EMISSIVE DISPLAYS AND DISPLAY METROLOGY

Information DISPLAY

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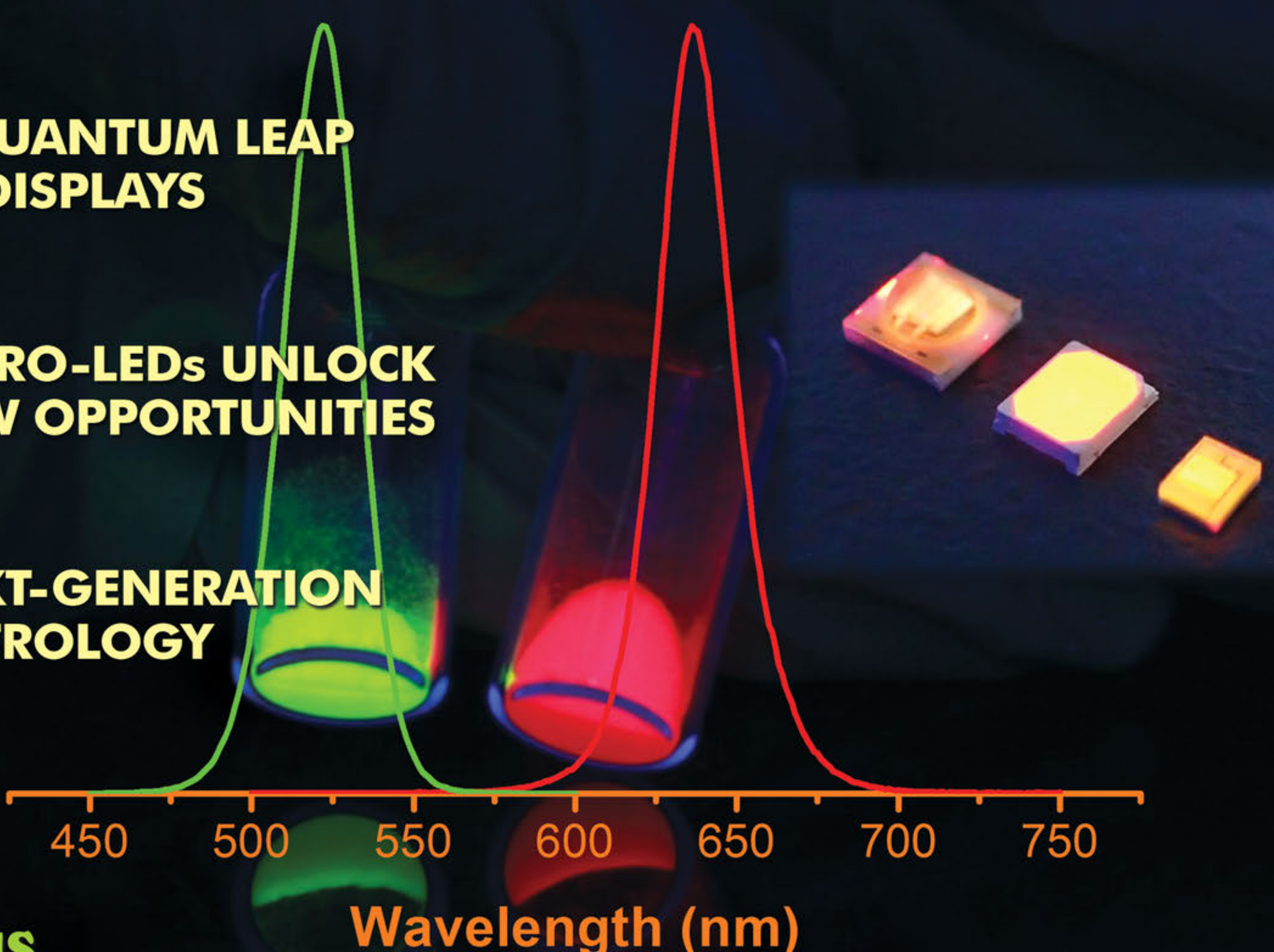
The Bright Future of New Emissive Technologies

A QUANTUM LEAP IN DISPLAYS

MICRO-LEDs UNLOCK NEW OPPORTUNITIES

NEXT-GENERATION METROLOGY



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2017 ID Media Kit

Interview with CYNORA's CMO

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ON THE COVER: *With the advent of quantun dots and micro-LEDs, emissive displays are once again going to play a major role in the next generation of displays.*

Cover Design: Acapella Studios, Inc.

In the Next Issue of *Information Display*

Issues in Applied Vision

- Minimizing Stereoscopic Artifacts
- Using Scene Statistics to Focus Devices
- Head Tracking for AR/VR
- Market Outlook for Next-Generation Displays
- The Long View for Batteries

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editorial

A Bright Future Is Coming

by Stephen P. Atwood

I have been looking forward to this issue ever since we first put it on the calendar because there are so many recent innovations in the field of emissive technology. My excitement was further piqued when Guest Editor Qun (Frank) Yan (professor, industry advisor, and chair of SID's emissive display subcommittee) pitched his story ideas, which included one on micro-LEDs and another on quantum dots and quantum rods.

Those of us who remember watching CRT televisions certainly have seen our share of ideas for emissive displays over the years, including electroluminescent (EL), vacuum fluorescent (VF), light-emitting diode (LED), and, of course, plasma. (I maintain that plasma TVs were one of the best technologies of their time, and I still enjoy my 60-in. plasma TV almost every evening.) But when organic LED (OLED) technology became commercially viable, I began to think that the future could truly be changed by emissive technology. Frank also considers this historical context in his Guest Editorial, where he describes his view of the significance of new emissive technologies for the future of displays. We are very grateful for the excellent effort Frank has made to bring this topic to you this month. OLEDs will certainly be a big part of the future, but as you will read this month, other forms of emissive technology may play as big or even bigger a role in transforming the current paradigms we work in as display engineers.

I was privileged to get a first look at quantum-dot (QD) technology about a decade ago when a company called QD Vision first began its work up here in New England. Seth Coe-Sullivan, one of the company's founders, came over to our New England SID chapter meeting with some small vials of fluid that would glow bright red and green when excited by LED light. Being a skeptic, I immediately started looking for the trick behind the demonstration. Was it some kind of optical illusion? Was it a prismatic effect that split the source light and somehow only passed through the color being shown? No, as Seth explained, it really was a secondary self-emitting technology in which the energy was coming from the source light and being re-emitted by the quantum dots at the exact wavelength prescribed by the dots themselves. Wow! I still remember that night and the ideas that were spinning around in my head as I drove home from the meeting.

When the first demonstrations of QD-enhancement films for LCDs were shown, I liked the concept a great deal but felt this was not nearly the goal line for the technology. It is fun to be right once in a while, and I think you will really like our first Frontline Technology article from authors Kai Wang and Xiao Wei Sun titled "Quantum-Dot and Quantum-Rod Displays – the Next Big Wave," as much as I did. The authors describe first the current state of the art of QDs as backlight enhancement components for LCDs, including actual QDs embedded on LED chips. They go on to introduce a new structure called a "quantum rod (QR)," which is described basically as "…a kind of core-shell nanocrystal with an aspect ratio of more than 1:1 (*e.g.,*. 5:1)." In other words, a long thin rod that behaves just like the dots, absorbing electric field or light energy and re-emitting at prescribed wavelengths. However, in the form of crystalline rods they have an additional property through which they can emit polarized light along their long axis, potentially making them even more ideal as backlight sources for LCDs.

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AMA Report Stirs LED Lighting Controversy

In recent years, municipalities around the world have begun swapping out existing street lamps for more energy-efficient varieties. The new primarily LED-based lighting looks different – it tends to be whiter and "glarier" than its mellower sodium-based predecessor. Coincidentally, this initiative is taking place at the same time that on a research level much is being discovered about the effects of light on human – and animal – health. Exposure to blue light, in particular at night, has been linked to a number of maladies, from poor sleep to greater chances of developing certain cancers. Since light is light, whether it comes from a street lamp or a glowing screen, displays are also a crucial part of this light/health balance.

A lighting "conversation" among various organizations began last summer, when the American Medical Association issued a report titled "Human and Environmental Effects of Light-Emitting-Diode (LED) Community Lighting," in which the authors recommended the conversion of conventional street lighting to LED-based lighting.[1] Additional recommendations included "the use of 3000K [as measured in correlated color temperature or CCT] or lower lighting for outdoor installations such as roadways," proper shielding, and the reduction of blue-light emissions to the greatest extent possible.

Numerous publications picked up the report, streamlining and adjusting the main message as primarily anti-LED. A representative piece from CNN carried the headline, "Doctors issue warning about LED street lights."[2] In turn, agencies such as the Office of Energy Efficiency and Renewable Energy (OEERC) and the Lighting Research Center (LRC) at Rensselaer Polytechnic Institute issued statements of their own.

From the OEERC: "Some media coverage of concerns about blue light, light at night, and dark-sky issues can give the impression that LEDs are the enemy when in fact they are a critical part of the solution, which the AMA acknowledges. It is important to remember that these issues have been around for decades, long before the emergence of LED technology."[3]

The LRC issued an 8-page response to the AMA report,[4] as well as a press release[5] with the following bullet points:

- Predictions of health consequences from light exposure depend upon an accurate characterization of the physical stimulus as well as the biological response to that stimulus. Without fully defining both the stimulus and the response, nothing meaningful can be stated about the health effects of any light source.
- Notwithstanding certain sub-populations that deserve special attention, blue-light hazard from In-Ga-N LEDs is probably not a concern to the majority of the population in most lighting applications due to human's natural photophobic response.
- Both disability glare and discomfort glare are mostly determined by the amount and distribution of light entering the eye, not its spectral content.
- In-Ga-N LED sources dominated by short wavelengths have greater potential for suppressing the hormone melatonin at night than sodium-based sources commonly used outdoors. However, the amount and the duration of exposure need to be specified before it can be stated that In-Ga-N LED sources affect melatonin suppression at night.
- Until more is known about the effects of long-wavelength light exposure (amount, spectrum, duration) on circadian disruption, it is inappropriate to single out short-wavelength radiation from In-Ga-N LED sources as a causative factor in modern maladies.
- Correlated color temperature (CCT) is not appropriate for characterizing the potential impacts of a light source on human health because the CCT metric is independent of nearly all of the important factors associated with light exposure; namely, its amount, duration, and timing.

For additional feedback and analysis, *Information Display* checked in with Jennifer A. Veitch, Principal Research Officer at the National Research Council of Canada and Director of Division 3 (Interior Environment and Lighting Design) of the International Commission on Illumination (CIE). Veitch authored the article "Light for Life: Emerging Opportunities and Challenges for Using Light to Influence Well-Being" for the Nov./Dec. 2015 issue of *ID*.

Veitch said she agrees with the LRC's response: "LEDs are not intrinsically more harmful to humans than other types of lighting, though they do have the potential of being harmful," she says. She also noted that CCT is a poor indicator of a spectrum's exact wavelength. "It's a useful metric for indicating the general color appearance," she added, "but simply to say that all lighting more than 4000K is harmful is wrong."

ID asked Veitch if LEDs might be particularly suspect because people do not find them aesthetically pleasing. She replied: "As with most lighting installations, it is not the fault of the light source. It is in the way that you apply it." And, she noted, that people tend not to be comfortable with new types of light sources. (Interestingly, the "warm" yellow glow of the sodium lights most of us consider normal dates back only as far as the 1970s and 1980s, when the older, and much whiter, mercury vapor lamps introduced in the late 1940s began to be phased out. The sodium lights were unpopular at first too.)[6]

One reason why LED lighting strikes so many people as harsh is that it is not being used to its best advantage. For financial and logistical reasons, towns and cities want to keep the existing physical infrastructure for lighting – the same number of poles spaced the same way, at the same height, *etc.* – and this arrangement often does not employ the new lighting technology to its best effect. "There are a number of products out there that are quite glary, but that has nothing to do with the spectrum," said Veitch. "Any misapplied light source will give a bad outcome." Veitch also made the point that LEDs are more controllable that previous light sources – they can be dimmed.

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[1]http://www.ama-assn.org/ama/pub/about-ama/our-people/ama-councils/council-science-public-health/reports/2016-reports. page?

[2]http://www.cnn.com/2016/06/21/health/led-street-lights-ama/index.html

[3]http://energy.gov/eere/ssl/articles/get-facts-led-street-lighting

[4]http://www.lrc.rpi.edu/resources/newsroom/AMA.pdf

[5]http://www.lrc.rpi.edu/resources/newsroom/pr_story.asp?id=320#.V_ZUe-ArLIV

[6]https://en.wikipedia.org/wiki/History_of_street_lighting_in_the_United_States

guest editorial

Emissive Displays Rise and Fall – and Rise Again

by Qun (Frank) Yan

An information display is simply an electronic device designed to share information, especially the visual representation of information. An emissive display is an electronic device that converts electric energy to light directly at the individual pixel level. Emissive displays have a long history as people's information display of choice. The cathode-ray tube (CRT), one of the earliest information displays, was a type of emissive display that dominated the industry for almost 80 years, ever since it became commercially available in 1922. Another type of emissive display, the plasma display, introduced us to the era of large-sized flat-panel TVs. This new form factor was truly a revolution in display technology, as the larger size, flatter format, lighter weight, and better pixel resolution of flat plasma display panels (PDPs), and later LCDs, quickly pushed small-sized, bulky, heavy, and low-resolution CRTs into extinction.

I remember that it was quite exciting when I first became engaged in PDP technology at Plasmaco in Highland, New York, back in 1997. The PDP was a hot topic within the emissive-display community for 50 years – since 1965 – and especially when large plasma TVs entered the marketplace at the end of the last century.

One similarity between CRT and PDP displays is that both emit light through vacuum electronic devices. Lighting through solid-state devices, such as light-emitting diodes (LEDs), has proven to be more energy efficient in terms of converting electric energy into photon energy. Therefore, LCD panels with LED backlighting eventually gained the upper hand against PDPs due to the economy of scale, lower power consumption, and strong marketing – even though plasma TV always won performance shootouts over LCD TV in terms of image quality and video performance. Organic light-emitting-diode (OLED) displays, based on emissive and solid-state display technology, are now gaining some momentum against non-emissive LCD technology in small and flexible formats (such as for smartphones).

OLED technology, which used to be under the emissive display wing at Display Week's annual technical symposium, became mature enough that it was given its own sessions at Display Week. Without OLEDs, and with PDPs having faded away from the consumer market, emissive displays seemed to be losing visibility at the annual symposium. However, thanks to quantum dots (QDs), emissive displays are once again a "hot" area.

QDs first became a popular topic because they could be applied to LCD backlighting systems. QDs can produce light with a much narrower emission spectrum than phosphor-based light sources, hence providing a more saturated or "pure" color. When employed as part of an LCD backlight system using a blue LED as the stimulus, a much wider color gamut can be achieved than previously possible.

Recent progress in electroluminescent quantum-dot LEDs (QLEDs) has also increased interest in developing QLED devices with a structure similar to that of OLED displays – these could even potentially replace OLED displays. For this reason, I solicited the article, "Quantum-Dot and Quantum-Rod Displays – the Next Big Wave" by Kai Wang and Xiaowei Sun from Southern University of Science and Technology. This article provides a very good review of both photoluminescent and electroluminescent applications of QD materials. I am sure it will help readers better understand the latest developments in this area.

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Quantum-Dot and Quantum-Rod Displays – the Next Big Wave

Photoluminescent and electroluminescent quantum dots and quantum rods are the subject of rapidly expanding research efforts. These materials possess performance benefits – particularly in the areas of luminescence and color – that the authors believe will reshape the display industry as we know it.

by Kai Wang and Xiao Wei Sun

ALTHOUGH there are different opinions as to what the hottest topics in display technology currently are, no one can deny that quantum dots (QDs) are among the hottest. At Display Week 2016, we witnessed a dramatic increase in quantum-dot activity. The first quantum-dot presentation at SID's annual Display Week technical symposium – an invited paper from Samsung – was made in 2010. It was, therefore, amazing to find that just 6 years later there were five full sessions dedicated to QDs and quantum rods (QRs) and eight sessions containing QD/QR presentations. There were a total 51 papers related to QDs/QRs at Display Week 2016, including both oral and poster presentations.

Defining Quantum Dots

QDs, QRs, the larger perovskite QDs, and other luminescent nanocrystals (LNCs) have rapidly been developed in both academia and industry due to their outstanding luminescence. Their performance is especially good for color, including highly saturated colors (narrow-bandwidth emission), precisely tunable emission wavelengths based on quantum-size effects, and high quantum yields, which are beneficial for wide-color-gamut display and high-quality (meaning a high color-rendering index) lighting. In 2013, Sony released the first commercialized QD-enabled display – its Triluminous TV, in which a Color IQ optical subsystem from QD Vision was adopted to enhance LCD panels. According to a report from Custom Market Insights earlier this year, the overall QD flat-panel-display market will reach US$110 billion by 2017.[1]

There are two types of QD/QR displays: photoluminescent (PL), in which QDs/QRs are used as backlights for LCDs, and electroluminescent (EL), in which QDs/QRs are self-emissive through electrical excitation. For PL, the next challenges concerning LNCs for the display and lighting industries will probably concern new materials that are more environmentally friendly, with higher quantum yields and even better color saturation (narrower emission) as well as new LNC composites with better long-term operational stabilities. Moreover, some rod-shaped LNCs with strong polarized emission also have huge potential in decreasing the power consumption of LCD panels. For EL, there are many issues that need to be resolved, such as QD surface modification for EL applications, QD ink for printed displays, balance in carrier injection, appropriate hole-transport materials, *etc*. In this article, we will provide a brief review of the emerging QD and QR display technologies, including those designed to meet the aforementioned challenges that were presented at Display Week 2016.

Quantum Dots for PL Applications

Due to environmental regulations surrounding cadmium, performance benchmarking between cadmium-containing and cadmium-free QD displays has been highlighted of late. At Display Week 2016, QD Vision demonstrated quantitatively that cadmium selenide (CdSe) based systems outperform indium phosphide (InP) based systems in terms of luminance, color gamut, and power consumption.[2,3] The TVs used in the study included four different configurations of backlit LCDs: (1) CdSe QDs in edge-optics configuration, (2) QD enhancement film (QDEF), (3) InP-based QDEF, and (4) conventional white LEDs with red and green phosphors. The demonstration showed that the CdSe QD solutions achieved the widest color gamut and the highest energy efficiency. Though improvements have been made in InP QDs, their deficiencies in full width at half maximum (FWHM), efficiency, and operational stability indicate a performance gap compared to that of CdSe QDs. InP QDs show a wider FWHM, causing a drop in color gamut. Moreover, the lower external quantum

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efficiency of InP QDs decreases the luminance and increases the energy usage of these displays. In addition, non-QD solutions showed even poorer performance compared to their QD counterparts. At the exhibition at Display Week, QD Vision showed a demo of three QD-backlit LCDs and an OLED display. Figure 1 shows performance benchmarking of TVs based on OLEDs (203 W), CdSe QDs (148 W), InP QDs (202 W), and white LEDs (160 W). The TV based on CdSe QDs shows the most vivid display performance and the lowest power consumption. (Note: specs including the model and year of the OLED TV used for comparison are not known.)

It should be noted that quantum-dot-maker Nanosys also had a similar side-by-side TV demonstration at Display Week 2015 (for which the company won a Best-in-Show award), and also in 2016.

QD Vision also proposed a new standard called "Color Nits" for measuring brightness and luminance in the latest high-performance displays that support high dynamic range and wide color gamut.[4] The "Color Nits" metric is derived from a formula that takes into account varying spectral profiles and the subtle differences between perceived brightness and actual luminance. The new concept integrates aspects of the so-called Helmholtz–Kohlrausch effect, which states that more-saturated colors can appear brighter than less-saturated ones of equivalent luminance, meaning that wider color gamut results in higher perceived brightness levels. QD Vision called the measuring standard the first comprehensive metric that will be able to compare the brightness of all Rec.2020 display implementations.

Although LCD TVs that use cadmium-containing QDs have the potential to provide the best display performance, according to the European Union's Restriction of Hazardous Substances (RoHS) regulations, the cadmium concentration in consumer-electronics products must be less than 100 ppm in order to be compliant. Currently, there is an exemption in the European Union for cadmium in display applications, but it is due to expire in June 2018; therefore, a "greener" QD is a high priority for the industry.

Nanosys has developed a new type of "greener" quantum dots, its Hyperion QDs, by combining green CdSe and red InP QDs.[5] The FWHM color saturation of Hyperion QDs is less than 25 nm for green and 42 nm for red. [25 nm is very narrow for green QDs, but 42 nm is rather large for red QDs. The FWHM of red QDs is always less than 35 nm (even 30 nm) for cadmium-based QDs.] Benefiting from this, LCD panels using quantum-dot-enhanced film (QDEF) with Hyperion QDs are able to reach a high level of >90% BT.2020 gamut as shown in Fig. 2(a). Most importantly, the cadmium concentration of the Hyperion QDs is less than 95 ppm, which fully meets the requirements of RoHS. This is an important advancement in color performance for consumer electronics.

Fig. 1: QD Vision showed side-by-side performance benchmarking of TVs with different technologies demonstrated at the show. Top left: OLED; top right: CdSe QDs (Color IQ); bottom left: white LED; bottom right: InP QDs.

Nanoco demonstrated a new heavy-metal-free QD film, CFQD, at Display Week, as shown in Fig. 2(b), by using a roll-to-roll manufacturing process.[6,7] This red QD film is flexible, color tunable, highly efficient, easy to handle, and can be cut to any shape. The film can be integrated into an existing light fixture with paired phosphor/LED backlights to produce a light with an appropriately correlated color temperature (CCT) of 6500K (to replicate daylight) and a high color-rendering index (CRI) with $R_a > 95$ and $R_9 = 92$, at a luminous efficiency of 109 lm/W.

Chinese quantum companies also showed eye-catching performance. Najing Technology Company, with support from Zhejiang University, showed a new method to synthesize QDs with narrow FWHM (<20 nm) and high PL quantum efficiencies at a low temperature of 160°C.[8] In products, the PL quantum yield of the QDs for light-converting devices remained high. In addition, QD light-converting films based on the QDs were demonstrated, as shown in Fig. 9(a).

Zhonghuan Quantum Tech, another rising QD company with the support of the authors' institution, the Southern University of Science and Technology (SUSTech), released a new technology based on quantum-dot luminescent microspheres (QLMS).[9,10]. QLMS, as shown in Fig. 3, is a new type of a highly robust QD composite featuring high efficiency, narrow FWHM, and excellent long-term operational stability. It is actually a sphere full of QDs coated with inorganic and organic protection layers.

QLMS is fully compatible with current LED packaging processes and can be used as phosphors for direct on-chip applications, meaning tubes or films are not required.

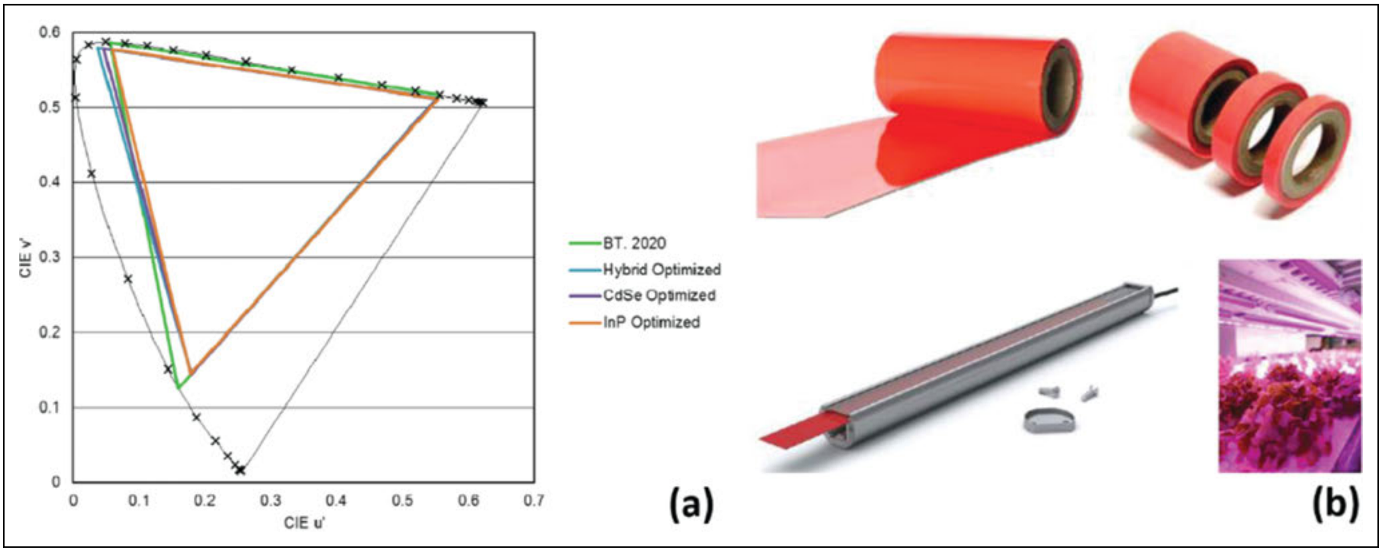

Fig. 2: (a) Nanosys modeled gamut coverage of different films with wavelengths optimized for maximum BT.2020 coverage.[5] (b) Nanoco has developed cadmium-free quantum-dot film rolls and strip lights.

QLMS will make it more convenient and cost effective for manufacturers to adopt QDs in flat-panel displays with wide color gamut and LED lighting with better color rendering. For example, QLMS-based white LEDs with a CCT of 5500K, high luminous efficiency of 142.5 lm/W, and a high color-rendering index of $R_a = 90$ and $R_9 = 95$ provide more vivid rendering colors of objects.

Yonsei University proposed an advanced LCD with patterned QD film and a short-pass reflector (SPR) that uses the principle of distributed Bragg reflection.[11] As shown in Fig. 4(a), the patterned QD film and SPR are applied to an LCD to enhance the optical efficiency dramatically by separating the green and red QDs matched with their respective color filters (CFs) to reduce light-energy attenuation by using color-filter selection and absorption and reflecting the backward emission of QDs to a forward direction, preventing the absorption loss of backward emission by the backlight unit.

Compared to an LCD with a mixed QD film, the optical power of blue, green, and red light in an LCD with a patterned QD film and SPR is increased by 869%, 256%, and 85%,

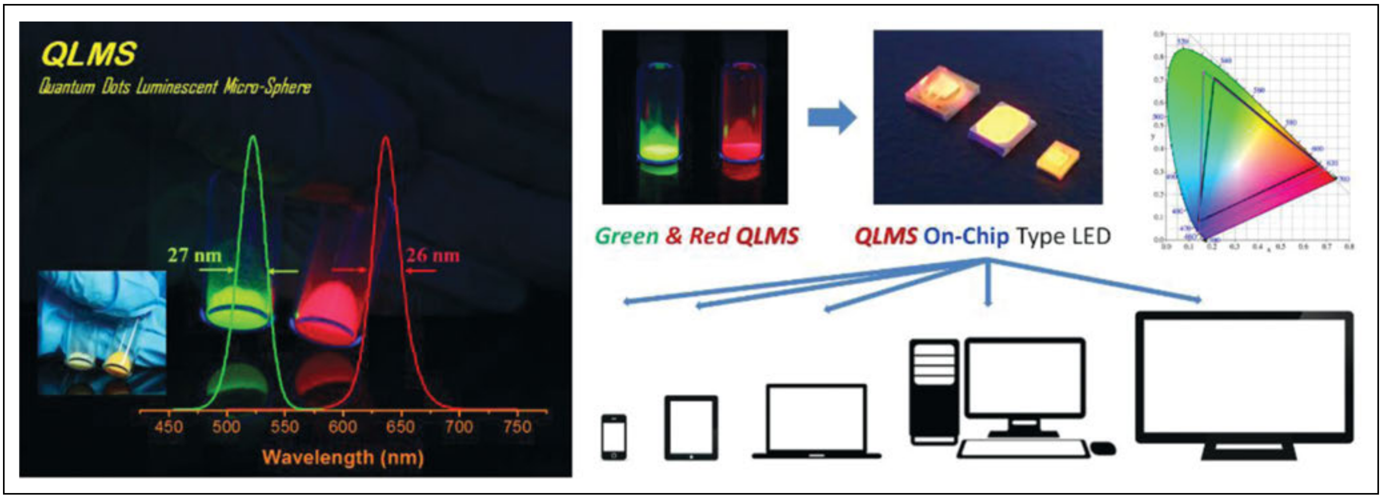

Fig. 3: Zhonghuan Quantum Tech has developed quantum-dot luminescent microsphere (QLMS) technology, which incorporates on-chip-type LEDs based on green and red QLMS and their display applications.[9,10]

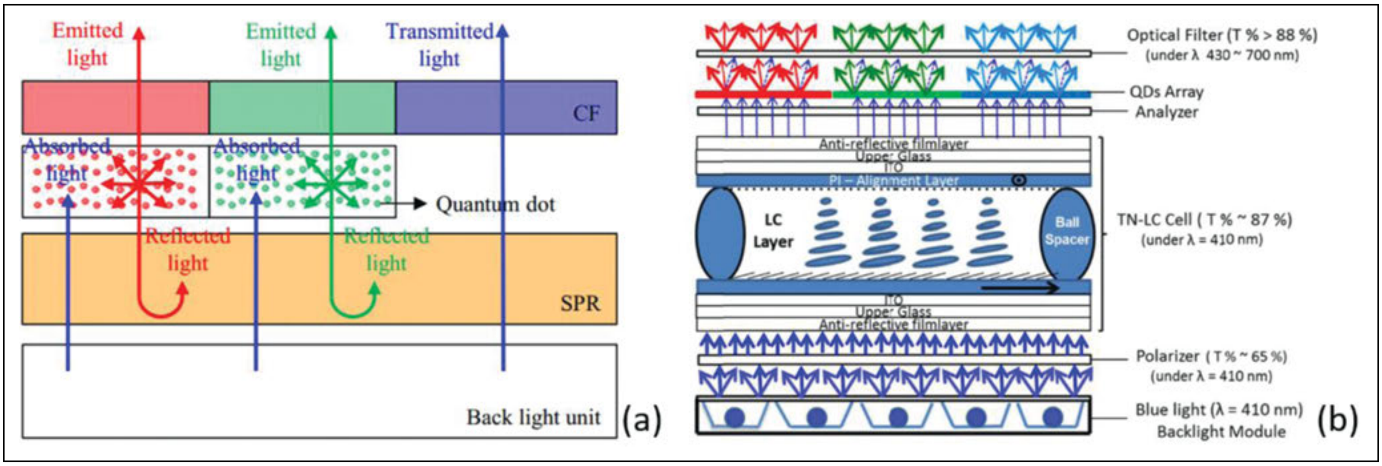

Fig. 4: (a) The schematic mechanism of an LCD with patterned QD film and SPR structure[11] and (b) an eco-QD array on a twisted-nematic LC cell architecture.[12]

respectively. Moreover, the LCD with the patterned QD film and SPR results in an increased color gamut with a broad-band color filter while maintaining the maximum optical intensity.

National Chiao Tung University proposed a new method to deposit low-heavy-metal (ZnCdSeS) and heavy-metal-free (ZnCuInS/ZnS) (Cd<100 ppm, Pb-free) based RGB quantum dots on top of the conventional twisted-nematic (TN) liquid-crystal device to improve the viewing angle of the LCD, as shown in Fig. 4(b).[12] The non-vacuum low-materials-consumption solution process by aerosol-jet deposition has the advantage of direct printing on black-matrix-patterned glass. The eco-QD-array TN-LCD demonstrates wide viewing angle, high transmittance, and fast response time (<3 msec) under low driving voltage (4 V).

The University of Central Florida optimized optical efficiency and color gamut simultaneously to realize Rec.2020 for PL QD LCDs.[13] Results indicate that 97% of the Rec.2020 color gamut can be achieved while maintaining a reasonably high optical efficiency for both fringe-field-switching and multi-domain vertical-alignment LCDs by properly selecting QD wavelengths and slightly modifying the transmission spectra of the color filter, which means the Rec.2020 color gamut is no longer exclusive to laser displays.

Since the expected lifetime of a television product is at least 20,000–30,000 hours, accelerated test methods and platforms should be developed for QD backlights specifically. 3M developed measurement techniques that allow researchers to directly measure and then estimate how long the QD-based film can survive in many typical display applications.[14] 3M created four accelerated aging platforms – High Intensity Light Testers (HILTs), Screening High Intensity Light Testers (SHILTs), Testboxes, and Mini Testboxes – to help predict in-device lifetime. These systems enable various levels of control over the sample temperature and the blue flux to which the sample is exposed. Table 1 shows the specifications of the accelerated aging platform proposed by 3M for QD-based film.

Quantum Rods for PL Applications

Besides QDs, semiconductor quantum rods are attractive emerging nanomaterials that have been applied to displays and lighting. A quantum rod is a type of core-shell nanocrystal with an aspect ratio of more than 1:1 (*e.g.*, 5:1). There are two main types of quantum rods: dot-in-rod and rod-in-rod. Display and lighting applications utilize the characteristic properties of QRs, *e.g.*, tunable emission spectra, large absorption cross section, large Stokes shift, and especially polarized emission along their long axes derived from their anisotropic crystal structures. A backlight that emits linearly

Table 1: 3M's specifications for its accelerated aging platform for QD-based film include High Intensity Light Testers (HILT), Screening High Intensity Light Testers, (SHILT), Testboxes (Testbox), and Mini Testboxes (Mini).[14]

		Accelerated Aging Platform			
Parameter	**Application**	**SHILT**	**HILT**	**Testbox**	**Mini Testbox**
Temperature (°C)	~50	50–85	85	50–85	50
Blue Incidence (mW/cm^2)	<10	~1000–7500	300	~20	400
Configuration	Recycling System	Single pass	Single pass	Recycling	Recycling
Time to L85*/ Δx, Δy < 0.01 (hours)	20,000–30,000	~10–50	1200	~1500–3000	150

*L85 = 85% of luminance emission at beginning of life.

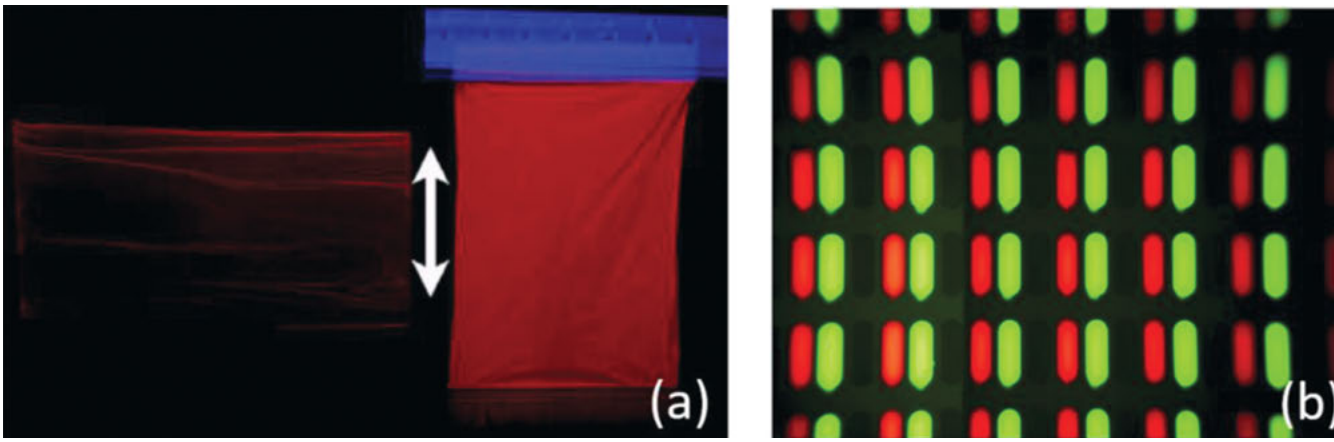

Fig. 5: (a) A polarized emission of the quantum-rod nanofiber sheet image and (b) a micrograph of color pixels filled with green and red QRs. (Merck).[15,16]

polarized light would make it possible to increase the transmission through the polarizers. Such properties are universally applicable for colloidal core-shell QRs, *e.g.*, heterogeneous CdSe/CdS dot-in-rods. These features make QRs promising for low-power and wide-color-gamut LCDs.

Merck demonstrated the use of cadmium selenide/cadmium sulfide (CdSe/CdS) in two configurations for display applications, including the backlight and emissive color pixels for LCD and OLED panels, respectively.[15,16] For the backlight, sheets consisting of nanofibers with embedded QRs were fabricated by collecting electrospun nanofibers on a drum rotating at high speed. The sheets, as shown in Fig. 5(a), exhibited polarized fluorescence emission with a polarization ratio of 0.6 as well as a very high out-coupling efficiency. Moreover, Merck fabricated QR emissive color pixels with a resolution of 81 ppi using an ink-jet-printing process, as shown in Fig. 5(b). The color gamut of the pixels covers 70% of the BT.2020 standard. This demonstration indicated that it is possible for QRs to be used in color pixels in LCDs.

The Centrum for Angewandte Nanotechnologie successfully developed a continuous flow reactor for producing high-quality CdSe/CdS quantum rods in red and green for optoelectronic devices.[17] The polarization of a single QR reaches 0.9. This development is important for the systematic investigation of yield and polarization of these QRs in relation to properties such as length, width, and core size.

Ghent University showed that QRs can be aligned with their long axis parallel to an applied electric field with sufficient amplitude by using the dip-coating technique.[18] A substrate with ITO electrodes in a finger pattern was slowly pulled out of a suspension with CdSe/CdS quantum rods while an ac electric field was applied. The Ghent researchers demonstrated that this procedure makes it possible to align and fix the QRs in the desired orientation. The resulting layer emits linearly polarized light with a high degree of polarization, as shown in Fig. 6(a).

The Hong Kong University of Science and Technology disclosed thin liquid-crystal polymer (LCP) films with uniformly dispersed QRs.[19] Photoalignment has been used to align the QR in the LCP thin film as shown in Fig. 6(b). An order parameter of 0.87 was achieved. The QR films illuminated by the blue light emit polarized light with an extinction ratio of 5:1. The proposed QREF film shows an extended color gamut like QDEF film, but also an increase in the polarization efficiency by 20% compared to the existing system.

The Southern University of Science and Technology (SUSTech) proposed a new tributylphosphine-assisted method to synthesize uniform CdSe/CdS quantum rods having a peak emission at 630 nm, high absolute quantum yield, a narrow FWHM of 27 nm, and a large Stokes shift of 165 nm.[20] The alignment of the quantum-rod nanofibers was achieved by electrospinning. A large-scale active luminance enhancement film (ALEF) based on well-aligned quantum-rod nanofibers was fabricated with a polarization of 0.45 over a 5-cm^2 area, as shown in Figs. 7(a)–7(c).[9,21] When the ALEF is adopted in a backlight, the luminance of the LCD can be improved by 18.4%. This research indicates that ALEF is a very promising backlight solution for highly efficient and wide-color-gamut LCDs.

Some perovskite QDs also possess the feature of polarized emission. Nanograde showed cadmium-free $CsPbX_3$ (X=Cl, Br, and I) perovskite QDs, with an FWHM of 20 nm for a 530-nm peak wavelength and 30 nm for a 630-nm peak wavelength, for wide-color-gamut displays.[22] This RoHS-conforming material depicts a performance better than that of CdSe. Moreover, SUSTech demonstrated full inorganic $CsPbX_3$ (X=Br, I, and mixed halide systems Br/I) perovskite QDs with peak wavelengths from 517 to 693 nm and narrow FWHM from 22 to around 30 nm, which can meet 103% of the Rec.2020 standard,[23] More importantly, as shown in Fig. 7(d), some perovskite QDs showed highly polarized photoluminescence. The polarization of $CsPbI_3$ is as high as 0.36 in hexane and 0.40 in film without any alignment. The $CsPbX_3$ perovskite QDs with a narrow FWHM and high polarization properties seem to possess great potential for display applications.

Quantum-Dot LEDs (QLEDs)

Thus far, we have discussed the latest progress of PL QD/QR displays presented at

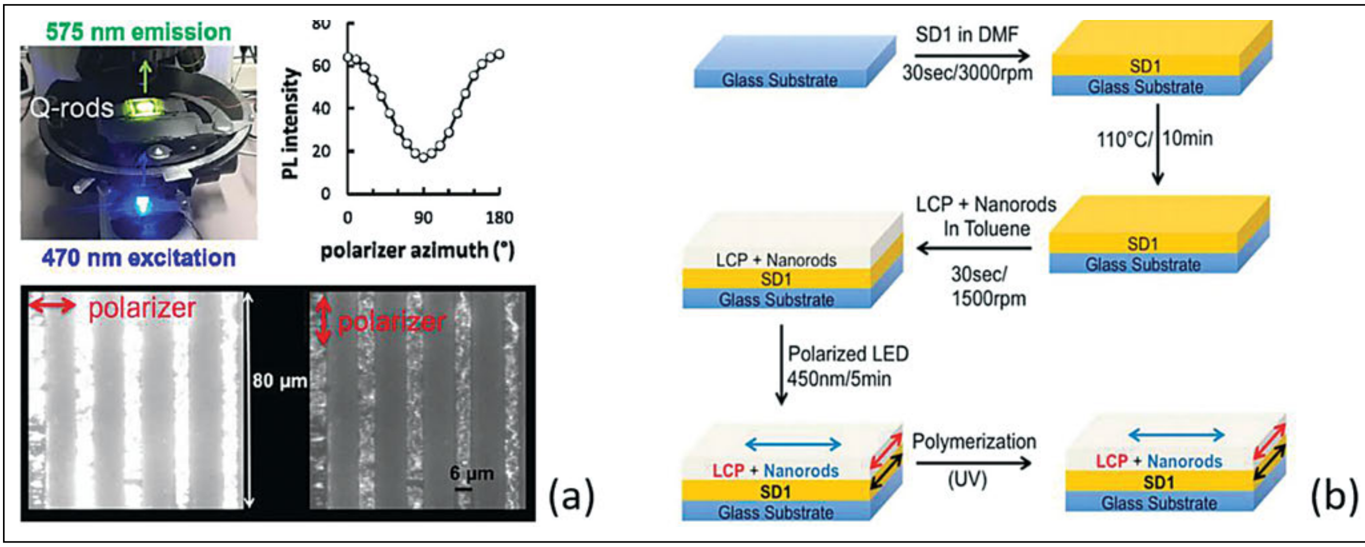

Fig. 6: *Images from Ghent University include (a) top left: the fluorescence of oriented QRs under a polarizing microscope; top right: the dependency of the PL intensity on the azimuth angle of the polarizer; and bottom: the fluorescence microscopy of a particular region on the substrate with oriented QRs with the polarizer parallel (left) and perpendicular (right) to the applied electric field.*[18] *(b) Hong Kong University of Science and Technology's image shows the process flow of QR-dispersed aligned LCP films.*[19]

Display Week 2016. Although PL QD/QR displays can achieve very impressive performance in terms of wider color gamut and lower power consumption, EL QD displays possess more advantages, not only in wide color gamut but also in flexibility, fast response, and printable displays. Many companies, such as Samsung, BOE, TCL, *etc*., have put a lot of effort into EL QD displays. The QD LED (QLED) is the core device for EL QD displays. In the following, we will introduce QLED technologies showcased at Display Week 2016.

NanoPhotonica demonstrated multilayered QLED structures that exhibited high current and power efficiencies of 6.1 cd/A and 5.0 lm/W, 70 cd/A and 58 lm/W, and 12.3 cd/A and 17.2 lm/W for blue-, green-, and red-emitting QLEDs, respectively, as shown in Fig. 8.[24] The QLEDs exhibit highly tunable emission spectra, constituting the first report of QLEDs covering a wide color gamut of ~90% of the Rec.2020 standard. The QLEDs also show a nearly Lambertian angular emission pattern, desirable for wide viewing angles in displays. Furthermore, they demonstrated a champion green QLED exhibiting 21% external quantum efficiency (EQE), 82 cd/A, and 79.8 lm/W, the highest reported green QLED efficiency in the literature and also comparable to phosphorescent OLEDs used in commercial AMOLED displays. In addition, encapsulated green and red QLEDs

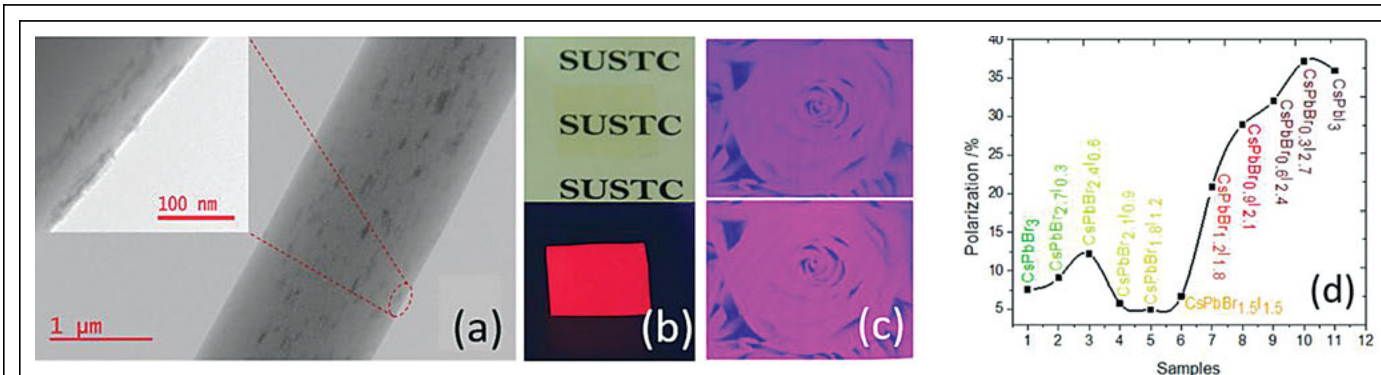

Fig. 7: *These images from SUSTech include (a) a transmission-electron-microscopy image of quantum rods in QRs/PMMA nanofiber; (b) an ALEF under daylight (top) and 365-nm UV light (bottom); (c) an LCD without ALEF (top) and with ALEF (bottom)*[21]*; and (d) polarizations of different perovskite QDs.*[23]

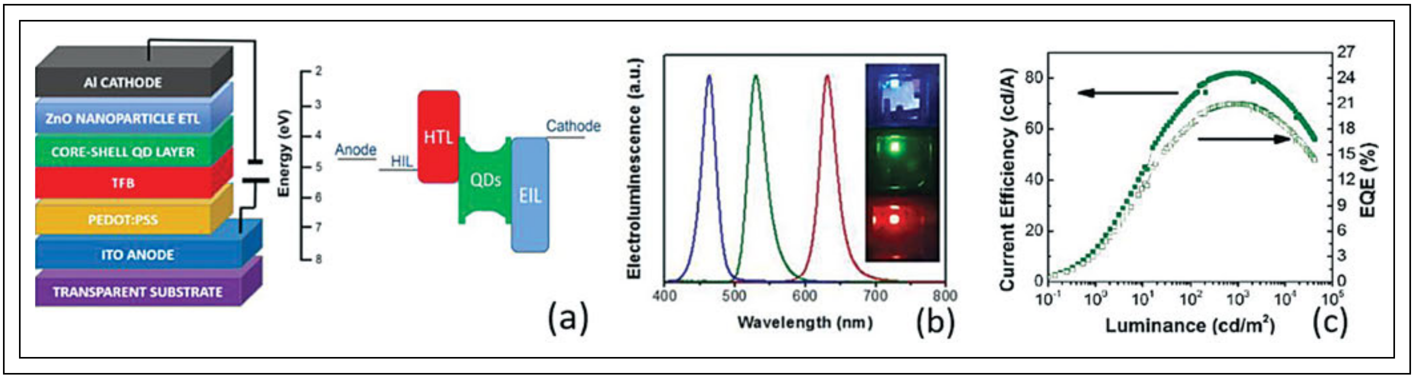

Fig. 8: Images from NanoPhotonica include (a) a schematic of the device structure and energy-level diagram of existing QLEDs with ZnO nanoparticles as the electron-transport layer; (b) the normalized EL spectra of red, green, and blue QLEDs with a multilayered structure and an inset of images of red, green, and blue QLEDs; and (c) the current efficiency and EQE vs. luminance of a champion green QLED from NanoPhotonica.[24]

show outstanding lifetimes of >100,000 and >280,000 hours (as predicted from early life-testing data).

Najing Technology Company also showed RGB-colored QLEDs with EQEs of 20%, 18%, and 14% for red, green, and blue colors, respectively, as shown in Fig. 9(b). With EL peaks at 640 nm (red), 467 nm (blue), and 520 nm (green), one could obtain QLEDs in a wide color gamut, namely, 106.7% of Rec.2020.[8]

Brunel University in the UK reported red QLEDs that exceed the color coordinates requirement set by Rec.2020.[25] By using appropriate device architecture and QD size, researchers achieved a high current efficiency of 4 cd/A for A CIE(x, y) of (0.708, 0.292), meeting the Rec.2020 specification. A high efficiency of 10 cd/A at 10,000 cd/m^2 and 5.8 lm/W for A CIE(x, y) of (0.695, 0.305) was achieved by employing a novel hole transporter. The researchers also demonstrated devices that exceeded the Rec.2020 color coordinates (namely, 0.712, 0.288). Besides using these red QLEDs alone in HDTV with a wide color gamut, this development promises the possibility of hybrid pixels (red QD, green PHOLED, and blue TADF) in the near future.

The University of Central Florida proposed a hybrid white OLED (WOLED) technology that combines QD narrow red emitters with existing state-of-the-art blue and green organic emitters for high-efficacy high-color-quality solid-state lighting, as shown in Fig. 10(a).[26] Spectra analysis indicates this approach will lead to white OLEDs (WOLEDs) that could achieve high color quality (CRI $\geq$ 91, $R_9 \geq 32$) at a high luminous efficacy of radiation ($\geq$359 lm/W). In addition, the University of Central Florida researchers demonstrated an integrated sensing platform based on QLEDs.[27] The use of QLEDs as an excitation source can improve the power efficiency by 57% and above.

SUSTech has developed transparent and all-solution-processed QLEDs.[28] Sputtered ITO was adopted as transparent electrodes. To reduce the plasma damage caused by the sputtering, ZnO nanocrystals with a thickness of 82 nm were employed as buffer layers and electron-transport layers. As a result, damage-free QLEDs were demonstrated with a high averaged transparency of 70% as shown in Figs. 10(b) and 10(c). The transparent QLEDs exhibited an EQE of 5% and a current efficiency of 7 cd/A, which is comparable to that of devices using conventional Al electrodes.

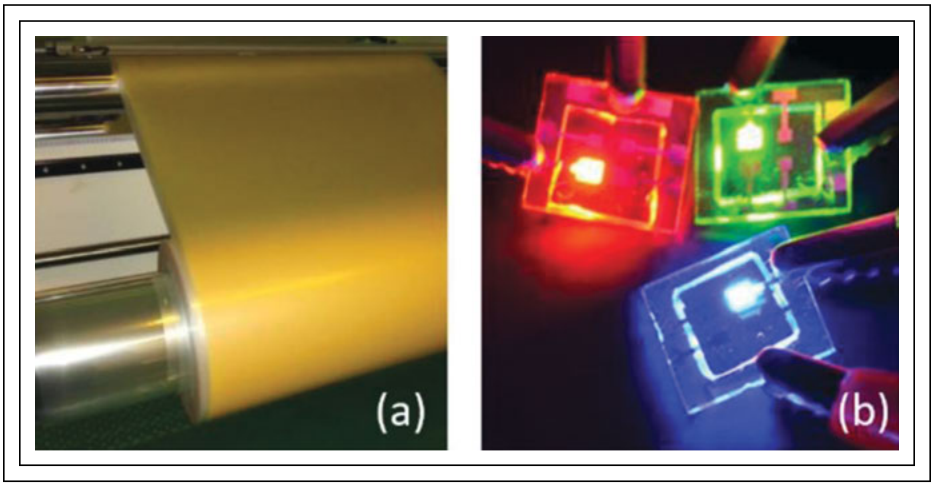

Fig. 9: A QLCD with film types (QLCF) in manufacturing lines and (b) QLED devices in operation (Najing Tech).[8]

Prepare for a Quantum Leap

With the advantages of wide color gamut (narrow FWHM), size-dependent emission wavelength, high quantum efficiency, low power consumption, flexibility, printability, and low cost, QD/QR technology is emerging in displays. This represents a revolution in color: PL QD/QR display technology will rejuvenate LCD technologies in terms of color, and EL QD technology based on QLEDs will challenge the dominant position of OLEDs in

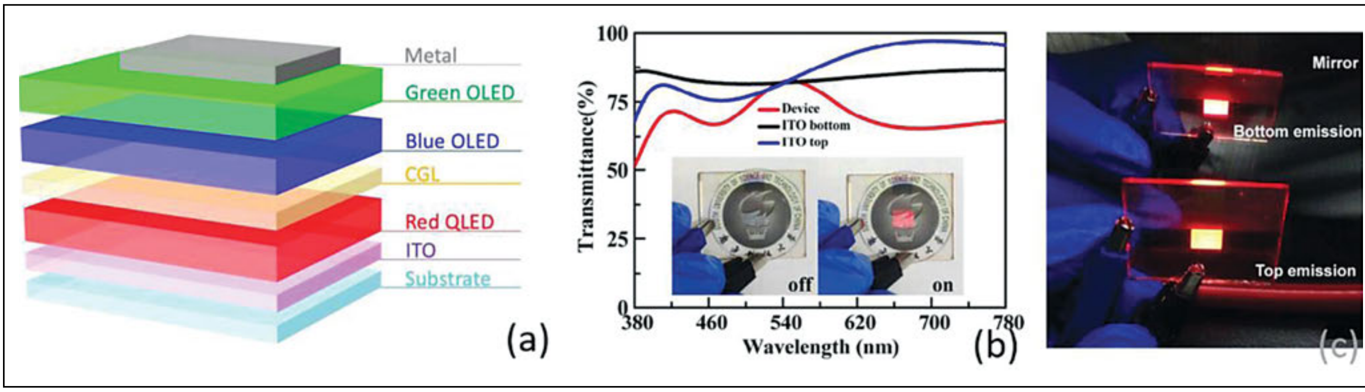

Fig. 10: *Image (a) shows a tandem structure for a red QLED integrated hybrid WOLED.[26] Image (b) demonstrates the transmission spectrum of the ITO electrodes and devices, along with an inset of the QLEDs. Image (c) is a photo of the transparent QLEDs in front of a mirror (SUSTech).[28]*

flexible displays. The next big wave of display technology is coming. By using quantum dots and quantum rods, we may anticipate some change in the game of displays.

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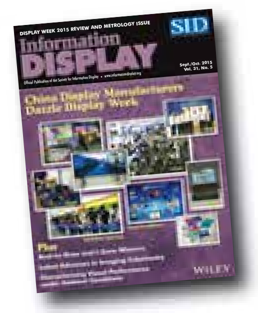

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Issue	Editorial Coverage	Ad Closing Date
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March/April	**Display Week Preview, Display Materials** **Special Features:** SID Honors and Awards, Symposium Preview, Display Week at a Glance, MicroLEDs, Progress in OLED Manufacturing, Disruptive Materials, Nine Most Important Display Trends from CES **Markets:** OEMs, deposition equipment manufacturers, entertainment industry research and developers, display and electronic industry analysts	February 27
May/June	**Display Week Special, Automotive Displays** **Special Features:** Display Industry Awards, Products on Display, Key Trends in Automotive Displays, Head-up Designs for Vehicles, Novel Interfaces for Automobiles **Markets:** Consumer products (TV makers, mobile phone companies), OEMs, research institutes, auto makers, display module manufacturers, marine and aeronautical companies **Bonus Distribution: Display Week 2017 in Los Angeles**	April 18
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Micro-LED Technologies and Applications

Light-emitting diodes (LEDs) offer extraordinary luminance, efficiency, and color quality, but to date are largely used in displays as backlights or packaged pixel elements in large-area LED billboard displays. Building high-performance emissive displays in a smaller form factor requires a new micro-LED technology separate from what is used for large LED billboards. Several approaches have been proposed to isolate micro-LED elements and integrate these micro-LEDs into active-matrix arrays. Technologies that use micro-LEDs offer the potential for significantly increased luminance and efficiency, unlocking new possibilities in high dynamic range, augmented/mixed reality, projection, and non-display light-engine applications.

by Vincent W. Lee, Nancy Twu, and Ioannis Kymissis

THE luminance and power efficiency of a light source are the key factors for determining suitable applications. Light-emitting diodes (LEDs) offer very high luminance levels, greater than 50,000,000 cd/m^2, giving them a proven ability to perform in high-ambient display applications. LEDs also offer some of the highest efficiencies for converting electrical power to optical power. Depending on the material system, an energy conversion of over 60% can be achieved. Due to these benefits and the small solid-state form factor, emissive LEDs can become a solution for display applications of all sizes.

In today's display applications, LEDs are most commonly used as the illumination source for liquid-crystal displays (LCDs) of practically all sizes, including 100-in. TVs to 0.5-in. microdisplays. Individually packaged LEDs are also used as the direct pixel element in large-area billboard displays, which are currently the only format of directly emissive LED displays. What remains underexploited is the use of LEDs as individual pixel elements in all other smaller display formats.

In large-area displays, discrete packaged LED pixels, each containing a red, green, and blue LED chip in the package, form the active elements in emissive video walls. Emissive video walls are attractive for stadium and advertising applications given the high luminance (excellent viewability under bright ambient light conditions) and energy efficiency of LEDs. Although the size of each packaged LED pixel is relatively large, full-resolution displays are easily achieved in these large-area applications. Building smaller displays with packaged LEDs is more difficult. When using the smallest available packaged LED pixels (approximately 0.75 mm), 70 in. is the current minimum achievable size for a FHD-resolution (1920 × 1080) full-color display. When using packaged LED pixels, displays smaller than 70 in. can be produced, albeit with lower resolution.

New applications such as high-dynamic-range (HDR) television and augmented reality are demanding the same high-performance specifications as that of large-area displays, but at dimensions that are difficult to scale for fully packaged LEDs. For example, TV displays require a peak luminance of 10,000 cd/m^2 for future HDR content, and microdisplays need to reach 100,000 cd/m^2 to support the luminance needs of augmented-reality and mixed-reality (AR/MR) glasses. These requirements are easily satisfied by LEDs, which can have luminances up to 50,000,000 cd/m^2. Like other emissive displays, an emissive LED display offers the luminance and efficiency of the pixel source without the typical loss associated with light selection and modulation elements (polarizers, color filters, *etc*). Emissive LED arrays therefore have a huge luminance advantage

High-luminance emissive FHD-resolution LED displays smaller than 70 in. cannot be made from packaged LED pixels, and thus require the development of new manufacturing techniques and technologies. Specifically, these smaller display formats require fabrication and use smaller LED elements or "micro-LEDs." Loosely defined, micro-LEDs are

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devices in which the LED emission area per pixel is below 50 × 50 µm, or 0.0025 mm^2. An array of micro-LEDs makes up a micro-LED display, which ranges in size from fractions of an inch up to 70 in.

Micro-LED displays take advantage of the exceptional luminance of LEDs by spreading the generated photons over a larger area than the area occupied by the micro-LEDs themselves, either by distributing the LED elements spatially or by dispersing light optically. This is illustrated in Fig. 1. There are wide differences between these two technologies, despite confusing nomenclature that refers to both as "micro-LED." The former technology, shown in Fig. 1(a), distributes LED elements spatially and can be used to build displays ranging from 3 to 70 in. In this article, these are referred to as "direct-view micro-LED displays." The latter technology, shown in Fig. 1(b), disperses light optically and is used to build displays < 2 in., which are referred to as "micro-LED microdisplays."

In direct-view micro-LED displays, micro-LEDs are fabricated with a small pixel pitch, separated into individual dice, and transferred to an active-matrix backplane using pick-and-place methods. This allows for the development of an LED display in which the active LED area occupies only a small fraction of the total area. The area expansion allows for direct viewability of high-luminance micro-LEDs (up to a full 50,000,000 cd/m^2 per LED) because the micro-LEDs are spatially separated, resulting in a lower apparent luminance per pixel. The area unoccupied by micro-LEDs is available for a black matrix and integration of interconnection electronics. With larger current-distribution buses available, this approach allows for passive-matrix display development and integration and also lends itself to active-matrix approaches using large-area electronics.

Micro-LED microdisplays use semiconductor integration techniques to combine an array of small pixel-pitch micro-LEDs with a transistor back plate, which are then integrated with an optical system such as projection lenses or see-through glasses. Because the < 20-µm pixel pitch of micro-LEDs for microdisplays is even smaller than that of direct-view displays, the scaling of micro-LEDs for microdisplays requires full integration at the wafer-fabrication level. There are several strategies to perform the semiconductor integration between micro-LEDs and transistors, including pixel-to-transistor bonding, LED epitaxial transfer to silicon CMOS, and integration with thin-film-transistors (TFTs).

Because of fundamental differences in technology approaches and display sizes, micro-LEDs for direct-view displays and micro-LEDs for microdisplays target different markets. Together they offer the promise of replacing all displays now and in the future with the most efficient and highest-luminance systems possible.

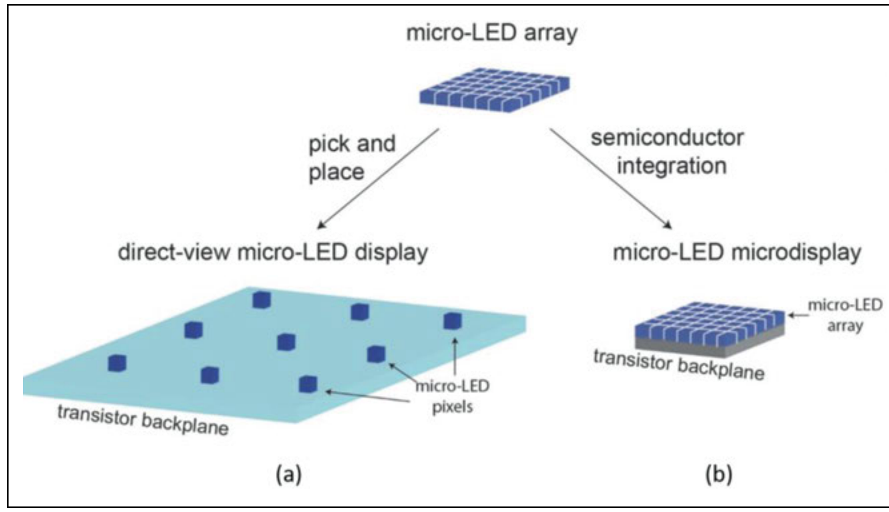

Fig. 1: *Shown are two approaches used to build micro-LED displays. Both methods start with a micro-LED array but use either (a) a pick-and-place technology for direct-view displays or (b) semiconductor integration for microdisplays.*

Direct-View Micro-LED Displays Using Pick-and-Place Technologies

Today, stadium and large street displays use fully packaged surface-mounted LEDs in a

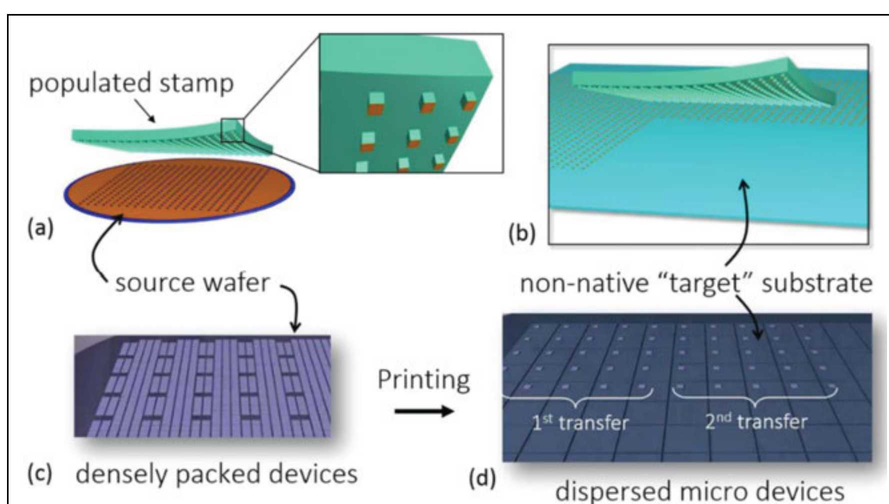

Fig. 2: *In (a) and (c), selected individual chips are picked from a wafer using an elastomer stamp. In (b) and (d), the stamp is then moved to a non-native "target" substrate where the devices are placed, typically in a sparse array. Multiple devices are picked and placed in each transfer, and multiple transfers are used to complete a final display.*[1]

tiled format. With reductions in packaged LED sizes, large-area tiled displays have scaled to smaller sizes and higher resolution displays, as small as 70 in. with FHD resolution. Direct-view micro-LED technologies are the natural extension of efforts to further shrink stadium-sized LED displays for new applications. Instead of using packaged LEDs, direct-view micro-LED technologies use smaller unpackaged LED dies and pick-and-place techniques to build emissive LED displays in the 3–70-in. size range. The resulting direct-view micro-LED displays show increased luminance and improved color gamut for HDR displays, provide different form factors for wearable and flexible displays, and address the push for ever-increasing power efficiency in these applications.

Several academic groups and companies have demonstrated pick-and-place approaches for transferring LED dies to a substrate board and connecting the elements to each other. All of these techniques begin with fabrication of densely packed small-pitch micro-LEDs. The micro-LEDs are then separated into individual dies, transferred to a secondary substrate, and physically spread out to a large pitch via proprietary pick-and-place processes. The choice of secondary substrate depends on the specific application and resolution. Applications such as flat-panel displays use a secondary glass substrate with active-drive transistors, while wearables such as watches and wristbands can use a flexible secondary substrate.

While several pick-and-place methods are being developed, few are publicly disclosed in detail. One paper by Bower *et al*. from X-Celeprint highlights some key aspects of pick-and-place processes.[1] Figures 2(a) and 2(c) show an array of densely packed devices (micro-LEDs) from which a subset of devices is sparsely picked up by an elastomer stamp. This stamp is moved to a secondary substrate, shown in Figs. 2(b) and 2(d), placing the devices in a dispersed array. The stamp can pick up many micro-LED devices at one time to lower the number of transfers needed to populate a full display.

Figure 3 shows X-Celeprint's process for transferring a small-pitch (~20 µm) micro-LED array to a larger pitch (~200 µm) on a glass substrate.[2] The micro-LEDs have a sacrificial release layer that is engineered into the LED epitaxial growth and later undercut to release the micro-LEDs from the growth substrate [Fig. 3(b)]. The micro-LEDs are then picked up by the elastomer stamp and transferred to a glass substrate with some pre-defined metal lines [Fig. 3(c)]. A second metal layer is then deposited [Fig. 3(d)] to electrically connect the transferred micro-LEDs to the glass substrate. By using this transfer process, X-Celeprint demonstrates a 100 × 100 color passive-matrix display [Fig. 3(e)]. Active-matrix formats can also be achieved by transferring the micro-LEDs to a secondary substrate with indium gallium zinc oxide (IGZO) or low-temperature polysilicon (LTPS) transistors.

Sony's micro-LED technology, initially demonstrated at CES in 2012, was recently released. Based on available technical data,

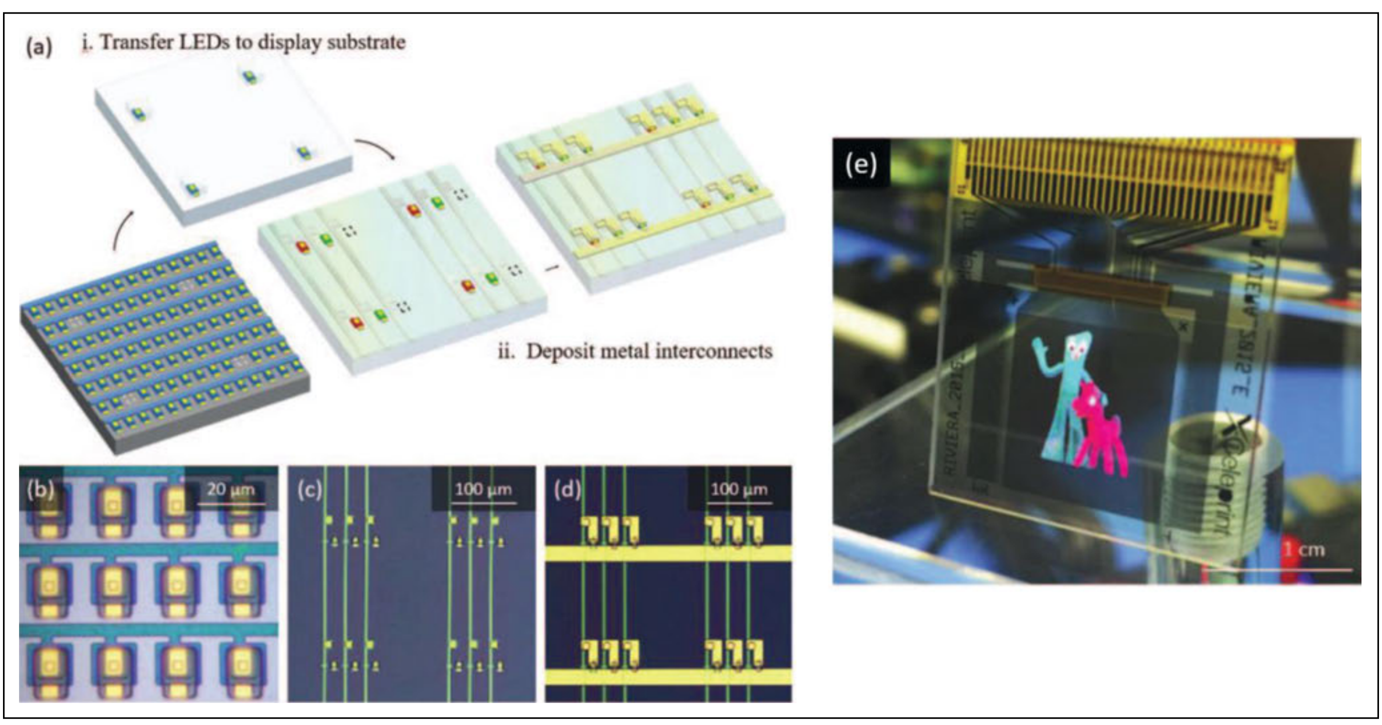

Fig. 3: Image (a) shows the pick-and-place process of micro-LEDs to a secondary substrate. Image (b) is a micrograph of ready-to-transfer micro-LEDs on a source wafer with an undercut etch of the sacrificial layer. The LED size is approximately 10 x 10 µm. Images (c) and (d) are micrographs of transferred micro-LEDs and deposited metal layer for interconnection between micro-LEDs and a secondary substrate, respectively. Image (e) shows a full-color passive-matrix micro-LED display.[2]

micro-LEDs approximately 50 × 50 μm in size are placed on a 320 RGB × 360 tile.[3] Much like conventional stadium displays, these micro-LED based tiles are then further arrayed to form the FHD display. Not much is known about the pick-and-place method or the backplanes used in Sony's demonstrations. Two other companies in the space are InfiniLED and LuxVue. InfiniLED's micro-LED technology uses a unique parabolic micro-LED structure for light collimation and light extraction [Fig. 4(a)].[4] This type of shaping allows for control of the micro-LED emission angle and potential improvements to the overall efficiency of the display. LuxVue, recently acquired by Apple, uses a MEMS-based pick-and-place process for micro-LEDs.

For pick-and-place technologies, the manufacturing challenges are similar across all of the techniques. The primary challenge is pixel transfer yield, as modern displays require nearly zero dead pixels across a FHD screen. To reach the needed pixel yields, some groups have proposed transferring redundant micro-LEDs,[4] as shown in Fig. 4(b), or performing individual pixel repair transfers for dead pixels.[2] These workarounds will add to either the base material cost or manufacturing time to build a display, reducing scalability. In addition, each pick-and-place process requires careful engineering of the LED materials, sometimes even custom LED epitaxy, to ensure that the electrical and optical performances are not affected throughout the fabrication process (LED ohmic contacts, undercut etch of the micro-LEDs, transfer of pixels, *etc*).

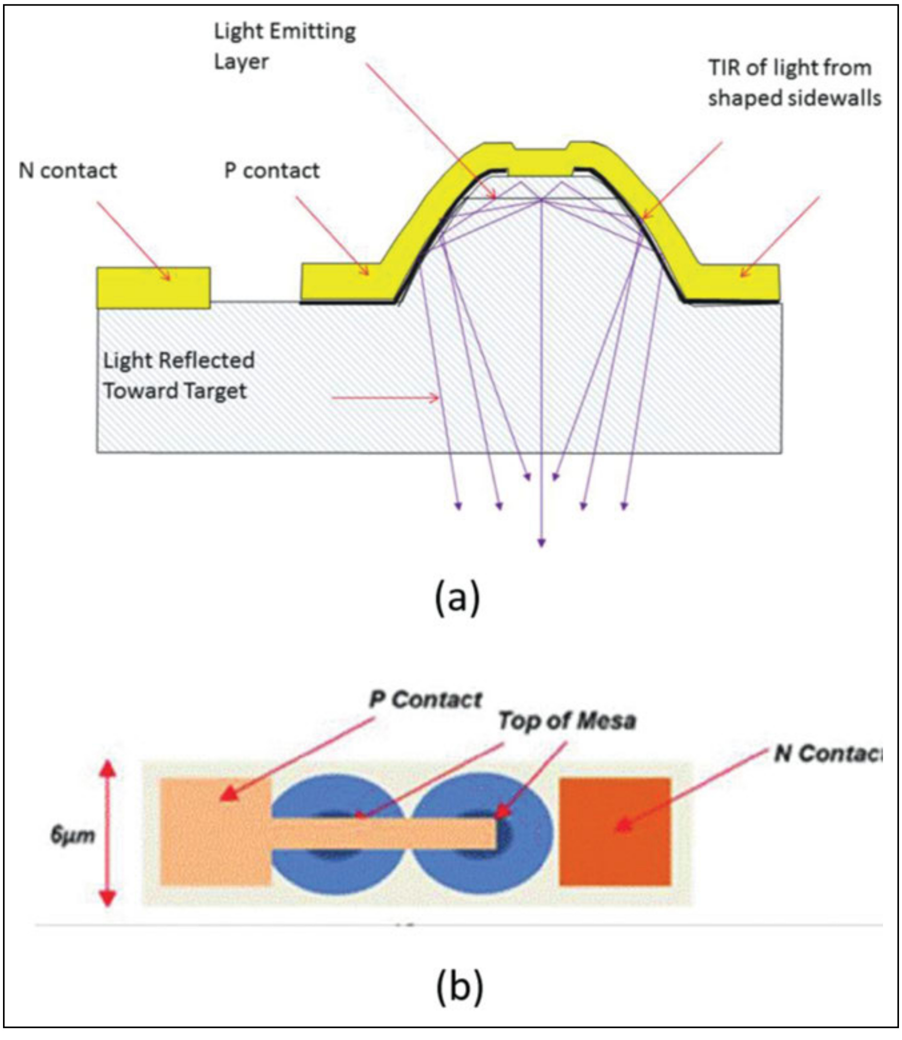

Fig. 4: The top image (a) shows a micro-LED schematic with reflective sidewalls and a curved shape for light collimation and extraction. The lower image (b) demonstrates a top-view design of a twin micro-LED emitter for redundancy and improvement of micro-LED yield.[4]

Micro-LED Microdisplays Using Semiconductor Integration Technologies

For microdisplays with a panel diagonal < 2 in., pick-and-place technologies cannot scale to the smaller pixel pitch required for FHD displays. Microdisplays < 2 in. using passive-matrix schemes also cannot achieve sufficient resolution or luminance, even though small pixel pitches have been demonstrated.[5,6] Building bright high-resolution < 2 in. microdisplays requires direct integration of micro-LED arrays with arrays of transistors that provide active-matrix switching. There are several transistor technologies and approaches to building the integrated active-transistor matrix. At a high level, these technologies can be sorted into the three categories as shown in Fig. 5: (a) chip-level

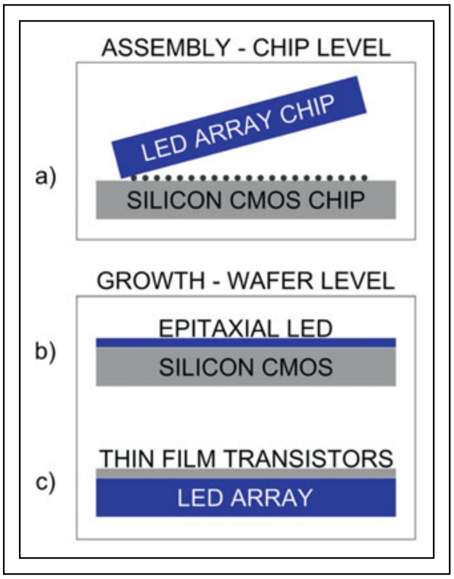

Fig. 5: Shown are three approaches to the integration of silicon transistors and micro-LED arrays for microdisplays: (a) chip-level hybridization of foundry CMOS chip with micro-LED arrays; (b) wafer-level transfer of LED epitaxial layers to CMOS wafer; and (c) wafer-level fabrication of TFTs directly on micro-LED arrays.[7]

micro-LED pixel–to–CMOS-transistor bonding, (b) LED epitaxial transfer to silicon CMOS, and (c) micro-LED array integration with TFTs.

Under first consideration is chip-level micro-LED pixel–to–CMOS-transistor bonding, a process also known as flip-chip bonding. Because of the ubiquity of foundry CMOS processes, many technologies in this category start with a completed silicon chip and work within back-end processes to add functionality, namely, chip-level assembly of micro-LED arrays as shown in Fig. 5(a). The LED arrays are fabricated by lithographic patterning of contacts and mesa etches. Bump bonds are then fabricated either on the silicon CMOS chip or on the micro-LED array. Next, the micro-LED arrays are die separated and bump bonded to the silicon CMOS chip. This fabrication flow offers researchers the advantage of using the highest-performing transistors, demonstrated by researchers at the University of Strathclyde,[8] the Hong Kong University of Science and Technology,[9] the Industrial Technology Research Institute,[10] and mLED.[11] Devices fabricated by mLED with conventional flip-chip bonding have been hybridized and demonstrated up to nHD (640 × 360) resolution with a pixel pitch as low as 20 µm.

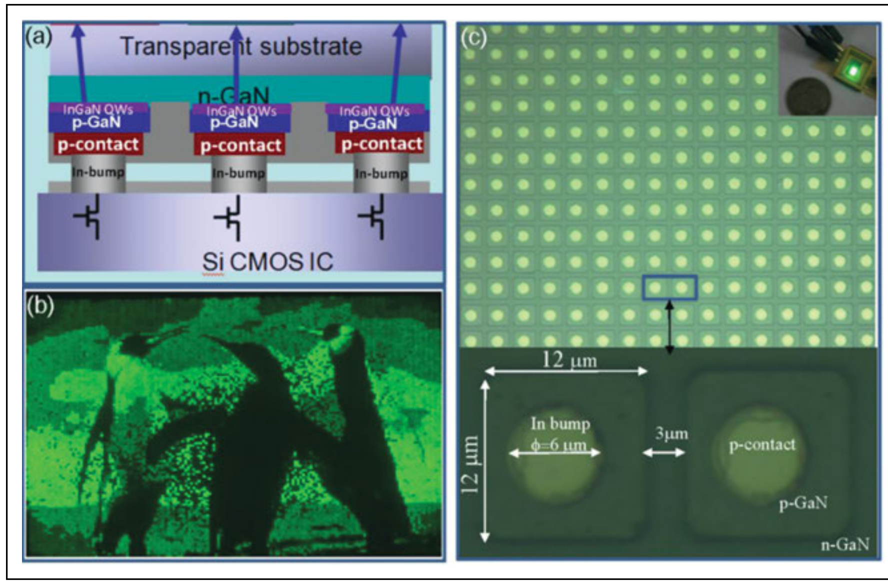

Fig. 6: Image (a) shows a cross-section schematic of a silicon CMOS IC flip-chip bonded with a micro-LED array using indium bump bonds. An image of a monochrome microdisplay appears in (b) and a micrograph of a micro-LED array with indium bonds prior to flip-chip bonding is shown in (c).[12]

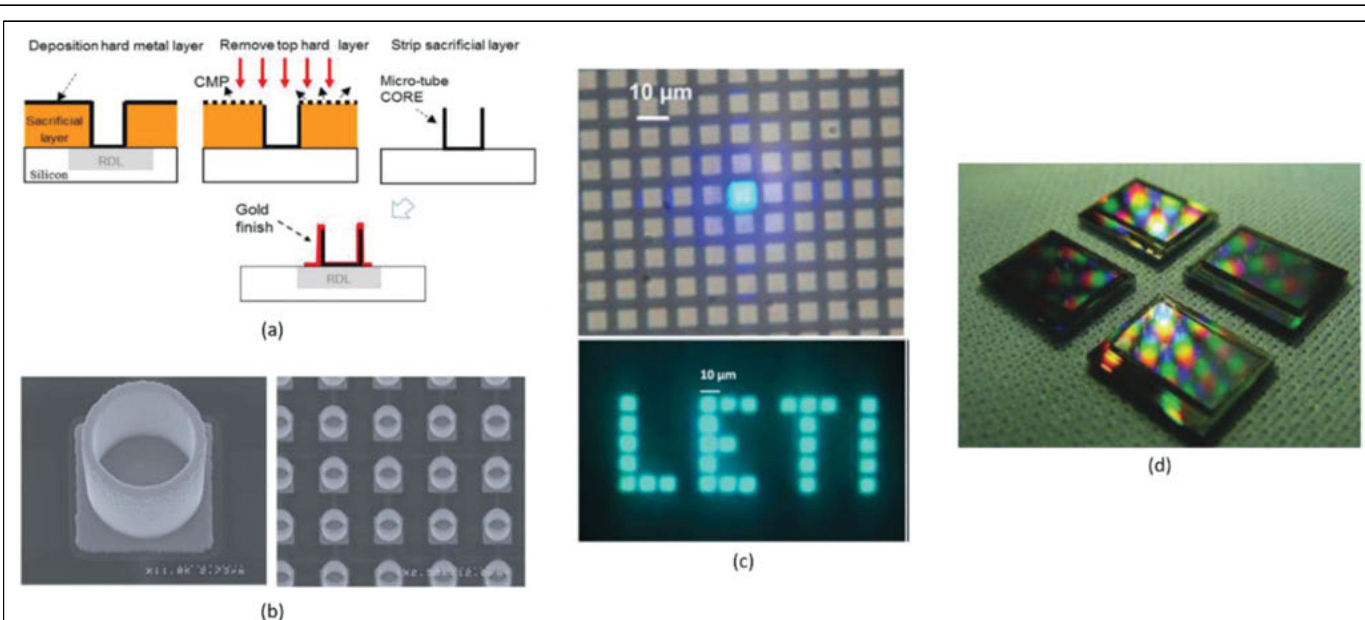

Fig. 7: Image (a) shows a schematic cross section of the micro-tube fabrication process. Image (b) shows a scanning electron micrograph of micro-tubes fabricated on a CMOS wafer. In (c) and (d), micrographs and a photograph of flip-chip bonded micro-LED arrays with a 10-µm pixel pitch are shown.[13,14]

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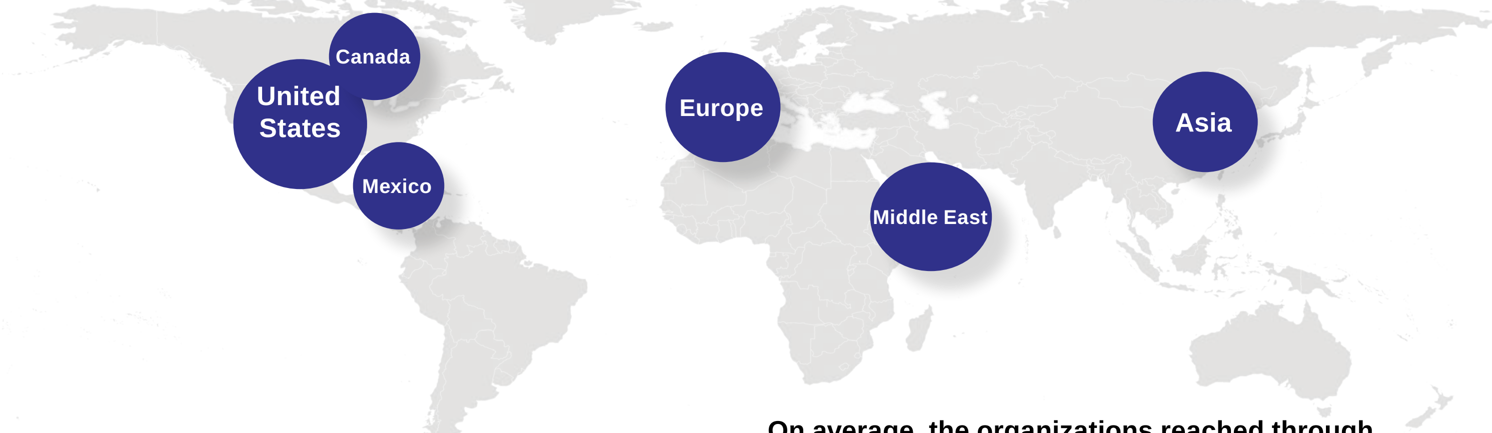

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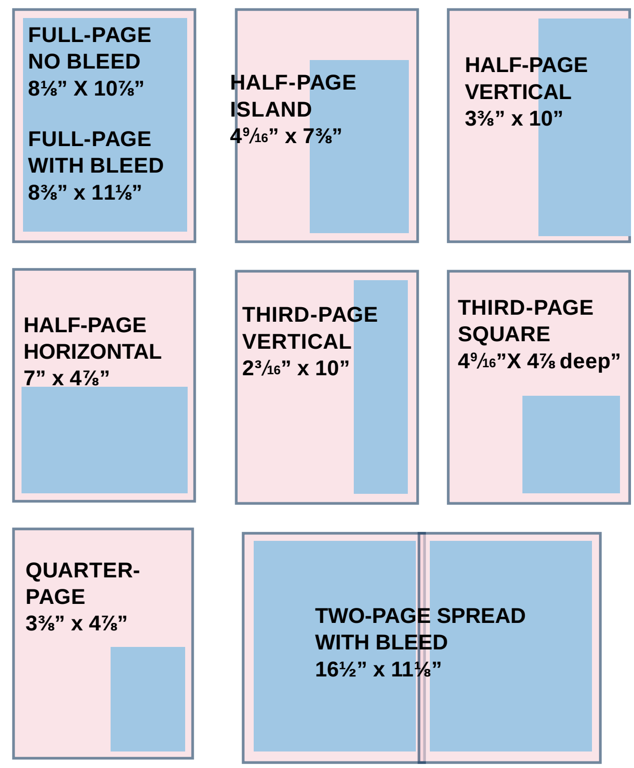

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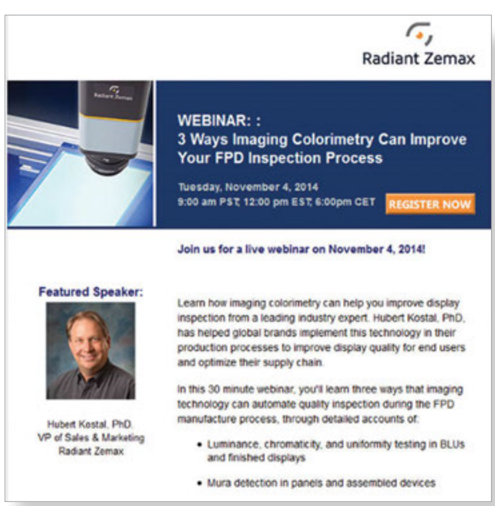

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Within flip-chip bonding, as pixel-pitch shrinking becomes more aggressive, non-traditional bonding processes are being developed. Devices by Day *et al*. use indium bumps to bond a 160 × 120 array at a 15-µm pitch [Fig. 6(b)].[12] Fabrication of this device, shown in Fig. 6(a), starts with foundry-silicon CMOS and a micro-LED array. The micro-LED array is then coated with indium through thermal evaporation and lithographically patterned to form indium bumps [Fig. 6(c)]. The indium-patterned micro-LED array is then flipped and mated with the corresponding CMOS silicon contact and heated to reflow each of the LED-transistor contacts.

More recently, Templier *et al*. at CEA-LETI demonstrated an innovative micro-tube technology to perform the bonding process. As in other approaches, a silicon CMOS chip and a micro-LED array are first fabricated separately. The silicon CMOS chip then continues through a series of back-end processes to form micro-tubes, as shown in Figs. 7(a) and 7(b).[13] The micro-tubes are created through the use of a sacrificial layer and deposition of a hard metal layer. This is followed by a chemical mechanical polish and removal of the sacrificial layer to form the micro-tube core. On the micro-LED array, a soft metal is formed to be compressed into the micro-tubes during the die assembly process. The resulting hybridized chip, shown in Figs. 7(c) and 7(d),[14] contains 6-µm micro-LEDs with a 10-µm pitch, a resolution of 873 × 500, demonstrating luminances up to 10,000,000 cd/m^2.

An alternative to flip-chip bonding is been being developed by Ostendo. Here, the process starts with silicon CMOS wafers, but instead of flip-chip bonding a completed array of micro-LEDs, LED epitaxial layers are transferred to the CMOS wafer. The LED material is then patterned and fabricated into the structure shown in Figs. 8(a) and 8(b).[15] In addition, vertical waveguide hole structures are fabricated into the surface, which can define the light-output cone angle. By changing the size of the hole structures, cone angles between ±17° to ±45° can be achieved. Ostendo has shown transfer of three colors (RGB) and a stacked RGB structure yielding a full-color microdisplay. In particular, nHD (640 × 360) and 720p (1280 × 720) resolution displays at 20,000 cd/m^2 have been demonstrated, as shown in Fig. 8(d).

Lumiode, the authors' startup, integrates micro-LEDs with a thin film of silicon transistors in a fully monolithic process, meaning all fabrication work is done on a single wafer. As illustrated in Fig. 5(c), the process starts with the LED substrate, upon which pixels are patterned into a micro-LED array using photolithography.[7] The pixel pitch can ultimately

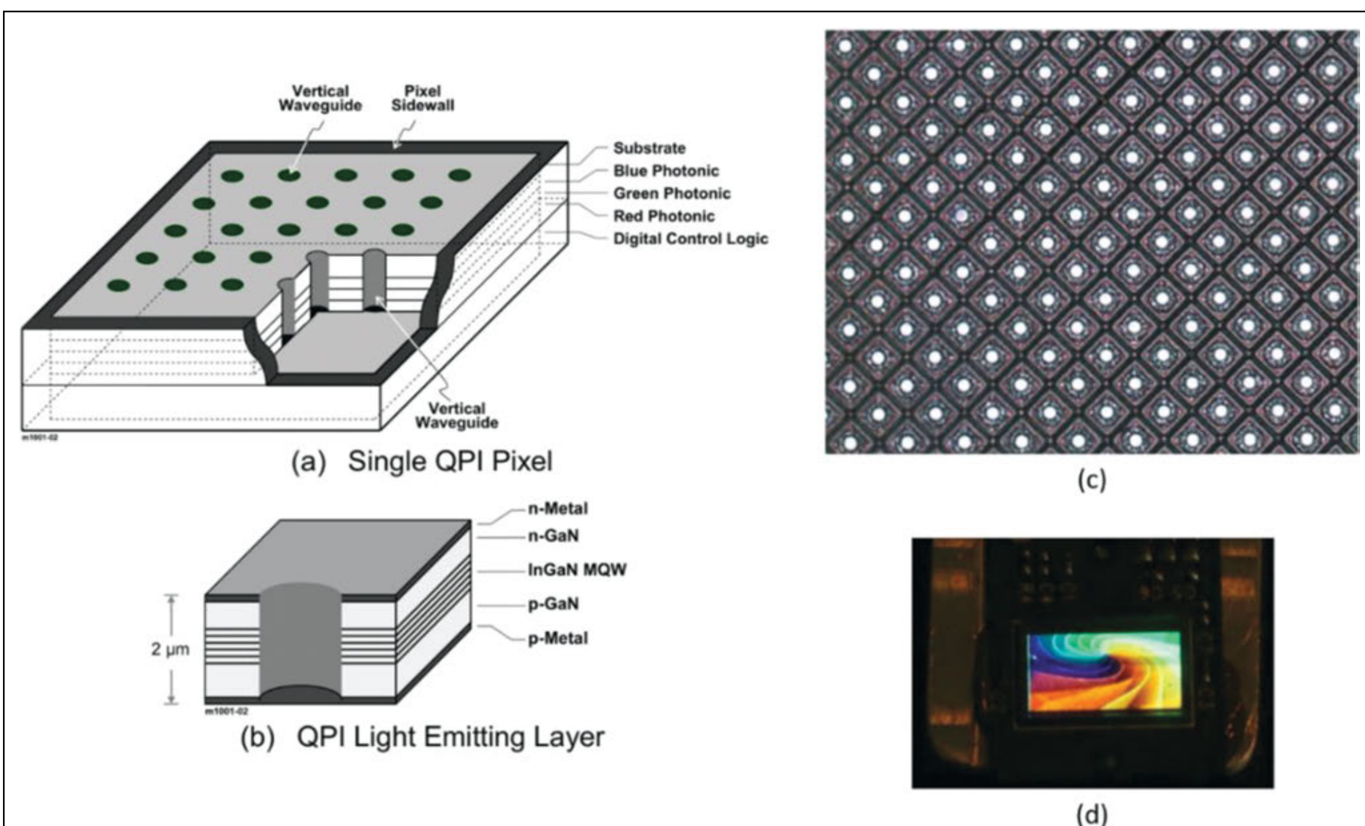

Fig. 8: A cross-section schematic of a single stacked micro-LED pixel with vertical waveguides appears in (a). Image (b) shows a cross-section schematic of each light-emitting layer within the stacked micro-LED pixel. An image of a micro-LED array after front-side processing appears in (c), and in (d), a photograph of a test image shown on a 720p micro-LED microdisplay is shown.[15]

scale to the limits of wafer-level photolithography tools. Next, instead of using a foundry CMOS process and bonding to the micro-LEDs, layers of silicon dioxide and silicon are deposited to form the active TFT films. Standard materials from nearly all LED suppliers can be used as the starting LED substrate, with the caveat that the maximum process temperature is limited to what the LEDs can withstand. Thus, the challenge is to build a high-performance low-temperature transistor process. This is achieved by using laser crystallization to convert the low-electron-mobility amorphous silicon to high-mobility polycrystalline silicon. This laser crystallization is similar to low-temperature polysilicon (LTPS) processes employed in flat-panel displays. Transistors are fabricated in the polycrystalline silicon to form the necessary display driving circuits. Figure 9 shows a cross section and top view of an integrated device.

While significant strides have been made with regard to micro-LED microdisplays, much work still remains to be done before commercial products reach the marketplace. The integration of color-generating materials is a challenge, although some work has been demonstrated in using an optical combination of three micro-LED microdisplays[16]; integration of phosphor materials[11]; and stacking of red-, green-, and blue-LED epitaxial layers.[15] Another challenge for micro-LED microdisplays is the scalability of the integrated semiconductor processes. Flip-chip, LED epitaxial transfer to CMOS, and TFT methods all have unique factors that affect overall scalability and the ability to yield high-resolution displays. Overall, these factors will drive the associated costs and thus associated addressable markets.

Micro-LED microdisplay technologies all aim to address markets where small panels and high luminance are the primary requirement, the largest market being displays for augmented reality and mixed reality (AR/MR). Glasses-based devices for AR/MR require a microdisplay focused through a see-through optic that can be viewed in outdoor environments. This will require luminances well above 100,000 cd/m^2, luminance levels that only emissive micro-LED displays can provide. In addition to AR/MR, micro-LED microdisplays have been demonstrated in a wide range of applications, including projection formats[10,17] and light-field displays,[18] as well as non-display markets such as maskless photolithography,[19] optogenetics,[20] and visible-light communications.[21]

Micro-LEDs Will Maximize LED Usage

Today's consumer markets rely on LEDs as the illumination source for general lighting and nearly all displays. By extending the application of LEDs beyond illumination to directly emissive pixels, the specifications needed for next-generation displays can be satisfied. In this review, we categorized the activity within the micro-LED space by the two display-size regimes: direct-view displays (3–70 in.) which use pick-and-place technologies and microdisplays (< 2 in.) which use semiconductor integration technologies. While the science behind micro-LEDs is straightforward, the success of any particular technology will depend heavily on overcoming the unique engineering and manufacturing challenges associated with each technology. Once commercialized emissive LED displays have the ability to replace all displays and can span the entire size range from 0.5-in. microdisplays all the way up to a 1000-in. stadium displays.

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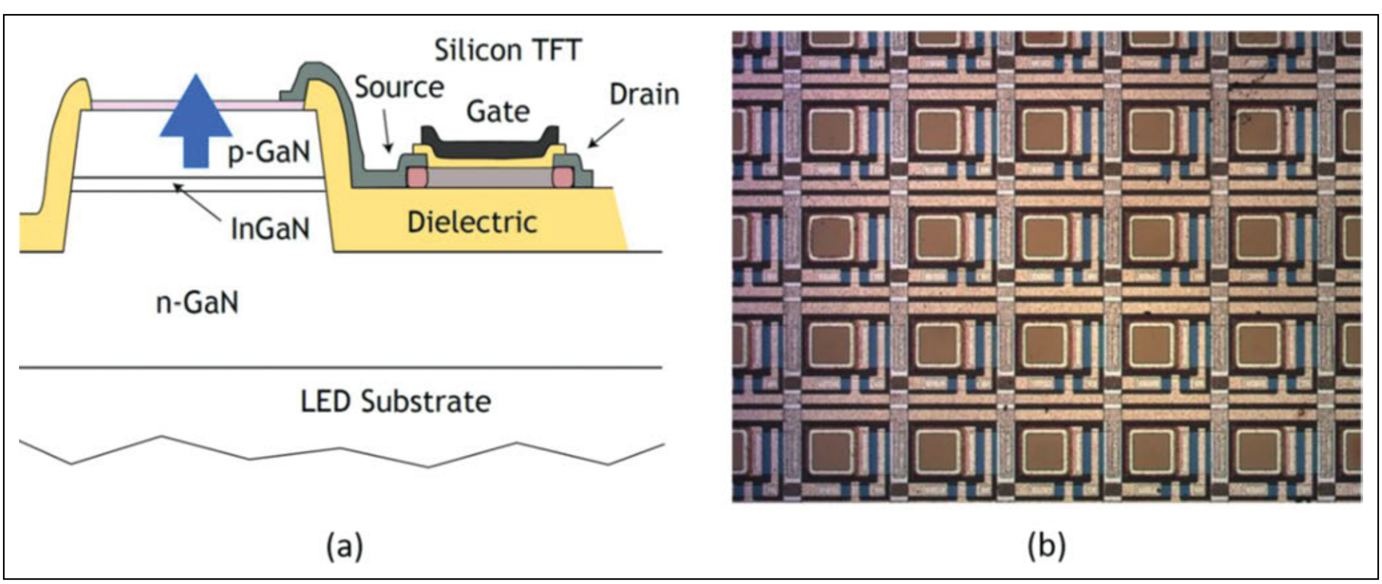

Fig. 9: (a) A schematic cross section of a micro-LED pixel is integrated with a thin-film silicon transistor. Image (b) shows a micrograph of a prototype active-matrix micro-LED microdisplay.[7]

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Next-Generation Metrology Facilitates Next-Generation Displays

Impressive advances in production technology have created high-density displays operating over wide color gamuts, but what is built must be tested, and improved production requires improved metrology. Color presents a particularly challenging metrology problem because even high-quality color cameras are not traceable to spectral standards. Spectrometers provide accurate color information but without the spatial resolution required to faithfully capture display color quality. As described in this article, the author's team assembled an instrument that combines the strengths of both spectrometers and high-quality cameras to provide rapid and reliable metrology for color displays.

by Peter Notermans and Nathan Cohen

IN an increasingly cost-driven market, display manufacturers continue to innovate, searching for performance advantages that distinguish their products. Extraordinary color quality is high on the list of potential discriminators. The higher the quality of a display, the tighter the requirements on its metrology. Research-grade equipment can measure display characteristics with high fidelity, but the cost is high and the measurement time is long. Alternatively, manufacturers can have trained employees qualitatively inspect their displays prior to shipment – but that approach introduces inconsistency at the very end of the production pipeline.

Recent efforts from Admesy, a developer of test and measurement systems, and Imperx, a maker of cameras for manufacturing applications, have resulted in a system that combines the spatial resolution of a charge-coupled-device (CCD) camera with the spectral accuracy of a spectrometer to provide full characterizations of display quality in a short amount of time.

The resulting process is conceptually straightforward. The spectrometer gathers all the light from within its field of view and provides a measurement of intensity as a function of wavelength. That data is processed to recover the CIE XYZ tristimulus values. Simultaneously, a co-aligned CCD camera acquires an RGB image. A pre-aligned known region of the CCD image corresponds to the area sampled by the spectrometer. The CCD image is processed to recover the sum total of the RGB values for the identical region sampled by the spectrometer. The ratio of the two measurements yields a conversion factor. To obtain XYZ values from regions outside the spectrometer's field of view, one need only multiply the RGB values by the conversion factor to arrive at tristimulus values across the entire CCD. The rest of this article describes the challenges of developing such a system and how our team proceeded.

Meeting Multiple Requirements

Although each display may have its own test requirements, frequently manufacturers must verify color and luminance uniformity, if even on the scale of the LED backlight. More rigorous inspection can require a measurement of black mura, for example – a measurement of "dark" or missing pixels. For inspecting displays with small pixels and a large color gamut, the metrology instrument must be capable of measuring with both high spatial resolution and accurate color determination. Another complication is that display colors are specified in terms of CIE luminance values rather than RGB values. That means the color determination must be in terms of CIE XYZ values – levying additional requirements on the metrology instrument.

The requirements for spatial resolution and color accuracy are a bit conflicting. Color CCD cameras offer high resolution but provide RGB data rather than the required CIE XYZ values. RGB values do not correspond to XYZ coordinates, so they cannot be converted directly to specifications related to visual quantities. Spectrometers give accurate

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color information that can be processed to produce XYZ values but without spatial information. For this reason, we decided to develop an instrument that combines both those capabilities.

The requirements for a metrology instrument depend not only on the details of the display under test, but also on the purpose of the measurement. To validate a new process or technology, for example, one could choose to perform pixel-by-pixel colorimetry. One approach could be to use a high-resolution CCD with interchangeable filters designed to match the X, Y, and Z spectra. But that is too expensive and time-consuming to use for 100% inspection quality control. Essentially, this kind of test protocol requires three separate images of each display test configuration. Such an inspection procedure will take about three times longer to complete than a protocol in which only a single image is necessary. In concrete terms, a final inspection protocol that requires three times the test duration will require three times the manufacturing floor space to get the equivalent throughput. So, an instrument that can replace the current practice of visually inspecting every display needs to be accurate and consistent, and it also needs to measure quickly.

Admesy's Atlas 2D Analysis System (Fig. 1) meets the above requirements by integrating a CCD color camera and a spectrometer in a pre-aligned and calibrated system. The synergy between the capabilities of the two separate elements of the system delivers performance not possible with either part individually, but only because the CCD camera and the spectrometer are highly capable on their own. (In the limited deployment to date, Admesy has seen 2–3× reduction in overall measurement time compared to filter wheel techniques.)

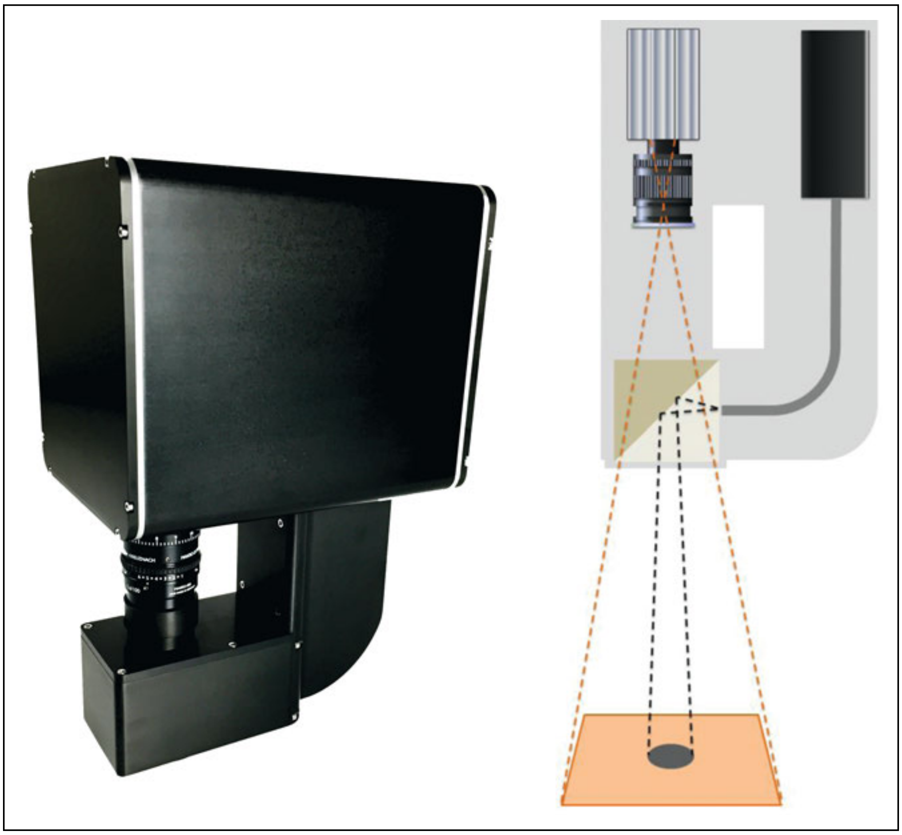

Fig. 1: The Atlas color-display metrology system (left) combines a CCD camera with a spectrometer to provide several measures of display quality. The diagram at right shows the system's operating setup.

Imaging the Displays

Color digital cameras are now ubiquitous, so one might seem an obvious choice as a key component of a color display-metrology system; but charge-coupled device (CCD) sensors do not make accurate spectral measurements. Bayer filter CCDs provide red, green, and blue image information, but RGB data is not a full representation of the color spectrum. Even with spectral data coming from an independent spectrometer, camera performance specifications are still important. The goal is to correlate RGB data from the CCD camera with wavelength information from the spectrometer. That correlation can then be used to convert the camera's pixel-by-pixel RGB information into CIE XYZ coordinates across the entire field of view. The absolute spectral accuracy of the RGB data is not critical, but it is essential that the RGB pixels across the CCD sensor are uniform (Fig. 2). The RGB to XYZ conversion must not fluctuate either, so stability of the camera is also paramount.

Our team evaluated several high-quality cameras, and tests of the Bobcat series cameras from IMPERX showed excellent uniformity, linearity, and stability, which are paramount for this application. The cameras also exhibit exceptionally low noise, another essential factor for maintaining overall system performance. The Atlas is available in several different configurations, equipped with 2-, 8-, or 16-Mpixel CCD cameras. The choice of camera resolution, as well as the choice of optics, is determined by the size of the display under test, its pixel format, and the required tests. For example, to measure the color and luminance uniformity of an LED backlight without particle detection, the 2-Mpixel camera will be sufficient. In contrast, if the manufacturer wants to measure color and luminance uniformity and black mura on a 480 × 800 automotive display, the 8-Mpixel version would be an appropriate starting point.

The optical magnification and the CCD format determine the imaging scale. In general, the goal is to match the resolution of the human eye, but there may be specific circumstances where the desired resolution deviates from that rule. A high-magnification lens can project a single display pixel onto several CCD pixels. Typically, though, one does not require that degree of magnification.

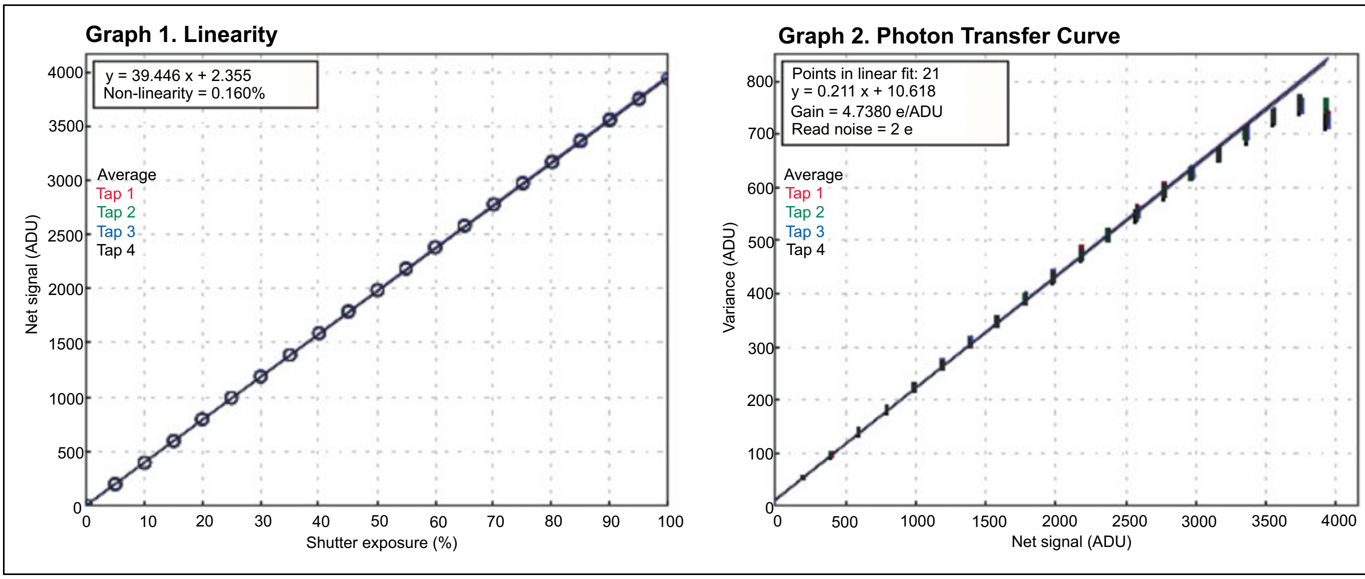

Fig. 2: The CCD camera leverages the spectral data beyond the field of view of the spectrometer, so it must have a (left) linear response and (right) low noise.

The standard result is an accurate 2-D RGB map of the imaged area. The next step is to collect spectral information.

Detecting Spectra

Admesy has a long heritage of building spectrometers, such as the Hera series. So when incorporating a spectral measurement component in the Atlas, it was natural for us to build it around the Hera array spectrometer with selectable spectral resolutions from 0.5 to 10 nm over a spectral range of 380–780 nm, with different configurations offering various fields of view. The spectrometer collects light from a portion of the field of view of the camera. The spectral information from that portion of the field is captured and converted to X, Y, Z values – for that portion of the display-under-test. The final task is to connect the data collected from the spectrometer with the data from the camera.

Integrating the Sensors

The Atlas can be integrated in many ways into an inspection protocol, but the basic measurement cycle is designed for ease of use. The display-under-test is loaded, and the Atlas takes a snapshot. The snapshot is used to detect the active area and to straighten the image.

The display-under-test is commanded to a given state; for example, uniformly red at 70% intensity. The Atlas's camera acquires an RGB image of the display (Fig. 3).

The spectrometer samples a portion of that same field and produces CIE XYZ values. The NIST-traceable calibration of the spectrometer ensures accurate luminance and color values. The Atlas correlates the XYZ values with the RGB values for the same region to create a conversion factor. That conversion factor is then applied to the RGB values outside the spectrometer's field. The result is an XYZ map of the full display. The full spectral coverage of the Atlas allows complete characterization of the display, including white-point adjustment.

Depending upon the manufacturer's need, the display-under-test can be cycled through a number of states: various colors at different intensities or a set of gray-scale steps. Because the Atlas produces a complete luminance map

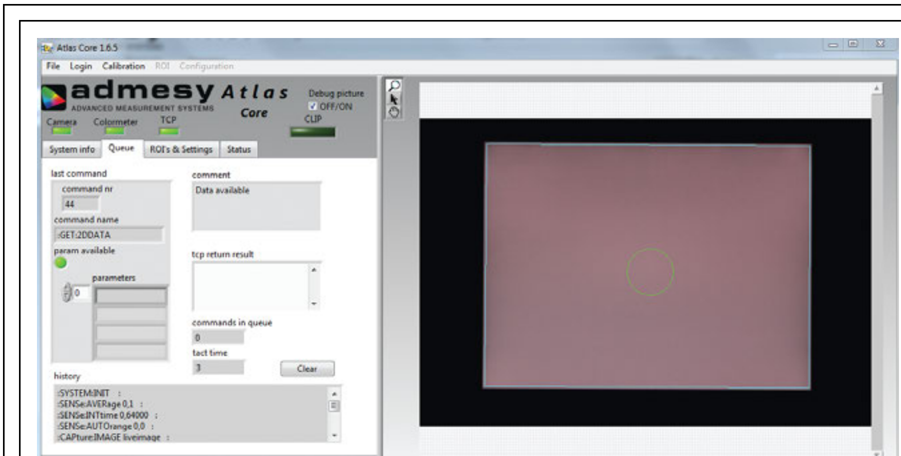

Fig. 3: The interface allows for rapid acquisition of an image of a complete display in, for example, a production environment.

of the display with a single snapshot, acquisition times are short. With the addition of processing power – more cores and/or higher speed – inspection time can be even further reduced.

The Atlas comes preprogrammed with a set of defect inspection protocols, some following the German Flat Panel Display Forum (DFF) standards and some defined by Admesy. Overall, the goal is to produce inspection criteria that reflect what the human eye can see in normal device usage. The instrument allows manufacturers to tune calculation settings and test criteria to reach their desired test limits (Figs. 4 and 5).

The built-in criteria include inspections for uniformity, line defects, pixel defects, blob defects, d*u*′*v*′, and other common acceptance tests. The Atlas also provides for a straightforward measurement of LCD backlight flicker at low frequencies, high frequencies, or both. The source of this flicker is a DC offset that is minimized through adjustment of the common voltage (V_{com}).

The baseline Atlas can also be modified to characterize LED-display walls. Flicker in LEDs is due to the rapid response of the LEDs to modulation of the drive current. Spectrometers are not fast enough to measure this flicker, so to measure LED-display walls, the Atlas is fitted with a luminance meter or colorimeter, which can either replace or supplement the spectrometer. Flicker can be sampled at up to 180 ksamples/sec, and then measured according to contrast min/max or contrast RMS, or JEITA or VESA methods. The biggest operational differences in LED-display testing are due to the dark areas surrounding display pixels and the fact that LED-display walls are typically tested on a module level, rather than a single test on the full display.

The ultimate end goal is to have a fully calibrated LED wall with interchangeable modules independent of LED batches. That can be achieved by white-point calibration of each LED module. That means that the Atlas must be able to measure the color information for each single LED on that particular module for RGB/W test images (Fig. 5).

That requirement drives the selection of optics for the Atlas and the needed CCD

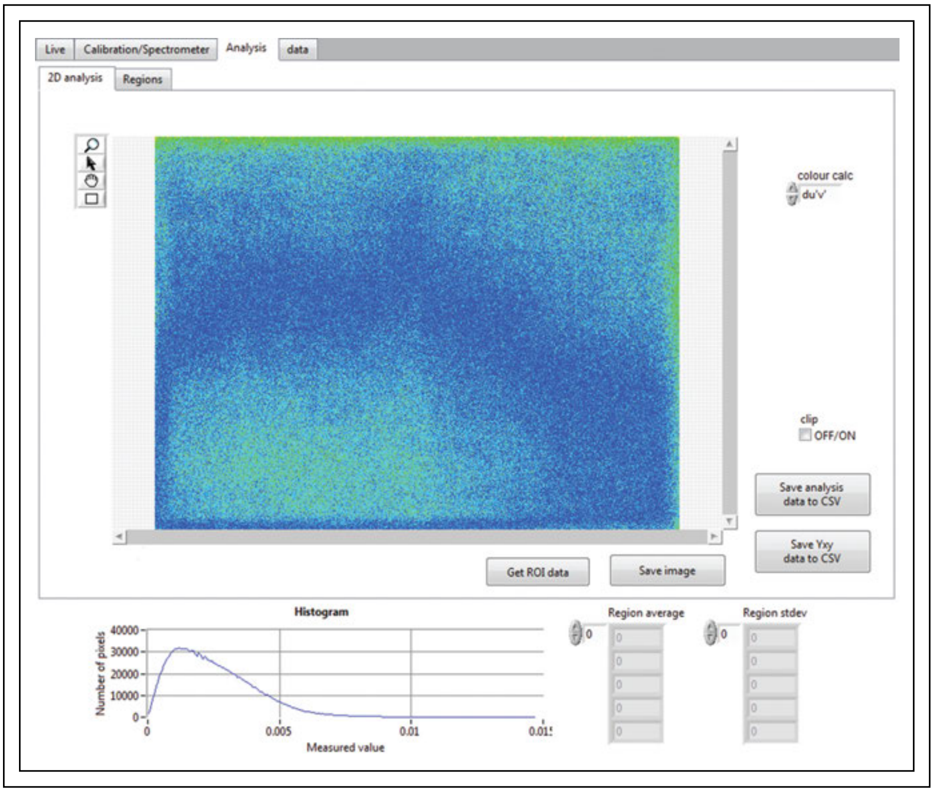

Fig. 4: *Once the conversion between RGB and XYZ values has been determined in the overlapping fields of the spectrometer and CCD, the conversion can be applied to the full field. This allows for the calculation of parameters such as du′v′.*

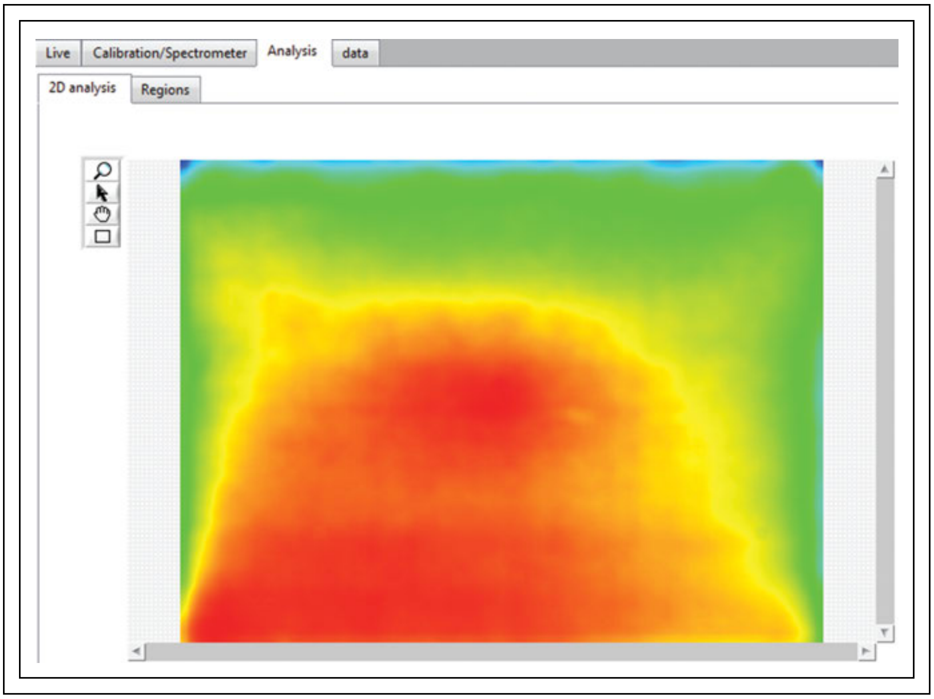

Fig. 5: *With an integral luminance meter, the Atlas can provide a luminance map of a full display.*

configuration. The output data contains information for the LED module controller to adjust the R/G/B currents for each individual LED.

Optimizing Throughput

It is common practice within the mobile-display industry to have human inspectors visually examine every device as the final acceptance test prior to shipping. The Atlas is designed to replace those operators with automated testing – bringing decreased inspection time and higher test reliability to display acceptance testing. Inspection time is highly dependent upon characteristics of the DUT and the manufacturer's inspection protocol, but with no filter wheel to slow down the process, the Atlas's single snapshot acquisition minimizes the impact on manufacturing flow. The Atlas is more reliable than human inspection and less complex, less costly, and faster than competing colorimetry systems.

Display metrology is not an easy task. Displays are becoming more capable – producing high-quality color at very fine spatial resolutions. But that trend has sparked a new level of consumer awareness, driving the need for ever greater quality. To ensure consumers perceive displays as being of high quality, manufacturers have tended to employ human inspectors to check for defects. That approach makes sense, except that when human inspectors get tired, they may have inconsistent standards, and inspection protocols can be time consuming. Still, human inspection has been a reasonable process because automated alternatives were expensive, complex, and equally time consuming. The Atlas approach of integrating a high-uniformity CCD with an accurate spectrometer provides speed, reliability, and measurement fidelity from an automated 100% inline 2D inspection instrument. ■

Journal of the
Society for Information Display

Announcements

Award winners

Dr. J. Kimmel is the winner of the 2015 Best Paper Award.

Ms. S. Hoeckh is the winner of the 2015 Outstanding Student Paper Award, generously sponsored by LG Display.

Discontinuation of IEEE-JDT

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

Update of the editorial board

Inactive and retired associate editors were removed and replaced by new volunteers. See the updated list at tinyurl.com/jsideb. We are proud and thankful that some of the associate editors of IEEE-JDT agreed to join our board.

Review and publication speed

The time between publication date and actual publication was reduced to less than one month, mainly thanks to the Production Editor at Wiley, Teodylito Gonzales.
Also the review process was sped up. The average time to first decision was reduced from 73 days in 2014 to 39 days in 2015.

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EarlyView

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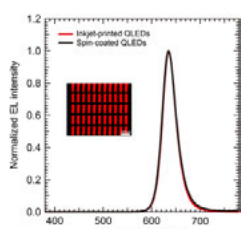

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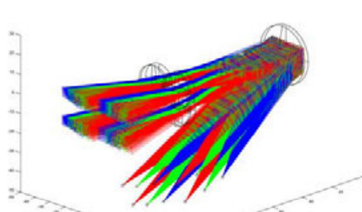

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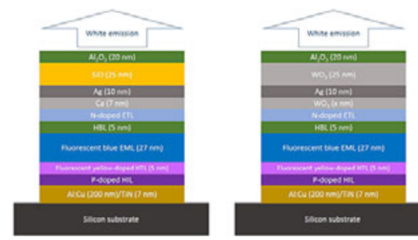

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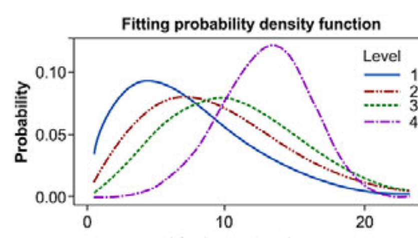

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Herbert DeSmet
Editor-in-Chief

ID Interviews Andreas Haldi, CMO of CYNORA GmbH

ID magazine recently had the opportunity to talk with Andreas Haldi, the newly appointed Chief Marketing Officer for CYNORA GmbH which develops blue OLED emitters based on thermally activated delayed fluorescent (TADF) technology. Haldi has worked with OLEDs on three continents. A native of Switzerland, he earned his M.S. degree from the Swiss Federal Institute of Technology in Zürich, then wrote his Master's thesis at the Optical Sciences Center at the University of Arizona before going on to earn his Ph.D. in electrical engineering from the Georgia Institute of Technology. Haldi began his professional life with OLED developer Novaled in Dresden, Germany, eventually moving to Seoul to open a Korea-based office for Novaled. Last August, he joined CYNORA to lead promotion and sales activities. CYNORA was founded in 2008 and is based in Bruchsal, Germany.

Conducted by Jenny Donelan

ID: Tell us a little about CYNORA.

AH: For the last 5 years, CYNORA has focused on developing thermally activated delayed fluorescent (TADF) blue emitters. While we were initially focused on materials for printed OLEDs, we decided in 2015 to shift our focus to materials that can be used in today´s OLED production methods, which are based on vacuum evaporation. Luckily for us, the technology remains the same, which means that we can still make use of the know-how we accumulated previously.

CYNORA is a materials developer, meaning our company will remain fabless while we focus our efforts on R&D and marketing. We plan to use subcontracting to produce the first large amounts of material for our customers, drawing on existing chemical expertise – within Europe. OLED display manufacturing itself is done exclusively in Asia.

Right now, I would say 80% of our activities are based in R&D, but we are currently intensifying our marketing and sales activities since we expect to have a product for sale by the end of 2017. We are a privately held company and have been growing strongly during the last year (doubling the number of employees). We have about 60 right now and are on target to have around 70 by the end of 2016.

Jenny Donelan *is the Managing Editor of* Information Display *Magazine. She can be reached at jdonelan@pcm411.com.*

ID: What is an emitter, and what is its relationship to an OLED?

AH: An AMOLED is a multilayer structure with about 15 very, very thin layers. The emitter is just one component of the OLED – the part that makes the light. We can decide what color the emitter will be through the chemical design of the material – red, green, blue – but it is also possible to create white OLEDs by combining two or more colors.

In the emitting layer of an OLED, the positive and negative charge carriers recombine and form so-called excitons, which can be converted into light by the emitter material. The energy of the excitons depends on the stack structure of the OLED and the materials from which it is built. Excitons come in two forms: singlet excitons and triplet excitons, occurring with a ratio of 1:3. For highly efficient OLEDs, both types of excitons have to be converted into light. The TADF concept can convert triplet excitons into singlet excitons after thermal activation, hence the name.

In short, TADF helps us to generate very high efficiencies by making sure that all the electrical charge going into the OLED is converted to light.

ID: What are CYNORA's emitter materials made of?

AH: The main point is that they are organic materials – mostly carbon and hydrogen atoms. We do not use any heavy metals. Therefore, our materials are not adversely affected by RoHS regulations.

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ID: Why are blue emitter materials so important to AMOLED displays and why focus just on blue?

AH: In an AMOLED display, two or three colors are needed, depending on the structure: red + green + blue (RGB) or yellow-green + blue (WOLED + CF). While efficient emitters for red, green, and yellow are already commercially available, there is still no OLED material that efficiently converts electricity into blue light. Current fluorescent blue emitters are not efficient enough, and this has a negative effect on the efficiency of the whole display panel. Therefore, OLED manufactures are looking for stable and efficient blue emitters

With our TADF technology we can combine long lifetime and high efficiency of our material. Our blue emitters will enable device makers to provide OLED displays with significantly reduced power consumption and higher display resolution.

Andreas Haldi

ID: How does all this relate to commercial devices?

AH: For mobile devices, more efficient blue OLEDs mean longer battery life and higher resolution. Both improvements will significantly increase consumer satisfaction. For TVs, an efficient blue could mean that the manufacturing process can be simplified by using fewer layers.

ID: So, CYNORA is creating a TADF blue emitter material that should enable OLEDs that are more efficient and stable. Are there other approaches to the "blue OLED problem?"

AH: Some materials suppliers are still working on phosphorescent blue emitters. The problem is that a deep blue color is very difficult to achieve with phosphorescent blue materials, and this usually goes hand in hand with short lifetime. Furthermore, a lot of effort has already been put into the development of phosphorescent blue materials but blue phosphorescence has not yet met display makers' requirements.

ID: How many companies are in this race to create the best blue, and if I were an investor, is there a place for me to bet my money?

AH: Several companies are trying to make a better blue emitter material. However, not many have officially announced their work on high-efficiency blue materials. As of this moment, the only three companies working on high-efficiency blue emitters are CYNORA, a small Japanese company called Kyulux, and Universal Display Corp. (UDC). CYNORA uses the TADF technology while UDC works with phosphorescence.

CYNORA is currently a privately held company, but since we do not have a final product for the market yet, we still need some investment to cover our costs until we do. In fact, now would be a very good time to invest in CYNORA, since we are expecting to have our first products for mass production by the end of 2017, which will increase our company value significantly again!

ID: There has been a lot of research into ink-jet printing of OLED materials. Currently, your products are applied through vacuum deposition. What are your thoughts about printing as a future deposition method?

AH: In our opinion, ink-jet printing of OLEDs is long-term – 2020 or 2021. It sounds very exciting, and printing methods are becoming more and more advanced, but the technology is not advanced enough yet in terms of uniformity and performance. Nevertheless, we are aware of this technology and we will adapt our materials to the printing process once we have a product for the current evaporation process. For that reason, we recently signed a Memorandum of Understanding with the Juhua company in China, which is a cooperation platform formed by some of the biggest display makers in China focusing on printing technologies for OLEDs.

ID: Germany seems to be a hotbed of OLED development, with nearly a dozen companies committed to this research. Why is that?

AH: Germany and the EU have supported OLED development with public funding for many years. Most of these projects require strong collaboration among universities, research institutes, and companies of all sizes, and such collaboration has been particularly successful in Germany.

ID: What is CYNORA's timeline for its products, and its overall plans for the future?

AH: Our timeline has three major stages: The first is to have production-ready materials for our customers by the end of 2017. The second is to have our material implemented at customer sites – so they can use it in their mass production tools – by the middle of 2018. And the third stage is for our material to be selling and used in the production of panels in 2018 and 2019. Simultaneously, we will start working on green and red emitter materials so that we can offer all colors to our customers.

With our first product introduction by the end of 2017, we expect first revenue by 2018 with a significant increase in 2019. As an OLED material supplier, we are currently in a very good market environment, with some market analysts such as UbiResearch expecting around 70% annual growth just for flexible OLED displays. The boom in this market will give us a lot of opportunities and we expect significant revenues quickly even if we plan conservatively.

ID: What are the biggest challenges your company is facing, and what challenges do you see for the AMOLED field overall?

AH: We currently see a challenge in our internal organization as we grow quickly and move from being an R&D company to more of a marketing company. Luckily, this challenge is manageable since everybody in our company is excited to see the positive development of our materials and the positive feedback from our customers upon testing them.

In terms of the industry, it is known that the production of OLED panels is significantly more challenging than the production of LCD panels, which has caused quite a delay in OLED production startups for many companies, especially in China.

We believe that AMOLED will change our future. Flexible, foldable, and thin-as-paper displays will make it possible to design devices in a completely new way and to create new application concepts. But as I mentioned above, OLED displays need to be more energy efficient to reduce the size of the battery and to enable flexible and even transparent displays. For this, AMOLED displays need efficient emitters. And that's our job. ■


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The fun really begins when the authors discuss the potential to build electroluminescent (EL) displays using quantum-dot-enhanced light-emitting diodes (QLEDs) and describe some recent demonstrations. One such example, which you will recognize from our cover of this issue, are R, G, and B QLED devices made by Najing Technology Company that achieve electrical quantum efficiencies of 20%, 18%, and 14% for red, green, and blue colors, respectively. This technology may become a companion or alternative to OLED in many of the same display form factors being served by OLED today.

Our next Frontline Technology feature is titled "Micro-LED Technologies and Applications" by authors Vincent W. Lee, Nancy Twu, and Ioannis (John) Kymissis. Micro-LEDs describe a class of LED devices that have an emission area smaller than 50 µm × 50 µm and a similar die size. This makes them highly valuable for an almost endless array of display form factors, including flexible, projected, and possibly even three dimensional. They also can achieve an almost unbelievable amount of luminance, making them suitable for an array of demanding high-light-output display applications. But what brings this home for me is that the authors have taken the time not only to explain the technology well but to describe the many ways that creators are actually attempting to develop and commercialize their processes to build these devices into working displays. Some of this manufacturing technology you have no doubt seen before, but some of it is truly original and being developed specifically for micro-LED display manufacturing. Micro-LED technology clearly has a viable foundation and will continue to grow in its potential.

Of course, a lot of the work in emissives comes from fundamental research on new materials. An example of these are the thermally activated delayed fluorescent (TADF) emitters being developed by a company called CYNORA. We had the opportunity to speak with Andreas Haldi, Chief Marketing Officer of CYNORA GmbH, who was eager to talk about the young company's business and the future prospects for its technology, and we are pleased to offer this installment of Market Insights, a Q&A put together by Jenny Donelan. CYNORA is a great example of the type of highly focused companies that I think we will need to build the eco-system of future emissive-display achievements.

Switching topics, display metrology is a subject that often invokes either groans or glee, depending on who you are and what problem you are trying to solve. Research people love the great performance they can get from high-end metrology setups in their labs – if they can afford them. Manufacturing people often hate the special environments and time requirements needed to implement even a small number of optical measurements in a production line. Those of us close to the subject know there are lots of painstaking ways to get really good measurement results under near-ideal laboratory conditions, but getting high-quality repeatable fast measurements in a production environment can be very challenging. This is particularly true when applied to today's high-dynamic-range, wide-color-gamut, and high-resolution display products.

As explained in our third Frontline Technology feature, "Next-Generation Metrology Facilitates Next-Generation Displays," by authors Peter Notermans of Admesy and Nathan Cohen of IMPERX, the solution is to combine the best features of two types of instrumentation: CCD camera and spectrometer. The authors describe how the development team overcame the shortcomings of high-speed CCD-based photometry: by combining the light paths of a CCD imager with a spectrometer and then implementing a sophisticated calibration technique to allow the system to collect 2-D high-dynamic-range color and gray-scale information much faster than other incumbent methods such as filter-wheel systems. The result is a system that provides the performance advantages of each of the two core instruments with a measurement speed suitable for today's production demands.

In addition to our features introduced above in this issue, we also have our regular departments of Industry News and SID News, as well as some special coverage of the latest smartphone displays.

As I write this note for the November/December issue of *ID*, it is still fall outside my window and the weather has not yet grown too cold. But, like every year before, winter is coming. I am not sad because by the time you get to read this, the holidays we all celebrate will be near at hand. By that time, I'll be angling to get as much time away from work as I can and eagerly looking forward to special time with my family and now grown children. They are building their own lives from the foundation we gave them, as well as from their own ambitions and passions. I am proud of the people they are today and of what they are striving do for their own futures. As you approach the holidays, I urge you to take the time to cherish your family and recognize them not only for who they are today but who they will become tomorrow, and the day after, and in the years to come. And so, I wish you a wonderful holiday season and a very bright future in the New Year. ■

continued from page 4

It has been an exciting journey for display-technology evolution over the last 20 years. We have successfully entered the age of thinner and lighter panel displays, the key aspect of the second generation of display technology. As shown in Fig. 1, we are still in the second generation, a period of continuing evolution leading to better pixels (wider color gamut, high dynamic range, higher resolution, and faster frame rate). Currently, LCD technology dominates the display market and OLED technology is challenging LCD technology, especially in terms of small-sized panels and flexible applications.

Although there is still a great deal of work to be done in order to perfect the performance of second-generation display technology, third-generation display technology, with highly realistic interaction, is already on the horizon. One key element of the next-generation displays is that content will "float" in space instead of on the panel surface, which will allow human interaction to occur more naturally. Micro-LEDs are a technology that can very likely achieve this goal.

Micro-LED displays, as the name implies, use individual lighting elements that can be as small as a micrometer – maybe even sub-micron size in the not-too-distant future. The very-high-density light rays that can be generated by micro-LEDs may become a key enabler for light-field displays – an exciting technology that can produce true 3D display images in real time. At the Innovation Zone at Display Week 2014, Ostendo showed some promising 3D floating images that used a quantum-photonic-imager (QPI) light-emitting layer and won the I-Zone's Best Prototype Award. The current development of this technology, however, is still on the scale of 10–50-µm pixels, due to various challenges, and its application is still mainly at the micro-display level.

This issue's micro-LED review article by Vincent W. Lee, Nancy Twu, and Ioannis (John) Kymissis delivers a comprehensive review of various approaches to micro-LED integration with semiconductor technology. Micro-LED technology could be touching off an era of truly high integration between display and IC technology..

Emissive displays were historically the first dominant technology for information displays. QDs as a wide-color-gamut emissive material have become a major part of LCD backlighting, and QLEDs as emissive display devices can potentially replace another emissive technology — OLEDs. Last of all, emissive micro-LEDs have the potential to bring us into a new era of truly immersive and interactive experience.

I hope this special issue on emissive technology will highlight the current status of emissive displays and generate more positive interest in future emissive-display technology. We are starting to ride the next wave of new emissive-display technology. ■

***Dr. Qun (Frank) Yan** is a well-known expert on emissive-display technology. He specializes in converting early innovative technology into manufacturing technology and in creating successful consumer-electronics products with high-yield mass production. He is now a Distinguished Professor at Fuzhou University in China, Chief Technical Advisor for Changhong Electrics Group, and Director of SID's Beijing Chapter. He also chairs SID's emissive-display subcommittee.*

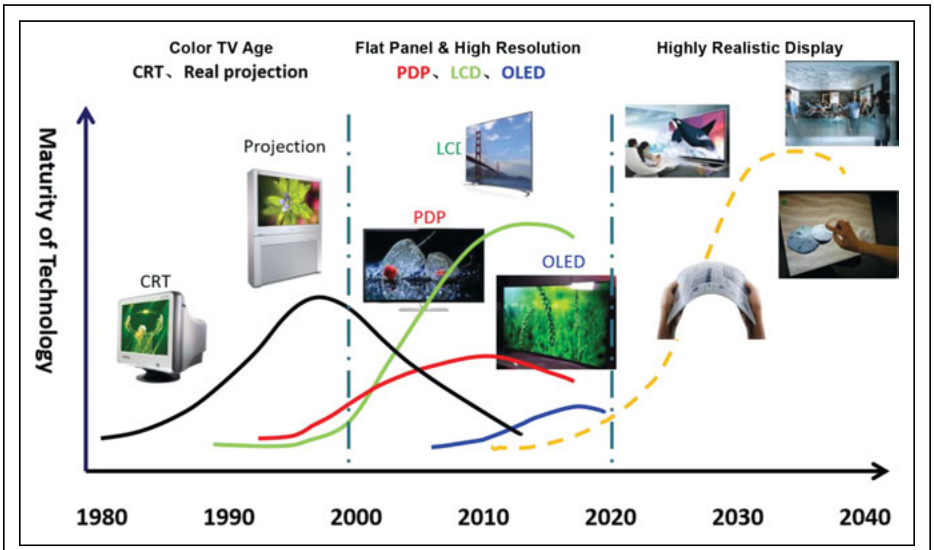

***Fig. 1:** The display-technology evolution will eventually move to another important emissive technology that will enable the flexible, interactive, and highly realistic displays of the future. The CRT represented the first generation of display technology while PDP, LCD, and OLED represent the second generation. Revolutionary third-generation display technologies are on the horizon.*

continued from page 3

The important thing to keep in mind, she said, and this affects display makers and users as much as city planners, is that what counts is the lighting we are exposed to before we go to bed, not its source. "Your body does not care what the source is," said Veitch, adding, "Of course, with street lighting, it is not only people who are affected but animals." With the research – and the controversy – continuing, it is a pretty sure bet that in years to come, we will find ourselves looking more carefully at the light we expose ourselves to, especially that from laptops, televisions, and smartphones – and particularly before we go to bed.

Applied Materials Tailors e-Beam Review Technology for Displays

Applied Materials, Inc., recently introduced what it says is the first high-resolution inline e-beam review (EBR) system for the display industry. The new system is designed to increase the speed at which manufacturers of OLED and UHD LCD screens can achieve optimum yields.

Applied Materials, based in Silicon Valley, supplies hardware, software, and services to semiconductor manufacturers. The company is an industry leader in EBR, with more than 70% market share in 2015. (EBR and optical scanning are the two primary inspection methods for wafers.) In order to reach display-industry customers, Applied Materials has combined the scanning-electron-microscope capabilities used in its semiconductor device review with a large-scale display vacuum platform. The result is an inline EBR technology designed to quickly and effectively discover and address the root causes of crucial defects in mobile and TV displays.

Fig 1: Applied Materials has combined its semiconductor scanning-electron-microscope technology with a large-scale display vacuum platform to create a system to help display makers find defects quickly and accurately.

Applied Materials says it has received orders for its EBR system (Fig. 1) from six of the top 10 largest display manufacturers in the world (Tianma is one of these).

Dr. Jun Ma, Vice-President at Tianma Microelectronics Co., Ltd., said, "Applieds' EBR system will enable us to reduce the start-up time at our Wuhan fab and accelerate our ability to bring more advanced display technologies to market."

Merck Debuts Award for Young Display Researchers

Merck KGaA, Darmstadt, Germany, recently announced the recipients of its new Displaying Futures Award, which provides young display entrepreneurs and researchers with individual mentoring, access to a global network, and funding. The inaugural winning teams are from the University of Central Florida, Kent State University, and the Eindhoven University of Technology.

According to Merck, the award was developed to help the company identify new applications for its materials and to support further development of these materials. In a pre-selection stage, more than 30 submissions were narrowed to 10 teams, who presented innovations related to liquid crystals. A jury from Merck, consisting of various specialists from different areas of the company, chose three winning teams. The winners were evaluated based on the criteria of novelty, business potential, and impacts on society and the environment. The awards were presented at the company's headquarters in Darmstadt in September, 2016.

The winning project from the University of Central Florida focuses on e-skin displays. These highly efficient, thin, flexible displays utilize ambient light and can also be used in very bright daylight. Kent State University's project involves liquid-crystal sensors to detect the presence of hazardous chemical gases and display the results visually on a surface. And the team from Eindhoven has developed "fresh strips," a technology that changes color to indicate whether foods or medical supplies have been exposed to excessively high temperatures and can still be consumed or used.

The winners of the Displaying Futures Awards will receive mentoring from experts within and outside of Merck KGaA, Darmstadt, Germany, access to the company's global network, and $50,000 each from Merck. ■

– Jenny Donelan

Nominate the Year's Best Display Products Now

The Display Industry Awards are our industry's most prestigious honor, given annually by the Society for Information Display to recognize the year's best new display products or applications. *Information Display* urges its readers to get involved in the process: If you have seen or used a new display product this year that you really like, let the rest of the industry know by nominating it for a Display Industry Award. There are three Awards categories: Display of the Year, Display Application of the Year, and Display Component of the Year. Winners are selected by the Display Industry Awards Committee based on nominations from SID members and non-members alike, and the awards are announced and presented at Display Week. Winning a DIA not only tells a company that it is doing a great job – it helps build brand recognition both inside and outside the industry.

To nominate a product, component, or application that was commercially available in 2016, send an e-mail titled DIA 2017 Nomination to drocco@pcm411.com. The Display Awards Committee will review your suggestion.

If your favorite products happen to be your own company's products, you can and should nominate them yourself. Visit http://www.sid.org/About/Awards/DisplayIndustryAwards.aspx, download the appropriate nomination form, complete it entirely (including supporting documentation), and send it to drocco@pcm411.com by December 30, 2016.

SID Creates New Prize for Researchers Under 40

Starting in 2017, a new prize is being added to the roster of the Society for Information Display Honors and Awards. The Peter Brody Prize will join ranks with the Karl Ferdinand Braun Prize, the Jan Rajchman Prize, and other prestigious awards that SID bestows each year to outstanding individuals in the field of displays. The Peter Brody Prize (named after the physicist who invented active-matrix TFT display technology) was developed to honor the outstanding contributions of young (under age 40) researchers who have made major contributions to the develop-

(continued on page 39)

Free-Form Displays Proliferate at Vehicle Displays Symposium in Michigan

by Ken Werner

The Society for Information Display's Metropolitan Detroit Chapter sponsored its 23rd Annual Symposium on Vehicle Displays in Livonia, Michigan, on September 27 and 28. This year's edition was called "Vehicle Displays and Interfaces 2016."

Attendance jumped to 400 people, up from 300 last year, and the organizers found a new venue, the Burton Manor Conference Center, to accommodate the attendees, in addition to the 60 exhibitors that included many Tier 1 suppliers. The conference sponsors were Denso, Continental, Yazaki, Radiant Vision Systems, Sharp, Visteon, and Tianma NLT USA.

Among the highlights of the exhibition was Varitronix, the industrial display company purchased by BOE in May of this year. Varitronix will be the automotive displays division of BOE, said the company's Engineering Manager Kenny Kwok. Varitronix was showing a-Si based LCDs in Detroit, but is also working on OLED and LTPS, which should be ready for Display Week this coming May in Los Angeles, said Kwok.

Of most interest in the Varitronix booth were what the industry is calling "free-form" displays. Varitronix showed two round displays, one of which (Fig. 1) is currently used in the Nissan Leaf, according to Kwok. In addition, there was a demonstration instrument-cluster display with a camel-backed contour similar to displays Sharp has shown in the past.

***Fig. 1:** This Varitronix circular LCD is used in the Nissan Leaf battery electric car. (Photo courtesy Ken Werner)*

When asked if Varitronix was making its free-form displays with a "Sharp-like" technology, the answer from the company was a somewhat vague affirmative. In response to a question about whether there were any IP conflicts between Sharp's and Varitronix's free-form displays, Sharp's Greg Milne replied no, that Varitronix uses a technology different from the IGZO and distributed gate drivers that Sharp uses.

Sharp had several free-form examples in its booth, all of which were shown at Display Week 2016. Milne explained that Sharp has customers for free-form as well and that we will see Sharp free-form displays in cars "in a couple of years." With its IGZO and distributed gate drivers, Sharp is technologically advanced in this game, but it is significant that a second supplier is participating in the free-form arena and with a different approach. The speedy – at least in the automotive context – adoption of free-form displays can only be enhanced by having more than one available supplier.

__Ken Werner__ is Principal of Nutmeg Consultants, specializing in the display industry, manufacturing, technology, and applications, including mobile devices and television. You can reach him at kwerner@nutmegconsultants.com.

Smartphone Displays Get Better and Better

Two smartphones with astounding new displays entered the market this fall – the Apple iPhone 7 and the short-lived Samsung Galaxy Note7.

Compiled by *Information Display* Staff and Based on Reports from DisplayMate and IHS Markit

September brought us the usual round of new product announcements from Apple – including the Apple Watch S2 and the iPhone 7 and 7 Plus. While enthusiastically received by consumers looking forward to the latest Apple devices, both products were generally accepted to be incremental rather than major upgrades to their predecessors. To be sure, the iPhone 7 now offers water resistance, a faster processor, an improved camera, and other notable features, but the ones most talked about were somewhat controversial – the elimination of both the headphone jack and the mechanical home button. The display was also (greatly) improved, but was mentioned in just one sentence by Apple far down in its press release, below the new colors and glossy finishes: "The new iPhone features the brightest, most colorful Retina HD display ever in an iPhone, now with a wide color gamut for cinema-standard colors, greater color saturation, and the best color management in the smartphone industry."[1]

Yet, the iPhone 7 display, according to DisplayMate's Ray Soneira, merits far more mention. Here is what he had to say about the phone in his recent online review, "iPhone 7 Display Technology Shoot-Out"[2] "The display on the iPhone 7 is a truly impressive top-performing display and a major upgrade and enhancement to the display on the iPhone 6. It is by far the best performing mobile LCD that we have ever tested, and it breaks many display performance records."

Here are some of the highlights Soneira pointed out in his review:

- Two standard color gamuts: the new DCI-P3 wide color gamut that is used in 4K UHD TVs and digital cinema and also the traditional smaller sRGB/Rec.709 color gamut used for producing most existing consumer content for digital cameras, TVs, the internet, and computers, including photos, videos, and movies.
- The highest absolute color accuracy for any display (1.1 JNCD) – visually indistinguishable from perfect.
- The highest absolute luminance accuracy for any display (±2%) – visually indistinguishable from perfect.
- Peak brightness of 705 nits when automatic brightness is turned on in high ambient light, where high brightness is really needed.
- Record high contrast ratio for IPS-LCDs.
- Record low screen reflectance for smartphones.

(For many more iPhone 7 measurements, visit DisplayMate.com)

Writes Soneira: "Given the exceptional performance of the iPhone 7 LCD, there will be many consumers, journalists, reviewers, and even manufacturers wondering if Apple will actually be switching to OLED iPhone displays in 2017, as has been widely reported." About the lack of fanfare: "Steve Jobs clearly always highly valued display performance and loved bragging about Apple displays, so he would definitely be extremely proud of the exceptional performance of the iPhone 7 display, but probably be dismayed at how little public attention Apple has given to their outstanding iPhone 7 display – which provides a major competitive advantage that most consumers and reviewers are not yet aware of. Other manufacturers will need to play catch-up fast."

Fig. 1: *The iPhone 7's optional glossy black finish has received more press than the smartphone's exceptional new display.*

Galaxy Noted

In August 2016, Samsung began shipping the Galaxy Note7, the new and highly anticipated version of its OLED-based smartphone. In September, after reported problems with customers' Note7 devices overheating and catching fire, Samsung announced a global recall and replacement. Batteries were the suspected cause of the trouble, but replacement units with new batteries from a different supplier experienced the same issues. Samsung then issued a second recall and ceased production of the Note7 in October. The company has not announced the cause of the problem.

Obviously, this is a challenging development for Samsung and a disappointment for customers, especially because the phone had been receiving rave reviews: On August 9, IHS Markit noted the following in a press release[3]: "The Note7 ... includes all of Samsung's latest technologies, including speedy eye-based phone unlocking, edge display interface, innovative hover stylus, and new uses for the always on display enabled by Samsung's AMOLED screen technology. Impressively, Samsung includes all of the new innovations, as well as IP68 water/dust resistance, in a design which is more compact than older Note models."

Soneira was even more impressed with the Note7's display than he had been with the iPhone's. In his online review, "Galaxy Note7 OLED Display Shoot-Out,"[4] he wrote: "The Galaxy Note7 provides many major and important state-of-the-art display enhancements, with

[1]http://www.apple.com/pr/library/2016/09/07Apple-Introduces-iPhone-7-iPhone-7-Plus-The-Best-Most-Advanced-iPhone-Ever.html
[2]http://www.displaymate.com/iPhone7_ShootOut_1.htm
[3]https://technology.ihs.com/582378/galaxy-note-7-samsung-looks-for-continued-momentum
[4]http://www.displaymate.com/Galaxy_Note7_ShootOut_1.htm

mobile OLED-display technology now advancing faster than ever. It is the most innovative and high-performance smartphone display that we have ever tested." He noted its curved OLED display, color gamut, and HDR, as well as a new record high peak brightness of over 1,000 nits and much more. "What is particularly significant and impressive," wrote Soneira, "is that Samsung has been systematically improving OLED-display performance with every Galaxy generation since 2010, when we started tracking OLED displays."

While the discontinuation of the Note7 is obviously a disastrous setback for Samsung, perhaps it is not a long-term disaster. The company was swift in recalling all units once it was clear that a quick fix was not at hand. At press time, the company had begun offering exchange incentives – a $100 credit (in addition to the full exchange) to any customer who exchanged the Note7 for another Samsung smartphone and a $25 credit for customers who turned in their phones for full refunds or exchanged their Note7s for any other brand of phones, including iPhones.[5] That kind of support is likely to engender good will and customer loyalty. We hope we will see this OLED display in another Samsung smartphone offering soon. ■

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[5]http://www.samsung.com/us/note7recall/?cid=ppc-

sid news

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ment of active-matrix addressed displays. Specific areas under consideration are:

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

The prize was established with a generous donation from Dr. Fang-Chen Luo and will be awarded by the Board of Directors acting on the recommendation of the Honors and Awards Committee. It carries a stipend of US $2000. The 2017 Honors and Awards recipients will be announced in the March/April 2017 issue of *Information Display*, and the winners will be honored in a ceremony during Display Week 2017 in Los Angeles. ■

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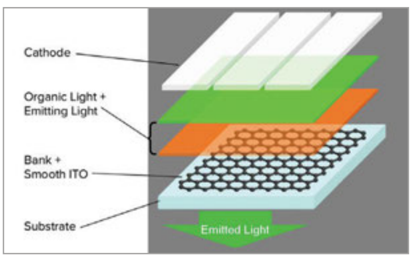

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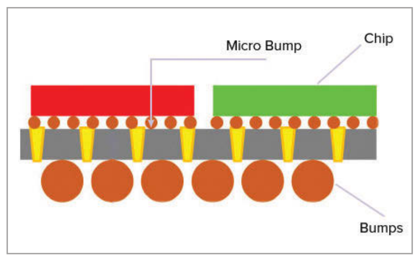

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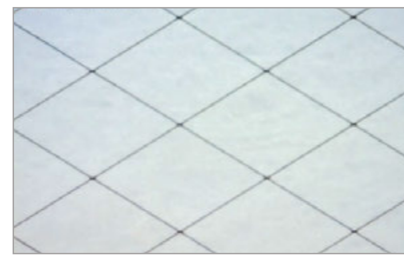

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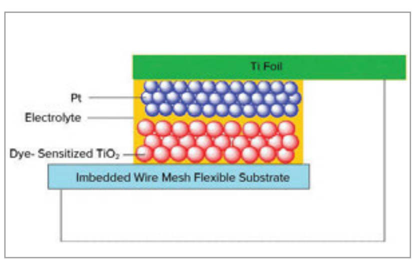

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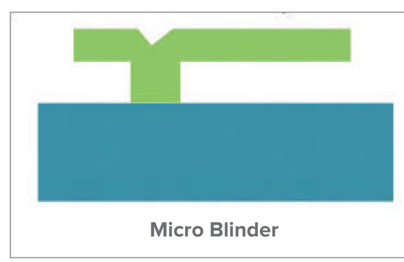

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