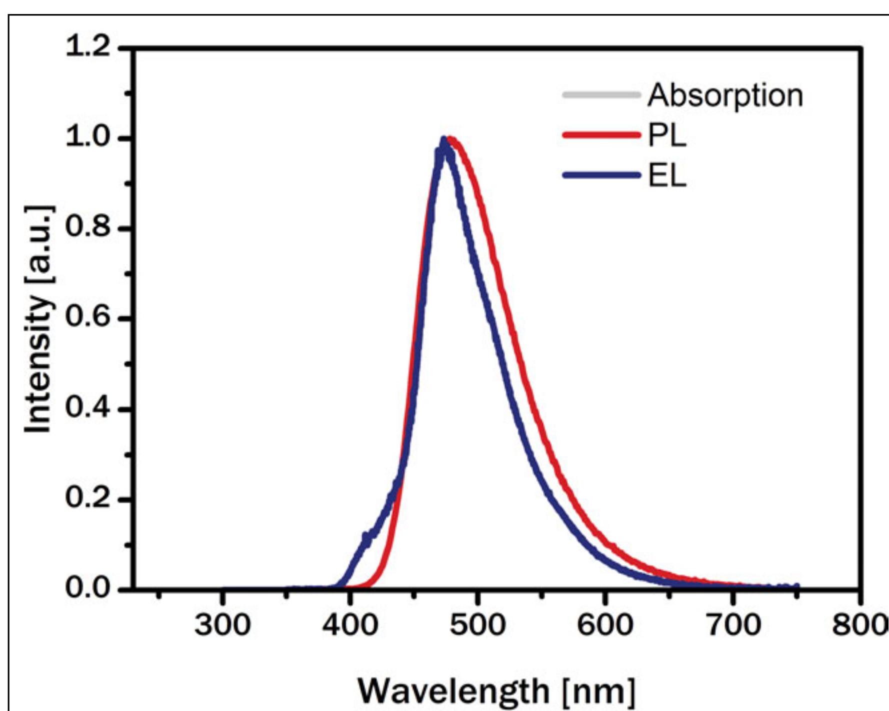

Fig. 8: Above is a comparison between the photoluminescence (PL) of a mid-blue TADF emitter and its electroluminescence (EL) performance in a bottom-emitting OLED.

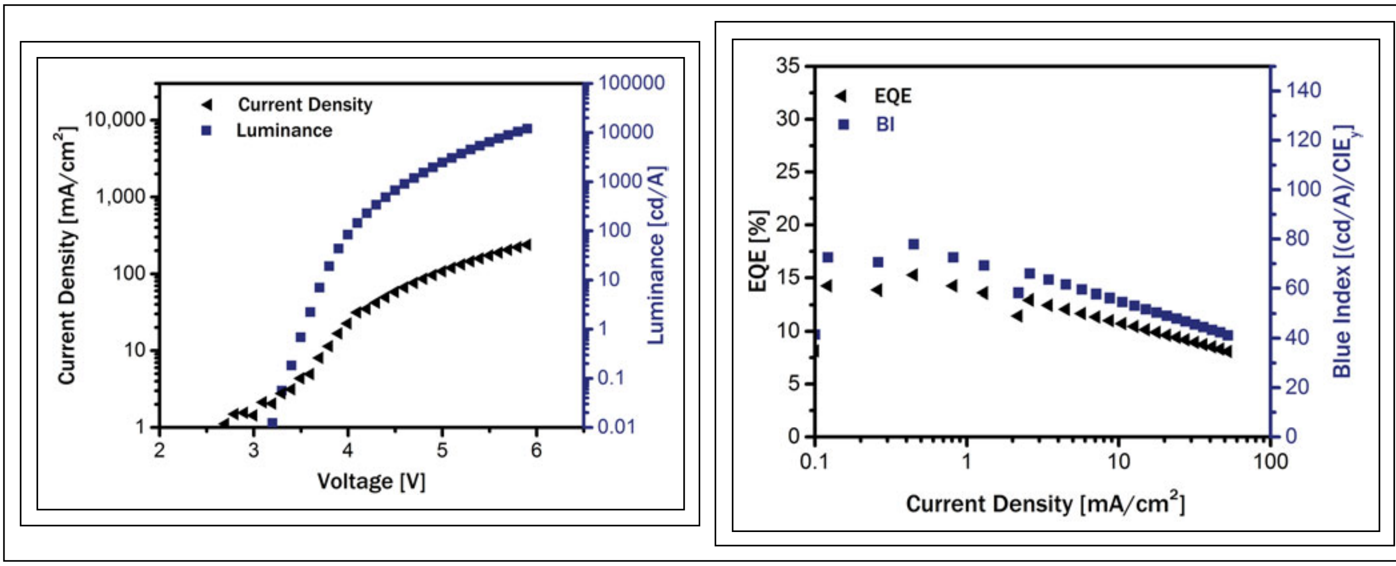

***Fig. 9:** Above is shown the performance of a recent deep-blue TADF OLED material, with voltage at left and luminance at right.*

since 2011,[6] these results demonstrate a significant development curve for TADF.

What to Expect from TADF Technology in the Future

By 2015, CYNORA and others[7] had established that it was possible to realize a favorable deep-blue color point with TADF material

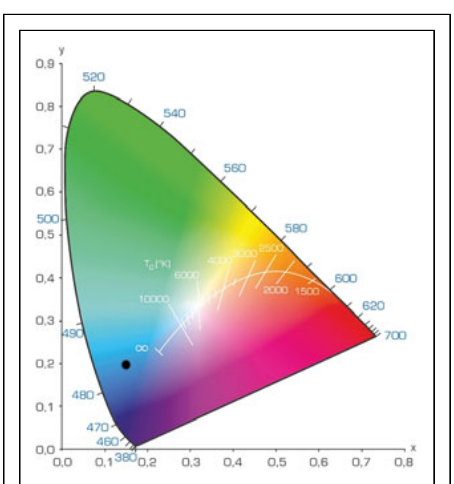

***Fig. 10:** The color of OLEDs is measured in the CIE 1931 color coordinate system. To satisfy the color expectations of the display industry, CIE_y values below 0.20 – ideally even around CIE_y 0.10 – are required. With current TADF materials, CIE_y values in the order of 0.15 can be reached.*

technology. Recently, great progress toward more stable blue TADF devices has been made, demonstrating materials with emission below 480 nm, 14% EQE, and lifetime values of LT80 at 420 hours (measured at 500 nits brightness).[13] Within a relatively short period of R&D, TADF emitters have now reached a performance similar to PHOS emitters with a blue color point. The cornerstone of these successes was a fast translation of quantum-chemical predictions from DFT-calculations into material design and a continuous improvement of the underlying theory, which led to improved materials in each learning cycle. Following this trend, blue TADF technology should reach market readiness by the end of 2017, according to CYNORA's roadmap.

Further improvement can be expected through the realization of more sophisticated stack architectures. For example, mCBP, a component used in the aforementioned early-stage devices with CYNORA's material, is known to have several stability issues, potentially limiting the stability of these OLEDs.[16] This indicates that using other, more stable hosts will lead to even longer lifetimes.

Nevertheless, it is also clear that the basic stability of both the materials and the stack architectures still need to be improved fundamentally. Looking back at a very steep learning curve displayed by research-driven companies such as CYNORA, as well as great academic progress,[10,17,18] this necessary advancement seems achievable in a short amount of time. TADF will soon contribute to the next material-driven advancement of the OLED industry, making OLEDs ready for even more applications soon.

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(continued on page 44)

SID Recognizes Outstanding Members of the Display Community

*This year's winners of the Society for Information Display's Honors and Awards include **Hiroyuki Ohshima**, who will receive the Karl Ferdinand Braun Prize for his contributions to LTPS technology and the mobile-display industry; **Shui-Chih Alan Lien**, who has earned the Jan Rajchman Prize for his contributions to LCD science and technology; **Martin S. Banks**, who will receive the Otto Schade Prize for his research into the causes of viewer discomfort and misperceptions in depth and motion; **Deng-Ke Yang**, who has earned the Slottow-Owaki Prize for his contributions to the education of students and professionals in the field of liquid-crystal displays; **Kenneth I. Werner**, who will receive the Lewis and Beatrice Winner Award for his services as editor, teacher, technologist, and SID proponent; and **Yi-Pai Huang**, who will receive the inaugural Peter Brody Prize for his contributions to the development of wide-view MVA-pixel technology and field-sequential-color driving methodology.*

by Jenny Donelan

The popular notion of a gifted scientist is often that of a driven individual toiling away in some laboratory through the dark hours of the night. And while such efforts may describe many of this year's winners at certain points during their lives, it's important to note that they rarely worked alone. The 2017 Honors and Awards recipients point to the synergies they experienced as members of a team, or as attendees at a conference such as Display Week, as a driving force for their research.

Hiroyuki Ohshima, winner of this year's Braun Prize, began his life's work in TFT LCDs as part of a team that was tasked by its employer to develop something new – a broad directive that would have been daunting if taken on alone. Jan Rajchman Prize winner Shui-Chih Alan Lien remembers discovering the contagious excitement generated by researchers presenting at Display Week – their zeal made him work harder. And when he and his co-workers finally solved a tough viewing angle problem, he was "happy and proud to be part of the team that developed this exciting and useful technology." Martin S. Banks, winner of the Otto Schade Prize, was already a successful vision-science academic when he found a new direction after meeting SID researchers and learning how his expertise could inform display research. Slottow-Owaki winner Deng-Ke Yang is a gifted teacher (as well as researcher) who through his mentoring has sent many highly skilled display professionals into the global workplace. Kenneth I. Werner, who has been named recipient of this year's Lewis and Beatrice Winner Award, discovered that as much as he gave to the Society for Information Display through participating in its events and publications, he got back through enrichment to both his personal and

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The 2017 winners will be honored at the SID Honors & Awards Banquet, which takes place at 8:00 pm, Monday evening, May 22, 2017, during Display Week at the Hotel Indigo in Los Angeles. Tickets cost $100 and must be purchased in advance – they will not be available on site.

Visit www.displayweek.org for more information.

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professional life. The winner of this year's Peter Brody Prize, Yi-Pai Huang, was also changed by visiting a SID symposium, where he was sparked by the excitement of the researchers there.

It is inspiring to see the humility with which these great scientists offer credit to the colleagues and mentors who helped them along the way. Please join us in congratulating this year's award winners. Their collaborative efforts have contributed to a stronger society, and thus to a stronger display industry.

2017 Karl Ferdinand Braun Prize

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

Hiroyuki Ohshima, SID fellow and CTO of Japan Research Center for Huawei, receives this year's Braun Prize "for his outstanding contributions to the research and development of LTPS technology and his leadership in the mobile-display industry."

After graduating from the University of Tokyo, Ohshima's first job was working on semiconductors in the R&D department at Seiko Epson. In the early 1980s, the company relocated most of Ohshima's colleagues to a new semiconductor fab, leaving Ohshima and a few other researchers behind with instructions to leverage their semiconductor experience toward developing new technologies. Ohshima's team eventually decided to focus on thin-film transistor (TFT) LCDs because they thought the technology had potential for creating new flat-panel displays. That thought was novel: At the time, notes Ohshima, few people were aware of TFTs or their possible application to LCDs. "This was the start of my long journey with TFT-LCDs as my life work," he says.

As part of that journey, Ohshima helped develop low-temperature polycrystalline-silicon (LTPS) TFT technology. He also helped commercialize it for mobile displays, making possible the mobile device era in which we live today.

According to Tatsuo Uchida, SID fellow and professor emeritus at Tohoku University, "Mr. Ohshima was engaged in the research and development of LTPS TFT from a very early time, when it was still unexplored. He solved many problems relating to LTPS TFT for LCD drivers and peripheral circuits, and the resulting technology is now used for various high-definition active-matrix LCDs and

Hiroyuki Ohshima

OLEDs. Without his outstanding achievements, current high-resolution displays would not have been realized."

Ohshima notes that considerable challenges still exist for LTPS technology. "I call LTPS 'giant microelectronics,' he says, explaining that the technology integrates an enormous amount of micro devices onto "giant" glass substrates. "LTPS technology is so complicated by nature, and requires great technical maturity and careful alignment between product design and manufacturing processes." These considerations make it challenging to implement LTPS on a mass production basis. However, recent market trends require LTPS solutions for both LCD and OLED applications. This means that more companies interested in implementing LTPS are entering the market, and these companies represent new research and career opportunities for the next generation of display scientists.

When asked if he has advice for that next wave of display scientists, Ohshima says, "Looking back in history, we should remind ourselves that many new display technologies have been proposed with successful demonstrators, but eventually failed in industrialization and/or business." In order to avoid such failures, he recommends that displays be considered not by themselves but in relation to a variety of aspects, including supply chains both upstream and downstream, infrastructures, material supplies, manufacturing equipment, design tools, and global market trends.

2017 Jan Rajchman Prize

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

Shui-Chih Alan Lien, SID fellow and CTO of China Star Optoelectronics (CSOT), receives the Jan Rajchman Prize "for his outstanding contributions to LCD science and technology, especially for the development of multi-domain VA LCDs, extended Jones matrix, and 110-in. curved televisions."

Shui-Chih Alan Lien's career has been marked by a wide range of achievements within the field of liquid-crystal displays. He was instrumental to the development of multi-domain vertical alignment (VA) LCDs, which helped create LC displays with wider viewing angles. He developed the extended Jones matrix, which calculates polarization changes through each layer of an LCD and the LCD's optics for the oblique incidence of light. And he led an R&D team at CSOT to develop the world's first 110-in., ultra-high-definition TFT-LCD panel with multiple touch and 3D functionality. (That product won a Display of the Year Silver Award from SID.) These are just three of the breakthroughs that Lien has helped bring about during a long career that has included positions at Optical Imaging Systems, IBM, AUO, and TCL, in addition to CSOT.

Lien says he was lucky because the LCD industry was just beginning while he was working on his Ph.D. degree in physics at the University of Minnesota. "I was fortunately able to find a job in the field of TFT-LCDs after finishing my degree. I liked the technology and have continued to work with it throughout my career."

In 1987, Lien joined the IBM T. J. Watson Research Center. By that time, "the LCD industry was blooming," he says, adding that narrow viewing angle issues were a major challenge for LCDs. "It was an exciting time to join the SID symposium each year," he says, "since a variety of multi-domain technologies were being proposed and demonstrated to solve the viewing angle problem. I really enjoyed discussing these topics with colleagues working in the same field – it stimulated many new ideas. Because of the exciting and hard work of engineers and scientists, the narrow viewing angle problem of TFT-LCD was solved." He describes that breakthrough as one of the most important in his career. "I am very happy and proud to be

Shui-Chih Alan Lien

part of the team that developed this exciting and useful technology."

Now the LCD industry is facing a challenge from AMOLEDs, says Lien, especially for small- and medium-sized panels. AMOLED has advantages in terms of response time, flexibility, and formability. "The LCD industry needs to overcome these three disadvantages in order to compete with AMOLED for the small and medium panel." According to his associates, it is typical of Lien that he considers the next challenge in terms of the big picture. Says Hidefumi Yoshida, research director at Sharp, "Dr. Lien has great leadership in both development and commercial fields."

2017 Otto Schade Prize

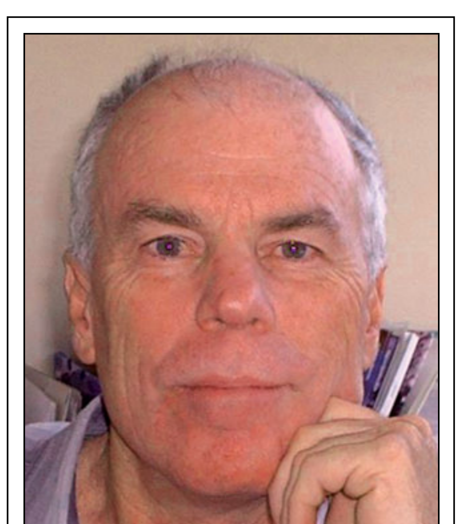
The Otto Schade Prize is awarded for outstanding scientific or technical achievement in, or contribution to, the advancement of functional performance and/or image quality of information displays.

Martin S. Banks, professor of optometry and vision science at UC Berkeley, receives the Otto Schade Prize "for his research into the causes of viewer discomfort and misperceptions in depth and motion and the creation of volumetric technology to mitigate these effects."

At first glance, Martin Banks' educational path would not seem likely to lead to a career in vision science and optometry and to research in stereoscopic user discomfort and misperception that has changed the way displays are designed. As an undergraduate, Banks majored in psychology and minored in physics. After teaching in Germany for a year, he earned a master's degree in experimental psychology, and then a Ph.D. in developmental psychology at the University of Minnesota.

"I always had an interest in the harder side of psychology and that got me interested in perception," says Banks. His early work was in hearing research, but he switched to developmental psychology, at the time a rapidly growing field. Then he became interested in adult vision, and managed to get himself assigned to teach a binocular vision class. "I spent a summer learning as much as I could about the field so that I'd be able to teach competently when the class convened," says Banks. Apparently, he was successful: "I really liked the topic and that got me into stereoscopy. "

The next career step – to displays – came about as a result of a couple of fortuitous events: First, Banks was invited to speak about vision science to a group of engineers at an SID meeting in Southern California. "I realized at the time how these folks were starving for more information about the visual system," says Banks. Second, he met Kurt Akeley, one of the founders of Silicon Graphics, and together they began exploring the interfaces of computer science, vision science, and display engineering. That research generated a great deal of interest from the display community, and Banks has been doing some form of it ever since.



Martin S. Banks

"I've read several papers by Marty during the years and have been very impressed by his great analytic methods and knowledge about the visual system and applications related to displays," says Adi Abileah, display consultant and 2012 Otto Schade Prize winner. "Specifically and most recently, his models about vergence and accommodation conflicts, which cause discomfort and nausea in stereoscopic displays, are of great interest. His overall contribution to the understanding of the human vision system is an asset to the display industry."

According to Banks, the challenges that vision science researchers are working on right now include color, high dynamic range, and especially the reproduction of focus cues (blur and accommodation) with high fidelity. Progress in vision science has been very steady, says Banks. "But display engineers have become increasingly interested in what vision scientists have to tell them. And many vision scientists have become increasingly interested in working with display engineers. The level of interaction between these two fields is so much greater now than it was a decade ago."

2017 Slottow-Owaki Prize

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

Deng-Ke Yang, SID fellow and professor at Kent State University, receives the Slottow-Owaki Prize "for his contributions to the education and training of students and professionals in the field of liquid-crystal displays."

Deng-Ke Yang's major technical achievements are in the areas of bistable cholesteric reflective displays and polymer stabilized cholesteric texture light shutters. These scientific contributions are documented in two books, five book chapters, more than 120 publications, and 21 issued and pending patents.

But it is his work as an educator and mentor that has earned him the 2017 Slottow-Owaki Prize. "I have known Professor Yang for over 20 years and I am proud to say I am one of his many students at the Liquid Crystal Institute (LCI) at Kent State University," says Ray Ma, director of flexible OLED R&D at Universal Display Corporation. "Professor Yang takes pride in his work as a teacher and regards teaching as one of the highest honors," Ma continues. "Even today, I still keep my notes

Deng-Ke Yang

from his class in my office and will reference them once a while."

Over the years, Yang has advised more than a dozen graduate students, many of whom are now working in companies such as 3M, Apple, Corning, Kodak, Tianma, and UDC. "They are all playing important roles in the display industry because of the solid training they received from LCI under the guidance of Professor Yang," says Ma.

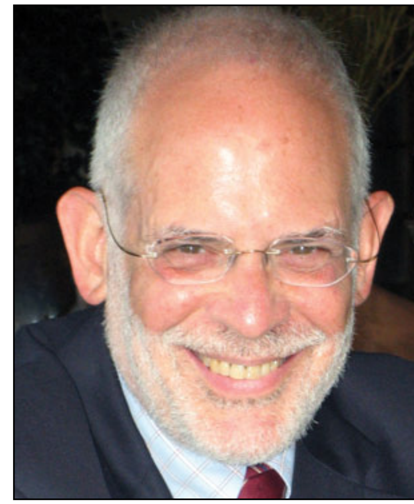
Yang also teaches classes at various universities around the world. He has authored two books with Shin-Tson Wu, *Reflective Liquid Crystal Displays* and *Fundamentals of Liquid Crystal Devices*. Both are extremely popular references for students and professionals in the field of liquid-crystal displays the world over.

Yang became interested in the study of liquid crystals when he entered graduate school 33 years ago. "I realized that liquid crystals are interesting in terms of fundamental science and are also important for practical applications. Furthermore it does not cost much to do liquid-crystal research!" Yang continues to research cholesteric liquid-crystal devices. The biggest challenge for this technology, he says, is to develop video-rate, high-image-quality transflective displays that can be used everywhere, from dim indoor lighting to bright sunny outdoor conditions.

2017 Lewis and Beatrice Winner Award

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

Kenneth I. Werner, journalist, analyst, consultant, and principal of Nutmeg Consultants, receives the Lewis and Beatrice Winner Award "for his dedicated services as editor,



Kenneth I. Werner

author, teacher, technologist, and, most importantly, one of the strongest proponents of SID."

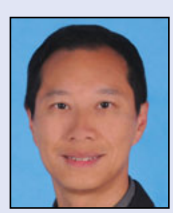
Ken Werner's connections to SID date back to a time when he was managing editor of *IEEE Spectrum* and happened to edit an article on display technology by Larry Tannas, founder of Tannas Electronic Displays and a past president of SID. Two years later, when the Society needed an editor for this magazine, Tannas remembered Werner's work and

2017 SID Special Recognition Awards

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

Masaki Hasegawa *"for his invention of decomposition-type photoalignment used in IPS and FFS LCDs to achieve a high contrast ratio and low power consumption."*

Dr. Hasegawa is a manager of Merck Performance Materials Ltd. He earned his Ph.D. degree in engineering from Tokyo Institute of Technology.

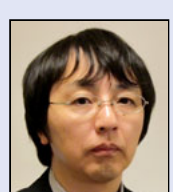


Raymond Kwong *"for his pioneering research on and commercialization of high-efficiency and high-stability phosphorescent OLED materials and devices."*

Dr. Kwong is currently the director of Universal Display Corporation HK Ltd. He received his Ph.D. in chemistry from the Univ. of Southern California.

Jang Hyuk (Jeremy) Kwon *"for his pioneering research on OLED displays, especially on the top-emission device architecture in AMOLED displays."*

Dr. Kwon is a professor at Kyung Hee University. He has a Ph.D. in chemistry from the Korea Advanced Institute of Science and Technology (KAIST).



Kenichiro Masaoka *"for his leading contributions to the research and development of a wide-color-gamut UHD-TV display system and gamut-area metrology."*

Dr. Masaoka is a principal research engineer with the Advanced Television Systems Research Division, NHK Science and Technology Research Laboratories. He received his Ph.D. in engineering from the Tokyo Institute of Technology.

hired him for *Information Display*. Werner stayed at the magazine from 1987 to 2005, bringing the magazine to what was universally recognized as a new standard of excellence. "During Ken's time with *Information Display*, the magazine became truly professional," says Tannas.

After his stint with *Information Display*, Werner continued to work in the display industry, as he does to this day. Years earlier, after leaving *IEEE Spectrum*, he had founded Nutmeg Consultants, which specializes in display industry manufacturing, technology, and applications, including mobile devices and television. He continues to run Nutmeg Consultants, and is also a senior analyst for display research firm MEKO, Ltd.; a founding co-editor of MEKO's *Display Daily;* and a regular contributor to HDTVexpert.com

Werner has also stayed involved with SID, serving as program chair or co-chair for several of the Los Angeles chapter's one-day conferences – a long-running and very successful series.

He has also supported various display activities in Brazil, culminating with the formation of the Latin American Chapter. "Ken has been a key contributor to Latin Display over the years," wrote Alaide, Victor, and Carlos Mammana (Latin America Chapter chair, director, and member, respectively) in a statement recommending Werner for the award. "Over many years, Ken not only disseminated knowledge about displays but championed the SID organization, explaining its goals and helping to foster the creation of the Latin American Chapter for SID. He continues to motivate the industry to increased participation in SID activities."

Werner's background is not that of a typical wordsmith. He has a degree in physics and started out as an engineer at RCA. "I found that I enjoyed the first six months of each project when I was trying to figure out which way was up, and then found the next 18 months of wrapping up the details to be horribly tedious," says Werner. "So I looked for an area where I could use my technical expertise as a generalist, rather than a hyper-specialist." This led him to publishing, and eventually, to SID.

Werner says, "I received great satisfaction from covering SID's major conferences for *Information Display*, which gave me the opportunity to make many friends in the display industry and to view display technology and manufacturing around the world close up." He also enjoyed running the promotion and press relations program for Display Week, though he is quick to point out that the person who did most of the work of keeping the press happy was his friend and colleague Dian Mecca.

When asked about the significance of the award to his career, Werner replies: "I didn't do these things in order to win an award, even one as prestigious as the Lewis and Beatrice Winner Award. I did them because people asked me. And by simply saying 'yes,' I wound up greatly enriching my professional and personal life. This award is icing on the cake."

2017 Peter Brody Prize

The Peter Brody Prize (new this year) is awarded to honor outstanding contributions of young researchers (under age 40) who have made major-impact technical contributions to the developments of active matrix addressed displays in one or more of the following areas:

2017 SID Fellow Awards

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

Toshiaki Arai *"for his distinguished contributions to high-reliability high-performance oxide-TFT technology for AMOLED displays."*

Dr. Arai is a chief technologist at JOLED Inc. He received his Ph.D. degree from the Nara Institute of Science and Technology.

Hyun Jae Kim *"for his original contributions to LTPS TFTs using excimer-laser annealing and for implementing the annealing process into the commercial production of LTPS TFT-LCDs and AMOLED displays."*

Dr. Kim is a professor in the School of Electrical and Electronic Engineering at Yonsei University in Seoul, Korea. He received his Ph.D. degree in materials science and engineering from Columbia University.

Sin-Doo Lee *"for his outstanding contributions to fast-switching and wide-view LCD technologies, ranging from vertically aligned nematic to defect-free ferroelectric modes."*

Dr. Lee is a professor in the School of Electrical Engineering of Seoul National University. He received his Ph.D. degree in liquid-crystal physics from Brandeis University.

Sang-Hee Ko Park *"for her development of the first AMOLED display with oxide TFTs."*

Dr. Park is a professor at the Korean Advanced Institute of Science and Technology. She earned a Ph.D. in chemistry from the University of Pittsburgh.

Qun (Frank) Yan *"for his outstanding contributions to plasma displays, especially for inventing and developing the calcium magnesium oxide protective layer for the mass production of high-luminous-efficacy PDPs."*

Dr. Yan is a distinguished professor at Fuzhou University and chief technology advisor for Changhong Electric Group Co., Ltd. He received his Ph.D. in physics from Vanderbilt University.

• *Thin film transistor devices*
• *Active matrix addressing techniques*
• *Active matrix device manufacturing*
• *Active matrix display media*
• *Active matrix display enabling components*

Yi-Pai Huang, professor and associate dean of R&D at National Chiao-Tung University, earns the inaugural Peter Brody Prize "for his innovative contributions to the development of wide-view MVA-pixel technology and the invention of the field-sequential-color driving method to achieve imperceptible color breakup."

An appreciation for art and imagery led Yi-Pai Huang to a career in displays. "My father is a photographer, so I enjoyed seeing beautiful pictures when I was a kid," says Huang. While at graduate school at National Chiao-Tung University, he had the chance to visit Professor Han-Ping Shieh (a display pioneer in his own right and winner of a Slottow-Owaki Prize). There in Shieh's lab, he saw many new TFT-LCD technologies powering displays with beautiful imagery. "Therefore, I decided to join Shieh's group to do research for improving the optics and picture quality of displays and TFT-LCDs," says Huang.

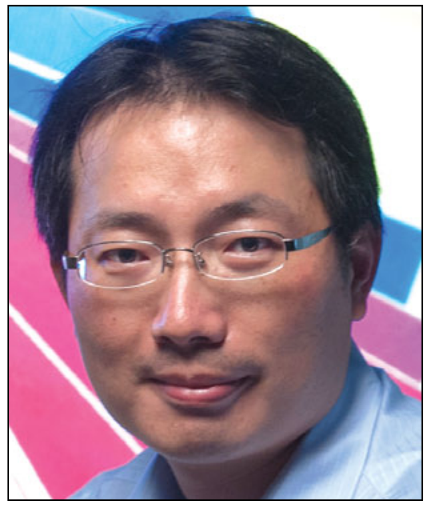
He went on to develop advanced-MVA TFT-LCD for reduced color washout, invent a stencil-FSC driving method to achieve imperceptible color break-up, and implement an LC-lens array for various 3D applications. He has published 60 journal papers, 133 conference papers, and 3 book chapters. He holds 98 issued patents.

"Huang is an outstanding scientist who has made tremendous accomplishments at a young age," says Fan Luo, retired CTO for AUO, who worked with Huang at AUO. "Professor Huang has also been very active in SID activities, serving as chair of the Taipei Chapter and program chair for the technical symposium."

Huang notes that growing up, he was drawn to sports as well as science. He might have become an athlete or a physical education teacher, he says, had his mom not steered him toward science when he was 18 and applying to undergraduate programs.

The 2017 Honors and Awards Committee members are:

Shin-Tson Wu, *Chair*
Paul Drzaic
Min-Koo Han
Ingrid Heynderickx
Chris King
Fan Luo
Haruhiko Okumura
Jun Souk
Ching Tang
Andrew Watson
Larry Weber



Yi-Pai Huang

He credits SID with providing a great deal of inspiration early on. "I joined my first SID symposium in 2001 and saw many researchers engrossed in display technology and excitedly reporting their most innovative achievements in the symposium," he says. "That really encouraged me to focus more on display research." In 2009, Huang became the officer of SID's Taipei chapter and the program committee member of SID. He says he has learned a great deal from senior scientists in this society, in terms of both leadership and technology. "I really have to give my sincere appreciation to SID," he says, "and especially to my senior mentors, Professor Han-Ping Shieh, Professor Shin-Tson Wu, Dr. Fan Luo, and Dr. John Chen."

When asked what advice he might give to young researchers starting out, Huang offered this:

"Young people have 'fresh' brains, so they shouldn't be bounded by old technology. The displays of the future could be some arbitrary type – we could have images floating in the air, or even imaging directly into the brain. I would like to encourage young people to use their imaginations to develop a future type of display in their minds, and then try to realize it solidly, because your achievement will never be greater than your dream." ■

show review

The 11 Best Display-Related Finds at CES 2017

The most exciting near- and medium-term developments seen at the Consumer Electronics Show in Las Vegas revolved around quantum dots. And there were other surprises.

by Ken Werner

There were lots of displays at the latest Consumer Electronics Show, held January 4–8, 2017, in Las Vegas, but only in a few cases were developments in display technology front and center. More frequently, displays were important as enabling components in larger systems, notably automotive human-machine interfaces (HMIs), advanced driver assistance systems (ADAS), and autonomous vehicles. But leaving the self-balancing motorcycles, *etc.* aside, we will focus on the 11 display technologies and display-centric products (including one exhibit) that were the best in their own right, and we'll define "best" as we go along.

1. Best Product That Isn't What It Says It Is

Samsung introduced its new "QLED" TV technology, although it wasn't based on what the technical community would call quantum dot light-emitting diode (QLED). We'd better get used to it, though. When Samsung's marketing army decides to call an apple an orange, it's going to be an orange. (That's what happened when, a few years back, Samsung decided to call an LCD-TV with an LED edge-light an "LED TV." And so it remains to this day.)

Today, Samsung is making very good 4K quantum-dot TVs under the label S-UHD. But Samsung representatives have said the label hasn't been very exciting or informative for consumers, and that brings us to QLED.

In 2016, Samsung acquired the assets of quantum-dot company QD Vision. QD Vision had developed significant intellectual property around QLED technology – true QLED technology – and Samsung also acquired rights to the "QLED" name.

True QLED refers to a structure that resembles an organic light-emitting diode (OLED) structure, but with the organic emitting layer of OLED replaced with quantum dots (QDs). While QDs in current TVs are excited by photons, the QDs in QLED are excited by an electric field. This very different approach will take years of additional development before it appears in commercial TV sets, but many industry-watchers regard it as possibly the best TV display technology under development today.

This is not the technology in Samsung's "QLED" TV sets. These sets have the conventional quantum-dot structure, but the dots – made by Nanosys – *are* constructed differently from other QDs, including the QDs in Samsung's 2016 S-UHD TV sets. The sets showed in Samsung's booth at CES looked very good, but we will need to compare test results to see if they are better than competing sets.

In Samsung's CES press conference, Joe Stinziano, executive vice president for Samsung Electronics America, said the QLED sets cover "nearly all of the DCI color space," incorporate high dynamic range (HDR), and generate a peak white luminance of 1,500 to 2,000 nits. The panel, he said, is optimized for the new QDs, which presumably means the matrix color filter is tuned for the wavelengths and widths of the QD peaks. The QLED set adapts to room illumination, said Stinziano; the panel connects to the box via optical cable, and the set mounts on the wall, for those who opt for wall-mounting, with virtually no gap. Samsung showed 65-in. and 88-in. examples on the show floor. The QLED line, which was introduced at the start of this year's show, won a Consumer Technology Association (CTA) Innovation Award.

Samsung's announced strategy is to skip OLED technology completely and jump directly to true QLED. But, when it does, what will Samsung call it? Samsung is already trying to resolve the issue by calling the current photoluminescent QD technology "photoluminescent QLED," and using "electroluminescent QLED" for the QLED technology to come.

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

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2. **Best Real QLED and Air-Stable Quantum-Dot Technology Demonstrations**

Samsung's QD supplier Nanosys demonstrated a true QLED in its suite in the Westgate Hotel. The demo consisted of four bright blue pixels (Fig. 1), indicating that 1) Nanosys can make them, and 2) we're a long way from a true QLED TV set, confirming a widely held belief in the field.

Nanosys gave a primitive, lab-bench style demo of air-stable quantum dots behind closed doors last May at SID's Display Week. The company's air-stable demo in its CES suite this year was far more sophisticated than what it showed last May. (Nanosys now calls the technology "ambient processable," which is accurate but hard to wrap your tongue around.) The demo showed what is widely called a "filter" because the intent is for it to replace the matrix color filter in an LCD, even though it isn't a filter in the conventional sense.

Jeff Yurek, Nanosys director of marketing and investor relations, said the materials issues for the air-stable QDs have been solved. Photolithography produces a clean pattern, which was verified by looking at the sample, although the pixel density was limited by the lab-level lithography equipment used, said Yurek. The materials are compatible with lithography for 4K panels and beyond, he said. The QD filter pattern will probably be applied to the back side of the LCD's front glass, although it could be applied to the front side. That will be up to the panel-maker, Yurek said. He concluded our conversation by saying the air-stable QDs "could be commercial in 2018; 2019 for sure."

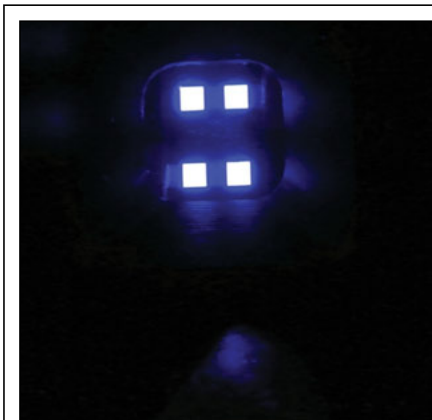


Fig. 1: Above are four true QLED subpixels as demonstrated by Nanosys. The subpixels are blue, but so bright they appear white even with the camera's exposure compensation set to maximum underexposure. Photo courtesy Ken Werner.

After leaving the Nanosys suite I had a private meeting with Matt Bootman, CEO of QD developer Crystalplex, and business development director Ken Acer. Bootman and Acer showed me samples of their company's sapphire-passivated air-stable QDs deposited on polymer film. Each of the three samples produced a different color when a laser was aimed at it. Not as flashy as a multi-colored pattern, but sufficient to show the dots work in air and can be coated onto film.

3. **Best LCD TV That Doesn't Use Quantum Dots**

LG is notable for not using quantum dots in its higher-level TV sets, but with wide color gamut (WCG) becoming a requirement for high-end ultra-high-definition (UHD) sets, this is becoming an untenable position – or is it? In its booth on the CES show floor, LG had an elaborate but unclear booth presentation promoting its new "nano-cell display." LG claimed "accurate colors maintained at any angle" for its new technology, and also claimed that colors are enhanced. The company said the nano-cell technology consisted of 1-nanometer particles uniformly distributed on the LCD cell.

What LG was calling "nano-cell display" on the show floor, LG Display (in its invitation-only suite in the Las Vegas Convention Center's North Hall) was calling "IPS NanoColor." There are two distinct types of IPS NanoColor. The current version, which is what LG was showing, is called just IPS NanoColor. Here, the nanoparticles – which are approximately 2 nm in diameter, not 1 – are indeed distributed on the front surface of the LCD, where they serve as a color filter and, perhaps, as a diffusion layer that improves the viewing angle.

Since it serves as an additional color filter, the IPS NanoColor layer obtains its increase in color purity at the expense of some efficiency. LGD said the technology delivers a color gamut of 90% Digital Cinema Initiative (DCI), compared to 96% for quantum dots. However, it claims a backlight unit efficiency of 78%, in contrast to QD's 70%. LGD also claims that with IPS NanoColor, the color gamut at 80 degrees is still 91% of what it is normal to the screen surface, while the equivalent QD number is 28%. I look forward to seeing if independent testing supports these numbers.

The second-generation technology, IPS NanoColor II, takes a different approach. Here, the backlight uses blue LEDs, and 1 nm nanoparticles are arrayed between the LCD cells and the backlight. Some of these nanoparticles convert the blue light to red, while others convert to green, as quantum dots do. But these particles are too small to operate on the basis of quantum confinement. Another possibility is that these are phosphor particles, but phosphor particles are typically 50–100 times the diameter of LGD's particles. LGD personnel were not permitted to provide any additional details, but they could say the particles had been developed in cooperation with LG Chemical.

NanoColor II, LGD said, will have a color gamut about the same as QDs, with a BLU efficiency slightly less than the first-gen NanoColor, but still slightly more than QD. The LGD reps suggested we could see IPS NanoColor II TV sets in 2018. For now, it will be very interesting to compare Samsung's impressive new quantum-dot technology with the first-gen IPS NanoColor.

4. **Best TV Display Less Than 1 mm Thick**

In its suite, LGD showed the 77-in. "Wallpaper" OLED panel that will soon appear in the LG Signature OLED TV W, LG's top-of-the-line OLED TV. (The 65-in. version is available now at an MSRP of 1 cent less than $8000.) The panel itself is 0.95 mm thick. The TV in which it will appear is 5 mm thick, with the electronics in a separate box that is connected to the set with a cable.

The set incorporates all of the high-end features you would expect and then some, including an HDR system that supports HDR10, Dolby Vision, and hybrid log-gamma (HLG) HDR. The internal audio system supports 4.2 audio with Dolby Atmos immersive sound.

But the primary distinguishing factor of the W is that it is so thin (and sufficiently light at 27 lbs.) that it can be mounted directly on the wall – yes, like wallpaper. (The separate AV box weighs another 28 lbs.) It is impressive (Fig. 2).

Fig. 2: LG's "Wallpaper" OLED TVs are thin enough and light enough to mount directly to a wall. The effect is striking. The price is high. Photo courtesy Ken Werner.

5. Best Biggest-Yet Electrophoretic Display

If you thought the largest active-matrix electrophoretic display you could buy was only 32 in. on the diagonal, it's time to think again. In the Las Vegas Convention Center's seemingly endless South Hall, E Ink showed its new 42-in. display in cooperation with QuirkLogic, whose networked whiteboard system (called "Quilla") is the display's first application. Both companies preferred the designation "eWriter" to "whiteboard."

Quillas can wirelessly connect to Quillas in other offices down the hall or around the world for active collaboration and sharing. The 42-in. display has 85 ppi and 16 levels of gray, making the Quilla appropriate for the connected eWriter application.

Each Quilla normally hangs from a wall mount that delivers power and connects to broadband. Simply lifting the Quilla off the mount switches it to battery power and a WiFi connection. The unit weighs a bit over 20 pounds and will run all day on a battery charge.

QuirkLogic and E Ink claim that Quilla offers the feel of pen on paper, and I can verify that. There was just enough latency between moving the stylus and having the line on the display follow the stylus point to be annoying. E Ink Chief Strategy Officer Paul Apen and QuirkLogic's Mike Maby agreed that the latency is primarily a software issue, and that QuirkLogic is confident of solving it in the near term. In addition to the connected business and design applications shown in the booth, QuirkLogic and E Ink see architecture as an important market. The companies expect to have more to say and show by the time of SID's Display Week in May.

6. Best Glasses-Free 3D Display

Philadelphia-based Stream TV Networks showed the latest incarnation of its Ultra-D 3D system – the best (and, as far as I could tell, the only) glasses-free 3D system at CES. I was not impressed with early versions of the system, but the current one is very good and clearly benefits from starting with a 4K panel. There are no sweet (or sour) spots, with the 3D field seeming to be continuous over a wide range of viewing angles (Fig. 3, left).

There is a visible artifact: diagonal "raster" lines. (There isn't really a raster but the lines look like the raster lines from an old CRT TV.) This shouldn't be a deal breaker for most people, but you can see them (Fig. 3, right).

The Ultra-D system consists of a proprietary multi-layer optical stack with a precision layer laminated to a 4K screen. "The film's unique design is based on the panel's pixel layout and provides refractive and [diffractive] elements to create a 140-degree continuous light front," according to a Stream white paper. The lamination equipment is operational at Pegatron, the company's manufacturing partner. A TV or monitor maker must buy this display module from Pegatron. Another essential part of the system is a "rendering processor that decodes Ultra-D formatted content and assigns depth values to each of the 24 million subpixels for a natural and immersive effect." Yes, the content must be in the Ultra-D format, but processors and tool sets are available that implement real-time conversion, native creation, or pre-conversion.

As good as Ultra-D is, I remain convinced that there are basic visual and psychological reasons why 3D TV is not generally appealing over the long term, with glasses or not (with the possible exception of gaming). But that still leaves a wide range of consumer and professional monitor-based applications up for grabs, with gaming high on the list.

7. Best Product Prediction from a TV Maker

The 35-year-old Chinese company TCL prides itself on its vast size and vertical integration. It is the world's third-largest TV maker and the fastest growing TV maker in North America. It also holds the largest stake in panel maker CSOT, which is currently building a Gen 11 thin-film transistor and OLED plant at a total investment of US $7.7 billion.

TCL chairman and founder Li Dongsheng made introductory comments at TCL's press conference. He read from prepared notes, and it was clear that speaking in English was not easy for him, but his efforts to do so anyway indicated the company's seriousness about further expanding its penetration of the North American market.

Li and other executives talked up TCL's extensive TV line-up, including its 4K, quantum-dot, and HDR technologies; its TCL Roku smart TVs; and (at 110 in.) the world's largest 4K curved TV. I have spoken dismissively of curved TVs in the 55- and 65-in. range – and sales figures confirm that this is a fad in steep decline – but at really large sizes curved screens make geometrical and ergonomic sense. (Not that anyone is going to sell very many 110-in. TVs.)

Ranjit Gopi, marketing director and head of overseas marketing, emphasized the com-

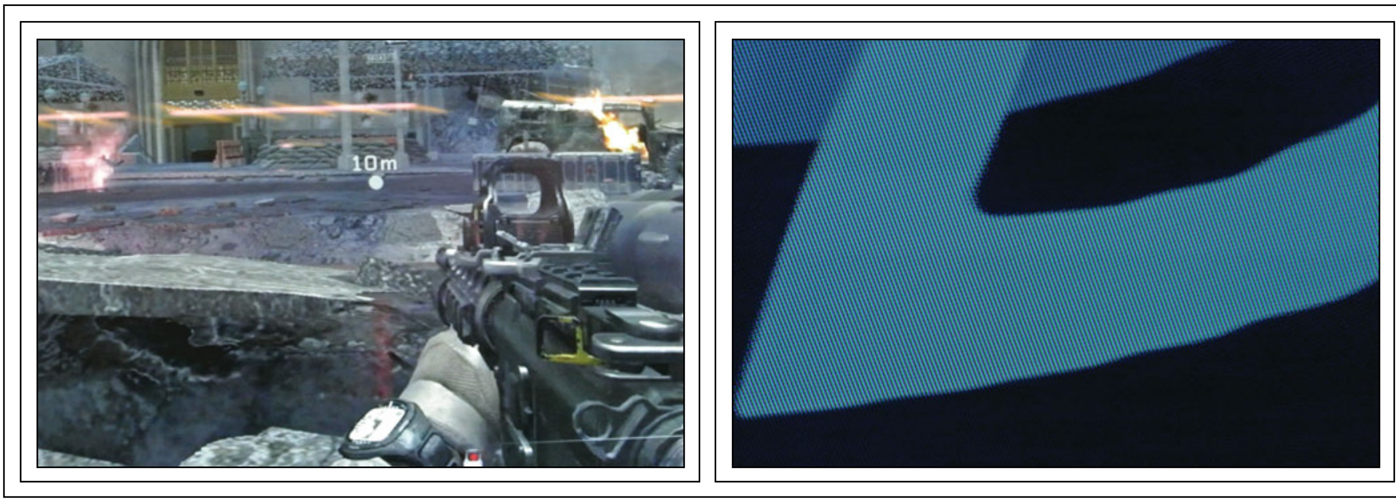


Fig. 3: Left: Stream TV's glasses-free 3D system provides an immersive gaming experience that is far more comfortable than one that involves wearing VR goggles. Right: Stream TV's autostereoscopic effect is provided over a wide viewing angle without conventional sweet and sour spots. The trade-off is these diagonal lines, which are noticeable at normal viewing distances but probably not a deal breaker for most viewers. Photos courtesy Ken Werner.

pany's major investments in global brand building, smart television technology, and smart manufacturing technology. The company has research centers around the world, he said, including one in Silicon Valley and a cooperative research center at MIT.

But for those in the audience who understood it, Gopi's most interesting comment was this: Quantum-dot-on-chip TV is coming! He wouldn't say when, but he did say it would be "sooner rather than later." Why is this a big deal? Currently, the dominant approach to making quantum-dot-enhanced backlights is to distribute the QDs in a medium that is encapsulated between polymer films that protect them from oxygen and moisture. The multi-layer structure of this quantum-dot enhancement film (QDEF, which is a trademark owned by Nanosys) is more expensive than the QDs that are incorporated within it. An attractive alternative would be to deposit the QDs directly on the LED chips that are the backlight's source of illumination, doing away with the film sandwich entirely.

One problem with this is that the QDs deteriorate rapidly when they are subjected to high luminous flux and, especially, heat. And LED chips are hot. Several companies have been working on this problem, including the recently sold QD Vision, whose IP was acquired by Samsung last fall. Another is Pacific Light Technologies (Portland, Oregon), whose CEO Doug Barnes was previously VP and GM of the specialty displays business at Planar. Could PLT be working with TCL? Barnes politely refused to comment.

With the technical difficulties confronting this technology, a dot-on-chip TV "sooner rather than later" would be a major step in the now-rapid evolution of QD-enhanced TVs.

8. Best "Me-Too" Product

With its A1E series of Bravia OLED TV sets, Sony is making an impressive entry into the very limited field of OLED TV manufacturers. Sony is using LGD OLED TV panels, of course, so there is no product differentiation there, but it has done its best to create a high-end product that includes impressive industrial design and presumably top-notch electronics. Whether the picture quality differs significantly from the LGD competition remains to be seen, but the image looks very good indeed (Fig. 4).

On display were 65- and 77-in. 4K HDR OLED sets featuring Sony's Acoustic Surface technology, which incorporates transducers that produce sound by vibrating the entire display panel. This idea is not new, of course. At the beginning of this decade the British company NXT was working with the same idea, and showed prototypes of notebook computers using the technology. NXT customers produced a variety of thin speakers that were sold commercially.

One problem NXT encountered was interference between the screen's pixel structure and the screen vibrations at lower acoustic frequencies. The solution was to cut off the frequency at 150 Hz and use a separate woofer, which presumably made the approach less attractive for laptop computers. We will soon see how Sony has dealt with this issue. What Acoustic Surface, and NXT's SurfaceSound before it, can do is localize a sound at any point on the screen. Reportedly, Sony has done a good job of co-locating the origin of the sound and image content with a good deal of precision.

But this was a me-too feature as well. LGD was showing its Crystal Sound OLED in its North Hall suite. It's hard to differentiate your product when the core technology comes from your supplier.

9. Best Display Product Without an Obvious Market

Arovia's Spontaneous Pop-Up Display (SPUD) is a Kickstarter-funded product conceived by enthusiastic alumni of Rice University. Shown at the CES Unveiled press and analyst event, SPUD is an inflatable display with a Texas Instruments Digital Micromirror Device (DMD)-based projector and 24-in. rear-projection screen (Fig. 5).

Arovia says its "ideal initial customer is the 'mobile millennial.' " But the market has

Fig. 4: *It's difficult to say if Sony's electronics get a better picture out of LG's OLED panel than LG's own electronics, but the image quality of Sony's A1E series of Bravia OLEDs is excellent. Photo courtesy Ken Werner.*

repeatedly demonstrated its lack of interest in rear-projection displays, and there are proven alternatives such as miniature projectors, lightweight monitors, large tablets, and economical notebook PCs with 15.6- and 17.3-in. screens. (You still need a PC or tablet to drive the SPUD.) Am I missing something? For the sake of these agreeable young entrepreneurs, I hope so.

10. Best OLED Notebook PC

Also at CES Unveiled, Lenovo showed its 2017 ThinkPad X1 Yoga convertible notebook PC with a Gen 7 Intel Core i7, 16GB of memory, and up to 1TB of SSD storage. You can buy one with a 14-in. wide-quad high-definition 300-nit OLED touchscreen for a $300 premium, and this is clearly the world's best OLED notebook because it's the only one. Lenovo showed the 2016 model at last year's CES, and said then that the OLED option was an experiment that would only be continued if sales justified it. Apparently, they did. But is the option being extended to any other models? Not this year, said Lenovo's David Harris.

11. Best Display Exhibit

This is easy, because it's always the same one: LG Display's by-invitation-only suite, which, this year, was in one of the Las Vegas Convention Center's North Hall meeting areas. LGD frequently shows what is under the hood of the products its sister company, LG Electronics, is exhibiting on the show floor. And it often shows products and technologies that are under development.

We've already described the OLED panel that is only 0.95 mm thick, and IPS Nano-Color. LGD showed a 55-in. full high-definition OLED with 45% transmittance. The combination of transparent clarity and color saturation was impressive. The panel is not a product yet, but LGD is exploring the technology for other applications.

One of those applications was an automotive see-through head-up display (HUD) mounted to the top of a mock-up car dashboard. In the well-lit demonstration area, the images were bright and clear, without the optical and viewing-angle limitations of projection HUDs. There is a problem, though. The National Highway Traffic Safety Administration specifies that any HUD must have a transmittance of at least 70%. An LGD engi-

Fig. 5: *Arovia's pop-up display inflates from 1.5 lbs. of folded polymer film to a 24-in. rear-projection DMD display. Photos courtesy Ken Werner.*

neer said the company is hopeful that it can get from 45% to 70% transmittance.

A clever use of the transparent OLED was to lay it over an LCD instrument cluster. Warnings were directed alternately to the LCD and the OLED, giving the impression of the indicator moving toward and away from the driver, which was attention-grabbing. The OLED was also used to overlay speedometer and tachometer pointers and some digits.

A plastic OLED was used to make a wave-like display over the entire dash with a convex portion of the wave over the instrument cluster, concave over the center, and convex in front of the passenger. This display dash looked continuous but it used three tiled panels. Plastic OLED is a growing market, and we were told that LGD is well positioned to participate in this growth thanks to a G4.5 and a G6 fab. We were not permitted to take photographs of the automotive OLED displays.

Another demonstration focused on LCD pillar panels, displays with extreme aspect ratios for high-end signage installations. These panels were fabricated directly on the mother glass, not resized from displays with traditional aspect ratios, an LGD engineer said (Fig. 6).

Last year, LGD showed its S(uper)-IPS panel, which used rubbing with a soft cloth to establish the surface alignment of the liquid-crystal molecules. In the very early days of twisted-nematic LCD fabrication, this rubbing was done by hand, and some operators had "the touch" for doing it and others didn't. Now, the rubbing is mechanized, with a rotating roller on which the rubbing fabric is mounted, but it's still a shockingly 19th-century-looking process for a 21st-century high-tech factory. This year, LGD was showing off its U(ltra)-IPS technology, which delivers better viewing-angle performance, an LGD rep said, thanks to creating the alignment layer with ultraviolet light, patterning, and a polymerizable layer instead of rubbing. UV alignment was developed many years ago, but has only fitfully been used in commercial products. Industry sentiment has often been that "rubbing is good enough," but this is a competitive world and sentiments change.

Quantum Dots Stole the (Display) Show

The most exciting near- and medium-term developments are still in quantum dots, including air-stable dots, dot-on-chip, and – down the line – true QLED. Flexible OLEDs for automotive and other applications should also be high on the list, as is solution processing to dramatically reduce the cost of OLED displays. We didn't see any of that at CES because it's not here yet, and is taking longer than many of us expected. Until it comes, the dramatic improvements in QD-enhanced displays will satisfy the market for all but super-premium large-screen products. ■

Fig. 6: *LGD's pillar displays have aspect ratios as high as 58:9, luminance of 700 nits, and a color gamut of 100% of sRGB. Photo courtesy Ken Werner.*

AR/VR, Digital Signage, Display Materials, Vehicular Displays, and Wearables Headline Display Week 2017 Technical Program in Los Angeles

A bumper crop of papers submitted to this year's symposium ensures that the field will be broad as well as deep. Highlights include novel technologies like aerial displays, perovskites, full-windshield automotive head-up displays, and tunable microlens arrays, as well as practical advances in manufacturing and metrology that will help you do your job better. This is your once-a-year opportunity to find out what's happening in the field of displays. The discoveries you'll make at Display Week will inform your business plans for months and years to come.

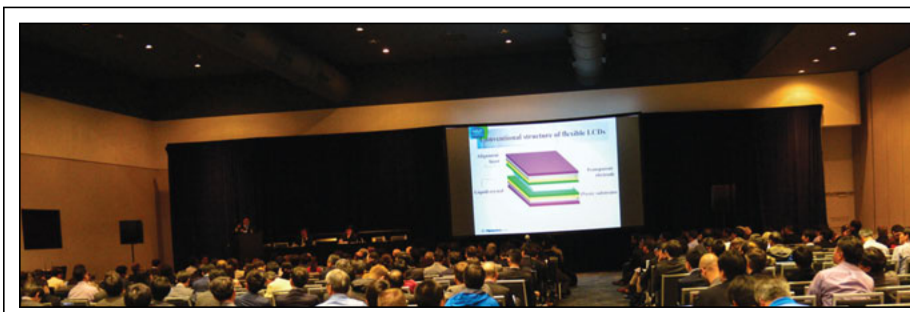
by Jenny Donelan

This is a big year for Display Week. Nearly 700 papers were submitted to the Society for Information Display's 2017 technical symposium. This is the highest number since 2011 (coincidentally or not, this was the last time Display Week took place in Los Angeles).

An impressive 30% of this year's submissions were from China alone. Another 20% were from Korea, making one half of this year's submissions from these two countries (approximately 75% of all papers are from the Asian nations of China, Korea, Taiwan, and Japan). "Display Week 2017 is shaping up to be one of the most technologically advanced and diverse symposiums we have hosted. It is a very exciting time to be in the display industry, anywhere around the world, and our speaker line-up aptly reflects this," said Technical Program Chair Rashmi Rao at the paper selection meeting last winter in Seattle.

This year's technical symposium runs from May 23 to 26, and will include 311 oral presentations and 240 poster presentations on a vast range of display topics. Obviously, that's many more papers than any one person can take in during the four days of the program, but you can focus on the ones that are most important to you if you plan ahead by accessing the preliminary program online at http://displayweek.org/2017/Program/Symposium.aspx and also by reading this article, in which we point out some of the highlights. Last but not least: don't forget to bring friends and colleagues along to cover what you can't!

Papers at Display Week are organized into sessions by technical focus: Active-Matrix Devices, Emerging Applications, Applied Vision, Display Electronics, Display Manufacturing, Display Measurement, Display Systems, Emissive Displays, e-Paper and Flexible Displays, Lighting, Liquid-Crystal Technology, OLEDs, Touch and Interactive Displays, and Automotive/Vehicle Displays. Each session consists of three to five 20-minute presentations.



Attendees take in one of hundreds of technical presentations at last year's Display Week in San Francisco. The symposium is the heart and soul of Display Week.

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DISPLAY WEEK LOS ANGELES 2017

Display Week 2017 Overview

Los Angeles Convention Center, Los Angeles, California, USA

May 21– 26, 2017

TIMES	Sunday May 21: Short Courses	Sunday May 21: Display Metrology Workshops	Monday May 22: Seminars	Monday May 22: Business Conf.	Tuesday May 23: Symposium	Tuesday May 23: OLED 30th Anniversary Celebration	Tuesday May 23: Market Focus Conference	Tuesday May 23: Exhibits Exhibitors Forum Sessions / I-Zone	Tuesday May 23: Investors Conf.	Wednesday May 24: Symposium	Wednesday May 24: Exhibits Exhibitors Forum Sessions / I-Zone	Wednesday May 24: Market Focus Conference	Wednesday May 24: CMO Forum / Women in Tech	Thursday May 25: Symposium	Thursday May 25: Exhibits Exhibitors Forum Sessions	Friday May 26: Symposium
8:00 AM				Business Conference	Session 1: SID Business Meeting											
8:30 AM			Seminars M1 - M3		Session 2: Welcome / Keynote Addresses								CMO Forum			
9:00 AM	Short Courses S-1 & S-2	Display Metrology Workshops								Oral Sessions 24-30	Exhibits / Exhibitors Forum / I-Zone	Market Focus Conference: AR/VR		Oral Sessions 45-49	Exhibits / Exhibitors Forum / I-Zone	Oral Sessions 71-76
9:30 AM																
10:00 AM																
10:30 AM			Seminars M4 - M6		Ribbon Cutting Ceremony					Oral Sessions 31-37				Oral Sessions 50-56		Oral Sessions 77-82
11:00 AM					Oral Sessions 3-9		Market Focus Conference Automotive (11:00-5:30)	Exhibits / Exhibitors Forum / I-Zone	Investors Conference							
11:30 AM																
12:00 PM				Lunch	Lunch					DIA & Best-in-Show Awards Luncheon				Lunch		Author Interviews
12:30 PM			Seminars M7- M9											Oral Sessions 57-63		
1:00 PM				Business Conference												
1:30 PM					Oral Sessions 10-16					Designated Exhibit Time						
2:00 PM																
2:30 PM																
3:00 PM	Short Courses S-3 & S-4		Seminars M10 - M12											Oral Sessions 64--70		
3:30 PM					Oral Sessions 17-23	OLED 30th Anniversary Celebration				Oral Sessions 38-44			Women in Tech			
4:00 PM																
4:30 PM														Author Interviews		
5:00 PM			Seminars M13 - M15	Bus. Conf. Recept.	Author Interviews					Author Interviews				Poster Session		
5:30 PM																
6:00 PM																
6:30 PM																
7:00 PM																
7:30 PM																
8:00 PM			Honors and Awards Banquet													
8:30 PM																
9:00 PM																
9:30 PM																

It's worth noting that while the technical symposium is the heart and soul of Display Week, there are many other valuable events going on: the Sunday Short Courses and Display Metrology Workshops; the Monday Seminars; the Business, Investors, and Market Focus Conferences; the CMO Forum; and the Wednesday night Special Networking event at the Grammy Museum. New this year are a forum aptly titled "Women in Tech," in which five distinguished women from technology fields will discuss their professional challenges and successes; and a special 30th Anniversary OLED Celebration, which includes talks from Ching Tang and Steve Van Slyke, the two researchers who delivered the first OLED paper at SID three decades ago. Visit www.display.org for a schedule.

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

Many Materials, Many Advances

Every year, SID creates areas of special focus that are designed to both reflect and encourage interest in specific areas of display technology. This year, these focus areas are AR/VR, Digital Signage, Display Materials and Processes, and Wearables. We'll start with Display Materials and Processes, because there's quite a bit going on here.

Thermally activated delayed fluorescence (TADF) emitters and perovskites are two "hot" new materials that are attracting a lot of attention, according to Ion Bita, co-chair for this year's Display Materials and Processes program. TADF emitters have the potential to improve OLED performance, and perovskites are an emissive nanomaterial that may be used in ways similar to semiconductor QDs. Bita notes that while the investigated perovskites contain more lead than QDs (many of which contain cadmium), the Restriction of Hazardous Substances (RoHS) limits for lead content are higher than those for cadmium content. Cadmium-based QDs have faced some market challenges in terms of environmental regulations, and this may give perovskites an edge. Bita is also the guest editor for this issue of *ID* magazine, and has brought us articles on both TADF emitters and perovskites. Make sure you read them so you're ahead of the curve before the show.

Speaking of QDs – they continue to be a popular research topic. It's exciting to see a technology move from the emerging to the commercial category in just a few years. The paper "Key Challenges towards the Commercialization of Quantum-Dot LEDs" by Lei Quian of TCL Corporate Research will be useful for anyone wanting to get up to speed on QDs and QLEDs. Lei's work covers performance, including efficiency and lifetime, as well as the development of printable QD inks (including ink-jet printing techniques), and blue QDs. To find out more about the environmental aspects of QDs, check out "Environmentally Friendly Quantum Dots for Display Applications" by Hyosook Jang of Samsung. This presentation describes the adoption of indium phosphide (Inp) based QDs as an alternative to cadmium-based ones.

Two other intriguing materials are carbon nanotubes and zinc-oxide nanorods. You can find out more about them in the presentations "Printed Carbon-Nanotube TFTs and Their Application in OLED Backplane Circuits" by Jianwen Zhao at the Chinese Academy of Sciences and "ZnO Nanorod Array Fabricated on Conductive and Transparent Gallium-Doped ZnO substrates for Sensing Applications in Displays" by Chaoyang Li of the Kochi University of Technology, respectively.

According to Frank Yan, chairman of the Emissive Displays subcommittee, research interest is strong in quantum-dot light-emitting diode (QLED) and micro-LED materials. Micro-LED papers increased from 3 to 7 this year over last, and emissive sessions expanded from 5 to 7. Submissions from China accounted for about half those papers. (Yan mentioned that the technical committee in China organized the International Conference on Display Technology [ICDT], encouraging scientists to submit papers to ICDT as well as to Display Week, which had a positive effect on both quantity and quality.) In terms of the emissive papers from all over the world, says Yan, "The overall quality was very high. We had to reject papers of reasonable quality this year that would have been selected in previous years."

Michael Weaver, chair of the OLEDs subcommittee, also mentioned TADF emitters as a popular topic, because it is a competing technology compared to phosphors as an OLED emitter material. Another trend for OLEDs that Weaver points to is digital cinema. A recommended OLED paper in this area is "Curved Kawara-Type Multidisplay Combined with an OLED Device for BT.2020 Color Gamut" by Daiki Nakamura of SEL, which describes a multidisplay capable of displaying a seamless image with few visible joints. The OLED display achieves an area ratio of 106% to the BT.2020 color gamut in the u′v′ chromaticity diagram.

Beyond Reality

Augmented reality and virtual reality devices, especially the head-mounted variety, frequently show up on the pages of mainstream media, but the devices themselves aren't in the mainstream in terms of usage. The challenge of making comfortable, useful devices that will take advantage of "killer apps" yet to come is also an opportunity for display makers. No further indication of such interest is needed than the Society's selection of Clay Bavor, vice president of virtual reality for Google, as one of the keynote speakers who will kick off Display Week. Google's best-known foray into this area was Google Glass, but it now makes the affordable ($15) Google Cardboard and the comfortable (fabric-covered) Daydream viewers. Bavor is sure to have lots to say about the state of the art and the future of VR and how display companies can be part of it.

The technical symposium will offer several AR/VR sessions with a large number of invited papers, including "Liquid Crystal Lenses in Augmented Reality" by Yi-Hsin Lin from National Chiao Tung University and "A Switchable Light-Field Display for Mobile Applications" by David Fattal of LEIA. (*ID* magazine interviewed Fattal in the January/February 2017 issue.) There is also an entire session dedicated to Light-Field Displays for AR and VR that is sure to offer a lot of insights into the promising territory of light fields.

A Large Display by Any Other Name...

All digital signs are electronic displays, but not all electronic displays are digital signs. The distinction probably isn't terribly important outside of Display Week, but for the purposes of categorizing papers for the symposium, the technical committees decided to designate displays larger than 120 inches as digital signage, says Gary Feather, chair of this year's digital signage focus initiative.

Display Week 2017 Symposium at a Glance

2017 SID Display Week Symposium at a Glance – Los Angeles Convention Center

Day	Times	Room 515A	Room 515B	Room 502A	Room 502B	Room 501	Room 503	Room 518
Tuesday, May 23	8:00 – 10:20 am	SID Business Meeting and Keynote Session (Concourse Hall 151-153)						
Tuesday, May 23	11:10 am – 12:30 pm	3 OLED Devices I	4 AR/VR Invited Session I	5 Flexible/Stretchable/Wearable Displays (Joint with e-Paper and Flexible Displays)	6 Quantum-Dot LEDs I	7 Advanced Integrated Circuits	8 Materials and Devices for Lighting	9 Advanced Driving Circuits I
Tuesday, May 23	2:00 – 3:20 pm	10 OLED Devices II	11 AR/VR Invited Session II	12 Wearable Sensors and Materials (Joint with e-Paper and Flexible Displays)	13 Quantum-Dot LEDs II	14 Solution-Based TFTs	15 Impact of Lighting	16 Advanced Driving Circuits II
Tuesday, May 23	3:40 – 5:00 pm	17 Flexible Substrates and Materials (Joint with e-Paper and Flexible Displays)	18 AR/VR (Joint with Liquid-Crystal Technology and OLEDs)	19 Micro Light-Emitting-Diode Displays (Joint with Emissive Displays)	20 Perovskite Quantum-Dot Materials (Joint with Emissive Displays)	21 Reliability of Oxide TFTs	22 Materials and Devices for Displays and Lighting (Joint with OLEDs)	23 HDR and Image Processing
Tuesday, May 23	5:00 – 6:00 pm	Author Interviews (Petree Hall)						
Wednesday, May 24	8:30 – 8:50 am			Vehicle Track Special Keynote Presentation				
Wednesday, May 24	9:00 – 10:20 am	24 Flexible/Foldable AMOLED Displays	25 Quantum-Dot and Micro-LED Displays	26 Future of Automotive Displays and HMI	27 Fast-Switching LCDs I	28 High-Resolution Active-Matrix Displays	29 Aerial Displays	30 Advaced Laser Processing (Joint with Display Manufacturing)
Wednesday, May 24	10:40 am – 12:00 pm	31 Flexible/Foldable AMOLED Displays II	32 Quantum Dots on LED Chip	33 Automotive Curved Display and Testing Methodology	34 Fast-Switching LCDs II	35 Novel Active-Matrix Techniques	36 Projection: Solid-State Illumination	37 OLED Material Thermal Evaporation
Wednesday, May 24	2:00 – 3:30 pm	Designated Exhibit Time (Exhibit Hall)						
Wednesday, May 24	3:30 – 4:50 pm	38 E-Paper and Reflective Displays	39 Quantum-Dot Materials (Joint with Emissive Displays)	40 Automotive Materials (Joint with Display Materials and Proceeses)	41 Alignment I	42 New Applications of Oxide TFTs	43 Digital Signage Optics (Joint with Display Systems)	44 Flexible and OLED Display Manufacturing
Wednesday, May 24	5:00 – 6:00 pm	Author Interviews (Petree Hall)						
Thursday, May 25	9:00 – 10:20 am	45 OLED Materials I (Joint with OLEDs)	46 Novel Technology for AR and VR (Joint with Augmented Reality and Virtual Reality)	47 Automotive Lighting and Systems	83 Alignment II		48 Topics in Display Measurement	49 In-Cell Touch
Thursday, May 25	10:40 am – 12:00 pm	50 OLED Materials II	51 Emerging Applications: AR/VR (Joint with Emerging Applications)	52 Automotive Visual Performance	53 Liquid Crystal Display Materials (Joint with Display Materials and Proceeses)	54 3D - Holographic	55 High-Dynamic-Range Display Measurement	56 Integrated Fingerprint Sensing
Thursday, May 25	1:30 – 2:50 pm	57 OLED Materials III	58 Advantage of Near-to-Eye Displays (Joint with Augmented Reality and Virtual Reality)	59 Automotive HUD / HMD (Joint with Display Systems and Augmented Reality and Virtual Reality)	60 High-Dynamic-Range LCDs	61 3D - Light Field and Autostereoscopic	62 Display Measurement Standards	63 OLED Touch
Thursday, May 25	3:10 – 4:30 pm	64 OLED Applications	65 AR/VR Display Measurement (Joint with Augmented Reality and Virtual Reality)	66 Emerging Electronic Materials	67 Wide Color Gamut (Joint with Emissive Displays)	68 Emerging Applications	69 Digital Signage: Visual Quality	70 Touch Materials (Joint with Display Materials and Proceses)
Thursday, May 25	4:30 – 5:30 pm	Author Interviews (Petree Hall)						
Friday, May 26	5:00 – 8:00 pm	Poster Session (Petree Hall)						
Friday, May 26	9:00 – 10:20 am	71 OLED Displays I	72 Light-Field Displays for AR and VR (Joint with Augmented Reality and Virtual Reality)		73 New LCDs I	74 Digital Signage: Emerging Applications (Joint with Emerging Applications)	75 Perception-Based Video Optimization	76 Advanced Manufacturing and Metrology
Friday, May 26	10:40 am – 12:00 pm	77 OLED Displays II	78 Optimizing Image Quality for VR (Joint with Augmented Reality and Virtual Reality)		79 New LCDs II	80 Emerging Technologies	81 Visual Quality of HDR Displays	82 Glass Substrates and Components
Friday, May 26	12:00 – 1:00 pm	Author Interviews (Petree Hall)						

TECHNOLOGY TRACKS KEY

Active-Matrix Devices	Applied Vision	Augmented Reality and Virtual Reality	Automotive/Vehicular	Digital Signage	Display Electronics
Display Manufacturing	Display Materials and Processes	Display Measurement	Display Systems	Emerging Applications	Emissive Displays
e-Paper/Flexible	Lighting	Liquid-Crystal Technology	OLEDs	Touch and Interactivity	Wearable Displays

"LCD is probably the major digital signage technology right now," says Feather. One popular trend is reducing the bezel so as to make display "walls" that can be configured to look like mirrors, or actual walls, or whatever kind of backdrop might be required.

Another trend is LEDs for digital cinema that would incorporate Dolby vision at 4,000 nits. "These would be ultra fine pitch, and fine pitch is the important thing," says Feather. (For more about high-resolution LED signs, see Feather's article, "Elemental Evolution of Digital-Signage Components," in the January/February 2016 issue of *ID* magazine.)

Find out more about both trends from the papers "Development of a Zero-Bezel Display Utilizing a Waveguide Image-Transformation Element" by Sejin Lee of LG Display Co., Ltd. and "Fine-Pitch Image Quality on LED Video Screens" by Jorge Perez Bravo of NanoLumens.

Exploring the High Dynamic Range

"The biggest trend in Applied Vision is HDR [high dynamic range]," says David Hoffman, subcommittee chair for Applied Vision. "We have a whole session on that. And we have an invited speaker from a [film] studio, Universal Pictures – we don't get studio people to speak to us very often. I think it's going to be really interesting." That paper, "Qualitative Exploration of HDR Display Performance," by Bill Mandel of Universal Pictures, considers HDR content in relation to HDR display capability. The author presents test patterns and related tools that explore contrast and saturation across HDR tone ranges, and argues for further exploration of HDR techniques in conjunction with human vision factors to continually improve the viewing experience.

HDR cropped up in Display Electronics as well, according to subcommittee chair Wei Yao, who noted there were quite a few papers on the topic – in fact there is an entire session devoted to HDR and image processing. "This is a 'soft' area, which is unusual for display electronics," says Yao, meaning that Display Electronics does not usually address aesthetics. "This is about processing the data, making it look nice for consumers who buy the TVs."

The other trend in Display Electronics – driving circuits for OLEDs – Yao describes as "less soft" and indicative of industry-wide interest in OLEDs.

Displays from Head to Toe

Currently, two of the hot areas for wearables research are displays and supporting electronics that can be worn on the body in the form of clothing or sensors, and display systems that are worn on the head, such as VR goggles.

The former category includes efforts to make stretchable and flexible systems that can ultimately mimic fabrics and protective clothing. Most of the stretchability papers have to do with the underlying electronics that allow the stretchability, notes Bill Cummings, co-chair of the Wearables program. He points to "Smart Fabrics Functionalized by Liquid Crystals" by John West at Kent State University as an especially interesting, out-of-the ordinary paper. It describes liquid-crystal functionalized smart fabrics fabricated by gas jet- or electro-spinning. According to the authors, "These fabrics retain all the stimuli-responsive properties of liquid crystals. Because they are flexible, self-supporting and have large surface-area-to-volume ratios, [they] are ideally suited for an array of sensing applications."

The other aspect of wearables is what Cummings describes as "things that attach to your head." These displays have to get better, he says. "People don't really want to put things on their heads. And they don't know what to do with it [head-mounted technology]." The need for head-mounted displays and the quality of the head-mounted displays must come together, he continues.

> **"What we're seeing is a merger of activity in microdisplays among established companies, start-ups, and university research labs. And when there's a lot of activity, there's a lot of innovation."**
>
> ***Bill Cummings***

In terms of the latter, a necessity is a very high resolution display near to your eyes, and companies are working toward that goal. "We're excited to see the activity at this conference," he says. "What we're seeing is a merger of activity in microdisplays among established companies, start-ups, and university research labs. And when there's a lot of activity, there's a lot of innovation."

There's also an entire session on micro-LED displays, including a good overview of this technology, the invited paper "Nitride Microdisplays and Micro-LED Displays," by Hongxing Jiang of Texas Tech University, which will discuss development, applications, and future possibilities.

Displays on Wheels

Vehicle designs incorporate ever-increasing numbers of displays for both information and entertainment purposes, and this is a welcome trend for display makers. According to Karl-heinz Blankenbach, chair of the Automotive/Vehicle Subcommittee, there is a trend toward larger and curved displays for infotainment as the industry looks toward autonomous driving. "There's a notion of cars as a third living space," says Blankenbach. In addition, high-concept interior and exterior lighting (often using LEDs) is increasing, with the latter even beginning to serve as branding by creating a uniquely recognizable look for the vehicle.

If you'd like a big-picture view of what's happening in vehicles, check out "How the Mobility of Tomorrow Influences the Technologies of Today" by Nadine Langguth of Merck KGaA. This paper considers autonomous driving, the connected car, urbanization, car sharing, transportation on demand, and many other use trends that will affect not only drivers but display makers.

Automotive topics, including human-machine interface (HMI), are covered in several sessions. An entire session is devoted to automotive HMIs, with four invited papers by prominent authors.

Making and Measuring Displays

Display Manufacturing received the largest number of papers in at least five years, according to subcommittee chair Dr. Tian Xiao. Hot topics include the application of emerging materials such as graphene in displays, and LTPS and oxide TFT manufacturing technologies that are compatible with flexible/bendable displays. The topic of oxide

TFT is not new, says Xiao. "But the ultimate goal is to make the manufacturing cost of oxide TFT on par with that of amorphous silicon TFT, and the race is on to make that happen!"

Another trend he sees is high resolution for OLEDs. There are many papers on how to manufacture OLED displays with very high-ppi values, Xiao says, adding that this is partially driven by AR/VR, where such high resolution is needed on very small display formats.

Another notable paper in display manufacturing combines both metrology and manufacturing disciplines. "Applied Materials [the author] is really helping the industry to improve the yield for high-resolution frontplanes and backplanes," says Xiao. "It involves using inline SEM [scanning electron microscope] technology on large panels." The invited paper is "Inline Electron-Beam-Review (EBR) Accelerates Yield Ramp-Up of Advanced Displays" by Xuena Zhang of Applied Materials.

The big news in Display Measurement, according to subcommittee chair Tom Fiske, is AR/VR and the new ICDM standard. There is an entire session on metrics for AR/VR. "People are proposing several different methods for NTE [near to eye] display measurements. These measurement systems, in some cases, attempt to measure optical performance parameters in ways that mimic what the human eye sees – or at least in ways that are relevant to the human visual system."

Not to be missed is an overview of the progress of the revised ICDM display measurements standard, which will include new methods of optical metrology for resolution, HDR, AR/VR, curved displays, and more. This presentation, by Joe Miseli of JVM Research, is called "Progress Toward the ICDM2 Display Measurements Standard." Says Fiske, "This is a very significant publication. A lot of companies are involved and care deeply about it."

> **"This [ICDM2] is a very significant publication. A lot of companies are involved and care deeply about it."**
>
> ***Tom Fiske***

Notable Papers

The following is a list of a few more notable papers (there are many more than can be named here) from various areas of the technical program:

How Lighting May Affect Your Health — "Biological Effects of Light: Can Self-luminous Displays Play a Role?" by Mariana Figueiro of the Lighting Research Center at Rensselaer Polytechnic Institute.

"This is a look at the impact of lighting on health," says Lighting Subcommittee Chair Marina Kondakova. "The author describes the effects of lighting, especially blue light, on circadian rhythms." The paper considers displays that produce more blue light in daytime and more amber light at night. This "tunable" lighting is being used in hospitals and in Alzheimer's facilities.

Investigating OLED Touch — "A Novel Touch-Control Method with Partial Scanning for LC, OLED, and Hybrid Displays Using an Oxide Semiconductor" by Kei Takahashi of Semiconductor Energy Laboratory Co., Ltd.

"We have a great OLED touch session," says subcommittee chair Jeff Han. This paper is one of three in that special session.

Illumination Decisions — "Lasers, Lamps, or Phosphors – Choices for the Future of Digital Cinema" by Michael Perkins of Christie Digital Systems.

The first generation of digital cinema projectors are now being deployed into the majority of movie theaters around the world. The illumination technology of choice for that first generation was Xenon lamps. Now that laser and laser-phosphor are mainstream illumination technologies, cinema projection engineers have a whole new set of decisions to make.

A Display You Can Dive Into — "An Aerial Display: Passing through a Floating Image Formed by Retro-Reflective Reimaging" by Hidetsugu Suginohara of Mitsubishi Electric Corp.

The authors have developed a 56-in. floating image that you can "dive" into. This is one of three papers in a special Aerial Displays session with Display Systems.

Better Surgery Through Augmented Reality — "Augmented-Reality Training System for Endoscopic Surgery" by Rong Wang at the Chinese Academy of Sciences.

The authors propose a 3D augmented reality (AR) system for perception training on the ablation of a tumor inside the kidney. The system consists of region-based visual tracking for localizing the kidney and tumor and a 3D display for visualizing AR results. They also integrate a virtual instrument in the system.

A Microlens Array for Surgeons — "Wavelength-Independent Electrically Tunable Microlens Array with a Chiral Nematic Liquid Crystal" by Kai-Han Chang with the Liquid Crystal Institute at Kent State University.

This is a late-news paper that describes a liquid-crystal microlens array with low operating voltage and wavelength-independent, electrically tunable focal length, qualities that make it suitable for full-color 3D microscopy and endoscopy applications.

Getting LCDs Ready for the Spotlight — "Can LCDs Outperform OLED Displays in Motion-Picture Response Time?" by Shin-Tson Wu of the University of Central Florida.

The author of this invited paper describes some metrics that would improve LCD motion-picture response time.

Super-stretchy LEDs — "Ultrathin Stretchable Oxide Thin Film Transistor and Active Matrix Organic Light-emitting Diode Displays" by Seong-Deok Ahn of ETRI.

The authors demonstrate ultrathin, stretchable oxide thin-film transistor and active-matrix organic light-emitting diode displays that can be operated as free-standing ultrathin films under 30% strain.

Introducing an 8K BT.2020 AMOLED — "An 8.34-in. 1058-ppi 8K x 4K Flexible OLED Display" by Tomoya Aoyama of Semiconductor Energy Laboratory Co., Ltd.

By combining an OLED device with a color filter and a specially designed top emission structure, the authors successfully fabricated a full-specification 8K AMOLED panel with the BT.2020 color gamut.

High Gamut Automotive Displays — "Quantum-Dot-Based Wide-Color-Gamut TFT-LCDs for Automotive Applications" by Rashmi Rao and Elijah Auger of Harman Inc. This paper will discuss the details of manufacturing a wide-color gamut LCD-TFT display using quantum dot film, and the testing procedures used to qualify such a display for automotive applications. ■

Q&A with IRYStec

ID interviews Tara Akhavan, Simon Morris, and Afsoon Soudi, the principals of IRYStec, a Montreal-based startup that makes Perceptual Display Platform (PDP), an embedded software technology that adjusts the characteristics of content displayed on devices to match how a viewer's eyes see it in different ambient light. IRYStec was founded by Akhavan and Soudi in Montreal, and closed its Series A financing round in June 2016.

Conducted by Jenny Donelan

ID: IRYStec's main product is called Perceptual Display Technology. Can you describe what that is?

Tara Akhavan: Perception is a missing link in the display industry. Display settings are not a guarantee of what we will perceive, because there are a lot of other influences on how we see information. The biggest one is ambient lighting. What you render on a display is not necessarily going to be perceived the same way when you are in a really dark environment as when you are walking in a park in the daytime. You need to change the way you are rendering according to the way eyes work in different ambient lighting. Another aspect is the personalized aspect of perception. Each of us has a unique visual system. We see stuff differently, according to age, gender, and background culture. This all affects the way we perceive information. You personalize it to make sure that what you perceive is what you were supposed to.

ID: How does your technology do that?

TA: We have close collaborations with a lot of physiologists and psychologists who understand how the eye works and reacts with regard to aging, ambient light change [*etc.*], and we model and compensate [accordingly]. So before content is shown in a dark room, the device knows you are in a dark room and renders that content differently.

ID: So at this point the device is determining what the ambient light in the room is.

TA: Yes. But in terms of the personalization, we need to collect the data – the age and the gender of the user. After that a tiny calibration is made and the content is rendered, based on that.

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

ID: Is this done on the fly or is this something the user needs to enter ahead of time?

TA: The ambient process is done on the fly, because the ambience can change pretty rapidly. The calibration for personalization is something you would do just once.

Simon Morris: The innovation is basically two forms: figuring out the algorithms and then figuring out a lightweight implementation for them, on a device. This process is pretty heavy computationally and often has to be in hardware, which is the approach that some of the competition has taken.

TA: Our product is pure software. That is the magic.

ID: The algorithms are embedded in software in a particular device?

TA: They would be embedded in an OS.

SM: This could also be integrated in an app, like YouTube or Facebook, but the most effective implementation is really at the OS layer, where all apps can benefit from IRYStec technology.

ID: What applications do you foresee? And devices?

SM: The need is greatest where a display is personalized – a smartphone, obviously, or a tablet. Any display that is moving while you are using it, from bright light to darkness. Automotive is another application. Especially motorcycles, which are going through the same transformation as cars, with the instrumentation cluster turning into a display.

TA: Only in movie theaters do you have control over the ambiance. Everywhere else you have displays where the environment is not controlled anymore. It's very dynamic. And while it is great to go from LED to OLED to quantum dot, the software side of the game needs to catch up.

ID: What stage is the technology at right now? For example, do you have partners?

SM: Well, we call customers, customers! We are working with a dozen or so handset manufacturers, of which more than half a

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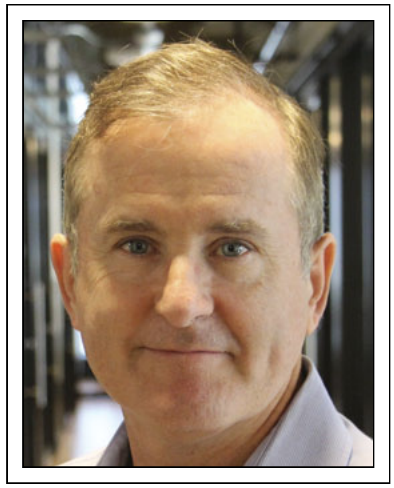
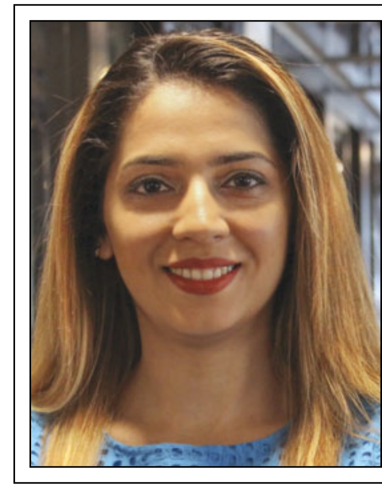
__Tara Akhavan__ is co-founder and CTO of IRYStec. She has a bachelor's degree in computer engineering and a master's degree in artificial intelligence. She is currently finishing her Ph.D. in image processing and computer vision at Vienna University of Technology in Austria. Akhavan is the vice chair for marketing for the Society for Information Display.



__Simon Morris__ joined IRYStec as CEO in early 2016. He was formerly CEO of CogniVue Corporation. He has also served as director at BDC Venture Capital and, from 1995 to 2006, in various senior leadership positions with Texas Instruments and Atsana Semiconductor. He has bachelor's and master's degrees in electrical engineering from the Royal Military College of Canada, and is a member of the Professional Engineers of Ontario.



__Afsoon Soudi__ is co-founder and vice president of R&D for IRYStec. Prior to founding IRYStec, Soudi led multiple research groups. She has a Ph.D. in physics from Washington State University. She has also been actively involved in various societies, including SPIE, and in promoting women in science and technology.

dozen are in detailed evaluation of our smartphone technology. We've brought one phone manufacturer to preproduction. We expect sometime in the second quarter to be in a production handset. And in automotive we signed our first actual licensing agreement and we're developing and supporting the software for what's called driver information systems. There's a slightly different use case for automotive, where safety is paramount, and there are some standards around contrast, so you have to maintain certain contrast levels. We are getting a taste of the VR market. We're trying to get a better feel for the exact use case for VR, but it's not the major focus right now.

ID: Can you describe your business journey so far? How did you get started, and what kinds of successes and failures have you had leading up to this point?

TA: We started 2.5 years ago in an incubator in Montreal with the original idea of just compensating for darkness, for night vision. My background is computer vision. I moved from Vienna, Austria, to Montreal to start this because of the funding available in the incubator. I discovered my brilliant co-founder [Afsoon Soudi] here in Montreal. I'll let Afsoon explain the challenges!

Afsoon Soudi: In 2014 there was this hype in Silicon Valley [for startups] but not so much in Canada. It was not that easy to get funding as a technical founder. But things were starting in Montreal, and TandemLaunch helped us start the process. The company started with just us and a couple of interns and a few professors and advisors from Europe and the US.

The biggest challenge initially was to find the right market fit for the technology we had. We had a lot of discussions with brilliant people to learn more about the business side and find the right way to position our product. That was how, later on, we came across Simon. He had the experience of delivering products in the automotive market and with very similar processes to how we wanted our product positioned. Having his

> **"I also wanted to add that from the beginning, SID has had a great impact on how we put our business together."**
>
> *Tara Akhavan*

complementary experience definitely added a lot of value and made our second round of financing possible in June 2016.

TA: Raising money, building a team, attracting professors to work with you – all of those are challenging for every startup. But on top of that we were two women co-founders. We went to Display Week together: Our first event was the I-Zone at Display Week. When people would visit our booth from other, bigger companies they were always asking us, who are the technical people, and we were like, that is us! Those were extra challenges and we have always faced them, but we have been so lucky to get people involved, like our CEO, and our investors, who support us.

SM: It's a challenge and I can see it happening. The first time I joined them [Tara and Afsoon] at CES, we had a booth in the startup area. Tara, Afsoon, and I were all dressed nicely, business-like. Inevitably everyone would come to me to ask me the technical questions.

ID: Do you have advice to offer people and especially young women going into the sorts of areas that you're in? Can you offer some encouragement?

TA: I've been thinking about this for a while now. If you are a technologist and you are a woman, even at school you are a minority. You are always facing this. But it gets more real when you start working in the industry. I think the answer is ... well, I have seen other people [in these situations] get angry or get offended. But you need to push through and surround yourselves with people who support you, like our investors and our CEO. They trust us and believe in us and we build on top of that. We might have a harder time getting there but we just push and don't give up.

AS: Nothing in life comes easy or at no cost. It's not gonna be all roses and rainbows and it can be hard. There are mornings when everything is great and then by the afternoon it's just horrible and bad. It's great if you can find partners like Tara and Simon who can get you through those difficult times. It's very important to have the right people to start with and build the culture of the company on that. Startups are difficult. Ninety percent of them fail in the first year, and another 70 to 80 percent fail in the second year, so it is a difficult thing to do. You have to push through it and not get discouraged.

ID: You've been going through this admittedly challenging stage, but soon you're not going to be an up-and-coming company selling a possible product; you're going to be a company selling a product. How does that look to you and inform your hiring practices and your involvement with the day-to-day business?

TA: The scaling is a real challenge. You have to start from the right place. We had this experience going from fewer than five people to more than 20 people. That was a big jump for us. You have to have the right strategies. Hire the right people with the right expertise and keep them motivated.

SM: It's a different skill set to deal with the various levels of the company as it grows. There actually aren't a lot of people who stay from a startup position to the very end. Mark Zuckerberg is one of them. As founders you've always got to be aware of your limits, strengths, and weaknesses, and then complement yourself with the right people as you move through the stages of growing the business. I think founders who have that perspective can grow nicely with the business.

TA: One thing about hiring that I'm very proud of is that we have one of the most diverse teams in terms of both technology background and also male/female balance. We're at almost 50/50 male/female, which adds a lot to the dynamics and health of our startup. We are from seven different countries.

[Skill] diversity is also a key point. A lot of the big companies are slow, and we are faster because we have a very diverse team. And that is since day one. When I joined I had a good software background, but I was always looking for complementary skill sets. Hardware is one of those, and that's where Afsoon, my co-founder, came in. And we had a great tech advisory board that would help us put together the bits and pieces.

SM: Diversity also concerns personality. There's a tendency to recruit people with similar personalities to yours. It's hard to avoid that and find instead someone who is going to complement and strengthen your team. You want to bring in people who are not necessarily going to agree with you – the ones who will critique you the most. Sometimes this leads to heated discussions, but it's healthier for the company. There's a tendency with startups to have everyone who thinks alike. And that's dangerous.

TA: I also wanted to add that from the beginning, SID has had a great impact on how we put our business together. I-Zone was our first outing as a company. Our first investor is now president elect. We were introduced to SID early on. The short courses, and all the Display Week events, helped us find the basic things we were looking for. And the I-Zone is great for start-ups. So we kind of have this feeling of semi-ownership, semi-gratitude toward SID. ■

> **"It's very important to have the right people to start with and build the culture of the company on that."**
>
> ***Afsoon Soudi***

> **"There's a tendency with startups to have everyone who thinks alike. And that's dangerous."**
>
> *Simon Morris*

Journal of the Society for Information Display

Announcements

Discontinuation of IEEE-JDT

One of the best publication platforms for display researchers, the Journal of Display Technology, has sadly been discontinued in December. At SID we are committed to offering display scientists an efficient and powerful publication platform of our own: the Journal of the Society for Information Display (JSID), published by Wiley and indexed in the Web of Science.
We are working hard to make JSID the best journal for display scientists.

Publons

In 2016, Wiley partnered with Publons. This allows reviewers to get verified credit for peer review without compromising their anonymity or infringing upon journal policies. It is a step in the good direction to make it possible to reward review work.

Distinguished Papers of Display Week

All Distinguished Papers of Display Week 2017 will have a peer reviewed expanded version published in JSID. This will both widen and lengthen their worldwide visibility and availability. A virtual JSID issue containing the expanded distinguished papers will be freely accessible during the Symposium.

Information about the Journal

JSID is published monthly by Wiley. Subscription fees apply, but all SID members and student-members have free online access via sid.org/Publications.aspx
Many universities also have an institutional subscription.
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EarlyView

Accepted papers about to be published can be accessed online via EarlyView: **tinyurl.com/jsidev**

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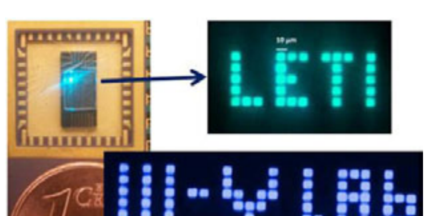

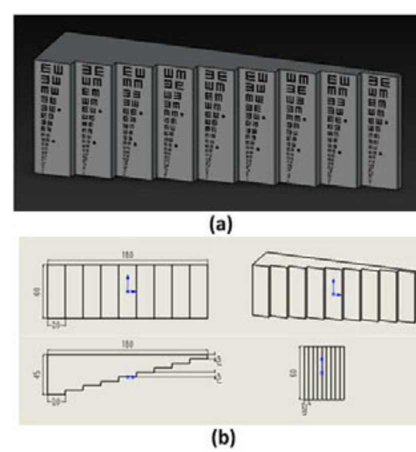

Herbert DeSmet
Editor-in-Chief

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Despite these battery challenges, it is worth noting that at the time of its release, the 5.7-in. quad high-definition 2560 x 1440-pixel OLED display in the Note 7 had the highest resolution for smartphones on the market and came with an array of impressive performance features that were highly praised by multiple reviewers.

[1]https://news.samsung.com/us/Samsung-Electronics-Announces-Cause-of-Galaxy-Note7-Incidents-in-Press-Conference
[2]http://money.cnn.com/2017/01/22/technology/samsung-galaxy-note-7-fires-investigation-batteries/

HDMI Forum Announces Version 2.1 of the HDMI Specification

The HDMI Forum, an open trade association that guides the direction of high-definition multimedia interface (HDMI) technology, recently announced the upcoming release of Version 2.1 of the HDMI Specification. This latest spec supports a range of higher video resolutions and refresh rates, including 8K60 and 4K120, "dynamic" high dynamic range (HDR), and increased bandwidth with a new 48G cable. Details of these highlights follow:

- The higher video resolutions and faster refresh rates will include 8K60Hz and 4K120Hz for immersive viewing and smooth fast-action detail.
- Dynamic HDR is designed to ensure that every moment of a video is displayed at its best values for depth, detail, brightness, contrast, and wider color gamuts – on a scene-by-scene or even a frame-by-frame basis.
- 48G cables enable up to 48Gbps bandwidth for uncompressed HDMI 2.1 feature support, including 8K video with HDR.

The new specification will be released early in Q2 2017.[3]

[3]www.hdmi.org/manufacturer/hdmi_2_1/index.aspx

Merger and Acquisition Briefs

Planar Systems, a display systems manufacturer, announced late last year that it had entered into a definitive merger agreement to acquire **NaturalPoint**, a global leader in optical tracking and motion capture solutions, for $125 million in an all-cash transaction. Planar itself was acquired by Leyard in 2015.

In February 2017, **BASF**, the multi-national chemical manufacturing company based in Germany, acquired the private company **Rolic AG**, which is headquartered in Allschwil, Switzerland. Rolic makes optical films for LCD and OLED panel makers. Both companies agreed not to disclose the terms of the acquisition.

OSRAM acquired **Maneri-Agraz**, a Texas-based lighting services provider, in February 2017. OSRAM is a global lighting and technology company headquartered in Germany. The terms of the acquisition had not been announced at press time.

SDVoE Alliance Launches at European Trade Show

In February, the new Software Defined Video over Ethernet (SDVoE) Alliance officially launched at the Integrated Systems Europe (ISE) show in Amsterdam. The SDVoE Alliance is a nonprofit consortium of technology providers collaborating to standardize the adoption of Ethernet to transport AV signals in professional AV environments, and to create an ecosystem around SDVoE technology that allows software to define AV applications.

The founding members of the Alliance are AptoVision, Aquantia, Christie Digital, NETGEAR, Sony, and ZeeVee. Just prior to ISE, the Alliance announced that eight additional companies had joined: Arista, Aurora Multimedia, DVIGear, Grandbeing, HDCVT, IDK Corporation, Techlogix Networx, and Xilinx. Additional new members are welcome.[4] ■

[4]http://sdvoe.org/

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Please send all press releases and new product announcements to:

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[9]H. Yersin, A. F. Rausch, R. Czerwieniec, T. Hofbeck, T. Fischer, "The triplet state of organo-transition metal compounds. Triplet harvesting and singlet harvesting for efficient OLEDs," *Coord. Chem. Rev*. **255**, 2622–2652 (2011).
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[14]G. Li, T. Fleetham, E. Turner, X. C. Hang, J. Li, "Highly efficient and stable narrow-band phosphorescent emitters for OLED applications," *Adv. Opt. Mater*. **3**, 390–397 (2015).
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[18]H. Nakanotani, K. Masui, J. Nishide, T. Shibata, C. Adachi, "Promising operational stability of high-efficiency organic light-emitting diodes based on thermally activated delayed fluorescence," *Sci. Rep*. **3**, 2127 (2013). ■

Display Week Debuts Women in Tech Forum

Display Week 2017 will host its first-ever "Women in Tech" forum this May in Los Angeles. "I think 2017 is THE year of women in tech events," says Women in Tech committee member Tara Akhavan, noting that other technical venues such as the Silicon Valley Forum in March are hosting women-centric events. (Akhavan, CTO and co-founder of IRYStec, has more to say about the role of women in technology in this issue's Market Insights Q&A feature.)

"I look forward to the day when there is so much diversity that we do not need a women-specific panel," says Akhavan. "Until then, I want to keep encouraging more women technologists into high-tech societies. I am passionate about this panel and happy that SID is emphasizing this important issue at Display Week 2017."

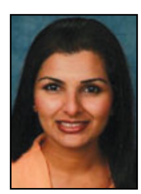

Niaz Abdolrahim


Julie Brown


Heidi Dohse


Candice Brown Elliott


Laura Rea


Rashmi Rao

The forum will feature five experts who will offer their unique insights and experiences as women in technology fields traditionally populated by men. This is a great mix of panelists whose discussion is sure to be thought provoking and inspiring.

- Niaz Abdolrahim, Assistant Professor, Mechanical Engineering and Materials Science, University of Rochester
- Julie Brown, Senior Vice President and CTO, Universal Display Corporation
- Heidi Dohse, Google Cloud Platform Program Manager, Google
- Candice Brown Elliott, Vice President, Technology, Leap Motion
- Laura Rea, Senior Technology Program Manager, U.S. Air Force Research Laboratory

The panel will be moderated by Rashmi Rao, senior director, advanced engineering for Harman and program director for the 2017 Technical Symposium at Display Week. Women who are interested in becoming entrepreneurs or leaders in a technology business should certainly plan to attend this informative and educational event. The Women in Tech Panel (www.displayweek.org/2017/Program/WomeninTech.aspx) takes place Wednesday, May 24, 2017, at 4 pm, at the Los Angeles Convention Center.

Be the Best – Win a Best in Show Award

Each year, fewer than half a dozen Best in Show winners are chosen by an independent panel of display experts who review the products, prototypes, and processes nominated for the awards on the show floor at Display Week. Winners are selected for great technology, but also for the way they display that technology on the show floor. Winning Best in Show exhibits have the ability to excite display experts and members of the general public and press alike.

Best in Show is open to all exhibitors on the show floor during Display Week 2017, and prizes will be awarded regardless of exhibit size. Self-nominations are encouraged! For details and to download a nomination form, visit:

www.sid.org/About/Awards/BestinShowAwards.aspx

EuroDisplay Calls for Papers

EuroDisplay 2017 will take place in Berlin, Germany, this fall. EuroDisplay is unique among European conferences for its emphasis on displays, electronics, and the ways in which both these impact society. This year's conference, held in conjunction with the Institute of Physics, will focus on 30 different types of displays, materials, and applications, including transparent conductors, quantum dots, printed electronics, graphene, perovskites, OLEDs, uses for liquid crystals beyond displays, 3D displays, and much more.

The conference will take place October 31 to November 2 at the Meliá Berlin, which is located in the heart of the city, just a short distance from the Brandenburg Gate, Museum Island, and Alexanderplatz. A two-day exhibition of products and techniques will be held in conjunction with the technical conference.

Abstracts for papers are due June 1, 2017. For information about the conference, including submissions, visit:

eurodisplay2017.iopconfs.org

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I encourage you to start with Ion's Guest Editor's note titled "Advances in Materials for Display Applications." If this is an area of interest for you, then this will be your year at the Symposium, with almost 40 presentations in the Display Materials and Processes tracks alone. Many more papers related to materials appear in other tracks as well. One of the hottest topics is self-emitting nano-materials such as quantum dots (QDs), which we have heard about before, and perovskites, which are much newer to most of us.

In our first Frontline Technology article, "Emerging Solution-Processable Luminescent Nanomaterials in Hybrid Structures Offer New Solutions for Displays and Lighting," authors Yajie Dong, Hao Chen, Juan He, and Shin-Tson Wu explain the state of the art for QDs, provide a detailed explanation of similar emerging optoelectronic materials utilizing the perovskite structure, and describe all the challenges of incorporating these materials into working light-emitting systems. One of the really clever things I learned from this article was about the authors' efforts to utilize the natural expansion and contraction properties of polymer films to encapsulate perovskites. Essentially, they describe a process by which solvents infused with perovskites are introduced to expand the molecular structure of a polymer film. Once the film expands, the solvent, including the perovskites, becomes embedded in the film. As the solvent is then evaporated away, the polymer matrix returns to its normal size and forms a coherent barrier layer around the remaining perovskite structures. Imagine: You simply expand the film, infuse it with the emitting nano-material, and let it dry out. You are left with a self-infused perovskite film providing all the needed environmental protections for the nano-material. It sounds so simple. I wish I had thought of it!

Another hot topic in this field is called thermally activated delayed fluorescence (TADF), and it represents a way to achieve blue emitters in OLED displays with virtually 100% potential efficiency from electrical energy to light-energy conversion. Today, as we know, OLEDs make blue-light energy using fluorescent materials that are capable of only 25% efficiency. Red and green light can be made from phosphorescent materials with 100% efficiency, but those materials are not sufficient for blue emission, hence the need and opportunity for TADF technology. In his article, "Thermally Activated Delayed Fluorescence Is a Key New Technology for OLED Displays," author Daniel Volz describes the challenges in today's OLED materials, the science behind TADF materials, and the opportunities, including what we might expect to see in the near future. I've been reading and following the OLED field for virtually my entire career and it fascinates me how much more work is still ahead of us despite how far we have come. This is another step in what will undoubtedly be an area of intensive activity and interest for years to come.

Symposium Preview

Turning our attention now to the other major theme for this issue, the preview of the annual technical program known as the International Symposium at Display Week 2017, it's worth noting that the industry must love to come to Los Angeles because once again the program committee saw over 700 abstracts submitted for consideration for one of the 311 oral and 240 poster presentation slots available. I like to cite the numbers because it provides a context to the scale and depth of the event, which in fact is just one part of the overall Display Week program. If you are looking for proof that innovations are plentiful in the world of displays, this will certainly do it. Aside from the sheer numbers, the rich array of technical focus areas such as AR/VR, Digital Signage, Display Materials and Processes, and Wearables will surely make for one of the most exciting symposiums ever. Starting with the seminars on Sunday, May 21, this year will pack more technical and business content into one week than any other display-industry event in the world.

To start planning your visit, consult the Display Week web site www.displayweek.org/2017/Attendee.aspx to register, then sit back and enjoy our Symposium Preview, "AR/VR, Digital Signage, Display Materials, and Wearables Headline Display Week 2017 Technical Program in Los Angeles," compiled by Jenny Donelan. I believe my favorite sessions may turn out to be those focused on digital signage and high dynamic range displays, or maybe the flexible and stretchable electronic fabrics being discussed in the wearables sessions, or maybe the great papers we accepted this year for the display metrology tracks, including the next generation of the ICDM measurement standards, or maybe…. Well, you get the idea. The exciting topics and in-depth technical content is un-matched anywhere else. (Don't forget to check out the handy "Display Week Overview" and "Symposium at a Glance" pages in the preview article.)

Displays at CES

CES is the annual Consumer Electronics Show (CES) in Las Vegas, which features the latest in actual products, including all manner of TVs, portable devices, wearables, and everything else you can think of that might use a display. CES is an important barometer for our industry and it's hard to find any major technical focus area that does not ultimately lead to a consumer application in some way. If you want to make a business in displays, you will almost always need to find a commercial consumer and know what their un-met needs are. CES is one of those annual events that provides that context. But even if you didn't get there don't worry – *ID* has your back! Ken Werner was onsite, and he did the hard work for all of us by compiling what he calls "The 11 Best Display-Related Finds at CES 2017" in his Show Review article. One of the notable things this year is something that I have predicted before: Once the display gets really good, the exciting story becomes one about the products that it enables instead. As Ken says in the beginning of his article "…displays were [more] important as enabling components in larger systems, notably automotive Human-Machine Interfaces (HMIs), Advanced Driver Assist Systems (ADAS), and autonomous vehicles." So, what were Ken's notable 11 things? Well, read the article and enjoy finding out.

Q&A with IRYStec

Two years ago at the I-Zone exhibit, I was introduced to a very talented young woman named Tara Akhavan, who, along with her equally talented business partner Afsoon Soudi, were showing a new technology they were working on to dynamically enhance the visual performance of displays under varying ambient lighting conditions. I say "dynamically" because in the past we've generally been able to manually adjust things like color temperature, contrast, luminance, *etc*. for varying conditions. In some cases, manufacturers have also included ambient light sensors for dynamic backlight and contrast adjustments. However, what Tara and Afsoon have done is taken a careful look at how the human visual system works, and developed algorithms that produce a consistent visual experience under widely varying ambient conditions. Their approach does this in real-time, so as you walk from inside your office to outside for your lunch break, your phone or tablet display should look the same to you. They even provide for a calibration to match your individual visual preferences, which is great, because the response of my 55-year old-eyes is very different from that of the eyes of my adult children. We wanted to know how this innovation was coming along and we were also curious about their experiences as women entrepreneurs in the display field, so we reached out to them at their company, called IRYStec, for an interview that you can find in this issue, "Q&A with IRYStec," by Jenny Donelan. I think you will enjoy learning about their progress and reading their candid observations about their experiences.

I hope you enjoy this issue as much as we enjoyed putting it together. Display Week is just around the corner – start planning! ■

guest editorial

continued from page 4

Due to the large overlap with semiconductor quantum dot (QD) applications, the authors also review the status of QD development and compare the merits of perovskite and QD materials for display applications. Notably, the thesis proposed by Professor Dong is one of finding synergies between these two material systems and pursuing applications that combine them in order to achieve near-term impact in displays and lighting applications.

For more details about these recent exciting developments in perovskite and quantum dot nanomaterials, we recommend this article prepared by Yajie Dong, Hao Chen, Juan He, and Shin-Tson Wu from UCF.

In the second article, Daniel Voltz from CYNORA gives an overview of thermally activated delayed fluorescence (TADF) and the development of highly efficient TADF emitter materials for OLED applications. Similar to the introduction of phosphorescent emitters, which made possible nearly 100% efficient electroluminescence (EL) from small molecule organics, TADF offers an alternative strategy for molecular design that enables efficient organic EL.

The efficiency improvement need addressed by TADF has to do with maximizing the fraction of electrically injected electrons (e^-) and holes (h^+) that recombine in the emitter molecule in such a way that their energy is converted to light rather than lost to nonradiative processes, *e.g.* to heat. Due to their typical molecular nature, organic emitters receiving *e-h* pairs transition into a mix of excited electronic states called singlet (S) and triplet (T) which, importantly, are formed in a 1:3 ratio (S:T). The S excited state has a net spin moment of 0 (*i.e.* opposite e^- and h^+ spin orientations) that matches the ground state of the emitter molecule, which is why S excited states can quickly and efficiently relax by emitting a photon. T excited states, on the other hand, have a net spin moment of 1 (*i.e.* parallel e^- and h^+ spins), which, by differing from the ground state, are forbidden from relaxing through light emission. Instead, molecules in this unfavorable high-energy state typically lose their energy through nonradiative mechanisms, such as heat generation. TADF represents a mechanism for converting T into S excited states and subsequently enabling efficient EL. This mechanism is possible in specially designed organic molecules that have a smaller energy difference between S and T excited states than the available thermal energy during device operation (which thus allows spontaneous T → S excited state conversion).

The team at CYNORA is one of the pioneers in developing molecules with high-efficiency TADF that are designed for OLED display applications. Please read the article prepared by Dr. Daniel Voltz to learn more about this exciting area.

I hope you enjoy both these articles about exciting new materials. I hope to see you all in Los Angeles in May. ■

Ion Bita *currently serves as the 2017 Chair of the Display Materials and Processes special topic track for the Society for Information Display's technical symposium at Display Week, and is a member and past Chair of the SID Display Manufacturing Committee. He can be reached at ion.bita@ gmail.com.*

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