INORGANIC EMISSIVE TECHNOLOGY

Information DISPLAY

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Exciting Materials Developments

THE EXPANDING ROLE FOR QUANTUM DOTS

PEROVSKITES: A PROMISING NEW DISPLAY TECHNOLOGY

QLEDs DRAW CLOSER TO COMMERCIALIZATION

CAN MICROLEDs AND QDs REVITALIZE INORGANIC DISPLAYS?

Plus

Q&A with Plessey

2019 ID Media Kit

WILEY

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NOVEMBER/DECEMBER 2018
VOL. 34, NO. 6

ON THE COVER: *One of the most exciting display trends is the re-emergence of inorganic emissive technology, including quantum dots and metal-halide perovskites.*

Cover Design: Acapella Studios, Inc.

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High-Performance Displays
- High-Dynamic Range
- Wide Color Gamut
- Automotive Displays
- The State of 8K

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editorial

The Future Is Bright for Emissive Technologies

by Stephen P. Atwood

Welcome to the final issue for 2018, and one that is especially forward-looking, as you can see from our cover. Throughout the year, we have heard a lot of discussion about emissive materials and their potential. They were a major theme at Display Week 2018, and they are clearly supported by a great deal of R&D spending around the world.

Emissive technologies, organic and inorganic, in various forms, have been around since the birth of information displays. CRTs used phosphors, which are inorganic emissive compounds that often utilized rare-earth metals, to make their images. Plasma displays also used phosphors, and there have been many other examples, such as vacuum-fluorescent and thin-film electroluminescent displays. Many of these displays worked in certain applications, but for various reasons lacked the ability to scale in terms of size (larger or smaller), resolution, optical performance, or other aspects that limited their commercial life. And yes, I know it's rather glib to write off 100 years of CRT technology as having "limited" commercial life. But as we know today, there are a multitude of product embodiments such as tablets, smartphones, and large-screen TVs that were never going to be achieved with CRTs. Hence the generational hunger in our industry for something more – the same hunger that continues to drive researchers toward even better solutions today. As you will learn in this issue, many hope to find those solutions through entirely new classes of emissive technologies.

One-Day Conference from the LA Chapter

However, before we dive into the emissive articles for this issue, I want to draw your attention to the terrific upcoming program on "Selecting and Customizing Display Products" being hosted by the Los Angeles Chapter of the Society for Information Display on February 8, 2019. I'm told this is the chapter's 15th year organizing this annual program, which proves time and again to be one of the most useful and practical technical seminars in SID's regional portfolio. I have attended several of these programs in the past, including ones on advanced television, LCD modules, and LEDs. I referred to the notes from the 2008 LED conference many, many times while designing ruggedized backlights over the years that followed. The organizing team in LA includes many well-known industry veterans, including this year's conference chair Larry Iboshi. The speaker lineup looks to be stellar as well. In our SID News department you can read more about the details of the event. And let's be honest: what's not to like about a trip to LA in early February, especially to spend a day at the Costa Mesa Country Club?

Emissive Progress

Our guest editor for this issue is Ruiqing (Ray) Ma, who is currently working as the director for QD devices at Nanosys. Ray has served both as a guest editor and contributing author for ID many times and continues to be one of our go-to experts for emissive technology. In his guest editorial for this issue, Ray expresses renewed excitement about the prospects for emissive technology to help define the future of displays. Whether through the further merging of quantum dots (QDs) and LCDs or through completely new emissive display architectures, the options are becoming more viable for breakthrough product designs. Thanks to Ray for all his hard work in developing our technical lineup for this month.

(continued on page 9)

Information DISPLAY

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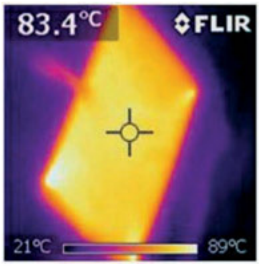
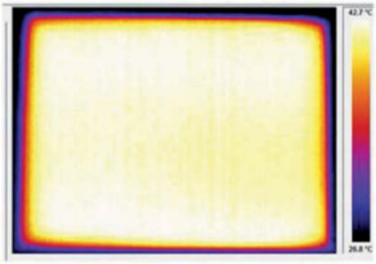
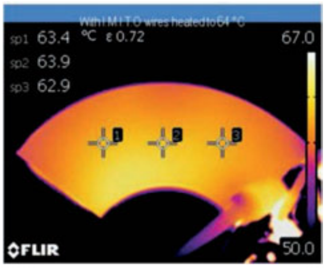


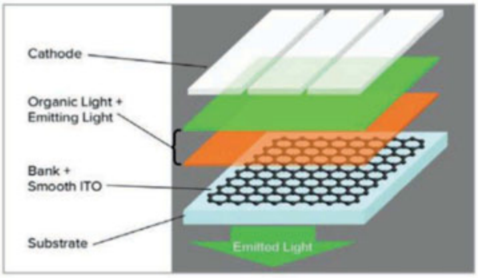
Heater / EMI Ruggedization



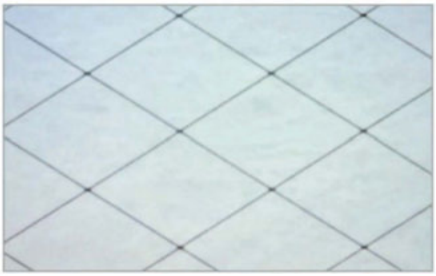
18" LCD Heat Distribution



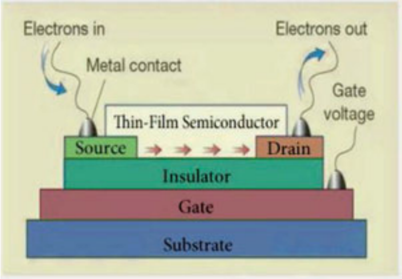
2" – 4" Drone Heater



OLED + Bank



Imbedded Mesh
(≤ 5 OPS, T% ≥ 90% @ 400-2µm)
Cu:CuO or Nb:Hf



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guest editorial

Exciting Times

By Ruiqing (Ray) Ma

In the 20 years since I entered the display field, I have never felt as much excitement about the future of display technology as I do today. One of the most exciting recent trends is the re-emergence of inorganic emissive technology. For example, at this year's Display Week, the two most-attended seminars were about microLEDs and quantum dots. In this special issue, we have compiled three excellent articles to cover the topic of inorganic emissive materials, with the focus on quantum dots and emerging metal-halide perovskites.

The emergence of quantum dots coincided with OLED succeeding in smartphones and entering the TV market several years ago. Quantum dot wasn't involved in the fight between OLED and LCD for smartphone displays because that battle wasn't about color. OLED succeeded because it possesses properties that are uniquely important to mobile devices: 1) power consumption is insensitive to high resolution; 2) thin, curved, or flexible form factors; and 3) fast switching for augmented-reality/virtual reality applications. In 2013, for the first time, OLED exceeded LCD in display resolution in smartphones, which more or less concluded the battle between the two technologies for that application. The same year also witnessed the start of the next battle, with the introduction of 55-in. OLED TVs. Was OLED going to take over the TV market too?

For large-format TV, the three factors critical to mobile applications are not as important. The competition is more about color, perceived brightness, contrast, viewing angle, and cost. In response to OLEDs entering the TV market six years ago LCD took the offensive in 2013 by bringing in quantum dots that claimed the advantage in, surprisingly, color. This was done by replacing the white LED backlight with a yellow (red plus green) QD film placed in front of a blue LED backlight. Because the spectra of QDs are narrower than those of typical inorganic phosphors and OLED emitters, the color of QD-based LCDs is more saturated, and remains saturated at high luminance levels.

QDs, QLEDs, and Perovskites

Since then, QD has established itself as the key enabler for wide color gamut (WCG). Its next move gets a lot more interesting. In the article "A New Frontier for Quantum Dots in Displays," researchers at Nanosys describe the use of a QD color-conversion (QDCC) layer to generate red and green colors at the front of the pixels, only electrically driving the blue color. By default, this configuration provides better color because of QD. But more important, by replacing the inefficient color filter with high-efficiency color-conversation QD materials, the display becomes more efficient. In addition, QDCC is a platform technology that works well with most other display technologies – LCD, OLED, and microLED. In fact, it provides additional benefit to each of those technologies. Remember the viewing-angle problem of LCDs? Gone. How about the patterning challenge for OLEDs? Gone too. The advantage for microLED is even more convincing – think about how much easier operations will be if one only needs to handle/transfer/drive one type of microLED instead of all three colors.

The battle between OLED and LCD for TV will likely be a long one, because neither technology holds significant advantage, and each still requires some solutions to fix shortcomings. This prompts the question: is there a "perfect" technology that can combine the advantages of both LCD and OLED? Surprisingly, the answer is yes. In "The Dawn of QLED for the FPD Industry," Dr. Cass Xiang and his colleagues at TCL report their latest progress in printing QD-based electroluminescent devices. QLED has basically all the advantages of OLED plus a more saturated color and a low-cost printing process. Of course, serious challenges still exist that need to be addressed before this technology can be commercialized, but good progress is being made by various groups around the world, including the TCL team.

What makes the field of inorganic emissive materials even more exciting is that quantum dot is not the only game in town. In the article "Metal-Halide Perovskites: Emerging Light-Emitting Materials," authors Lianfeng Zhao and Barry P. Rand from Princeton University report on their work on metal-halide perovskite-based light-emitting devices. There are a lot of similarities between metal-halide perovskites and quantum dots, together with some unique challenges. As direct-bandgap, defect-tolerant semiconductors, perovskites present intriguing possibilities and could find their roles in future displays.

Like two railroad tracks, LCD and OLED have been able to maintain their own identities while paralleling each other closely. With quantum dots, they start to collide and interact. If we add microLED and other display technologies to the mix, I can see many possibilities for future displays. I can't wait to find out where we'll be when we revisit this topic in a couple of years. Until then, enjoy reading these articles.

Ruiqing (Ray) Ma *has served and continues to serve in many capacities for SID and Display Week. He is currently director for QD devices at Nanosys. He can be reached at ruiqingm@gmail.com.* ■

Journal of the Society for Information Display

Invitation to submit review papers

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

Page charges for invited review papers will be waived.

Jiun-Haw Lee
Editor-in-Chief

Announcements

Special Issues

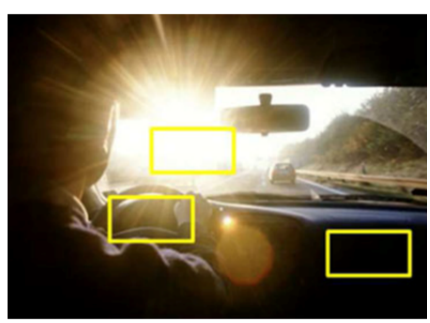
Seven notable papers from **'Best of EuroDisplay 2017'** are published in the September issue. The October issue includes five papers representing the first half of JSID's **'Best of International Display Workshops 2017'** coverage. The second half of the **'Best of International Display Workshops 2017'** special coverage will run in the November issue. The **'Best of International Conference on Display Technology 2018'** papers will appear in the December issue. The **International Conference on Display Technology**, sponsored by SID, was held in China in April 2018. This was the second year for **ICDT** and is the first year that ICDT content will be included in special issues of the **Journal of the Society for Information Display**.

A friendly reminder: The **'Expanded Distinguished Papers of Display Week 2018'** will remain "open access" through the end of 2018. There are 31 papers from issues ranging from February to May.

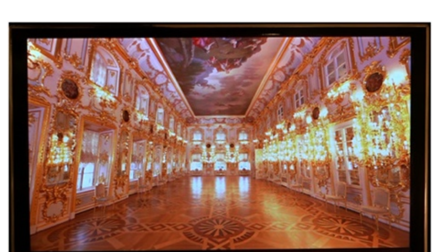
Highlighted recent papers

Advanced automotive display measurements: Selected challenges and solutions | Karlheinz Blankenbach | **DOI: 10.1002/jsid.625**

Due to the fast development of display technologies, today's trend in automotive displays is toward more, larger, and flexible panels. However, the requirements for cars are sometimes unique. For example, the displays must have long lifetimes (compared to consumer electronics such as mobile phones), especially in harsh environments (such as high temperatures inside a car when it is parked without air-conditioning). Besides, we must consider how to read displays in different positions (such as the three yellow boxes in the figure below). Many issues must be taken into consideration, such as: eye adaptation versus maximum luminance, reflections on the display, various positions, etc. This paper demonstrates some common requirements for automotive applications. New evaluations for anti-glare displays and black mura, which are important for automotive displays, are also discussed.



AlO sputtered self-aligned source/drain formation technology for highly reliable oxide thin film transistor backplane | Hiroshi Hayashi, *et al.*| **DOI: 10.1002/jsid.683**



In this paper, aluminum oxide (AlO) fabricated by a sputtering process was used as the barrier layer for thin film transistor (TFT) as the backbone of an organic light-emitting diode (OLED) display. A self-aligned top-gate oxide TFT was used, which is suitable for high-resolution and high-frame-rate displays. Sputtered AlO provides a superior barrier performance against impurity diffusion. Hence, good uniformity and reliability of the TFT backbone can be achieved, which is also suitable for large-size mass-production due to the sputtering process. Detailed analysis of the composition and crystallinity of the AlO material, the electrical characteristics of TFT, and reliability under high temperature stress (HTS) and bias temperature stress (BTS) are demonstrated. Such a backbone is used to drive 12-inch OLED panels with printing technology for achieving red, green, and blue emitters. Detail specifications of the OLED panels, including brightness, resolution, and color gamut, are provided.

Information about the Journal

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president's corner

SID Needs YOU

The Society for Information Display is an international network of thousands of display professionals spanning a variety of industrial and academic fields. SID organizes dozens of conferences, ranging from huge events like Display Week to small regional seminars focused on specific topics. We distribute a wide range of publications, run a training school, offer educational programs, and so much more. And all this is run by volunteers! With help from our small but dedicated office staff, our volunteers organize the events, review thousands of papers, and guide the overall direction of our society.

You Can Join this Group!

Our society needs dedicated volunteers who will do their part to make the next 50 years of SID as strong as the past 50. In the following, I will outline how SID operates and how volunteers can contribute at every level while experiencing great personal benefit through networking and technical advancement. I hope this will entice some of you to give just a bit more to our society.

At the highest level, SID is organized into three interconnected groups: local chapters, conference program committees, and the executive organization. I will dig into each group, explain the structure, and highlight opportunities for volunteers.

Chapter Organization

Our 28 (and growing) chapters are the foundation on which the society is built. Chapters are established in local regions to serve the SID membership of that region. Some chapters are almost as old as the society itself. The Los Angeles chapter can even trace its roots to the founding of SID at the University of California, Los Angeles, in 1962. Others, such as the Bangalore chapter in India, are much newer and are supporting the expansion of our society into emerging regions.

Regardless of history, chapters share a consistent structure. Each chapter is led by a small group of elected officers including the chapter chair, treasurer, and secretary. Many chapters also maintain several non-elected roles such as events managers and web coordinators. This leadership team works to provide a variety of membership services to local constituents. For example, most chapters arrange recurrent meetings, which often include speakers and sometimes even take the form of small conferences (see this issue's SID News about the LA chapter's 15th annual one-day conference in February 2019). Many of these events are also broadcast online as webinars. Other events might include recap sessions of the major SID conferences, local entertainment, or activities at universities in the region.

Our chapters are constantly looking for new volunteers to get involved in the community and help with the organization of events. Volunteering at the chapter level is by far the easiest entry point into the leadership of SID, because the volunteer activities are generally local to your area and contained in scope. Volunteering at the chapter level is also a great opportunity for those new to the display industry, because most of the activities rely on organizational skills rather than deep technical experience. Whether expanding their local network or gaining technical insights, local chapter volunteers will benefit greatly from involvement in a community of peers. I would encourage all of you to check out the website of your local chapter and see how you can get involved.

Conference Program Committees

If the chapters are the foundation of our society, then our conferences are the walls that define it. Within the SID umbrella exist a wide range of conferences including Display Week, EuroDisplay, LatinDisplay, International Display Workshops in Japan, IMID, IDCT, and many more. Collectively, these events attract tens of thousands of attendees who will listen to thousands of paper presentations. These activities define the scope of SID as the ultimate place to learn about all aspects of display technology, as well as its specialized applications supported by conferences such as the SID Vehicle Display Conference in Detroit.

All of these conferences are organized by volunteers. In general, each conference has a program committee led by a program chair and a general chair. The program committee varies in size, depending on the scope of the conference. Large conferences such as Display Week have over 200 program committee members who are split into various topical subcommittees (*e.g.* LCD, OLED, Display Electronics, *etc.*). The program committee solicits invited speakers, evangelizes the event, and – most importantly – reviews submitted manuscripts to select the best for presentation and publication. All of this is coordinated by the program chair, who is generally selected from among the more active members of the program committee. Finally, the general chair of the conference has broader responsibilities beyond the technical program, including keynote speaker selection, event marketing, and so forth.

Volunteer opportunities for program committees are limited to technical domain experts in the areas covered by that conference. Most volunteers are active researchers in the field. As a result, our program committees tend to be relatively static; volunteers often serve for many years in their area of specialty. Still, opportunities do open up, especially if a conference expands into a newly emerging field such as AR/VR, which would require new subcommittees to be formed. If you are interested in volunteering for a program committee and have the requisite technical expertise, I encourage you to contact the program chair of the relevant conference and offer your services. If you don't know which conference might be the best fit for you, then review www.sid.org for possible opportunities.

Executive Organization

Sitting on top of our chapter and program organizations is the executive team of the society. This group coordinates SID's global operations, manages our financial affairs, and sets our long-term strategic direction. Unlike many international organizations, the executive team of the society is entirely composed of dedicated volunteers – globally elected officers, regional representatives, and appointed leaders.

For regional representation, our chapters are grouped into regions representing approximately equal sections of our membership. There are currently seven regions, with three in the Americas (East/Central, Pacific/Latin, Bay Area), three in Asia (Japan, Cross Strait, Rest of Asia), and one covering Europe. Each region elects a regional vice president who acts as its representative on the executive board of the society. Regional vice presidents support the chapters in their region, govern financial decisions, and promote corporate member engagement in their region.

In addition to the seven regional vice presidents, SID's 12-member executive board consists of five executive officers: secretary, treasurer, president-elect, president, and past president. The first three officers are elected by the global membership and serve two-year terms (same as regional vice presidents). Once elected to president-elect, individuals will automatically advance to a two-year term as president, and finally to past president. This succession provides continuity in the governance mechanisms of the society, which is critical in an all-volunteer organization.

Beyond the 12-member executive board, the president of SID appoints a number of functional chairs to take charge of key operational areas. These are usually seasoned volunteers – often past officers or regional vice presidents – who have deep knowledge of the inner workings of the society. The major functional chairs are convention (accountable for all conferences and acting in liaison with the various program committees), publications (coordinates all our publication activities such as the *Journal of SID*), marketing (global brand marketing and web/social media outreach), and membership (accountable for membership services and growth). The major chairs are generally supported by vice chairs for specific aspects of their functional area. For example, the publications chair appoints three vice chairs who serve as the editor-in-chief of the *Journal of SID*, the editor of *Information Display* magazine, and the coordinator of the SID-Wiley Book Series.

Despite the electoral nature of the executive board, there are many volunteer opportunities in the executive organization, especially at the level of vice chairs supporting the major chairs. Often, volunteers get involved in those roles and are then selected for broader responsibilities with more senior roles once they have demonstrated their abilities. After successful service in one of the senior non-elected roles, they will then have a broad enough profile to stand for general election to the top echelon of the society. Similar to opportunities at the chapter level, these roles are primarily operational, so even individuals early in their career can leave a mark.

As you can see, there are opportunities to contribute in all three major areas of SID. My personal journey through the society has touched on many of these roles, and each has brought me great satisfaction. I had the privilege of serving on the Display Week program committee, rising to program chair and then to general chair. In parallel, I have served in appointed executive roles such as publications chair and ultimately the entire gamut of elected officer roles (except past president, which will come in a couple of years!). Over 15 years of service to the society in those roles, I have benefited tremendously from networking opportunities, technical perspectives, leadership development, and visibility into the many specialized areas that our industry has to offer.

Most importantly, I have met many long-term friends and collaborators extending far beyond SID into my professional and personal path. Service in a community of peers, at the level of excellence found in SID, has been a boon for me, and I hope that many of you will take up this challenge. Since the start of my presidential term in May 2018, I have had the pleasure of welcoming many new contributors – including a record number of women and younger society members – into volunteer leadership roles. I welcome your questions and comments (see contact information below) and I am committed to personally finding great opportunities within our society for every person who contacts me. Talk to you soon!

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

industry news

by Jenny Donelan

New Phone News

The annual Apple roundup has commenced: in September 2018, Apple announced that the iPhone XS, iPhone XS Max, and iPhone XR will replace the iPhone X, which launched in September 2017. The iPhone XS (5.8 inches with a 2,436 × 1,125 resolution) and iPhone XS Max (6.5 inches with a 2,688 × 1,242 resolution) both feature 458-ppi OLED displays and a dual-camera system. They support Dolby Vision and HDR10, run on the A12 Bionic chip, and cost $999 and $1099, respectively.

The iPhone XR (6.1 inches) starts at $749 and features an LCD – not an OLED – panel. It also comes with a smaller battery and a larger array of color choices (Fig. 1) than the iPhone XS models, which are available in gold, silver, and gray.

In October, Samsung announced a new midrange Android-based smartphone, the 6.3-in. Galaxy A9 (2018) featuring an OLED display with 1,080 × 2,220 resolution. The A9 runs on a Qualcomm Snapdragon 660 chip and features a four-camera setup on the back. This phone is scheduled to launch in Q4 in Europe starting at around €600. A US launch has not been announced.[1]

Fig. 1: Apple's new lower priced LCD-based iPhone XR comes in six finishes: white, black, blue, yellow (shown here), coral, and red. Source: Apple.

Samsung's flagship smartphone, the Galaxy S9, was released last spring. The next high-end iteration, the S10, will likely be available in early 2019. Design features haven't been officially announced, though a bezel-less design is a rumored possibility.[2]

The most talked-about news out of Samsung this fall came from the company's Mobile Division CEO, DJ Koh, at the A9 launch. Koh said that a foldable OLED phone, the Galaxy F, is definitely on the way. When folded it will be a phone, but when unfolded will extend to tablet size. What date the phone will actually ship and in what countries and at what price have not been announced. In fact, the phone hasn't even been officially announced – Koh hinted that this could take place at Samsung's developer conference in November 2018.[3] Taiwanese rival Huawei has also been public in its plans to launch a foldable OLED phone – there is definitely a race to market going on here.

Interestingly, Huawei overtook Apple in the second quarter of 2018 to become number two to Samsung's one in terms of global sales of cell phones. Last spring, Apple and Samsung reached a settlement in a patent infringement lawsuit that has been ongoing since 2011, over Apple's contention that Samsung copied early versions of the iPhone. The jury seems to have agreed in many respects, ordering Samsung to pay $539 million to Apple prior to the settlement, the details of which have not been disclosed.[4] In any event, none of this has broken Samsung's stride: Q3 sales have yet to be announced, but general consensus is that the rankings among the top three will not shift from Q2.

[1] https://thetechportal.com/2018/10/12/samsung-galaxy-a9-2018-announced/
[2] www.techadvisor.co.uk/new-product/mobile-phone/galaxy-s10-news-3680083/
[3] https://www.theverge.com/circuitbreaker/2018/10/12/17967078/samsung-foldable-phone-tablet-galaxy-x
[4] www.theverge.com/2018/6/27/17510908/apple-samsung-settle-patent-battle-over-copying-iphone

NEWS BRIEFS

Japan's **Sharp** has announced that it will offer OLED panels in its new smartphones, starting with the AQUOS Zero. For now, the Zero is only shipping in Japan.[5]

California-based **Netgear** has acquired California-based **Meural**, which makes a gesture-controlled WiFi-connected digital frame that displays classic works of art and photography, or your own art and photos (Fig. 2).

Fig. 2: For $595, a digital canvas in a black poplar frame from Meural allows you to display just about any work of art you wish in your home or office. Many artworks are free; additional ones are available for an annual fee of about $50. Source: Meural.

Advantech, a Taiwan-based provider of embedded and automated technology, has announced it will spend NT $200 million (US $6.41 million) to acquire a 15-percent stake in touch-panel maker Mildex Optical, also based in Taiwan, from Panjit International.[6]

[5] www.engadget.com/2018/10/03/sharp-aquos-zero-mobile-oled-market/
[6] https://digitimes.com/news/a20181015PD203.html

Plessey Partners with Jasper and AIXTRON

Plessey, also known as Plessey Semiconductors, has been busy formalizing relationships with other companies in order to move its monolithic microLED technology forward. In August, Plessey announced a partnership with smartglasses developer Vuzix for the co-creation of next-generation augmented-reality smartglasses. More recently, Plessey announced agreements with Jasper Display Corp. (JDC), a designer of spatial light modulators (SLMs) and microdisplays, and with AIXTRON, which makes metal-organic chemical vapor deposition (MOCVD) reactors for the semiconductor industry. Plessey plans to use silicon backplane technology from JDC for its monolithic microLED displays, which are made on its proprietary gallium-nitride (GaN)-on-silicon wafers. And Plessey purchased a new AIX G5+ C AIXTRON MOCVD reactor from AIXTRON to boost its in-house microLED manufacturing capability.

According to Plessey, it plans to unveil its first monochrome microLED array at the Consumer Electronics Show in Las Vegas in January 2019. ■

editorial

continued from page 2

Our first Frontline Technology feature is "A New Frontier for Quantum Dots in Displays." The use of QDs in backlight systems to enhance color spectrum for LCD TVs is widely known and well accepted in the marketplace. But QDs can be used in many other ways. Authors Ernest Lee, Chunming (Kevin) Wang, Jeff Yurek, and Ray Ma from Nanosys discuss the fundamentals of a "quantum-dot color-conversion (QDCC) layer" that can be integrated into today's LCDs as well as added to OLED structures for further enhancement of LCD performance within the subpixels and as part of a direct-emitting structure. Advantages include higher optical efficiency, wide color gamut due to very narrow tunable emission spectra, and manufacturability that is easy to adapt to existing processes.

Of course, building an emissive element from QD material and utilizing electrical excitation directly are intriguing goals for researchers. Getting very narrow spectral emission at high luminance levels without the burden of primary and then secondary emission seems like an obvious next step. Authors Chaoyu Xiang, Weiran Cao, Yixing Yang, Lei Qian, and Xiaolin Yan from TCL Corporate Research describe this research roadmap in their Frontline Technology feature, "The Dawn of QLED for the FPD Industry." A QLED is simply an LED that is combined with QD material to make a highly tunable narrow-band emitter. It sounds easy, but various challenges do exist, including lifetimes and efficiencies when QDs are driven by electrical *vs*. optical excitation. However, the authors describe several promising developments that begin to overcome these issues and outline how researchers in various organizations are getting some promising results. Hats off to all the people who are working on this very promising technology.

Another emissive technology showing promise is "Metal-Halide Perovskites: Emerging Light-Emitting Materials," described in detail by authors Lianfeng Zhao and Barry P. Rand from Princeton University. Similar to QDs, perovskites can emit light by optical excitation through downconversion of shorter wavelengths to longer wavelengths, or by direct electrical excitation with the color of the emitted light determined by the materials' bandgap energy. They are also highly tunable, producing very narrow color spectra at high efficiency. The authors describe their work in researching perovskite LEDs, achieving luminance and external quantum efficiency (EQE) values approaching those of much more mature OLED materials. These new materials are made in low-temperature solution processes that may be friendlier to flexible substrates than other materials and use inorganic raw materials that are in abundance. I think this is an emissive technology that has real promise for our industry.

Speaking of the industry as a whole and the relative maturity that organic LED tech has achieved, it is fun to see a resurgence of inorganic technology. While our first three features take on the core technology, the fourth, from author and analyst Paul Semenza, attempts to answer the broader question: "Can MicroLEDs and Quantum Dots Revitalize Inorganic Displays?" Paul addresses the state of the art for building various-size displays directly from microLEDs – which is not trivial, considering the challenge of assembling wafer-scale semiconductors into large addressable arrays for TVs and such. He also walks us through a broader overview of the various potential QD embodiments and what lies ahead in terms of opportunities and challenges. I think you will enjoy this balanced and very insightful perspective of both topics.

One notable company that has turned its development focus to microLEDs is Plessey in the UK. You've probably heard of Plessey Semiconductors for years, due to the company's many technical innovations, but most recently, it has been leveraging its considerable experience in gallium-nitride (GaN) on silicon to develop a variety of microLED illuminators and microLED display products. GaN on silicon has several advantages over other wafer approaches such as sapphire because of better thermal performance, lower inherent cost, and potential for larger scalability. In this case, size does matter, because building any large display from these wafers involves either transferring the individual emitting devices or somehow assembling the full wafers into addressable arrays for displays. Our own Jenny Donelan interviewed Myles Blake, business information director for Plessey, and discussed the company's plans for this technology as well as some of its overall history. I think you will find it very interesting reading in this issue's Business of Displays Q&A.

In addition to our technical and business features this month, I'm pleased to have the second of what will (hopefully) become a number of excellent columns from SID President Helge Seetzen. In this installment of President's Corner, "SID Needs YOU," Helge talks about how SID is organized and run, from the chapters, through the program committees, and ultimately to the executive board. The organization relies entirely on volunteers, and most of this effort starts at the local chapter levels. So, if you have not been to an SID local chapter meeting lately I would strongly encourage you to go, and if you can volunteer your time to help organize and manage activities, that would be even better. It's made a huge difference in the trajectory of my career and I'm sure it will have a positive impact on yours as well.

With that and our regular news features, it's a wrap. As we bid goodbye to 2018, I truly hope this year was as rewarding and successful for you as it was for me. I hope you had time to spend with loved ones and time to enjoy some leisure as well as your work. I also want to wish everyone safe and happy holidays. May you find peace, comfort, and joy during this holiday season. Cheers and best wishes! ■

A New Frontier for Quantum Dots in Displays

Quantum-dot enhancement film (QDEF) is giving LCD technology an edge as it battles new TV display entrants such as white organic light-emitting diodes (WOLEDs). Recent advances in quantum-dot properties are also enabling new and innovative implementations. This includes their evolving use in LCDs, their possible deployment in OLED and microLED displays, and their potential as emitter materials for future printable electroluminescent displays.

by Ernest Lee, Chunming (Kevin) Wang, Jeff Yurek, and Ruiqing Ma

THE Kindle Fire HDX tablet, released in 2013, introduced the display industry to quantum-dot enhancement film (QDEF), which was one of the first commercial uses of quantum dots in displays.[1] Two years later, in 2015, Samsung brought the first display using a cadmium-free quantum-dot film to the premium TV market.[2] Since that time, quantum-dot technology has moved steadily into the mainstream market, with dozens of devices available today from most of the world's top display makers. As a result, consumers can now buy an LCD TV enhanced with quantum-dot technology for roughly half the cost of a comparably sized OLED set.[3] In addition to TVs, monitors are now being made with quantum-dot film, including a number of models from Samsung, Acer, and Asus that are aimed at the gaming and creative professional markets.[4,5] Now that the display industry has embraced the use of QDEF, particularly in mainstream televisions and monitors, new implementations of quantum dots are poised to further improve the performance and quality of displays.

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Quantum dots are tiny semiconductor particles that emit light with a narrow spectral shape and at a wavelength dependent on their size. These two properties make quantum dots an ideal material for use in displays. Together they enable quantum dots to provide a larger range of pure colors compared with other light-generating technologies for displays. This in turn results in displays capable of reproducing larger color gamuts.

For example, UltraHD content that is recorded and mastered for Blu-ray and streaming relies on the BT.2020 color-gamut standard.[6] This new color specification is designed to capture over 99 percent of the colors found in nature for a truly lifelike image. Most displays currently employ phosphor-based white LEDs and rely on color filters to create the red, green, and blue primary colors for the RGB subpixels. However, these phosphors have limited wavelength tunability and relatively wide spectral distributions, even after filtering. As a result, many displays advertised as having wide color gamut achieve less than 80 percent coverage of BT.2020.[7] Despite better color purity compared with conventional LCDs, OLED displays limit themselves to smaller color gamuts such as DCI-P3 because the emission spectra of OLED materials are still too broad for high BT.2020 gamut coverage. Quantum dots, on the other hand, have both the unique wavelength tunability and color purity that enable them to deliver over 90 percent of the BT.2020 UltraHD color standard (see Fig. 1).[8]

QDEF, Cadmium, and Cadmium-Free QDs

Quantum dots would be a mere laboratory curiosity without other properties such as efficiency, stability, and manufacturing scalability. In addition, quantum dots need to be easily integrated into current manufacturing operations with minimal impact on

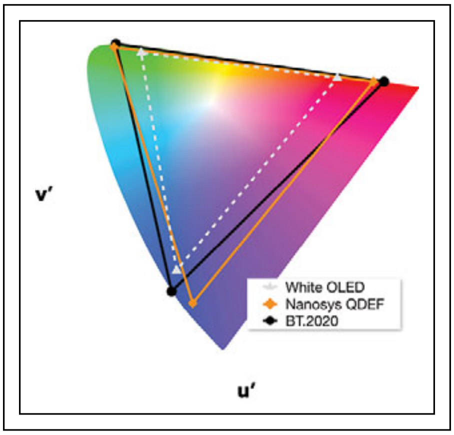

Fig. 1: *This color-gamut coverage chart for current display technologies compares WOLED, QDEF, and BT.2020.*

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display system design if they are to be widely adopted. To do this, Nanosys worked closely with major display manufacturers to develop the aforementioned QDEF, an optical film with a thin quantum-dot layer that is a simple, "drop-in" product that does not require any line retooling or manufacturing process changes.[9]

Designed as a replacement for an existing diffuser film in LCD backlights, QDEF combines red and green quantum dots in a thin, semitransparent sheet. When excited by light from blue LEDs, the quantum dots emit light at the desired green and red wavelengths. This green and red light combines with a portion of the blue LED light to provide a white light composed of highly saturated red, green, and blue light.

The first quantum dots to be incorporated into consumer displays were based on the element cadmium. At the time, these were the only quantum dots with the necessary efficiency and stability. Since cadmium is a regulated substance under the Restriction of Hazardous Substances (RoHS) Directive,[10] many manufacturers were hesitant about using quantum dots. This led to extensive work in improving the properties of cadmium-free quantum dots. However, the emission spectra for cadmium-free quantum dots are wider than those for cadmium-based dots, so these displays only managed to cover the smaller DCI-P3 color gamut.

Recently the gap in performance has narrowed considerably, as shown in Table 1. The high quantum yield for both cadmium and cadmium-free quantum dots enables high optical efficiency. In addition, the narrow emission spectra of Nanosys' cadmium-free quantum dots already provide greater BT.2020 color gamut coverage compared with other phosphor or OLED technologies.

Continuing improvements to stability enable QDEF to be used in even higher luminance displays. This vastly improves the appearance of the high-dynamic-range (HDR) content shown on QDEF-enhanced LCDs. Furthermore, these stability improvements can also be leveraged into reducing the cost of quantum-dot implementation by reducing the need for additional environmental protection.

With proven performance levels acceptable for commercial displays, quantum-dot manufacturers such as Nanosys and Hansol Chemical have scaled up capacity to produce enough quantum dots to supply millions of square meters of display area. Depending on the needs of the display manufacturer, the precise peak-emission wavelength can also be targeted to single-nanometer precision over a wide range of wavelengths for both green and red.

Table 1. Properties such as color and quantum yield for production-level quantum dots (both cadmium-based and cadmium-free) from Nanosys are shown below. The BT.2020 gamut coverage is for an LCD using QDEF.

QD Material System	Color	Quantum Yield	Emission FWHM(min/typ)	BT.2020 Gamut Coverage
Cadmium Selenide	Green	>90%	18nm/23nm	>90%
	Red	>90%	20nm/25nm	
Cadmium Free	Green	>90%	34nm/39nm	~85%
	Red	>90%	38nm/40nm	

New Implementations for Quantum Dots

Although the use of quantum dots through QDEF realizes the improved color performance capability of QDs, these displays still rely on conventional LCD modules, which are inherently inefficient. All LCD backlights generate white light that is then filtered to create the red, green, and blue subpixels. Quantum dots help to optimize this system, reducing waste by generating only the red, green, and blue light needed by the display in the backlight. Still, color filters block about two thirds of the light.

To avoid this inefficiency, an entirely new implementation of quantum dots in displays can be used: a quantum-dot color-conversion (QDCC) layer.[11] Since quantum dots are so small, a dense, thin layer of quantum dots can replace the color filters in a conventional LCD module and generate light right at the plane where the image is reproduced.

In such a device, the backlight provides only blue light as opposed to the white light of a conventional LCD. The blue subpixel can simply pass the blue light with minimal losses. The green and red subpixels, each with a layer of quantum dots instead of an absorbing color filter, absorb the blue light and downconvert it into green and red light, respectively. Not only does each green and red subpixel solely emit the desired color (and thus provide a saturated color primary for the display), the light throughput of each subpixel can in principle be much higher than in a conventional LCD. In addition to a significant efficiency improvement, an LCD with QDCC layers can have a wider viewing angle, since the light generated by the QDCC layer is at the front of the display.

Although the benefits are significant, incorporating QDCC layers into LCDs introduces several complications. Since the light emitted from a QDCC layer is both unpolarized and isotropic, this requires a change in the structure of the LCD module. The second polarizer in a conventional LCD module is located after the color filters, but with a QDCC layer it must be moved "in-cell." In addition, the blue light passing through the blue subpixel would require some form of scattering; otherwise, there would be angular color shifting. Finally, any blue light that leaks through in the green or red subpixel desaturates the color point, so optimally the QDCC layer would absorb 100 percent of the blue excitation light.

QDCC layers are not limited to LCDs. They can also be used to create green and red subpixels on a single-color blue OLED or microLED array (Fig. 2). Such a display with a QDCC layer provides the advantages of individual pixel control while needing only a single-color emitter layer, which vastly simplifies the manufacturing process. This new type of hybrid display would combine the benefits of electroluminescence (perfect blacks and wide viewing angles) with inorganic emitters for high luminance, saturated color, stability, and low-cost, solution-based manufacturing.

New Challenges

For QDCC layers to become a viable display technology, they must possess several additional optical and physical properties. As a

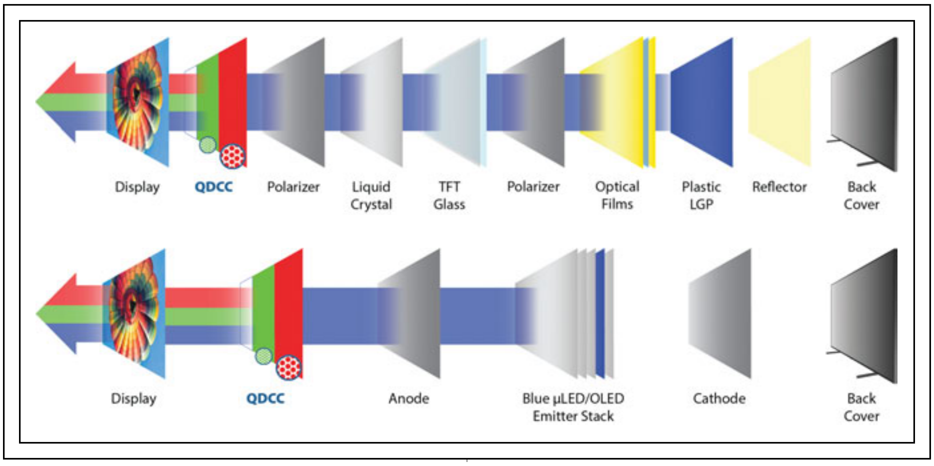

Fig. 2: The QDCC layer can be incorporated into LCDs, as shown in the top row, and into an OLED or microLED display, as shown in the bottom row.

color filter replacement in LCD panels, the QDCC layer must be thin (on the order of 6 to 10 microns) to be compatible with current LCD technology. Although using QDCC with OLED or microLED arrays could support thicker layers, keeping the QDCC thin is preferred. As we shall see in a following section, the requirement of a thin layer has profound implications for the necessary optical properties of the quantum dots.

In all formats, the QDCC layer must be patterned. This can be done through a photolithography process or through inkjet printing. Each method has its advantages and disadvantages. Photolithography can produce much smaller features than inkjet printing (5 microns *vs*. 50 microns). On the other hand, inkjet printing is much more efficient in terms of material utilization. For both cases, the quantum dots will need to be compatible with the process. This means that the quantum dots must be formulated into photoresist or an ink solution. These materials must be stable in air to leverage existing manufacturing equipment. They must also be stable during the various thermal and chemical processing steps that are not used for manufacturing QDEF. This imposes even more stringent stability requirements on the quantum dots. Finally, in order to comply with the RoHS limitation requiring that any homogenous layer of the system contain fewer than 100 parts per million of cadmium, the QDCC layer must be made from completely cadmium-free quantum dots.

In terms of optical properties, the QDCC layer must produce an efficient, highly saturated light output. Since quantum dots self-absorb a portion of the light they emit, the re-absorption losses in a highly concentrated QDCC layer reduce the optical efficiency of the entire layer. Thus, near-unity intrinsic quantum yield for the quantum dots is critical.

One additional requirement for achieving pure colors is for the QDCC layer to absorb all the excitation light. With optimized peak emission wavelengths, a display with QDCC layers can achieve greater than 95 percent BT.2020 color-gamut coverage if all the blue excitation light is absorbed. However, with 1 percent of the blue light leaking through each conversion layer, the BT.2020 color-gamut coverage would be about 86 percent (see Fig. 3). This desaturation of the color point is especially pronounced for the red color-conversion layer. Although the green color-conversion layer can tolerate more blue light leakage while maintaining high color saturation, the blue-light leakage still must be under 1 percent for a display using QDCC layers to achieve color-gamut coverages at least as high as conventional LCDs with QDEF.

The blue-light absorption of the conversion layer is directly related to the number of quantum dots in the layer. This is determined by both the thickness of the layer and the concentration of quantum dots in the layer. As noted earlier, the thickness of the layer is limited by manufacturing requirements.

The maximum concentration of quantum dots is limited by several factors. At very high concentrations, the quantum dots may aggregate, which reduces the quantum efficiency. For QD ink formulations, the concentration of quantum dots has a strong impact on the viscosity of the ink. This will affect compatibility with existing inkjet nozzles, printing equipment, and processing techniques. Since quantum dots strongly absorb ultraviolet light, the curing properties of UV-curable ink are also affected at high quantum-dot concentrations. Quantum-dot photoresists also have the same UV-curing constraints. In addition, high quantum-dot concentrations can adversely affect other steps in the photolithography process such as development and patternability.

With these thickness and concentration limitations, conventional Cd-free quantum dots have difficulty achieving the necessary level of blue-light absorption. One solution is to apply a simple, single-color blue-absorbing filter on top of the quantum-dot conversion layers. Although this can be done without significant loss in optical efficiency, it does introduce an additional processing step and therefore manufacturing complexity. To avoid having to use an additional filtering layer, the preferred solution is to increase the intrinsic absorption of the quantum dots themselves. This not only improves the color-gamut performance but also has the potential to reduce the cost of the display by requiring fewer quantum dots.

The intrinsic absorption is a function of the number of energy states between the excitation and the emission wavelengths. The energy spacing is only 300 meV (millielectron volts) between a 450-nm excitation and a 525-nm emission compared with an energy spacing of over 700 meV between a

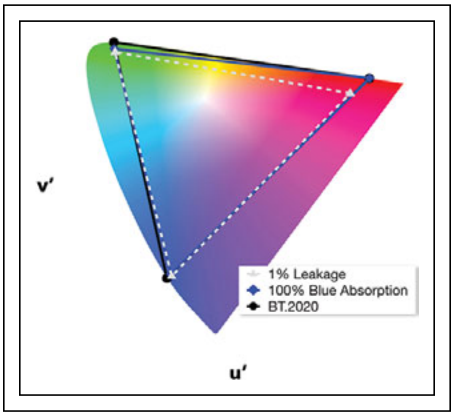

Fig. 3: Blue-light leakage has a significant effect on color gamut coverage.

450-nm excitation and a 628-nm emission. It is therefore especially challenging to increase intrinsic absorption for green dots due to the smaller number of available states in the conduction band. Techniques such as modifying the core-shell structure of the quantum dot or using an alternate material system based on other elements have shown promise in increasing the blue absorption of a fixed-thickness QDCC layer, as shown in Table 2.

With these additional improvements to cadmium-free quantum dots, Nanosys and collaborators have demonstrated patterned QDCC layers using both photoresist and inkjet printing.[12] Figure 4 shows an RGB-printed array with 280 µm × 80 µm subpixels demonstrated by Nanosys and ink maker DIC.[13] The green and red subpixels contain thermal-cure quantum-dot ink, while the blue subpixel contains a scattering media to better match the angular distribution of the emissions.

Table 2. The results of increasing the relative blue absorption of a green QDCC layer appear below.

Type of Green QD	Relative Blue Absorption in a Fixed Thickness Layer
Conventional Cd Free	1
Modified Cd Free	1.5
New Cd Free Material System	2.9

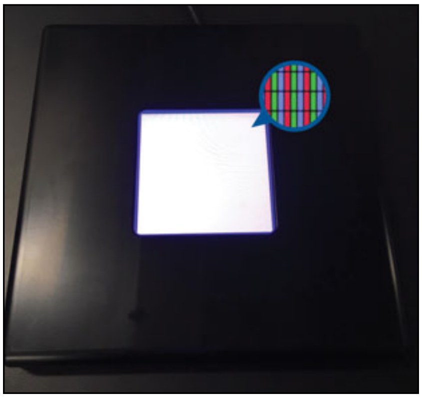

Fig. 4: Inkjet-printed QDCC layers are incorporated into a patterned RGB array.

The Move to Commercialization

As critical as it is, the quantum-dot color-conversion layer is just one component in the final display. Complementary technologies need to be developed to realize the full potential of this new display platform. One significant challenge in applying QDCC layers to LCDs is related to the configuration of the polarizers. In a conventional LCD, the liquid-crystal layer and the color-filter (CF) layer are both sandwiched between crossed polarizers. In this configuration, the polarizers can be easily laminated to both sides of the LC glass cell, which encloses both the LC and CF layers. This CF layer cannot be simply replaced by a QDCC layer because the light emission from quantum dots is unpolarized and thus would interfere with the LC switching. In this case, the QDCC layer must be relocated outside of the crossed polarizers. One of the fundamental requirements of display operation is to place the switching component as close as possible to the CF or QDCC layer to minimize optical crosstalk. As a result, to utilize QDCC layers in an LCD, a thin in-cell polarizer is required. Efficient in-cell polarizers are currently being developed,[14] but have not yet reached commercial release.

For OLED-based displays utilizing QDCC technology, the polarizer is not an issue. However, the design demands that all the light is initially generated by a blue OLED emitter. Currently, blue OLED emitters have the lowest efficiency and shortest lifetime among all colors.[14] Although their performance level is high enough for some applications involving QDCC layers, additional improvement in both efficiency and lifetime for blue OLED emitters is necessary for this combination to become widespread in use for general displays.

Compared to OLED blue emitters, inorganic LED sources are highly efficient and significantly more stable. Thus, the combination of QDCC layers and a single-color blue microLED array could be a powerful combination for display applications. Using QDCC layers eliminates the need for separate red and green LEDs to make full-color displays, which is one of the major technical challenges for microLED displays.[15] Other challenges exist for even single-color microLED arrays, but the use of QDCC layers has the potential to accelerate the development of commercial microLED displays.

In summary, quantum-dot color-conversion layers promise high efficiency, better color, and low-cost implementation for LCD, OLED, and microLED displays, as well as additional benefits for each specific technology. Improvements in both the optical properties and the stability of cadmium-free quantum dots, along with advancements in process technology, have brought QDCC layers very close to commercialization. Additional advancements in complementary technologies by panel makers have placed this new implementation of quantum dots in displays on the cusp of commercial realization.

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(continued on page 31)

The Dawn of QLED for the FPD Industry

Rapid improvements in the operating lifetimes of QLEDs, as well as investments into large-scale production lines for inkjet printing, are bringing the electroluminescent application of quantum dots for flat-panel displays closer to commercialization.

by Chaoyu Xiang, Weiran Cao, Yixing Yang, Lei Qian, and Xiaolin Yan

NOT long ago, colloidal quantum dots (QDs) emerged as excellent emitters for high-quality flat-panel displays (FPDs). These well-dispersed, nanosize semiconductors offer ideal optical properties for display applications. Due to quantum-confinement effects, QDs' electrons and holes are trapped in "quantum wells," bonded as excitons, which are like states in the molecules. The exciton confinement energy determines the QDs' optoelectronic properties.

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This is the beauty of QDs. The "quantum wells" structures, which define the lowest energy state for excitons, reduce the radiative recombination paths, enabling purer emission spectra. Changing the size and shape of QDs makes it possible to manipulate the confinement energy. As a result, the absorption and emission properties of QDs can be tuned to cover the full visible spectrum.

Moreover, the sizes and shapes of QDs can be easily controlled during the colloidal QD synthesis. After years of development, the so-called core-shell structure of QDs was widely adapted to improve photoluminescence quantum yield (PLQY) by enforcing the confinement effect through reducing the nonradiative recombination paths. Nowadays, near-unity PLQY can be achieved. All those properties and factors promise lower energy consumption, higher color purity, and larger color gamut through the use of QDs in FPDs.

Development of QD Applications in FPDs

QDs have been successfully incorporated into LCD products as the downconversion media that generate the white light in backlight units (BLUs). In 2014, several panel makers, including Samsung and TCL, launched their first QD-LCD products. Using QD enhancement films (QDEFs) enabled the panel makers to improve color gamut and enhance luminance at the same time. Thanks to the QDEF technology, LCD was able to rally in the market battle against organic light-emitting diodes (OLEDs) in the high-end, large-area TV market.

More advanced technologies using QDs for downconversion have been proposed in recent years; these include QD color filter (QD-CF) and QD-OLED (incorporating the downconversion of red and green light from QDs on top of blue light from OLEDs). However, a few technical obstacles exist regarding the mass production of these proposed QD photoluminescent technologies. Considering the developing states of red, green, and blue QD materials, the soonest foreseeable technology is the aforementioned hybrid QD-OLED. (Note: though lifetimes for blue OLEDs and blue QLEDs have been a bottleneck for developers, the lifetime for blue OLEDs is much better and is acceptable for commercial use. This is not yet the case for blue QLEDs.) The ultimate solution for QLED is an all-QD emissive display that replaces the blue OLED with QD electroluminescence. This can happen when the blue QD materials are ready (Fig. 1).

Using QD materials in displays has additional benefits. With regard to the fabrication process, QDs are more suitable for large-area printing. It is easy to produce colloidal QDs dispersed in different solvents through a ligand change, which enables the deposition of QDs on various underlayers. Compared to other solution-processed emitters, colloidal QDs have fewer problems with thin-film casting. For example, phase segregation is

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unlikely to happen during a QD ink-evaporation process. QD film structures, such as scattered monolayers, multilayers, and close-packed monolayers or multilayers, can be tuned by controlling the processing parameters. And the synthesis of colloidal QDs is simple, which promises a substantial reduction in fabrication costs. Due to the robustness of inorganic materials, QDs are more resistant than organic materials to defects and impurities introduced during the fabrication process. They are also suitable for mass production.

Improving Efficiency

The efficiency of QLED has been improved to the point where it is high enough for display applications. For example, red QLED efficiency was the first color to be reported with more than 20 percent external quantum efficiency (EQE), which is close to the theoretical limit.[1] The highest green OLED now shows an efficiency of 92 current efficiency (Cd/A) from bottom emission, which is also over 20 percent EQE.[2] Recently, the QD team at TCL has pushed the efficiency of blue QLEDs to more than 23 percent.[3]

Several efficiency loss factors have been resolved to achieve this high QLED efficiency. First, to incorporate QD into the LED structure, the balance between QD luminescence and electrical charge conduction has to be considered. In a QLED, QDs are close-packed into a 20- to 40-nanometer (nm) film. In this state, the greater the physical space between QDs, the better the operation of the QD luminescence. However, when the physical space is increased, the electrical charge's ability to move from one QD to another is reduced, leading to a higher resistance in the QD film, which in turn leads to higher power consumption. The surfaces of QDs are covered with surfactants, which protect the QDs during processing. The length of the surfactants and the QD film processing determine the physical space between the QDs, thus balancing QD luminescence and electric charge conduction.[4–7]

Unlike downconverted QDs, which are under light excitation when operating, QLED is under an electric excitation. Thus, electric fields and electric charges play a big role in possible efficiency losses. For example, due to the high resistance of QD film compared to the other layers in QLEDs, a very high electric field, usually an order of 1 MV cm^{-1} (megavolts per centimeter), must be applied

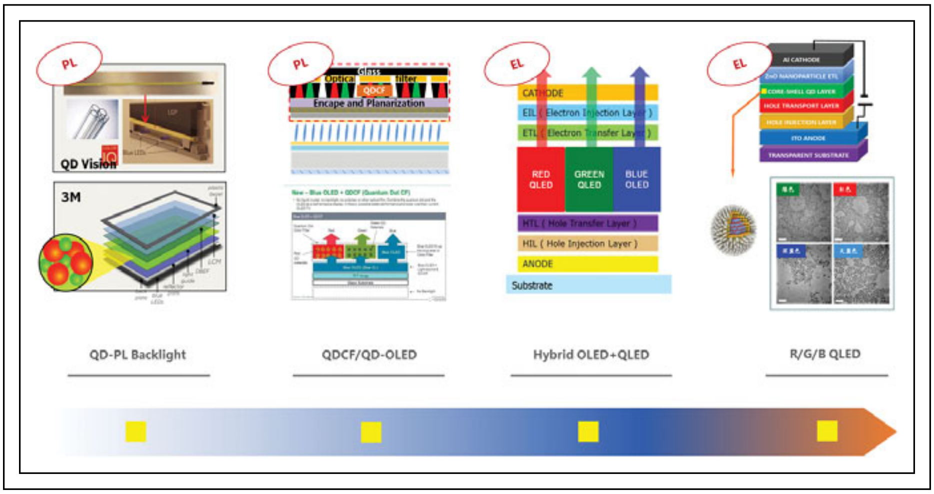

Fig. 1: *The evolution of QD technology in flat-panel displays began with QDs for downconversion backlighting and as part of a QDEF film. The next step is a hybrid OLED/QLED display, and the ultimate goal is a fully emissive RGB QLED-based display.*

across the QD layer for suitable operation. Device performance decreases under such high electric fields because of the possibility of positive and negative charges recombining to reduce light emission. Methods to minimize the influence of the electric field include designing new structures of QDs to make them more robust under high electric fields and creating new device architectures to move the QD layers out of the high-electric-field regions in the QLEDs. In the meantime, electric charges also cause a problem. The best scenario is that positive and negative charges are always equal during the QLED operation. However, due to the mismatching of the interface between the QD layer and the other layers in the QLED structure, the unbalanced charges could accumulate in QLEDs to quench QD light emission. This is why a great deal of interface engineering is needed for efficiency improvement.[8,9]

Lifetime Issues

Even though an EQE of more than 20 percent has been demonstrated for RGB QLEDs, the lifetime of QLEDs is far behind that of their OLED counterparts. Lifetime is the most critical factor for commercialization. This issue has therefore drawn immense research interest on a global basis. Lifetime progress since 2011 is summarized in Fig. 2. Considerable lifetime value was reported in 2011 by NanoPhotonica, with the introduction of solution-processable zinc oxide (ZnO) as the electron-transport layer (ETL), which provided better electron injection. A green-emitting QLED with a T50 (meaning a lifetime to 50 percent of initial luminance) of more than 5,000 hours lifetime at 100 nits was obtained.[10] In 2012, a red QLED with a T50 of 10,000 hours at 100 nits was reported.[8] Two years later, Zhejiang University demonstrated a T50 of 100,000 hours at 100 nits for a red QLED by manipulating charge balancing.[1] In 2015, using accelerated tests, NanoPhotonica demonstrated a red QLED T50 lifetime of 300,000 hours and a green lifetime of 90,000 hours initial at 100 nits.[11]

Although great improvement has been made, a T50 lifetime rating based on 100 nits (T50@100 nits) light output is not suitable for the display industry. Based on panel requirements, a lifetime to 95 percent of initial luminance at 1,000 nits (T95@1,000 nits) or higher is a good criterion to use. Such a criterion is set to make sure the display color quality is good enough during the product's life span. In 2018, the research team at TCL reported QLEDs with a T95@1,000 nits over 2,100 hours, which is about 10 times higher than previously reported for QLEDs.[12] Figure 3 shows the lifetime data. This number is the first in which QLED exceeds the industrial requirements of displays, making this technology truly viable for commercial applications.

The researchers took several steps to overcome the lifetime block. As mentioned in the

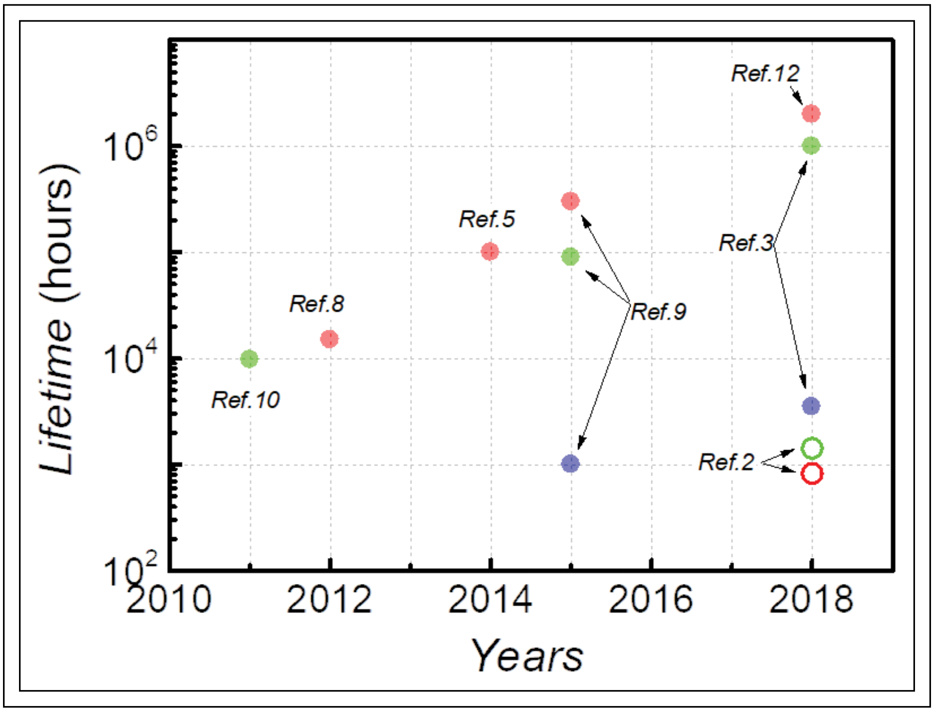

Fig. 2: QLED lifetime progress, especially for green and red, has advanced steadily over the past eight years.

previous section, balancing QD luminescence and electric charge conduction is critical in QLEDs. In state-of-the-art QLED devices, negative charges are sufficient while the positive charges are much more insufficient. Previous studies[1,10,12] focused on device structures by either matching the QDs' conduction band for positive charges or impeding negative charges through more complicated designs. TCL researchers took a different approach, targeting the QDs directly.

Thoroughly analyzing the QD structure, the TCL researchers discovered that by replacing the ZnS in QDs with zinc selenide (ZnSe), they could maintain a photoluminescence quantum yield value of more than 80 percent, achieving a high level of QD luminescence while also improving the electric charge equality in QLED and ultimately leading to better device performance. The ZnSe-QD device exhibits a maximum external quantum efficiency (ηEQE) and a current efficiency (ηA) value of 15.1 percent and 15.9 cd/A-1, respectively, which is good enough for commercial use. Moreover, benefiting from the improvement in electric charge equality, the ZnSe-QD-based device showed a moderate voltage increase and a T95 operation lifetime of more than 2,100 hours with an initial luminance of 1,000 cd/m^2, and a T50 lifetime at 100 cd/m^2 of more than 2 million hours.

Solution Processing

QLEDs are "born" to be solution processed. In earlier stages of QLED development, both Samsung and QD Vision demonstrated QLED panels patterned by transfer printing, although they had problems achieving larger sizes and mass production. Inkjet printing technology, due to its precise position control and mask-free capabilities, emerged as a promising method for QLED panel fabrication. In 2016, a research team from South China University of Technology demonstrated a 2-in., 120-ppi full-color active-matrix-QLED panel that contained some inkjet-printed layers and some evaporated layers.[13] One year later, big panel makers such as TCL and BOE showed their own demo of a full-color active-matrix-QLED (AMQLED) panel with all layers inkjet printed except for the electrodes. In term of mass production, inkjet-printing technology is also making fast progress. JOLED has already produced 21-in. 200-ppi AMOLED panels, using its own Gen 4.5 inkjet-printing line. LGD, BOE, and TCL have also announced the adoption of inkjet-printing technology for higher-generation production lines (Gen 8.5 and above).

A few problems must be addressed in order to commercialize the inkjet printing of displays. Most important is the gap between spincoating and inkjet devices. The efficiency and lifetime of inkjet-printed QLED devices are lower than those of spincoated ones. To date, the QLED performance numbers reported have been based on spincoating. Spincoating is a good method for materials development and screening and is used in primary tests, but it is not suitable for mass production. The ink that spincoating uses is not suitable for inkjet-printing processes, which require additional properties from solvents, including high boiling temperature, high viscosity, more functional groups, *etc*.

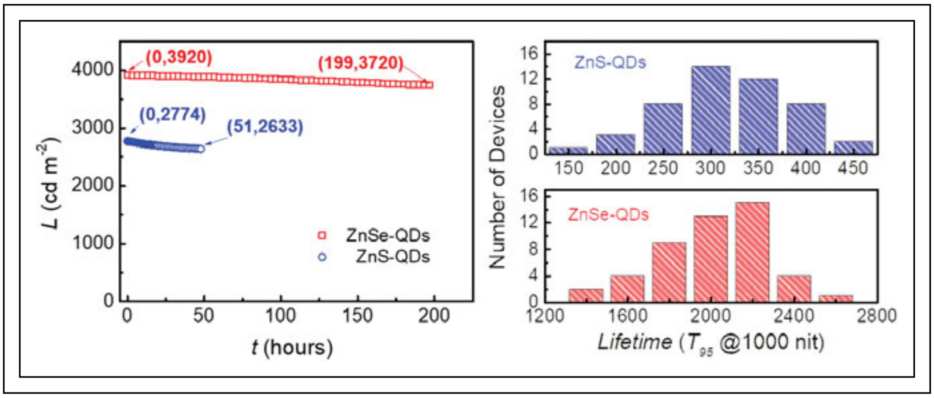

Fig. 3: The left plot shows the lifetime measurement data; the right plot contains histograms of T95 lifetime with initial luminance of 1,000 cd/m^2 measured from 48 ZnSe-QD devices and 48 ZnS-QD devices.[12]

Outlook

With recent rapid developments in both QD materials and panel-fabrication processes, QLED is a promising technology for next-generation displays. We can expect better and larger demos, and even mass production of AMQLED panels in the near future.

In order to make this technology appealing both to panel makers and to the market, however, several issues must be resolved. First, due to their high energy levels, blue emitters are always a problem, and this applies to blue QDs as well. Even though there are ways to compensate for the short lifetime of blue components at the panel level, the common requirement for blue QLED lifetime is hundreds of hours of T95 initial at 1,000 nits. Unfortunately, the T50 lifetime of blue QLEDs is less than 50 hours at 1,000 nits, far less than the lifetimes of red and green QLEDs.[3]

Another obstacle involves concerns over cadmium (Cd). So far, the QD materials with the strongest QLED performance are based on Cd compounds. Cd-based QDs have advantages in terms of optical properties and synthesis capability. However, Cd is a highly toxic element, and health and environmental concerns arise for its production, use, and recycling. Even though Cd-free QLEDs have reported EQE of more than 20 percent, their lifetime and color purity are still problematic. The frequently cited T50 lifetime of Cd-free QLEDs is less than 100 hours at 500 nits, which equates to around 1,000 hours at 100 nits (Fig. 2, circle points). The full width at half maximum (FWHM) of the electroluminescent (EL) spectrum is near 40 nm compared to 23 nm from Cd-based counterparts.

Other issues regarding QLED applications relate to making high-resolution panels. The resolution of inkjet printing is around 200 ppi for production lines so far, good for large-area displays with more than 4K resolution. If QLED is to be used on high-end medium- to small-size displays, higher resolution is required. Transfer printing is an easy way to increase resolution but doesn't work well for mass production in lines over Gen 6.5. For inkjet printing, higher resolution could be achieved through pixel arrangements, but this process is not ready for mass production yet.

In summary, QLED will be the next trend for flat-panel displays, combining electrical driving emission with the excellent emitting properties of QDs – sharp spectra, high luminescence efficiency, and solution-process capability. With recent progress and investment in the technology, we believe the commercialization of QLED is closer than ever.

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Metal-Halide Perovskites: Emerging Light-Emitting Materials

Perovskite LEDs are an emerging display technology with potential for low-cost manufacturing (from abundant materials), high light quality, and energy efficiency. These features make perovskites competitive with light-emitting materials such as organic molecules and quantum dots.

by Lianfeng Zhao and Barry P. Rand

THE desire for high color-quality, low-cost, and long-lasting lighting and display technology has driven intense research and development of better light-emitting materials and devices. Among the materials under investigation, metal-halide perovskites are emerging as a promising option.

Metal-halide perovskites are direct bandgap, defect-tolerant semiconductors, making them promising materials for optical devices such as light-emitting diodes (LEDs), lasers, solar cells, and photodetectors. A schematic for a metal-halide perovskite appears in Fig. 1. Given their direct bandgap, perovskites emit nearly monochromatic light, either under optical excitation (photoluminescence) or when electrically excited (electroluminescence), with the color of the emitted light determined by the materials' bandgap energy. Due to their defect-tolerant properties, metal-halide perovskites can be extremely efficient in electroluminescence and photoluminescence; thus, they can be used as efficient light emitters or downconverting phosphors.

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Correspondingly, perovskites can be used in two different configurations, as shown in Fig. 2. In the first (Fig. 2a), they are configured as red, green, blue (RGB) systems, in which multiple monochromatic-perovskite light-emitting diodes (*e.g.*, blue, green, and red) are used as individual pixels for displays or mixed to generate white light for lighting. In Fig. 2b, the perovskites are configured for wavelength conversion through excitation by an external light source (*e.g.*, a blue LED). The perovskites then downconvert incident

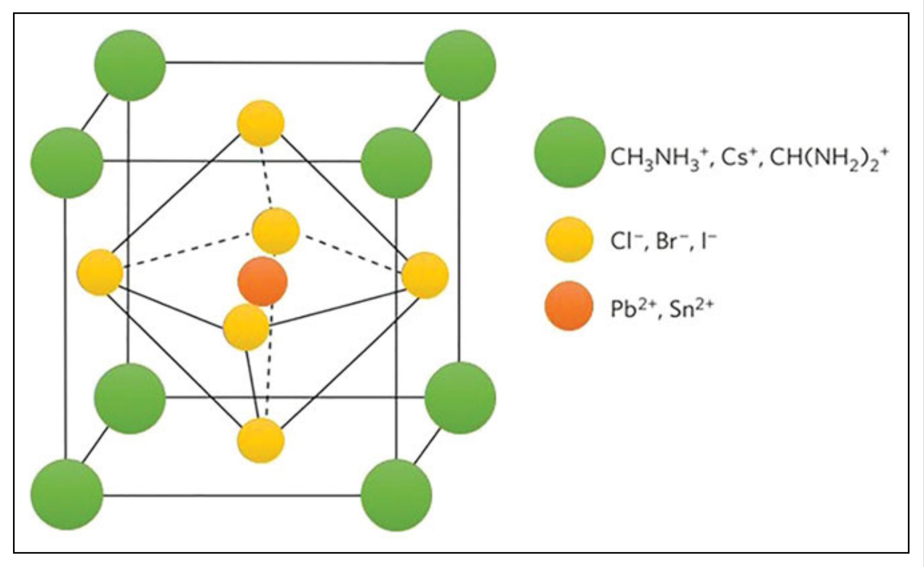

***Fig. 1:** Metal-halide perovskites are a class of materials with an ABX_3 stoichiometry and crystal structure, where A is a monovalent cation (e.g., Cs^+ or $CH_3NH_3^+$), B a divalent metal cation (e.g., Pb^{2+} or Sn^{2+}), and X a halide (Cl^-, Br^-, I^-). This diagram depicts a perovskite crystal structure in schematic format.*

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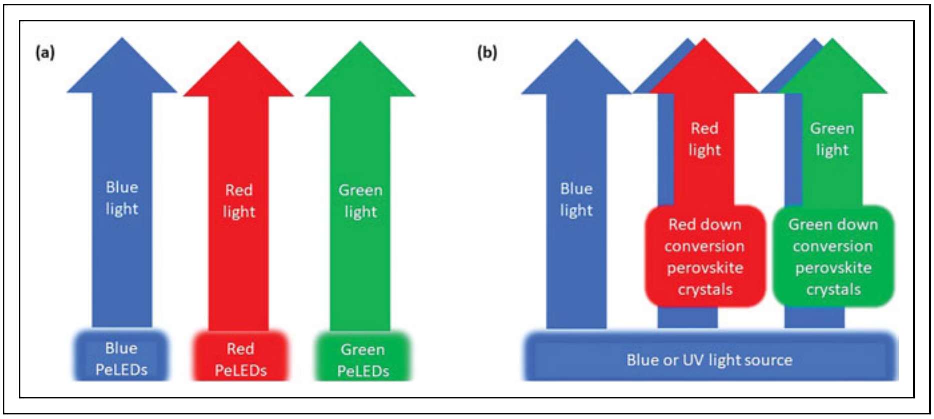

Fig. 2: *In these two example configurations of perovskites in LEDs, perovskites operate as active monochromatic light-emitting layers in (a) and as optical downconversion phosphors in (b).*

light to other colors such as green and red. For the RGB systems, either perovskite thin films or colloidal perovskite nanocrystals can be used. Currently, thin-film perovskites show better performance in general compared to their colloidal counterparts. However, for the purpose of optical downconversion, colloidal perovskite nanocrystals continue to be more applicable in comparison to thin films. Preparation techniques for colloidal perovskite nanocrystals and thin films will be discussed in the next section.

Solution Processing of Perovskites

One important potential advantage of perovskite LEDs over other inorganic or organic LEDs is their low cost. Perovskites can be synthesized and processed from solution at relatively low temperatures. This means perovskites are suitable for large-area deposition on a wide range of substrates such as glass or flexible plastic substrates. Perovskite preparation techniques, in general, can be divided into two categories, leading to two different product formats: colloidal perovskite nanocrystals or perovskite thin films. See Fig. 3 for a summary of several common methods for perovskite colloidal nanocrystals synthesis and thin-film deposition.

Direct synthesis of colloidal perovskite nanocrystals typically occurs via ligand-assisted reprecipitation or hot injection.[1] For ligand-assisted reprecipitation, perovskite precursors (*e.g.*, lead halide and organic halide salts) are dissolved in strong polar solvents and subsequently added to nonpolar solvents in the presence of ligands, often in large excess. The different solubility in polar and nonpolar solvents triggers the recrystallization of perovskite nanocrystals and the ligands prevent them from aggregating in bulky forms that would inhibit their ability to be suspended in a solution. In the hot-injection method, organic or cesium cations and metal cations are dissolved in nonpolar solvents and heated up to a desirable temperature (typically below 200 °C). Then halide precursors are injected to trigger the nucleation and growth of perovskite nanocrystals.

The process of ligand-assisted reprecipitation is simpler and often performed at lower temperatures in air, whereas the hot-injection method requires air-free conditions and a fine control of the reaction temperatures due to the sensitivity of the colloidal crystal size to reaction temperature. However, one major advantage of the hot-injection approach is an absence of polar solvents, which prevents any possible dissolution or decomposition of the formed perovskite nanocrystals. The hot-injection method is currently the most popular strategy, as it provides effective control over the size of the nanocrystals and their distribution.

As for perovskite thin-film deposition, common solution-processing methods are compatible with perovskite precursors, such as chemical bath, spincoating, dip coating,

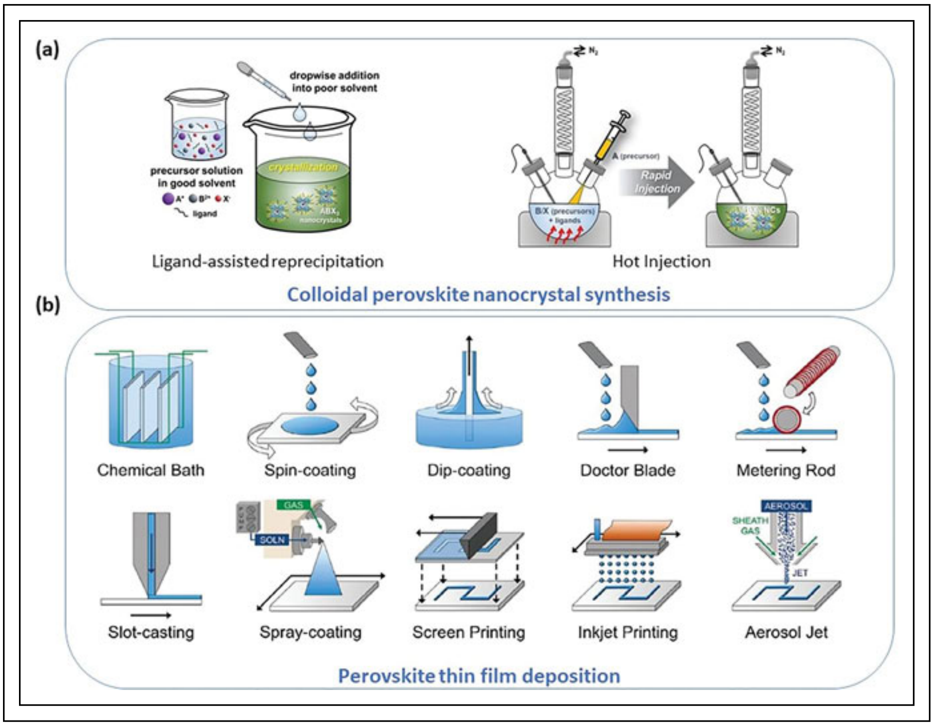

Fig. 3: *Examples of various methods applied to perovskite processing include (a) representative colloidal perovskite-nanocrystal synthesis methods (reprinted with permission,[7] copyright 2018, American Chemical Society) and (b) representative perovskite thin-film deposition methods (reprinted with permission,[8] copyright 2011, Royal Society of Chemistry).*

doctor blade coating, metering rod, slot-casting, spray coating, screen printing, inkjet printing, and aerosol jet printing.[2] Nonsolvent processing methods such as thermal evaporation are also available for perovskite thin-film deposition.[3] For high-performance perovskite LEDs, ultrathin and pinhole-free perovskite films are desirable. Notably, even in the form of thin films, special techniques are required to make properly passivated small grains in perovskite films for highly efficient light-emitting devices.[4] A well-accepted "solvent exchange" step (also often referred to as an antisolvent treatment) is performed during deposition, whereby dropping a nonsolvent (*e.g.*, toluene, sometimes with other molecules dissolved in it) onto the sample during film formation extracts the solvent rapidly, which freezes perovskite crystallization and grain growth *in situ*, resulting in thin, smooth perovskite films with relatively small grain sizes.[5] Introducing bulky organo-ammonium halide salts as additives in the perovskite precursor solution then leads to ultra-smooth perovskite thin films with a roughness of about 1 nm, and grain sizes ~10 nm.[6] The implementation of these techniques has proven useful to increasing perovskite-LED efficiency.

Color Tunability

Perovskites can be tuned to emit light within a very wide range of wavelengths, from violet to near infrared. This is made possible by changing composition, as shown in Fig. 4. For example, by controlling the stoichiometry of chloride, bromide, and iodide in lead-based perovskites, bandgaps can be tuned across blue, green, and red regions. This can be further extended to the infrared by replacing lead with tin. Furthermore, if the relatively small organic cations are replaced with bulkier organic cations, the perovskite crystal structure can be altered into two-dimensional Ruddlesden–Popper phases, which provide more opportunities for color tuning, into even the deep blue or violet spectral regions. Color can also be tuned by quantum-confinement effects when the perovskite nanocrystals are small (*e.g.*, 1–3 nm), analogous to the color tunability of quantum dots. However, such principles applied to perovskites are only in their infancy and are thus not addressed in this article.

Although halide mixing provides an opportunity to tune emitting colors, the emitting wavelength is not stable due to considerable halide-phase separation, which has been the central challenge that limits the practical use of mixed halides to control color. Recently, a promising way to overcome this obstacle has been demonstrated, which involves using bulky organic additives to stabilize the fine-tuned halide composition and avoid halide separation.[9] Color purity is an important indicator for display quality. Regardless of preparation techniques and grain sizes, luminescence spectra of perovskites are generally narrow (typical spectral widths of 0.07–0.09 eV, or 12 nm for blue-light emission, 20 nm for green, and 40 nm for red/near infrared), which makes perovskites suitable for high-end display applications. This represents an advantage over quantum-dot LEDs, because quantum dots require a narrow particle-size distribution to achieve narrow spectral width. This inevitably increases the fabrication complexity and cost, whereas narrow spectral widths can be manufactured easily for perovskites without dedicated processing techniques.

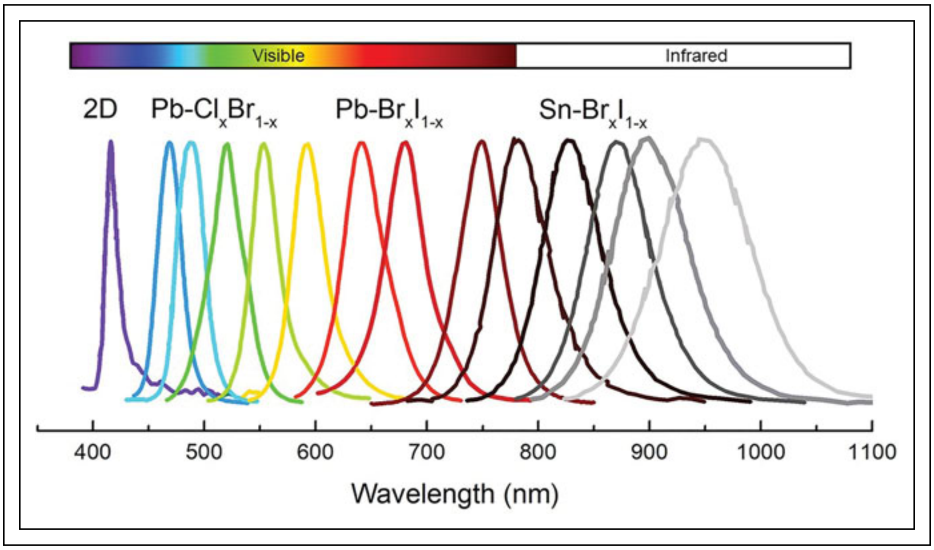

Fig. 4: Wavelength-tunable light emission from various perovskite compositions.

High-Efficiency Perovskite LEDs

Perovskite LEDs have achieved rapid and remarkable progress over the past several years. Figure 5 compares the highest external quantum efficiency (EQE) and luminance of organic LEDs, quantum-dot LEDs, and

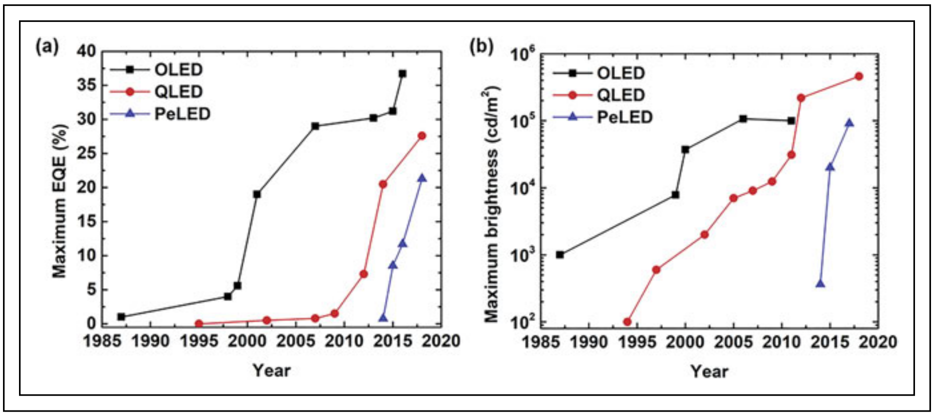

Fig. 5: Timelines show (a) maximum EQE and (b) maximum luminance for organic LEDs (OLEDs), quantum-dot LEDs (QLEDs) and perovskite LEDs (PeLEDs).[10–13]

perovskite LEDs fabricated to date.[10] Although the highest EQE of perovskite LEDs is still lower than that of OLEDs and QLEDs, the maximum luminance of perovskite LEDs is similar to that of state-of-the-art OLEDs. Further improvements in the EQE of perovskite LEDs are expected in the near future.

Notably, the highest EQE achieved for perovskite LEDs varies considerably in terms of emitting color. Table 1 summarizes representative perovskite LEDs of different colors. Green and red perovskite LEDs currently lead in performance, while blue and infrared perovskite LEDs require further attention.

Flexible Perovskite LEDs

Low-temperature processing makes perovskites compatible with the most commonly used flexible substrates. However, perovskite films are brittle, due to the salt-like perovskite crystal structure. This aspect has been recently overcome by introducing carefully selected bulky organoammonium halide salts as additives, which confine the perovskite grains during their formation to sizes of ~10 nm while surrounded by a flexible additive matrix.[4]

Flexible perovskite LEDs fabricated with this method show an EQE of 13 percent, similar to state-of-the-art perovskite LEDs on rigid substrates. Furthermore, no degradation is observed after bending for 10,000 cycles at a radius of 2 mm, showing the potential of perovskite LEDs for future highly efficient, robust, and flexible electronic-device applications (Fig. 6).

Device Stability

Although perovskite LEDs have improved rapidly in terms of initial performance, stability remains a major challenge. Perovskites are considerably redox-active[20] and moisture sensitive, resulting in rapid degradation under typical LED-driving conditions. As is the case for commercialized organic LEDs, sufficient encapsulation will be needed for perovskite LEDs to prevent extrinsic stability issues. In terms of intrinsic stability, operational lifetimes exceeding 46 hours have been demonstrated under relatively low current density,[16] but perovskite LEDs degrade rapidly when a larger current is applied or after operation for an extended period. Ionic processes (interface reactions and/or ion migration) are believed to be primarily responsible.[21] Due to halide migration, large concentrations of iodine have been found in adjacent layers in perovskite devices.[21] Furthermore, halide loss has been revealed as a spontaneous process for perovskites,[22] which calls for more attention to stabilize halide motion for stable perovskite device development. Better surface passivation, defect reduction, and perovskite composition engineering appear to be key to further improving device stability.

Nontoxic Element Alternatives

Although their semiconducting properties make perovskites promising for next-generation LEDs, the best-performing compositions contain lead and, as such, raise toxicity concerns. Therefore, the development of lead-free perovskites is important to increase the likelihood of commercial success. The three most promising elements being considered to replace lead in perovskites, due to their ability to retain the defect-tolerance properties, are: (1) tin, which is adjacent to lead in the same column of the periodic table; (2) bismuth, adjacent to lead in the same row of the periodic table; and (3) antimony, another less-toxic element in the same column with bismuth in the periodic table.[7] However, studies on lead-free perovskite emissions are still in their infancy. Currently, the most efficient photoluminescence for lead-free perovskites is achieved with $Cs_3Sb_2Br_9$ nanocrystals, which show a photoluminescent quantum yield (PLQY) of 46 percent in the blue region (410 nm).[23] The performance from these initial trials is encouraging, but still behind that attained from lead perovskites, which exceeds 90 percent PLQY. At this point, no electroluminescence has been achieved in lead-free perovskites except for tin-based infrared perovskite LEDs.[19] Nonetheless, replacing lead in perovskites

Table 1: State-of-the-art metrics are shown below for perovskite LEDs with different emitting colors. (PEA = phenethylammonium, MA = methylammonium, and FA = formamidinium.)

Color	Peak Emission Wavelength (nm)	Perovskite Composition	Maximum EQE (%)
Violet[14]	410	PEA_2PbBr_4	0.04
Blue[15]	475	$(CsMAFA)Pb(ClBr)_3$	1.7
Green[16]	525	$CsPbBr_3$	20.3
Red[17]	653	$CsPb(IBr)_3$	21.3
Near Infrared[18]	803	$MAPbI_3$	20.7
Near Infrared[19]	950	$CsSnI_3$	3.8

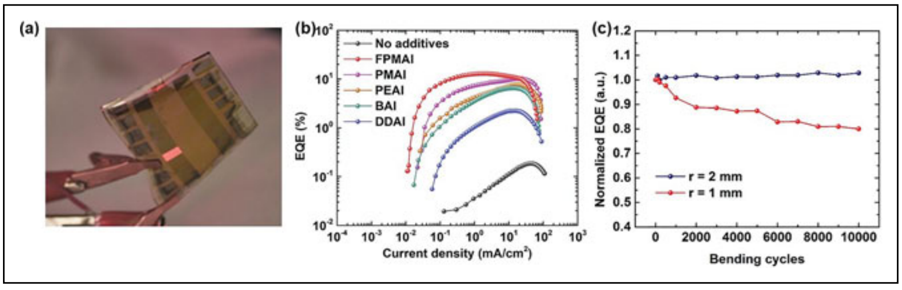

Fig. 6: *Flexible perovskite LED characterization and bending-test results include (a) a photo of a working flexible perovskite LED; (b) EQE* vs. *current density curves of perovskite LEDs with or without various additives; and (c) normalized EQE* vs. *bending cycles at bending radii of 1 and 2 mm. Adapted and reproduced with permission,[4] copyright 2018, Wiley.*

represents a critical issue that deserves further research and development.

Outlook

The implications and applications of perovskite LEDs are exciting, with potential for low-cost manufacturing from abundant materials, high light quality, and energy efficiency. These features make perovskites competitive in comparison with existing light-emitting materials such as organic molecules and quantum dots. In particular, the solution-processed, scalable fabrication technique makes this technology most suited to continuous emitting films for lighting. On the other hand, patterning techniques that are compatible with the solution-based fabrication process are required for display applications, and thus represent an area requiring more attention.

Before electrically driven perovskite LEDs can become a commercial reality, some challenges facing them need to be addressed; mainly device efficiency (most critically for blue) and stability. The fundamental operating mechanisms of perovskite LEDs represent an important area of further research and study, which can lead to an efficient and versatile technology. The commercialization of perovskite materials working as wavelength down-converters can be realized sooner than electrically driven perovskite LEDs, owing to fewer technological challenges. Other promising commercialization options for perovskites include large-area solar modules and x-ray detectors. In addition, given that optically pumped, continuous-wave lasing has been achieved based on metal-halide perovskites,[24] it is expected that after addressing the aforementioned issues regarding perovskite LEDs, the world's first solution-processed, electrically pumped laser diode based on perovskites may be within reach, with additional prospects for display and lighting applications.

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Can MicroLEDs and Quantum Dots Revitalize Inorganic Displays?

For the past several years, the flat-panel display technology battle has been between LCD and OLED. But innovations in inorganic semiconductor materials and devices have opened the door for microLEDs and quantum dots to move from supporting to leading roles – as dominant FPD technologies in their own right.

by Paul Semenza

LIGHT-EMITTING diodes (LEDs) have been used in displays for decades, as the emitters in low-resolution videowalls and monochrome displays, and as backlights for LCDs, particularly after they took off in large TV panels in 2008.[1] However, these applications use relatively large LED chips in bulky packages, placed in relatively sparse arrangements. Most backlight designs achieve high luminance with a small number of LEDs and use lightguide plates to distribute the light across the display. Large LED walls use RGB emitters in each pixel, but the chips are large and the pixel density is very low, due to the viewing distances.

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Two developments have created new opportunities for the use of LEDs in displays. First, the ability to create LEDs smaller than 50 microns on a side – so-called "microLEDs" – makes them viable as emitters in displays and backlights with very high pixel density. Second, the development of massively parallel transfer techniques opens up the possibility that millions of devices could be transferred from LED wafers to display or backlight substrates.[2]

As analyzed by Yole Développement and Knowmade, over 120 companies/research organizations have filed ~1,500 patents in more than 500 families relating to microLEDs.[3] In addition, companies including Apple, Facebook, and Sharp have made investments in or acquired startups in the space, while Sony and Samsung, among others, have developed prototype products using the technology. MicroLEDs are transferred from wafers and attached to substrates as bare dice, with no chip packaging. MiniLEDs are a transitional form between micro and traditional LEDs; they can be in the range of 50 to 200 microns on a side and implemented as bare dice or packaged devices.

Micro-MicroLED Displays

MicroLEDs have been used to construct two types of displays – small "microdisplays" used in near-to-eye or projection mode, and large-area, direct-view flat-panel displays. Generally, microdisplays are constructed by integrating microLEDs onto silicon wafers using flip-chip or wafer-scale integration, or by growing the LED devices on the silicon wafer; an alternative approach involves depositing TFTs onto the LED wafer.[4] These highly integrated devices have very high pixel densities, and the spacing can be similar to that of the devices as grown; combined with the fact that they are often constructed on wafers, this means that they can use direct-transfer techniques. Near-to-eye microdisplays often use monochrome LED arrays with a color-conversion layer, while projection-mode devices require very high luminance. In all of these cases, the ability to accurately and reliably transfer or otherwise integrate millions of microLEDs and electrically connect to the drive circuitry (TFT or silicon devices) is critical for commercial success.

MicroLEDs on the Big Screen

Direct-view displays, used in wearable devices, automotive displays, smartphones, tablets, mobile PCs, monitors, and TVs, among other applications, represent the vast majority of revenues in the display market. Thus, the potential for microLEDs to create a new type of flat-panel display is intriguing. In particular, existing LED manufacturing techniques can be used to produce more than

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100 million microLEDs on a single wafer. If such devices could be efficiently transferred to large substrates and connected to an active matrix, microLED displays could be cost competitive with existing LCD and OLED technologies.

The key challenge is the need to distribute the microLEDs over a much larger area than the wafer on which they were grown, and to do so with the minimum number of transfer steps (fewer transfer steps mean that more displays can be produced with a given number of transfer machines). For example, a typical wafer might be 6 inches in diameter, whereas a desirable target for a high-end TV might be a 55-in. diagonal panel. If the devices are transferred directly from the wafer to the substrate, many hundreds of transfer operations would be required. This has led to the idea of an intermediate transfer step, perhaps using an interposer or larger wafer, which can reduce the number of transfer operations by an order of magnitude or more.[5]

Cok *et al.* have simulated the number of transfer operations required to populate a full-HD display from 150-mm LED wafers. For the 6,220,800 devices required to construct 1,920 × 1,080 RGB pixels, populating the display using a roughly 1-in. square "stamp" would require 1,260 transfers; using a larger stamp and/or an intermediate substrate could cut the required transfers to less than 100 (Fig. 1). (For background on a monolithic process for microLEDs, see this issue's Business of Displays interview with Plessey.)

In addition to the potential for efficient creation of light-emitting pixels, microLED displays offer the intriguing potential of using the same transfer techniques to create the active-matrix drive circuits. Instead of TFT devices, micro-integrated circuits can be created using existing CMOS techniques, and transferred to the display substrate using the same processes and equipment as were used to transfer the microLEDs. Pixel controllers with more than 200 transistors have been fabricated in chips smaller than 40 microns on a side, transferred from silicon wafer to substrates, and used to drive RGB microLED pixels.[6] Such miniaturization opens up the possibility for transparent displays, as the microLEDs and controller might only fill 1/10th of the pixel area, depending upon the resolution. In an early demonstration, Semprius and Kodak used microcontrollers instead of TFTs in AMOLED displays.[7]

MicroLEDs thus have the potential to be used to produce large displays with the luminance, color, and contrast to provide high-dynamic-range (HDR) performance, but without the need for the thin-film transistors critical to large LCD and OLED panels. Manufacturing of such displays can utilize the existing LED supply chain for the microLEDs, and would thus only need to combine the transfer operation with relatively simple metallization to connect the LEDs and controllers. No vacuum processes would be needed, and the assembly process would not require multiple displays to be produced on each substrate, opening up the potential for modular display production lines. Thus, the capital expenditure, in the billions of dollars for state-of-the-art LCD and OLED fabs, could be dramatically reduced.

Micro- and MiniLEDs Take the Stage

At Display Week 2018 in Los Angeles, a high level of activity was evident around these new LED form factors, both in the backlight and for the display itself. For example, AUO won the Best in Show Award in part for its prototype 8-in. microLED display, boasting 1,280 × 480 pixels (169 pixels per inch or ppi). The prototype used an LTPS-TFT backplane and color conversion from blue LEDs to full color. In the I-Zone at Display Week, Jade Bird Display and PlayNitride were named honorees for their microLED demonstration displays. Jade Bird showed a 5,000-ppi, 3-million-nit projection microdisplay, while PlayNitride demonstrated a transparent 0.89-in.display with 64 × 64 pixels (105 ppi), as well as a 3.12-in. 256 × 256 pixel display. In addition, the Display Week Technical Symposium featured 15 technical papers relating to microLEDs.

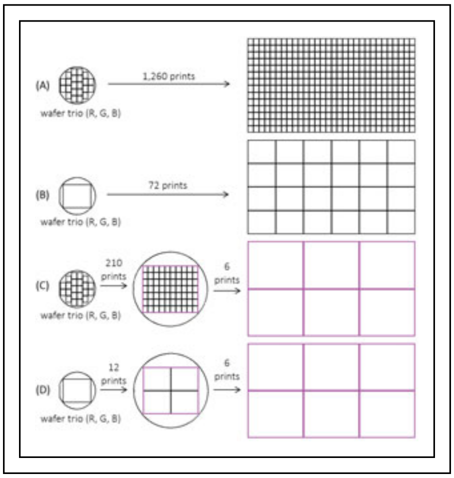

Fig. 1: *Representative schemes for populating a 1,920 × 1,080 RGB micro LED display include using (A) a 22.4 × 27-mm stamp, (B) a 112 × 94.5-mm stamp, (C) the small stamp with a 300-mm intermediate substrate, and (D) the large stamp and the intermediate substrate.*[6]

LCD panel makers AUO, BOE, Tianma, and others also showed panels with miniLED backlights, utilizing large numbers of chips to implement local dimming and high dynamic range. This could represent a step toward microLED displays, as the techniques used to fabricate miniLED backlights may be helpful in maturing the assembly processes.

In the meantime, such backlights can bring significant performance improvement to existing LCDs, thus continuing the competition in front-of-screen performance between LCD and OLED displays.

Quantum Dots: Nanotechnology Meets Displays

Quantum dots (QDs) are semiconductor particles at the nanometer scale that emit light at specific and tunable wavelengths if electricity or light is applied to them; the tuning is accomplished by the choice of dot size, shape, and material. Similar to the use of LEDs in LCD backlights, quantum-dot materials were initially adopted to improve LCD color gamut and power efficiency, particularly as LCDs faced competition from OLEDs. The narrow emission spectra available from QD materials enable purer primary colors, and thus a broader palette of total available colors to display. Quantum dots have become critical to meet the wide color-gamut performance required by standards such as Rec. 2020, which are becoming prevalent in high-end TVs and other displays. The use of quantum dots also improves system efficiency, as blue LEDs can be used, which are less expensive and more efficient than white LEDs. Since the light emitted from the QD material has narrow spectra, less light is lost at the color-filter layer.

To date, most quantum-dot materials used in displays have been embedded in a film that is part of the backlight (Fig. 2), though there have been cases of implementing the quantum dots via a "rail" along with edge-lit displays as well as in the LED itself. The QD material converts broadband light to narrow spectra. These applications are examples of photo-enhancement, to improve the performance of LCD backlights. As described by QD supplier Nanosys, there are two additional modes available for the use of QDs in displays.[8]

The next step is the use of quantum-dot material in a photoemissive mode. In this approach, similar to the backlight method, the light source is monochromatic (typically blue), and the QD material converts some of the blue light to red and green, while still transmitting the rest of the blue light. In LCDs, this would allow for the elimination of the color filter, which could provide significant gains in efficiency as well as color gamut. Another envisioned architecture is to combine the photoemissive QD with a backplane of blue OLED, which would be a simpler implementation than both existing LC and OLED displays. Finally, some developers of microLED microdisplays (near-to-eye) have used blue microLEDs with QD color-conversion materials, which means that full color can be achieved with only one type of LED (Fig. 3).

Perhaps the ultimate performance of a QD display would be achieved in the electro-emissive mode, in which QD material is used to create a direct-emitting display, based on the principle of stimulating the QD material electrically, rather than using a light source. In such a display (Fig. 4), QD materials emitting in red, green, and blue would be deposited on top of an active-matrix backplane. The emission spectrum (full width at half maximum) of QD materials is in the range of 20–30 nanometers (nm), compared to 40–60 nm for OLED, enabling a wider color gamut.

Because QD materials are available in solution, they can be deposited through low-cost processes such as spincoating and ink jet or screen printing. Such displays have been referred to variously as QD-LED, AMQLED, and QD-EL. BOE has reported producing 5-in. and 14-in. displays by printing the QD materials, using LTPS and IGZO backplanes, respectively.[9] It is not yet known what type of quantum efficiency might be achievable with such a display architecture.

Back to the Future

The emerging forms of LED and QD display architectures are interesting, given that some of the earliest display approaches were based on inorganic materials. The original display technology – the cathode-ray tube (CRT) – utilized inorganic phosphors to emit light when excited by a scanning electron beam (more recently, attempts were made to make thin versions of the CRT through field emission, also to excite phosphors). In the 1960s, plasma displays, using phosphors excited by a gas plasma, and thin-film electroluminescent displays, using electrical stimulation of inorganic materials, were both demonstrated. Decades of development of all of these technologies followed.

Ultimately, all of these inorganic-based displays were eclipsed by the LCD, which uses organic liquid-crystal materials to shutter externally generated light, generally through

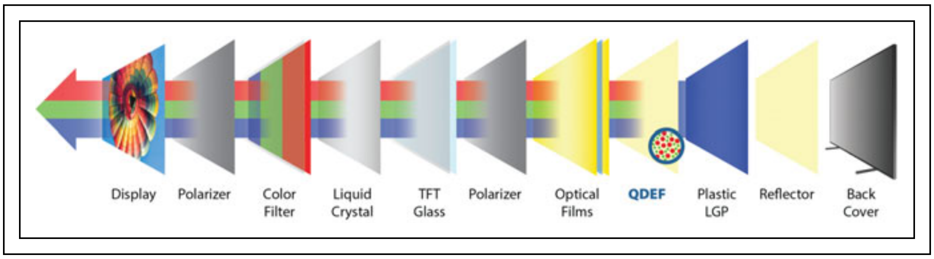

Fig. 2: Current quantum-dot implementation works by embedding the materials in a film (or coated on glass) in the backlight.[8] Source: Nanosys.

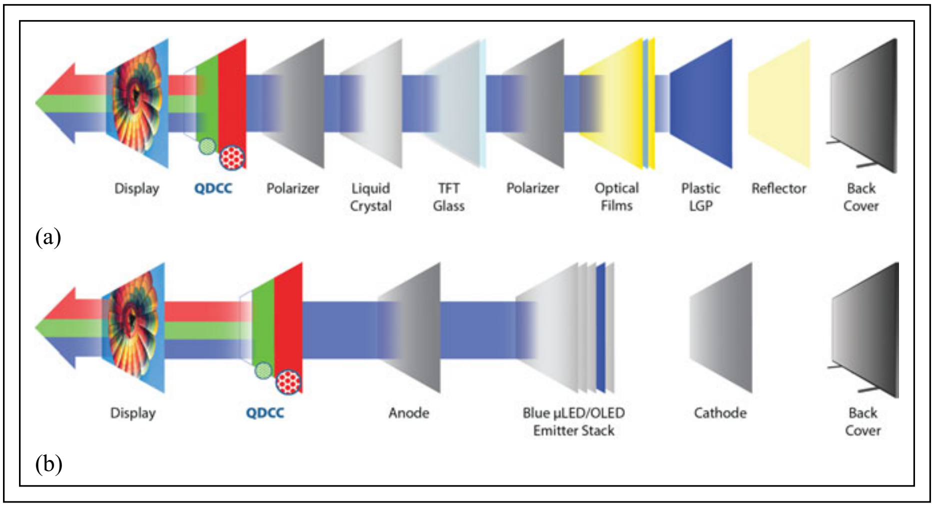

Fig. 3: In photoemissive mode, a patterned quantum-dot layer would convert blue light to red and green. This would allow for elimination of the color filter in an LCD (a) or of the green and blue emitters in an OLED (b).[8] Source: Nanosys.

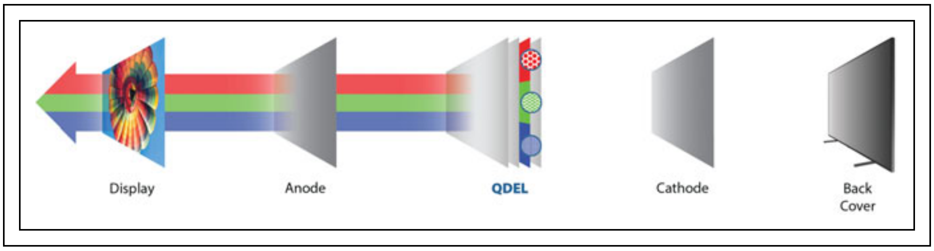

Fig. 4: An electro-emissive quantum-dot display would be an alternative to existing LCD and OLED display architectures.[8] Source: Nanosys.

control of polarization. The fact that LCDs need a high luminance light-source input, which is then modulated with very low total transmission efficiency, means that they are generally more complex – and expensive – than the inorganic display types. However, they offer excellent image quality and have for some time had the benefit of the largest number of manufacturers and supply chain participants.

There has long been a sense that there should be a less-complex approach to flat-panel displays than LCDs. In some ways, this desire has been answered by the OLED, which is self-emissive, like the inorganic approaches. OLEDs have been very successful, particularly in smartphones and in the emerging flexible display formats, but they have their own challenges, one of which relates to the fact that the semiconducting materials are organic, which means that they are susceptible to degradation when exposed to oxygen or water vapor. This is a particular challenge when using plastic substrates, which generally have unacceptably high water-vapor transmission rates, requiring encapsulation to protect the organic materials. Thin-film encapsulation using dyads of metal oxides and organic materials, which combine to create a tortuous path for the water molecules, have been developed, but these impose significant manufacturing costs.

Inorganic displays based on microLEDs and quantum dots offer the promise of simple, rugged, self-emissive displays. Of course, much development is still needed to achieve the potential, including material performance and manufacturing processes. Whether such displays will be able to be competitive with the incumbent LCD and OLED panels will depend on addressing manufacturing cost challenges. In the case of microLED displays, one of the key issues is the assembly cost – the equipment and processes for transferring millions of devices from wafers to substrates. For QD displays, material development, including lifetime, and optimization of the display design are challenges. Meanwhile, the majority of innovation in FPDs is in the form of incremental steps to improve the dominant LCD and OLED architectures, to which both LED and QD materials also contribute.

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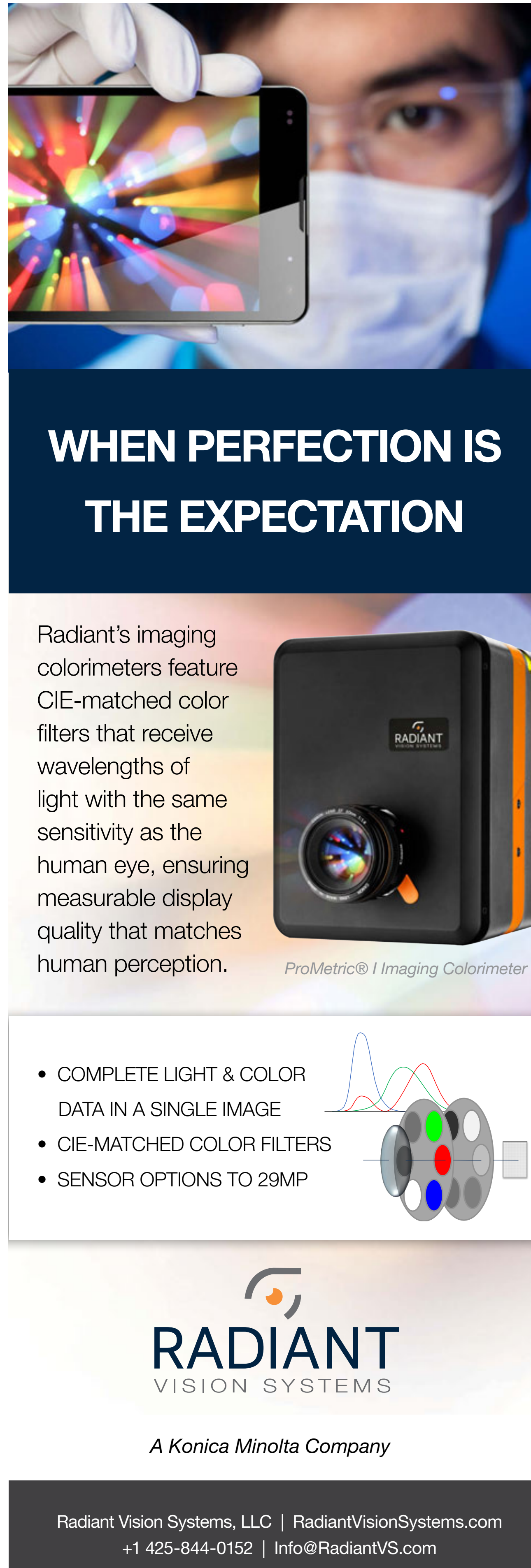


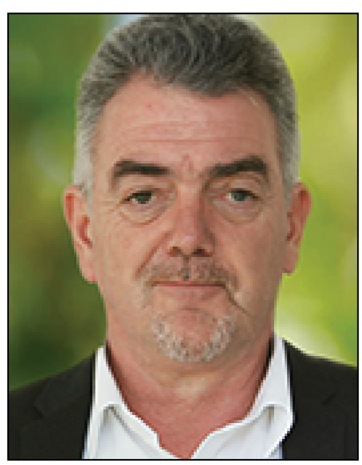
Q&A with Plessey

Myles Blake is the business information director for Plessey, a maker of advanced optoelectronic technology based in Plymouth, UK. He has more than 30 years of experience in the semiconductor industry, having joined Plessey Semiconductors in 1981 as a test engineer. Since then, Blake has helped guide the company through its IT processes, eventually moving from software development to project management.

Conducted by Jenny Donelan

Information Display: Plessey, which used to be called Plessey Semiconductors, has a long history. Could you give us a synopsis?

Myles Blake: The history, as far as the electronics side of it goes, dates back to around 1926. Plessey was involved in the Second World War, including the radar systems that came out at the tail-end of WWII. Plessey's electronics were in the Spitfire [fighter aircraft]. So, there is a lot of British history there, but as far as semiconductors are concerned, that all started in 1956.



Myles Blake

ID: Plessey has gone through a lot of changes over the years, including being acquired by GEC, Mitel, and then the German foundry firm X-FAB. When did your division of the company in Plymouth start on its current path?

MB: Right around 2009, a number of employees undertook a management buyout [from X-FAB], rebranded the company to Plessey Semiconductors, and began to focus on our core skills, which were largely around the sensor side of things. Quite rapidly after that, we acquired a specific technology from Sussex University for digital sensors, and later we acquired other capabilities from a Cambridge University spin-off. Then we put all of our focus into LED manufacturing.

The starting point for where we are now is our gallium-nitride-on-silicon (GaN-on-silicon) platform. This is the foundation technology on which we're building everything else. We have a number of "high-bright" LED products for solid-state lighting. However, I think it's fair to say that the competition in that general area is quite fierce. Yes, we have some key benefits, including lumens-per-watt capabilities, uniformity and our ability to integrate traditional electronics components. But this vertical segment has become a "me too" market, and on the commercial side, it is quite, quite difficult to attract people to our product as opposed to paying a far lower price for something out of China.

So our focus today is around microLEDs, which is a technology that is also based on GaN-on-silicon.

ID: How long has the company had this microLED focus?

MB: The microLED focus started for us around the tail-end of last year, with a project to produce a microLED printhead, although I think I would use the term miniLED.

ID: Those distinctions are somewhat fluid right now.

MB: Yes indeed. We would say that if the pixel is less than 50 microns, it's a microLED. Anything larger than that but less than maybe 100 would be a miniLED.

But I need to step back to the GaN-on-silicon platform, which is core to all of our technologies, especially microLEDs. There are huge benefits to GaN-on-silicon, not the least of which is the cost of the substrate – the silicon itself. This is obviously far lower than sapphire substrate, and a great deal lower again than silicon carbide. (Generally speaking, I'm doing a comparison with sapphire, the other main substrate that's on the market today.) And there are also scale benefits.

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

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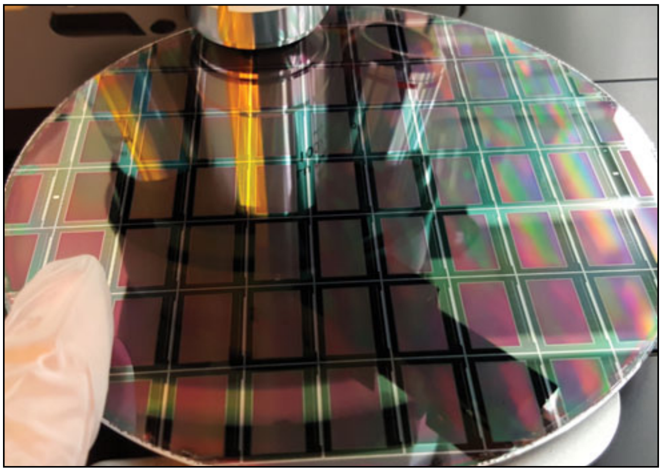
For example, we can manufacture gallium nitride on 8-inch wafers. Admittedly, today our standard capability is around 6 inches, but we are rapidly moving down the 8-inch capability route, and have proved that we are able to manufacture on 8-inch silicon wafers. And of course the time will come when we will move to 12 inches. That's a bit of a way off. It's only recently that sapphire has started to move from 4-inch to 6-inch wafers.

As for other benefits, silicon itself gives you better thermal performance than sapphire, which means you can lower operating temperatures and therefore achieve higher reliability. As far as the light-emitting surface is concerned, the GaN-on-silicon essentially has a mirror effect. It's actually putting the light where you want the light to be – out of the top of the die, not sort of bouncing through the die and substrate. This gives you an advantage in terms of any additional optical systems you need to add, because you're simplifying those optical systems. Yet another consideration is around our historical capabilities as a company, which include incorporating additional electronic and optical components at the wafer level. That is one of the key application benefits that we have in terms of microLED capabilities. So the GaN-on-silicon platform is essential to where we are heading in the microLED space.

ID: What applications are you targeting in terms of microLEDs?

MB: We are of course talking about augmented-reality and mixed-reality in smartglasses, and also about pico projectors, smartwatches, mobile phone displays, head-up displays, and TV displays. Displays in general, to be fair. There are a lot of areas to target with microLEDs.

Today we are focusing on two products – a microLED illuminator and a microLED display. The first targets the incumbent solutions for, say, smartglasses and pico projectors. We are looking at replacing a light-source solution that is made up of three separate colors – the red, green, and blue – and a whole complex microsystem of lenses and prisms and mirrors – with a single-solution light source that is placed directly in front of the fly's eye lens through to the LCOS or DMD.



This 6-in. wafer has multiple 1,920 × 1,080 pixel arrays.

This first product is almost like a step one. Step two is the production of our monolithic array solution. At this point in time when you read about microLEDs, I would argue that they're usually not microLEDs, but miniLEDs. They are manufactured through a pick-and-place mechanism, which means the manufacturer has to pick up, not individually, but in a cluster, red dice, then place them, then pick up blue dice and place them, then pick up green dice and place them, and repeat the process until the array is full.

ID: That process is a big stumbling block for microLED manufacturing right now, isn't it?

MB: Yes, absolutely. Whereas with our monolithic approach, you can, theoretically, within the bounds of your piece of silicon, produce a full array in one process. We are today producing pixels at the size of 8 microns. In terms of an RGB pixel array, that would be a 16-micron colored pixel, which would be structured from four 8-micron subpixels.

We have a way to go with this process. Today our array size is 0.7 inches on the diameter. From a monochrome point of view, this consists of 1,920 × 1,080 pixels, and the whole array runs at 60 frames per second. That's 1,920 × 1080 pixels at the subpixel level, so if you apply that to the RGB, you're looking at 960 × 540. Our intention is to have the monochrome array ready for CES in January 2019.

From there, we will move on to the second generation, probably in Q3 of 2019, which will be an RGB array that is 1,920 × 1,080 with 11.6-micron color pixels. It will have a slightly different structure, but that's an aside, really. This will be around half an inch on the diameter. I can't stress enough that this is a monolithic approach. We are starting with the 0.7 on the diameter and moving on to 0.5 inches on the diameter, full-RGB arrays.

Let's not forget that we have to use a backplane to actually control the individual pixels. So today we have a silicon backplane that we acquire from a third party, which is Jasper [see this issue's Industry News], and we have a chemical-mechanical polishing [CMP] process and a bonding line. We are in partnerships with other manufacturers to give us those capabilities.

The accuracy requirement for the bonding is phenomenal. Essentially we're taking two separate wafers and bonding them together; everything has to align absolutely perfectly. With the CMP you have to have a very flat surface in order to be able to bond those two things together. We recently entered into a partnership with AIXTRON [see this issue's Industry News] for the metal-organic chemical-vapor-deposition [MOCVD] reactors to give us the capability, accuracy, and consistency to manufacture all these microLEDs.

It's very exciting. We think the GaN-on-silicon and monolithic microLED process can be applied to the whole display market. Of course, there is no need with today's designs to have such small arrays in a TV. Samsung and LG are going the other route – these massive great display walls.

ID: What is the company's biggest challenge thus far?

MB: Most of the biggest challenges involved the design concept – how could we make this work? I'm not saying we don't still have problems to solve. We do. But the majority have been solved. Our biggest challenge going forward is how we can actually scale to manufacture and provide product into what is predicted to be a $5 billion market by 2023. How can we get all the partners together, and the supply chain, in a way that allows us to do this at a price that the consumer is going to accept? That's the biggest challenge.

ID: What products are you actually in the business of selling right now with regard to LEDs? Are you in the licensing business as well?

MB: We are now selling the light sources, replacements for existing solutions in a single-source small form factor to go in incumbent projectors and some form of smartglasses. Going forward we will be selling the full monolithic RGB emissive array, which, again, can sit in smartwatches, mobile phones, smartglasses, pico projectors and so forth.

Today we are not in the licensing business. But we're very proud of the fact that all of the key players in the market space are coming here to Plymouth to see our technology. As you know, we've got Vuzix [a maker of smartglasses and augmented-reality technology] and Huawei as partners, and there are quite a few others coming in from a customer perspective that I can't share right now.

ID: In terms of scalability, are you looking at manufacturing on a global basis? You can't do everything in Plymouth, I assume.

MB: Well we'd love to think we could, and there is a degree of expansion that we can achieve within the four walls that we already have in Plymouth, and by that I mean we can expand to around 14 MOCVD reactors. And we would like to do that here in Plymouth. But 14 MOCVD reactors will be a drop in the ocean for microLEDs in five years' time. So we will have to scale. Whether we do that through partners, through licensing, is yet to be determined. But we are fully aware of the fact that we have to scale and we are planning that as much as we can right now. It will be upon us before we know it.

ID: You're an old company, and yet you're a startup with this new technology. Can you tell us a little about your experience in those roles?

MB: Well, there have certainly been occasions when we have been too big for our boots. We come from that background of being a large, well-established business, and we expect all of our suppliers and customers to treat us like that, and we behave as if we're a big business. That is a habit we can't seem to get out of.

Another challenge, which is probably the biggest of all, and one common to every startup, is attracting investment, especially in the very early days. Yet another, and we are feeling it very strongly right now, is attracting the resources with the right skills. Part of the problem is our geographic location within the UK, a blessing and a curse. The specific skills that we need with this new technology that we've developed, the likes of optical engineers at this level, have been very hard to come by. We have to attract resources on a global basis because they are few and far between.

ID: So Plymouth is not a number one destination for engineering talent?

MB: It is a beautiful part of the UK, and tourism is probably the number one industry here. It's a great place to live but it is far from anywhere else. Things are a lot better now – we used to have problems with the infrastructure, such as the internet and the roads, and so on. That is all improving, but it's still not the best.

We have a particular highly skilled mix of people here in this building in Plymouth, and we can be grateful for that, because they have the right characteristics to make all of this technology magic happen. They're sitting down to design, develop, invent, and create things nobody ever thought of before.

ID: As an individual, you have been with Plessey for quite a while and changed focus completely over that time. Is this something that comes naturally to you?

MB: To me, yes. When I joined the company I was a traditional sort of test engineer. I rapidly moved into IT; not fixing PCs, but designing processes and developing solutions for the business. That was a previous role but I am still IT director. In this kind of a role, you need to learn new technology and develop an understanding of the foundation of the business in order to provide solutions for the business. The step from there to designing new technologies is a small one. So personally, I find it very easy and love the challenges on a day-to-day basis. ■

LA SID Chapter Hosts One-Day Conference on Selecting, Customizing Display Products

Each winter, the Los Angeles chapter of the Society for Information Display hosts a full-day workshop that focuses on a specific display-related topic. The usefulness of these conferences, which have featured LEDs, advanced television technology, consumer electronics, in-cell touch, and much more, can hardly be overstated. *ID* magazine's own Executive Editor Stephen Atwood saves his notes from these conferences and refers to them for years afterward.

The 15th annual conference, "Selecting and Customizing Display Products," will feature a discussion of different display materials, including LCDs, OLEDs, and microLEDs, along with their relative properties (luminance, contrast, viewing angle, *etc*.), environmental capabilities (withstanding shock, vibration, salt spray, *etc*.), and potential enhancements (night vision, touch, *etc*.). The event will take place, as it has since it was founded, at the Costa Mesa Country Club in Costa Mesa, California. The date is February 8, 2019, and the cost is $200 for approximately 8 hours of high-level display information you won't find anywhere else. Among this year's featured speakers are Rashmi Rao, head of Harman's user experience unit, and Bob O'Brien, president of Display Search.

According to conference chair Larry Iboshi, the LA chapter conferences began in order to maintain the flow of display-related information for Southern California researchers at a time when Display Week was scheduled to take place on the East Coast (in Boston in 2005). The organizers scheduled the first conference to fall a few weeks after the Consumer Electronics Show in Las Vegas. The chapter conference was such a hit that it has continued since then (with the exception of a one-year break), with participants from all over the country, and the world. "You will see an interesting mix of people here," says Iboshi. "They come from Silicon Valley, the East Coast, and even Asia and Europe." There are regulars who attend every year and also newcomers. "People will often tell us, 'My boss's friend told me I need to come to this conference,' " says Iboshi. The conference averages around 80 participants, with approximately 10 exhibitors. It is entirely organized by volunteers; Ken Werner of Nutmeg Consultants is this year's program chair.

SID's LA chapter is extremely active, which isn't surprising given that SID itself was "born" in Los Angeles, at UCLA in 1962. The chapter holds monthly meetings with invited speakers covering a variety of topics. Recent presentations have included: "The Cinema in Flux" and "Embedded Cameras in Consumer Devices." Iboshi notes that proceeds from the one-day conference go to scholarships for students who submit a paper to the Display Week Symposium. To register, visit www.sid.org/Chapters/Americas/LosAngelesChapter.aspx#6423269-conference.

SID Marks 25 Years of Display Industry Awards

The Society for Information Display is pleased to announce the twenty-fifth year of the Display Industry Awards, the industry's most prestigious honor. The DIAs, which recognize the best displays, components, and applications introduced to the market during the previous calendar year, are announced and presented each spring at Display Week. The 2019 awards ceremony will take place on May 15 at Display Week 2019 in San Jose, California.

Back in 1995, the first year for the Display Industry Awards, the winning Display of the Year was Texas Instruments' Digital Light Processing (DLP) Engine (a technology that is viable to this day) and the runner-up was Fujitsu's 21-in. color plasma display. In 2018, the Display of the Year winners were Apple's iPad Pro and Sharp's 70-in. 8K LCD TV. This year's winners will no doubt incorporate the next wave in state-of-the-art display materials and engineering.

In order to be a part of the DIAs, companies must nominate themselves. While submitting a nomination does not guarantee an award, *not* submitting a nomination guarantees that a company will *not* receive an award. "We hope to have the largest number of nominations ever this year, as we celebrate a quarter century of DIAs," says Wei Chen, chair of the Display Industry Awards Committee.

Display Industry Awards are presented in three categories: Display of the Year Award, Display Application of the Year Award, and Display Component of the Year Award. There is no fee to submit a nomination. To nominate a product, component, or application for a 2019 Display Industry Award, download the appropriate nomination form from www.sid.org/About/Awards/DisplayIndustryAwards.aspx, complete it entirely (including supporting documentation), and send it to the contact noted on the form. The deadline for nominations is January 15, 2019. ■

Mark Your Calendar for FPD China

FPD China, an international industry exposition focusing on the display and touch-screen manufacturing chain, takes place March 20–22, 2019, in the Shanghai New International Expo Centre. The event is co-organized by SEMI and CECC. This year, in addition to its world-class keynote speakers, technology conferences, workshops, and trade exhibition, FPD China will feature forums on innovation and investment and emerging displays. The former will focus on investment opportunities in light of China's new integrated circuit (IC) policy. The latter will investigate how companies are meeting demands that have arisen from AR/VR and AI applications, as well as 8K and flexible device technology. For more information, visit www.fpdchina.org.

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