MATERIALS AND METROLOGY ISSUE

Information DISPLAY

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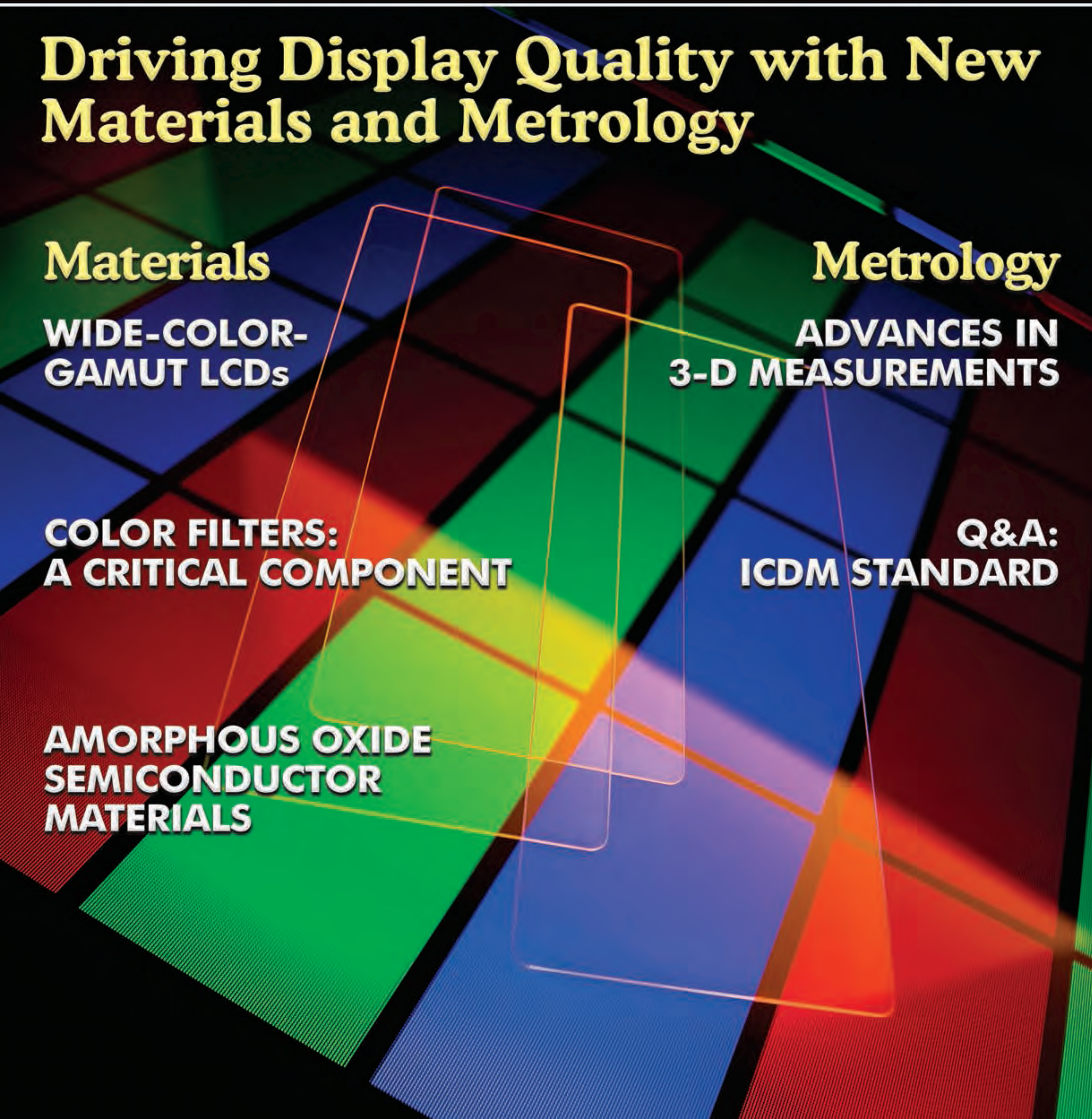

Driving Display Quality with New Materials and Metrology

Materials

WIDE-COLOR-GAMUT LCDs

COLOR FILTERS: A CRITICAL COMPONENT

AMORPHOUS OXIDE SEMICONDUCTOR MATERIALS

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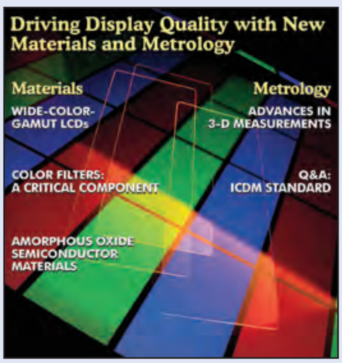
ON THE COVER: *Corning Lotus™ Glass is a high-performance display glass designed to enable cutting-edge technologies, including OLED displays and next-generation LCDs. It is formulated to perform exceptionally well in low-temperature polysilicon (LTPS) and oxide thin-film-transistor (TFT) backplane manufacturing environments. Next month's issue will contain an article by Corning on thin glass. Image courtesy Corning Incorporated.*



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editorial

Here's to 50 Years of Display Technology – and 50 More

by Stephen Atwood

Happy New Year and welcome to the year 2013. I write these January notes each year during our Christmas holiday in the U.S., and it's always a time for reflection as well as renewed optimism. By any measure, 2012 turned out to be a difficult year for many people either financially, politically, personally, or professionally. While the Mayans appear to have been slightly misunderstood, and the solar system was not consumed by an apocalypse of some kind, there were plenty of more earthly challenges to deal with, ranging from the economy, to politics, to severe weather, to delays in the commercial availability of OLED TVs. Through it all, we had a great gathering of the industry in Boston for Display Week and a SID 50th Anniversary celebration in Los Angeles. All year long, *Information Display* was here for you, focusing on the latest display technologies and industry happenings, both in print and on-line.

This year is my eighth as the magazine's Executive Editor, and I'm very proud to be part of this prestigious publication that continues to cover nearly every conceivable aspect of the display industry with stories you won't find from any other source. This year you will see some changes that I sincerely believe will make *ID* even better. The first is our new website, which at press time was on schedule to be launched by the time you read this. The site has been redesigned with a new look and feel and better navigation to provide easier access to information. It also requires much less overhead for our editorial staff to maintain – which translates to more timely updates of industry news and up-to-date information about everything going on in the display industry. We've also updated our on-line archives with a more powerful search engine and easier page viewing to make it convenient for you to find and review great articles from previous issues.

The other change for *ID* in 2013 is our new publishing calendar, which now follows a bi-monthly format. We'll be producing six issues in 2013, delivered in roughly two-month intervals, covering multiple technology topics and industry activities in each one. We'll average four Frontline Technology features in each issue along with our regular offerings of Applications, Display Marketplace, and Enabling Technology articles. We'll actually be producing more editorial content in 2013 than in 2012, while spacing out our printing schedule a little differently.

We begin 2013 with this issue on two diverse but highly interrelated topics: Display Materials and Display Metrology. The field of materials (as we call it) covers a vast landscape of films, coatings, chemistries, raw materials, and fabrication processes, with each area offering innovations to improve display performance. Once again, we welcome our Guest Editor Ion Bita from Qualcomm MEMS Technologies, who helped us create a great lineup of innovative achievements in this realm. His guest editorial in this issue provides some valuable background on these articles as well as his own views on the work they present.

We begin with our first Frontline Technology article, featuring different types of new semiconductor materials including oxides like Indium-Gallium Zinc Oxide (IGZO), which began to see adoption in 2012 for LCD and OLED TFTs. In their very detailed and extremely interesting article titled "Transparent Oxide Semiconductors for Advanced Display Applications," authors Arokia Nathan, Sungsik Lee, Sanghun Jeon, Ihun Song, and U-In Chung discuss the properties and underlying science behind

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Merck to Use Epson Ink Technology for Large OLED Displays

Chemical giant Merck and electronics-manufacturer Seiko Epson Corporation recently announced a partnership with regard to ink-jet inks used to make organic light-emitting-diode (OLED) displays. Under the terms of the agreement, Epson will supply Merck with ink technology that allows a compound to be formed when combined with the Merck OLED materials. The compound can then be ink-jet printed to deposit the OLED materials in a viable form for display manufacturing. The inks will be produced for commercial introduction by Merck to the display industry.

This announcement goes to the root of one of several manufacturing obstacles faced by OLED TV manufacturers: deposition (see the article "Large-OLED-TV Makers Face Manufacturing Challenges" in the November/December 2012 issue of *Information Display*). "Both the industry and our customers want deposition processes that can enable and facilitate large-sized OLED-display production," said Eddy Claes, Director of OLED Marketing & Sales in Merck's Performance Materials Division.

Claes said he was not at liberty to comment on when Merck's client manufacturers would begin selling products based on the new process. But he did stress that Merck and Epson have been collaborating "intensively" for the last 3 years to develop the ink formulations. "Fundamental roadblocks in terms of OLED material performance and durability in ink-jet processes have been resolved by both partners," he said, adding that display-industry companies are now conducting trials using the new ink on large-sized displays.

Merck, a global leader in liquid-crystal materials for LCDs, began investing in OLED technology in 2005 when it acquired Covion's OLED activities. Since then, according to Claes, Merck has continued to invest in the development of state-of-the-art materials for the production of OLED displays based on evaporation production processes.

– Jenny Donelan

Konica Minolta Optics Buys Instrument Systems

In December 2012, Munich-based Instrument Systems GmbH was sold to Konica Minolta Optics, Inc., of Japan for an undisclosed sum. Instrument Systems's subsidiary company Optronik Berlin GmbH was also included in the sale. Instrument Systems specializes in lighting measurement that will potentially expand the sensing division of the Japanese company, according to an announcement from Konica. The Instrument Systems brand and its locations in Munich and Berlin will be retained. Previous owner Richard Distl will also continue as President and CEO.

– Jenny Donelan

guest editorial

Advances in Materials for Display Applications

by Ion Bita

As we find ourselves at the turn of the year, let me first wish all of you a very Happy New Year and welcome you back to a new year of *Information Display* magazine. We start 2013 with a look at the topic of advances in materials for displays.

Reflecting back on 2012, what comes to mind is the celebration of the 50th anniversary of the Society for Information Display. This stands out not only because of the amazing evolution of displays during this time, but also, relevant to the context of this issue because we can find in this history a reflection of the very impact of advances in display materials coupled with cycles of device innovations. (For a description of the celebration, see this issue's SID News by Larry Weber.)

While CRTs dominated the commercial landscape for many decades, for about the last 10 years we have seen an unprecedented pace for the development and commercial introduction of new display technologies. In this timeframe, AMLCDs have pretty much become the *de facto* display standard, accounting for over 85% of total display sales. They span virtually the entire range of diagonal sizes and applications.

In parallel, just in the past 5 years, AMOLED displays have secured a firm place in the premium mobile-display market, and in 2012 came very close to reaching critical mass in terms of widescale production of high-performance TV sets.

Without trying to be exhaustive, I would also highlight the younger display technologies based on electrophoretic, electrowetting, and MEMS pixel devices, which further fuel the display-industry roadmaps. The rapid progression of these commercial milestones would not be possible without an underlying wealth of technology initiatives, many of which incubated in academic and industrial labs for much longer times than these "overnight" commercial transformations may suggest.

In this issue, we highlight a few such notable technologies that showcase particularly well the importance of applied materials research in enabling significant display-industry advances: amorphous oxide semiconductors, semiconducting quantum dots, and color-filter materials.

Professor Arokia Nathan from the University of Cambridge, UK, and co-authors Sungsik Lee, Sanghun Jeon, Ihun Song, and U-In Chung from the London Center for Nanotechnology, University College, London, UK, prepared this issue's opening article, which presents an overview of the development and use of transparent oxide semiconductors for advanced display applications. With the initial basic research on TFT devices employing these semiconductors dating back to 2003–2004, the ongoing introduction of these materials in production lines across Japan, Korea, Taiwan, and China is evidence of the impact of research synergies with powerful trends in the display industry. Transparent oxide semiconductors derive combined benefits from a large field-effect mobility (~50× larger than a-Si and about half that of LTPS) in amorphous films such as indium-gallium-zinc oxide (IGZO) and a relatively low processing cost.

Furthermore, because these materials and their TFT implementations are very compatible with existing a-Si TFT production lines, they became subject to an irresistible commercialization pull fueled by the need for differentiation in the display market. For example, as HD-resolution LCD panels have became widely available, flat-panel-TV trends indicate that higher-resolution 3-D LCDs (such as quadHD, 4K × 2K, or 8K × 4K looking further out) and 3-D OLEDs are likely candidates for the next generation of TVs – both of which greatly benefit from transparent oxide semiconductor TFTs. While not without challenges, as reviewed in the article by Professor Nathan, transparent oxide semiconductor materials such as IGZO have already been selected to enable production of next-generation displays such as LG Display's 55-in. 3-D OLED TV (recipient of a SID 2012 Best-in-Show award). Other examples demonstrated at

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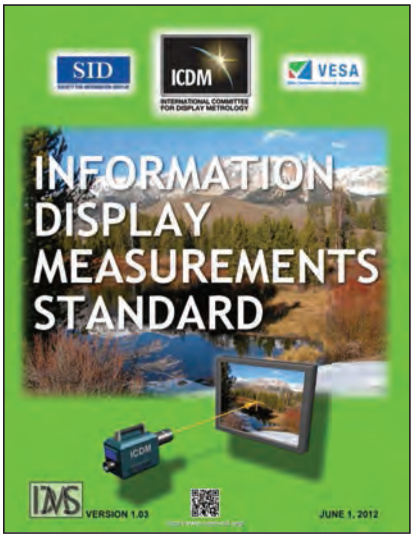
Measurements Standard



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Transparent Oxide Semiconductors for Advanced Display Applications

Amorphous oxide semiconductors continue to spark new technological developments in transparent electronics on a multitude of non-conventional substrates. Applications range from high-frame-rate interactive displays with embedded imaging to flexible electronics, where speed and transparency are essential requirements.

by Arokia Nathan, Sungsik Lee, Sanghun Jeon, Ihun Song, and U-In Chung

THIN-FILM TRANSISTORS (TFTs) for circuits and systems represent a key research area for future applications ranging from interactive displays and imaging to flexible electronics.[1] Systems-on-panel research stems from the quest for material systems with high field-effect mobility and ease of processing. In particular, transparency is a desirable attribute that enables seamless embedding of electronics for smart, immersive ambients.[2] Thus far, amorphous-silicon (a-Si) and low-temperature polysilicon (LTPS) transistors are widely used in displays. However, silicon has poor transparency and low mobility in the amorphous phase, in addition to cost issues associated with scalability to large areas as experienced by LTPS.

Recently, TFTs based on transparent oxide semiconductors, such as amorphous In-Ga-Zn-O film, have been gaining widespread interest.[3-9] In particular, this class of materials has a large bandgap, thus giving rise to high transparency.[10] Interestingly, it is less disordered due to the ionic bonding structure even in the amorphous phase, thus exhibiting higher electron mobility compared to an a-Si counterpart, which has a covalent bonding structure.[8,11] Therefore, transparent electronic systems, which were once viewed as science fiction, can now become a reality.

In this article, we discuss the progress and issues related to transparent oxide semiconductor (TOS) TFTs for advanced display and imaging applications. We compare the technological advances of TOS TFTs with conventional materials, such as a-Si and LTPS, from the standpoint of material properties and processing and device attributes (see Table 1). In particular, because of the low processing temperature of oxide semiconductors, successful integration of analog and digital circuits on paper has been demonstrated.[8] This can open up new opportunities for tomorrow's low-cost and green electronics where recyclability becomes an important consideration. For sensor applications, we review the photosensitivity and the effects of oxygen vacancies and their ionization under illumination. Based on these results, it is expected that TOS TFTs can be employed as

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Table 1: a-Si, LTPS, and TOS technologies are compared in terms of transparency, uniformity, and other characteristics. (PECVD is plasma-enhanced chemical vapor deposition; RT is room temperature.)

TFT Channel Materials	a-Si	LTPS	TOS
Transparency	poor	poor	good
Field effect mobility	~1 cm²/V-sec	~100 cm²/V-sec	~50 cm²/V-sec
Processing temperature	~250°C	>250°C	>RT
Fabrication technique	PECVD	PECVD	sputtering
Uniformity	good	poor	good
Transistor type	NMOS	CMOS	NMOS
Cost	low	high	low

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image sensors that absorb some part of the visible spectrum while providing sufficiently good transparency. This makes the technology a promising candidate for advanced display applications with embedded imaging for touch and touch-free operation.

Material Properties and Processing

TOS TFTs exhibit high transparency as well as high electron mobility even when fabricated at room temperature.[7-9] Compared to conventional a-Si TFT technology, TOS TFTs have higher mobility and sufficiently good uniformity over large areas, similar in many ways to LTPS TFTs. There are several types of TOS materials considered for TFTs: Zn-O,[10,11] In-Zn-O (IZO),[12] and In-Ga-Zn-O (IGZO).[11-15] While the TOS TFT shows high field-effect mobility (with values even comparable to LTPS TFTs), the binary oxides tend to be polycrystalline in structure, and like LTPS, they have grain boundaries that compromise the reproducibility and uniformity of device characteristics over large areas.[13] On the other hand, the amorphous-phase TOS TFTs are expected to have better uniformity and reasonably high field-effect mobility even when fabricated at room temperature on plastic substrates.[14] The summarized comparison of properties is given in Table 1.

Indeed, this class of materials shows high transparency due to a wide bandgap (~3 eV), whereas conventional materials such as silicon show poor transparency due to a narrower bandgap (1.1–1.8 eV). Thus, transparent displays, as seen in sci-fi movies, can become a reality sometime in the near future. Moreover, because the amorphous oxide semiconductor has higher mobility compared to that of conventional a-Si TFT technology, this allows higher-frame-rate display operation. This would greatly benefit OLED displays in particular because of the need for lower-cost higher-mobility analog circuits at every subpixel. In addition, oxide semiconductors enable integration of gate drivers that offer the promise of systems-on-panel realization at low cost. In terms of the uniformity of device parameters such as threshold voltage and mobility over large areas, amorphous oxide semiconductors are similar in many ways to LTPS TFTs, but with the potential to improve with the continuing progress that is being made in oxide materials and processes. This can lead to better display quality, keeping V_T compensation circuitry to a minimum.

Among the various TOS TFTs, a-IGZO TFTs have been most intensively studied, since they provide stability as well as high performance. The devices typically have a band mobility (μ_0) in the range of 20–50 cm^2/V-sec, depending on process conditions and film quality, a low off-current of ~100 fA, and a steep sub-threshold slope (S) of 0.1–0.2 V/dec. They are normally operated in enhancement mode; thus, the threshold voltage V_T is positive (1–5 V), depending on the doping density. To control V_T, Ga or Zn compositions can be varied. Also, a bilayered structure (IZO/IGZO) can be employed for the channel layer to control V_T.[15]

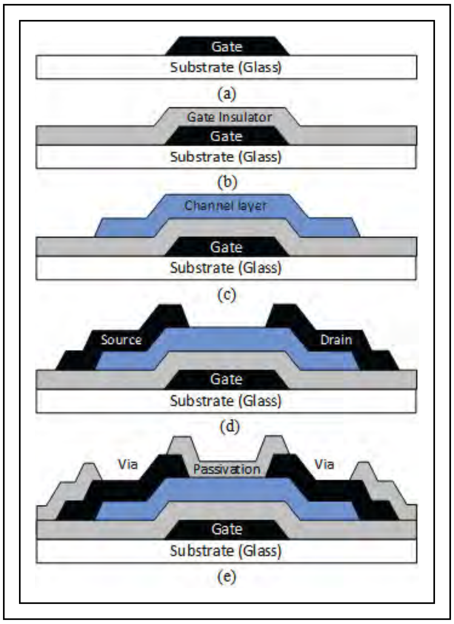

Fig. 1: Fabrication steps for TOS TFTs include (a) gate definition by lift-off, (b) gate-insulator deposition by RF magnetron sputtering, (c) channel layer deposition and definition by RF magnetron sputtering, (d) source/drain (S/D) definition by lift-off, and (e) passivation by RF magnetron sputtering.

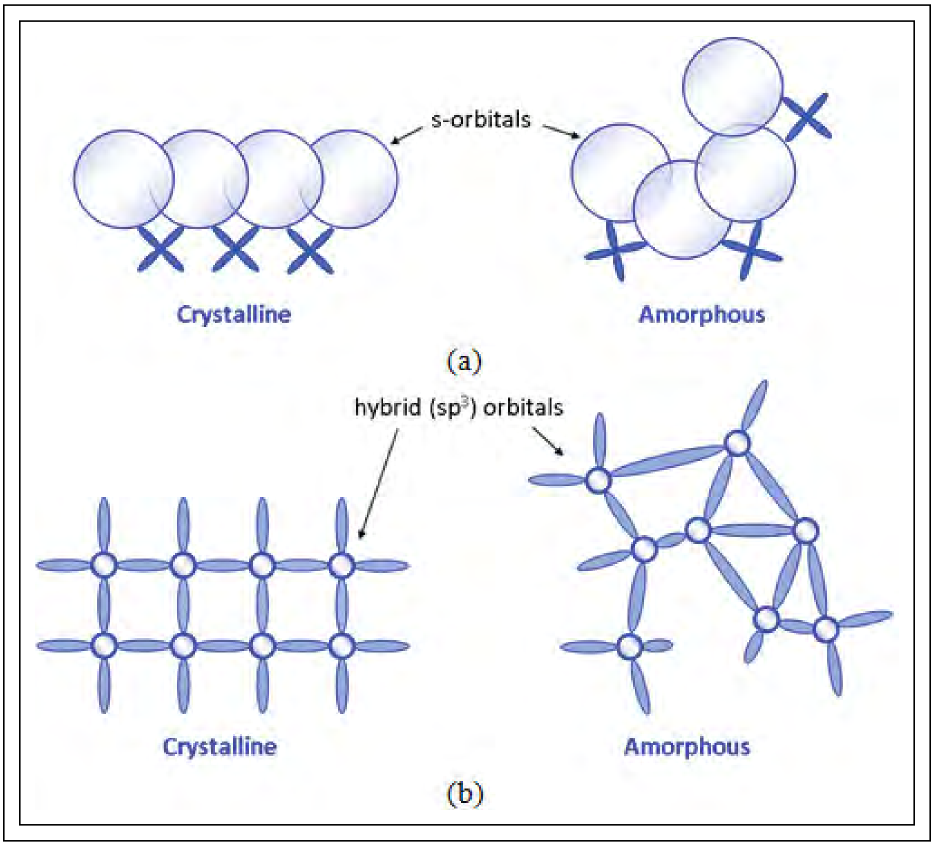

Fig. 2: Above are schematic illustrations of orbitals composed of conduction-band minima (E_m) in (a) oxide semiconductor (ionic bonding) and (b) silicon (covalent bonding) in crystalline and amorphous phases.

Two possible structures of the TFT (top gate and bottom gate) can be used. The latter is preferred because it is easy to fabricate and eliminates most of the processing-induced complexity and variation. The fabrication steps typically used are depicted in Fig. 1. A Mo (50 nm) layer is used for gate and source/drain (S/D) electrodes. These metal electrodes are patterned using a lift-off technique. The gate insulator (SiO_2/SiN_x) and the active layer (a-IGZO) are deposited by RF magnetron sputtering. After the active-layer formation and (S/D) electrode definition, an additionally sputtered SiO_2 capping layer is added, which serves as passivation for the TFT back channel. Finally, the TFT is subjected to a thermal annealing step (250°C) for 30 minutes. Details of the processing steps are discussed in the literature.[15–17]

The bonding structure in the amorphous oxide semiconductor, *e.g.*, a-InGaZnO (IGZO), is very different from that of conventional semiconductors such as a-Si and LTPS. In the oxide semiconductor, the atomic structure for conduction-band minima (E_m) is based on ionic bonding.[18] This implies that the connection between neighboring atoms is insensitive to variations in bonding angle, leading to high-quality film even in the amorphous phase. That is the main reason why this class of semiconductors provides higher mobility compared to a-Si. Figure 2(a) illustrates the orbital picture of E_m in oxide semiconductors in both crystalline and amorphous phases. As can be seen, there is a conduction path despite variations in bond angle. In contrast, the conduction band in silicon is based on hybrid orbitals (sp^3) with strong sensitivity to bonding angle variation, as shown in Fig. 2(b). Therefore, silicon in amorphous phase is less conductive, providing a much lower mobility compared to the oxide semiconductor counterpart. One of the issues in multi-component oxides (*e.g.*, In-Ga-ZnO) is the compositional disorder arising from a random distribution of metal atoms, *e.g.*, Ga and Zn.[18] This leads to conduction-band fluctuations, giving rise to potential barriers above the conduction-band minima (E_m).[19] Consequently, we have percolation conduction in addition to the conventional trap-limited conduction.[20] More importantly, because the oxide semiconductor has a large Bohr radius, this class of the material has a wide band gap (~3 eV) and thus high-optical transparency (~80%).[9,21]

However, the oxide semiconductor has a disadvantage. The presence of oxygen vacancies (V_0) located in the gap states near the valence band, as shown in Fig. 3 (a), can play the role of absorption sites for visible light. The resulting ionized V_0 is located in the vicinity of E_m and yields a highly conductive film upon illumination.[22] The problem is that the ionized V_0 has an outward relaxation with higher energy than the previous state V_0, as described in Figs. 3(b) and 3(c).[22] So, the ionized condition is maintained even after removal of the light source, suggesting persistence in photoconductivity (PPC), resulting in slow recovery. The same is also observed with threshold voltage shift (ΔV_T), as discussed in the next section.

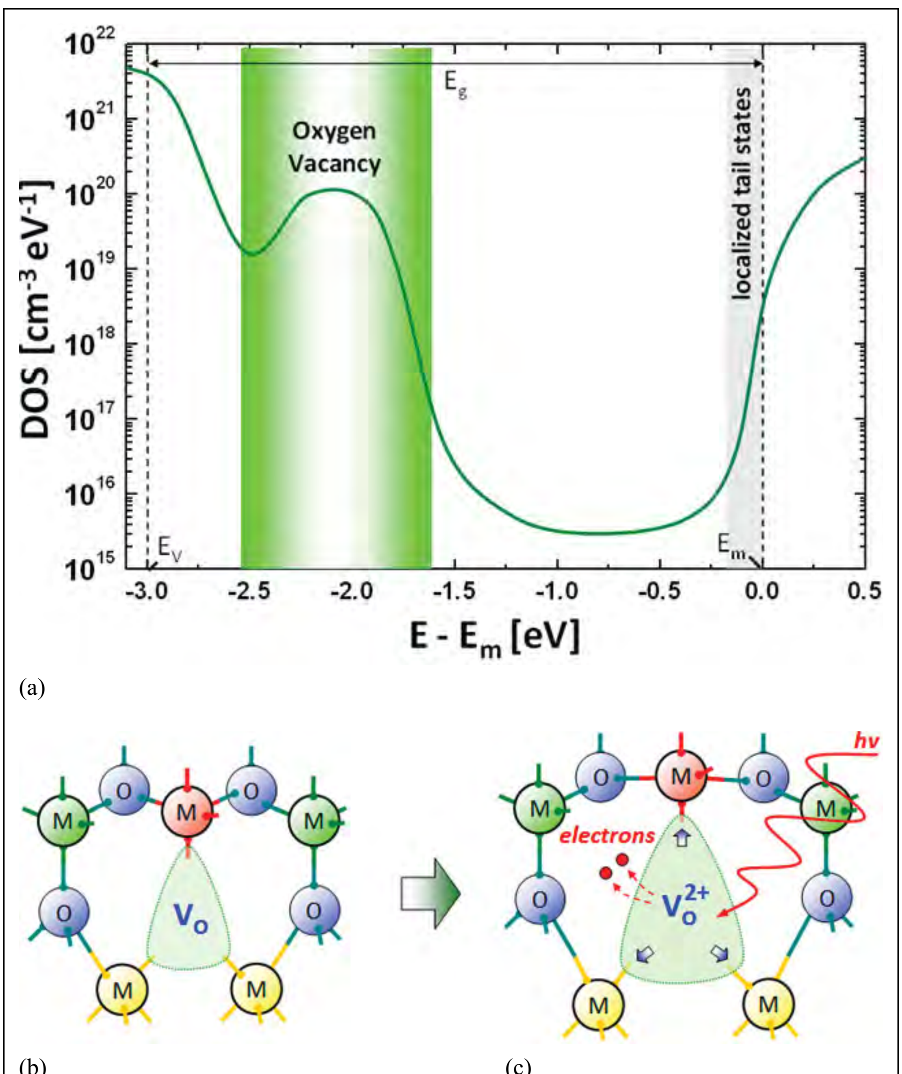

Fig. 3: (a) Typical density of states as a function of energy from the conduction band edge (E_m) of AOS TFTs indicate oxygen vacancy (V_0) sites in the middle of the gap (E_V) denotes valence band edge). Schematic bonding structures of the AOS semiconductor show (a) V_0 and (b) the ionized V_0 (V_0^{2+}) under illumination, respectively. Here, V_0^{2+} can release two electrons, having an outward relaxation, suggesting a higher energy compared to the previous state (V_0). Here, M denotes the metal atom, e.g., Ga and Zn, and O the oxygen atom.

Optically Induced Instability

The source of the PPC and threshold-voltage shift (ΔV_T) under illumination are believed to be the same. Figure 4 compares the transfer characteristics of TFTs after 3 hours of light stress combined with positive/negative bias stress. The spectrum of the light source used is shown in the inset of Fig. 4(a). The optical power is ~40 mW/cm^2, while the gate-bias values were 20, 0, and -20 V. As shown in Fig. 4(a), the transfer characteristics show a negative V_T shift regardless of bias polarity. This implies that the effect of the ionized oxygen vacancies is dominant and can be explained and described by

$$\Delta V_T \approx -\frac{\sqrt{2\varepsilon_S kT\, n_{IVO}}}{C_{ox}} \qquad (1)$$

where ε_S is the permittivity of the channel layer, kT is the thermal energy, and n_{IVO} is the density of the ionized oxygen vacancies. Charge trapping in the gate dielectric was found to be insignificant.

The PPC is gate-bias dependent, as shown in Fig. 4(b). Here, a negative V_{GS} pulse slows the recombination of PPC by separating the photo-generated e-h pairs. In contrast, a positive V_{GS} pulse accelerates the recovery, which is observed upon release of, and not during, the positive bias pulse. Therefore, a positive gate pulse enables an operational scheme for managing instability associated with PPC, accelerating recombination of ionization oxygen vacancies.[21]

Applications

Besides its obvious application in active-matrix displays, the TOS TFT technology, as mentioned earlier, can also be used as photo-sensors for visible-light applications because of the presence of oxygen vacancies in the sub-gap states.[21] For photosensor applications, we need to overcome the slow recovery due to PPC.[24] But techniques for adjusting the virgin V_T in a dual-gate photo-TFT through independent control of the gates has been reported based on a positive-gate-voltage control scheme.[21,24] In the example shown here, the TFT considered is a photosensor for imaging applications, in which a transparent conducting In-rich IZO layer is employed as the top gate as shown in Figs. 5(a) and 5(b) to yield minimum degradation in device photo-sensitivity. The huge responsivity of the photo-TFT observed [Fig. 5(c)] was attributed to high photoconductive gain (G_{ph})[24–26] because of efficient e-h separation by virtue of

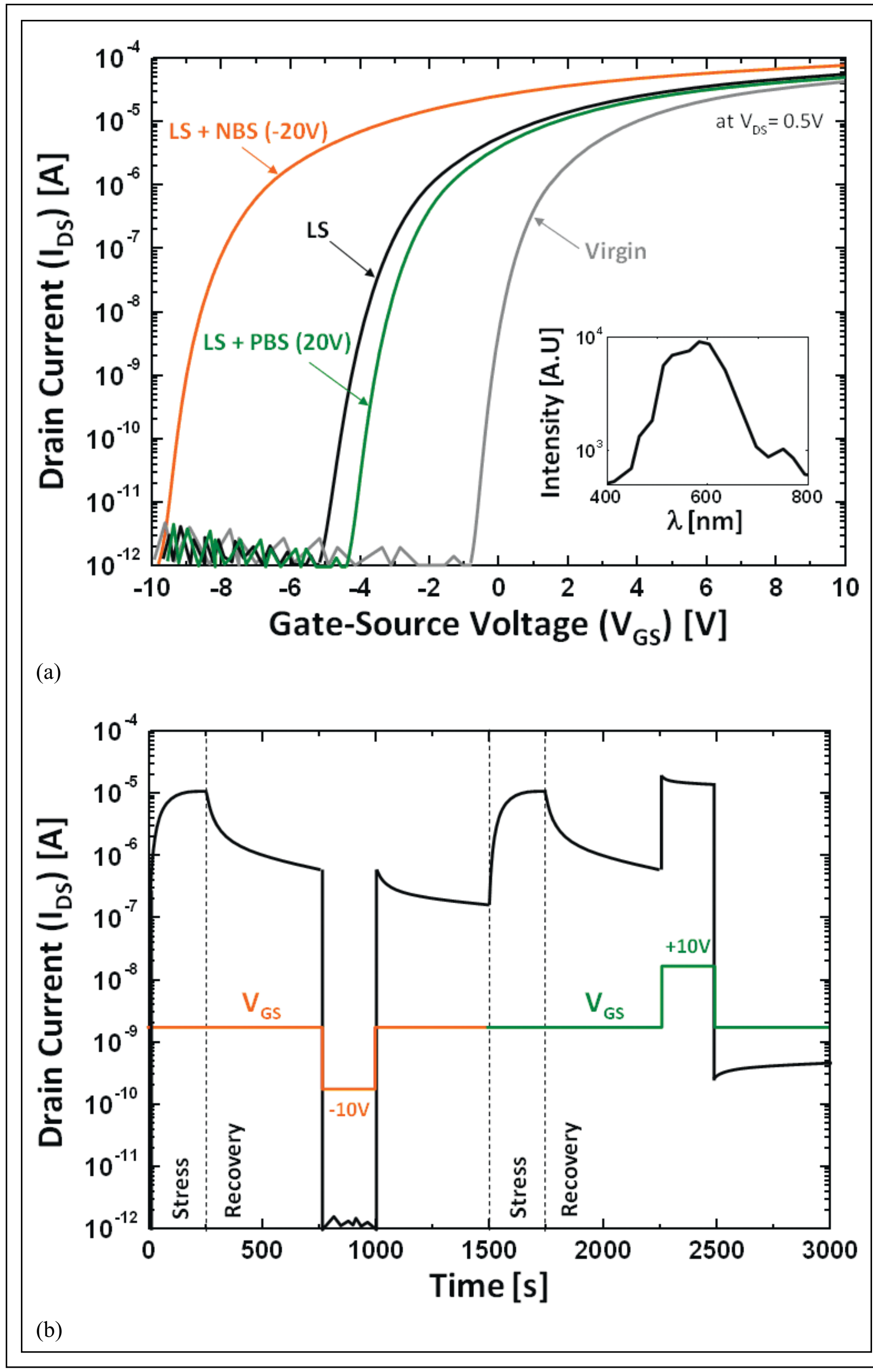

Fig. 4: (a): Shown above are transfer characteristics of IZO/IGZO TFTs subject to 3 hours of light-bias stress of different magnitude and polarity.[23] Inset: illumination source spectrum on a semi-log scale. (b) Drain-source current as a function of time subjected to illumination at intensities ~40 and 5 mW/cm^2 and recovery under different gate-bias conditions. The dashed lines trace the evolution of bias and light conditions with time. Here, negative V_{GS} slows recovery of PPC while a positive V_{GS} accelerates it.[24,25] [(Graphs adapted from K. Ghaffarzadeh et al., SID Symposium Digest of Technical Papers ***42**, 1154–1157 (2011).]*

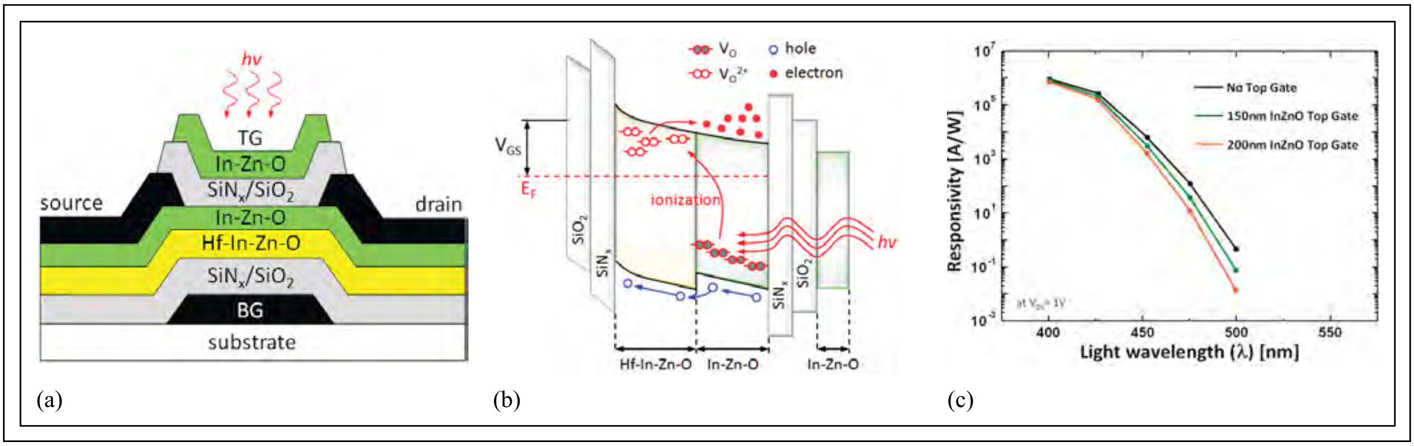

Fig. 5: A schematic diagram of dual-gate photo-TFT is shown in (a); a band diagram upon exposure to light in (b); and responsivity as a function of wavelength for photo-TFT as a function of thickness of top In-rich InZnO gate in (c).

band structure [Fig. 6(b)]. This retards the recombination rate, thus allowing for a longer carrier lifetime (τ_n). The gain can be represented as follows[26]:

$$G_{ph} = \tau_n/\tau_t \quad (2)$$

Here, τ_t is the carrier transit time from source to drain, which is independent on τ_n. The extended τ_n can be explained using the following equation[26]:

$$\tau_n = n_{IVO} / \gamma n_i^2 \quad (3)$$

where γ is the recombination rate and n_i is the intrinsic carrier density. Using this high optical sensitivity, visible-light sensing can be embedded into display panels for interactive applications[21,24,25] (see Fig. 6).

Looking Ahead

The oxide materials system can be judiciously tailored for display applications that also embed photosensor arrays based on the TFT architecture to enable fast recovery times overcoming issues related to persistent photoconductivity. The results demonstrated here signify the feasibility of transparent interactive active-matrix displays with embedded imaging that enable both touch and touch-free operation.

References

[1]R. Chaji and A. Nathan, *Thin Film Transistor Circuits and Systems* (Cambridge University Press, Cambridge, 2013).
[2]Corning's A Day Made of Glass, Corning (http://www.corning.com), New York (2011).
[3]J. F. Wager, *Science* **300**, No. 5623, 1245–1246 (23 May 2003).
[4]N. Neves, R. Barros, E. Antunes, J. Calado, E. Fortunato, R. Martins, and Isabel Ferreira, *J. European Ceramic Society* **32**, No. 16, 4381–4391 (Dec. 2012).
[5]J. F. Wager, D. A. Keszler, and R. E. Presley, *Transparent Electronics* (Springer, New York, 2008).
[6]Smart Windows Markets 2012, NanoMarkets, LC (Feb. 2012).
[7]K. Nomura, T. Kamiya, H. Ohta, K. Ueda, M. Hirano, and H. Hosono, *Appl. Phys. Lett.* **85**, 1993 (2004).
[8]R. Martins, A. Nathan, R. Barros, L. Pereira, P. Barquinha, N. Correia, R. Costa, A. Ahnood, I. Ferreira, and E. Fortunato, *Advanced Materials* **23**, No. 39, 4491–4496 (Oct. 18, 2011).
[9]R. L. Hoffman, B. J. Norris, and J. F. Wager, *Appl. Phys. Lett.* **82,** 733 (2003).
[10]J. Robertson, *J. Non-Crystalline Solids* **358**, 2437 (2012).
[11]R. A. Street, *Hydrogenated Amorphous Silicon* (Cambridge University Press, 2005).
[12]J. I. Song, J. S. Park, H. Kim, Y. W. Heo, J. H. Lee, J. J. Kim, G. M. Kim, and B. D. Choi, *Appl. Phys. Lett.* **90**, 022106-1-3 (Jan 2007).
[13]F. M. Hossain, J. Nishii, S. Takagi, A. Ohtomo, T. Fukumura, H. Fujioka, H. Ohno, H. Koinuma, and M. Kawasaki, *J. Appl. Phys.* **94**, 7768–7777 (Dec 2003).
[14]K. Nomura, H. Ohta, A. Takagi, T. Kamiya, M. Hirano, and H. Hosono, *Nature* **432**, 488–492 (Nov 2004).

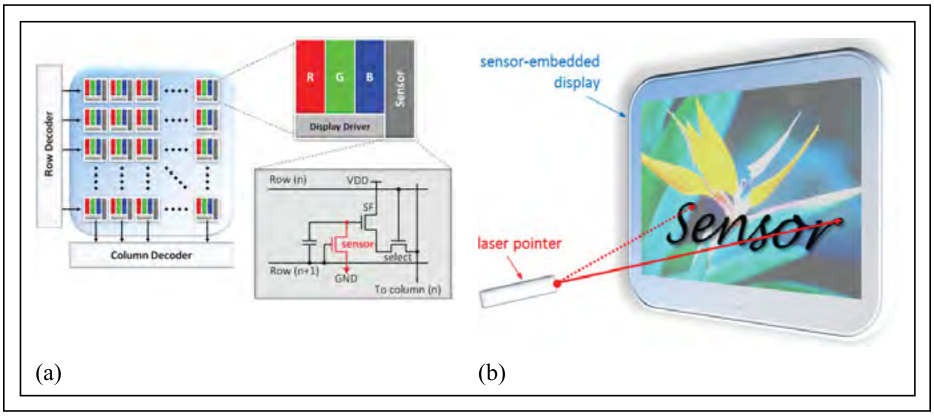

Fig. 6: Shown in (a) is a typical architecture of an image sensor embedded in an active-matrix display with the pixel structure.[24,25] Below, (b) indicates the desired display with the word "sensor" written by a laser pointer.[24,25]

[15]S. Jeon, S. I. Kim, S. Park, I. Song, J. Park, S. Kim, and C. Kim, *IEEE Elect. Dev. Lett.* **31**, No. 10 (2010).
[16]M. Ofuji, K. Abe, H. Shimizu, N. Kaji, R. Hayashi, M. Sano, H. Kumomi, K. Nomura, T. Kamiya, and H. Hosono, *IEEE Elect. Dev. Lett.* **28**, 273-5 (2007).
[17]H. Hosono *et. al.*, *J. Non-Crystalline Solids* **352**, 851-858 (Jun 2006).
[18]A. Takagi, K. Nomura, H. Ohtab, H. Yanagia, T. Kamiya, M. Hirano, and H. Hosono, *Thin Solid Films* **486**, 38–41 (2005).
[19]V. I. Arkhipov, E. V. Emelianova, and G. J. Adriaenssens, *J. Phys.: Condens. Matter.* **12**, 2021–2029 (2000).
[20]S. Lee, K. Ghaffarzadeh, A. Nathan, J. Robertson, S. Jeon, C. Kim, I. H. Song, and U. I. Chung, *Appl. Phys Lett.* **98**, 203508 (2011).
[21]S. Jeon, S.-E. Ahn, I. Song, Y. Jeon, Y. Kim, S. Kim, H. Choi, H. Kim, E. Lee, S. Lee, A. Nathan, J. Robertson, C. J. Kim, U-I. Chung, I. Yoo, and K. Kim, *IEEE IEDM Technical Digest*, 14.3.1–14.3.4 (2011).
[22]A. Janotti and C. G. Van de Walle, *Appl. Phys. Lett.* **87**, 122102 (2005)
[23]T. Kamiya and H. Hosono, *Intl. J. Appl. Ceram. Technol.* **2,** 285 (2005).
[24]S. Jeon, S.-E. Ahn, I. Song, C. J. Kim, U-I. Chung, E. Lee, I. Yoo, A. Nathan, S. Lee, J. Robertson, and K. Kim, *Nature Materials,* 11 (Feb. 2012).
[25]S.-E. Ahn, I. Song, S. Jeon, Y. W. Jeon, Y. Kim, C. J. Kim, B. Ryu, J.-H. Lee, A. Nathan, S. Lee, G. T. Kim, and U-I. Chung, *Advanced Materials* **24**, No.19 (May 2012).
[26]S. Lee, J. Robertson, and A. Nathan, "How to Achieve Ultra High Photoconductive Gain for Transparent Oxide Semiconductor Image Sensors," *IEEE IEDM Technical Digest* (2012). ■

Quantum-Dot Displays: Giving LCDs a Competitive Edge through Color

Quantum-dot technology is bringing wide color gamut to LCDs, giving them a leg up on another advantage that once belonged to OLEDs.

by Jian Chen, Veeral Hardev, and Jeff Yurek

SIXTY YEARS AGO, well before color TVs became widely available in the late 1960s, the National Television System Committee (NTSC) agreed on one of the first broadcast standards for color TV – the NTSC 1953 color standard. This new standard was a significant achievement, bringing color to a black-and-white world with a clever encoding scheme that tracked color separately from luminance. While the standard was based on the capabilities of the best-available cathode-ray-tube (CRT) phosphor materials, mainstream devices never really supported the full-color capabilities of NTSC 1953. The color primaries established by the standard would become more aspirational than truly standard over the next 6 decades.

That's not the case in 2013. Today, millions of people around the world carry a mobile device in their pocket that can reproduce more color than the 1953 NTSC standard, thanks to AMOLED-display technology. While historically limited to smaller devices by reliability and process issues, AMOLED displays may soon find their way into larger and larger systems. In 2012, 55-in. AMOLED TVs garnered significant attention and won awards at SID's annual Display Week exhibition.

Despite the emergence of AMOLED displays, the technology has yet to capture a large share of the overall display market, as LCDs remain the standard in nearly all product categories. After more than a decade of explosive growth in manufacturing capacity by LCD makers, the cost of LCDs of all sizes is tough to beat for upstart technologies such as OLEDs. Beyond cost, LCDs have been able to match just about every feature that new technologies have offered over the years. Advances such as local dimming, in-plane switching (IPS), and in-cell touch, respectively, have brought great contrast, improved viewing angle, and reduced thickness to LCDs. In most cases, manufacturers have yet to find an OLED advantage strong enough to compel them to move beyond LCD.

One area where LCDs have thus far failed to match OLEDs is color performance. Conventional LCDs face a ceiling in color performance, at best reaching the sRGB color gamut, or about 70% of OLED's capability, because of the white LED light source used in most LCD backlights. While LCD makers have experimented with other wide-gamut backlight technologies, such as discrete RGB LED and CCFL, all have proven too costly, too power hungry, or too bulky to be viable. For some time, it seemed that high brightness, portability, and wide-gamut color performance simply could not be had in the same LCD package at the same time.

That was until a new class of phosphor material called quantum dots became available to LCD makers. First developed in the 1980s at Bell Labs, quantum dots have the unique ability to efficiently emit light at a single spectral peak with narrow line width, creating highly saturated colors. In addition, the emission wavelength can be tuned continuously based on the size of the quantum dots. This capability enables display designers to custom engineer a spectrum of light to maximize both the efficiency and color performance of their display.

The term "quantum dot" was coined by Mark Reed, a physicist from Yale University who contributed to some of the early work on the technology in the 1980s. The dots are so named because of the quantum-confinement properties that are exhibited by the material. Quantum dots are semiconductors whose electronic characteristics are governed by the size and shape of the individual crystal. The smaller the size of the crystal, the larger the band gap becomes. In lighting applications,

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this means higher frequencies of light are emitted as the crystal size becomes smaller, resulting in a color shift from red to blue in the light emitted.

LCDs and Color

To better understand how quantum dots improve the color performance of LCDs, it is useful to know how LCDs work. A typical LCD consists of two major components: a light source called the backlight unit (BLU) and a liquid-crystal module (LCM) (see Fig. 1).

When an LCD is operating, the BLU provides white light to illuminate the LCM. The LCM contains millions of pixels, each of which is split into three subpixels, one each for red, green, and blue light. By controlling the amount of light each subpixel allows to pass through, a broad range of colors is created by mixing the individual red, green, and blue light. Thus, the fidelity of color in each pixel is a direct function of the subpixel color saturation. To determine the overall color gamut of the LCD, one must look at the chromaticity of red, green, and blue light in each subpixel.

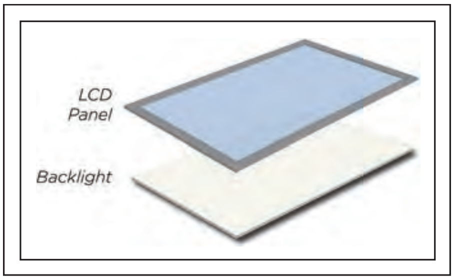

Fig. 1: A backlight unit, which these days generally uses LEDs as the light source, operates behind the LCD.

The color of each subpixel is determined by two factors: the spectral energy of the white light in the BLU and the effectiveness of the color filter at the subpixel. The color filter separates its component red, green, or blue color from the white light of the BLU. Thus, the red color filter on the red subpixels will cut off green and blue, attempting to let only certain wavelengths of red light though. To make a high quality red, the filter spectrum either needs to be very narrow, etting less undesired light through, or the red component in the white BLU light must be narrow and tuned to the desired peak red color wavelength in the filter. The same is true for the green and blue subpixels.

Unfortunately, narrowing the spectrum of the filters is expensive and results in substantial attenuation and loss of luminance.

Another solution to improving color fidelity might be to make a better white light. However, the LED light source at the heart of most BLUs in use today is not optimal for producing highly saturated red, green, and blue light, starving the subpixel filters of the colors that they really need to shine. While there are a variety of approaches to create white light from LEDs, YAG (yttrium-aluminum-garnet) phosphor combined with blue LED chips is the most common. This technology relies on a YAG-based phosphor to change the blue light from a GaInN (gallium-indium-nitride)

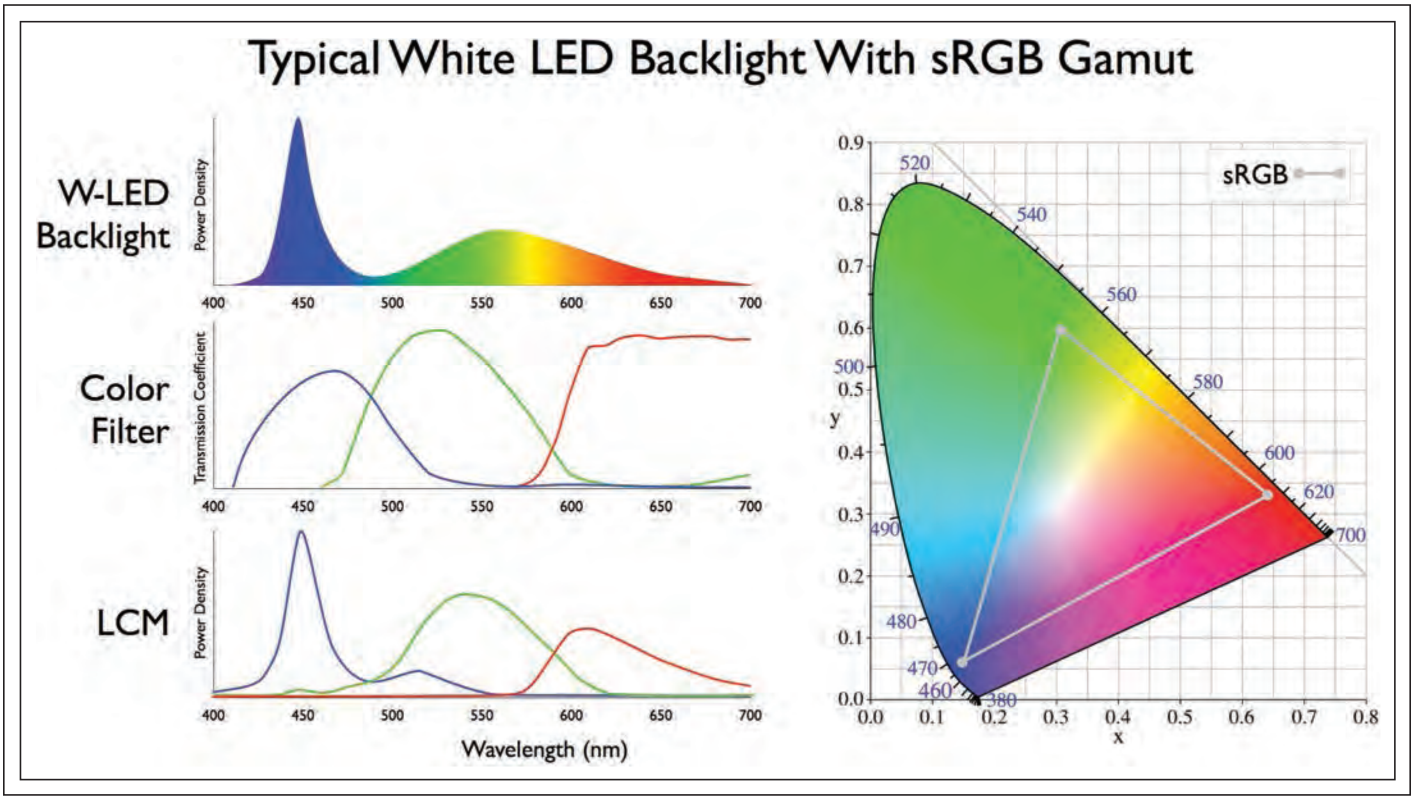

Fig. 2: Shown is the spectra from a conventional white LED (GaInN + YAG) backlight which does not provide a good match with red, green, and blue color filters in the liquid-crystal module (LCM). The resulting gamut, plotted in the CIE 1931 diagram on the right, covers a relatively small percentage of the total range of colors our eyes can see – only about 35%.

LED light source to a light that we perceive as white. This produces a spectrum rich in blue with a broad yellow component. It has a weak green and red content, and the spectrum is widely distributed from aquamarine through green, yellow, orange, and red (see Fig. 2). When this light is filtered into the component RGB filter colors in the subpixels, the primary colors are not pure enough to cover sufficient color space.

Knowing this, an ideal LED light source for an LCD should be capable of generating photons in the red, green, and blue wavelengths useable by the subpixel filters. For maximum efficiency, it should also not emit photons with wavelengths that are not matched to the red, green, and blue filters.

Quantum Dots

Quantum dots comprise a new class of material that can be tuned to emit light very efficiently at precise red, green, and blue wavelengths, thus creating an ideal light spectrum for LCDs. Unlike conventional phosphor materials, quantum dots, which are just nanometers in diameter, can be fabricated to convert short-wavelength light (*i.e.*, blue light) to nearly any color in the visible spectrum. The spectral output of a quantum dot is determined by its size. Bigger dots emit longer wavelengths, while smaller dots emit shorter wavelengths. It's a phenomenon of quantum mechanics called quantum confinement that describes what happens to electrons and holes when confined in nanoscale materials. Think of a guitar string – to use a classic physics analogy. When a guitar string is shortened, it produces a higher pitch, and, conversely, when it is lengthened, it creates a lower pitch. The tune of a quantum dot – the wavelength of the light it emits – behaves in a similar way.

Figure 3 pairs quantum dots of different sizes with corresponding output wavelengths. The best dots available today emit light with over 90% efficiency and with very narrow spectral distribution of only 30–40 nm at full-width at half-maximum (FWHM). Ranging in size from 2 to 6 nm, quantum dots made from the same material emit light in the visible spectrum at different wavelengths based upon size.

Quantum dots for display applications are generally made from II-VI elements such as cadmium selenide or III-V elements such as indium phosphide. They are typically synthesized via solution chemistry in high-boiling-point solvents using precursors and ligands that bind to the surface of the dots. By controlling different synthesis conditions, *e.g.*, precursor and ligand concentrations and the temperature and time of the reaction, quantum dots of different sizes can be obtained.

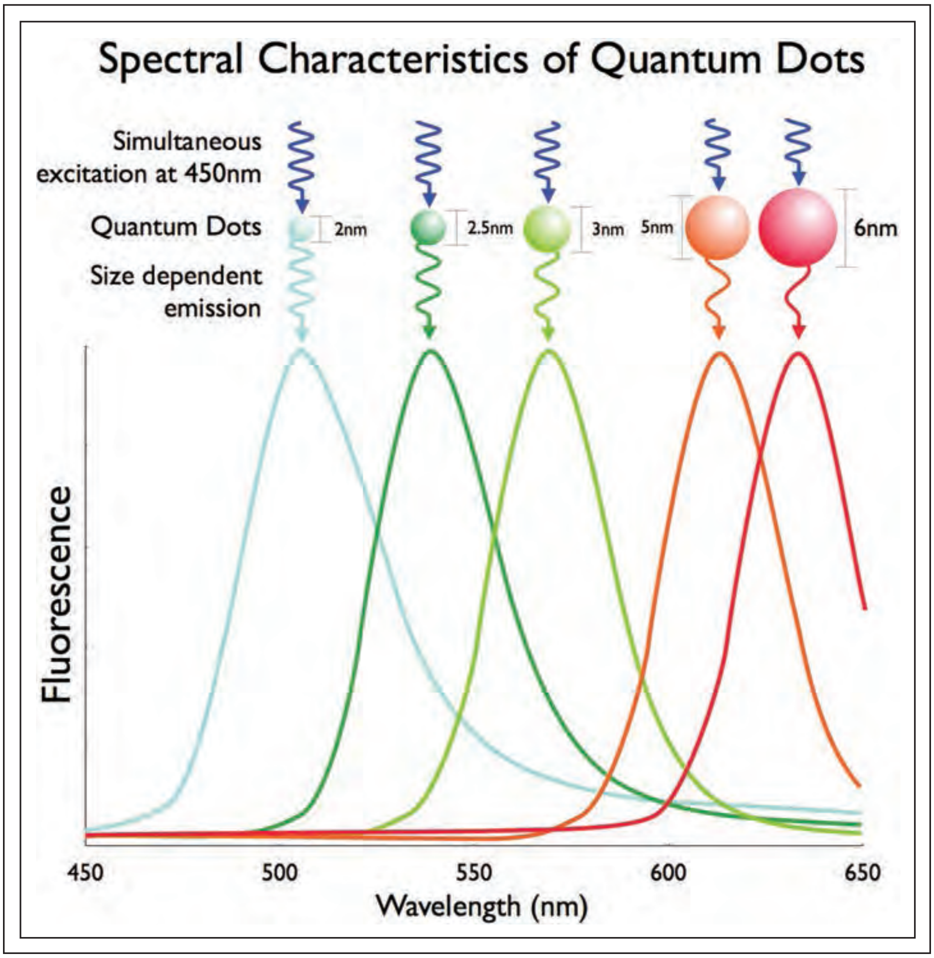

Fig. 3: *Quantum-dot size relates to emission wavelength. Quantum dots absorb higher-energy/shorter-wavelength light and down-converts the light into lower-energy/longer-wavelength light. The smallest dot represented here, at 2 nm in diameter, absorbs the light from a 450-nm blue source and emits light at 500-nm green wavelength while a larger 6-nm-diameter dot emits at 630-nm red wavelength. Precise control of quantum dots at manufacturing enables the dots to emit light at any wavelength in the visible spectrum.*

Packaging for Existing Manufacturing Processes

The light-emitting properties of quantum dots make them a promising technology, but that is not enough to drive adoption in the display industry. Manufacturers are usually unwilling to risk altering processes they have invested billions in to try a new, novel technology. If quantum dots are going to have an impact in the display industry, they need to be packaged into a process-ready system that is compatible with existing standard LCD-manufacturing processes. Nanosys has aimed to achieve this goal in creating its Quantum-Dot Enhancement Film (QDEF) product (Fig. 4).

QDEF is designed to replace an existing film in the BLU called the diffuser. The film combines trillions of red- and green-emitting quantum dots in a thin sheet that emits finely tuned white light when stimulated by blue light. Each sheet of QDEF comprises three layers – two plastic barrier films sandwiching a layer of quantum dots suspended in a poly-

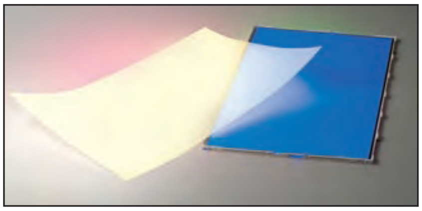

Fig. 4: *The quantum-dot enhancement film (QDEF) is designed to replace the diffuser in an LCD backlight unit (BLU) and is placed between the BLU and the LCM. The QDEF contains red- and green-emitting quantum dots that are tuned to each display system and is illuminated by blue LEDs in the BLU. In the above image, a sheet of QDEF (left) can be seen converting some of the blue light emitted by a BLU (right) into white.*

mer matrix. This deceptively simple optical system is enabled by two key breakthroughs aside from quantum dots themselves:

1. Surface functionalization, enabling reliable dispersion of quantum dots in solid matrix materials while maintaining brightness, and
2. The availability of high-performance optically clear oxygen/moisture barrier films.

In order to disperse quantum dots into a variety of different matrix materials such as epoxies, polymers, and UV-curable adhesives, Nanosys specifically tailored the surface functionality of the dots with a type of organic material, known as ligands. This surface functionalization keeps the quantum dots at a safe distance from each other, preventing adverse interaction. Keeping the quantum dots appropriately dispersed is important in maintaining both efficiency and reliability over long lifetimes. If the dots aggregate, the photon conversion efficiency degrades, resulting in a lowered output of green and red color. This leads to an undesired white-point change on the display. Stable and reliable dispersion into a matrix material allows quantum dots to be employed in manufacturing processes already in use throughout the optical-films industry, such as roll-to-roll coating, and helps to assure their long-term stability.

With the successful functionalization of quantum dots in matrix material, the final critical component of QDEF is the addition of a barrier film to protect the quantum dots from the outside environment. Similar to OLED materials, quantum dots are sensitive to oxygen and moisture. The dots will degrade and become less efficient over time with exposure to either. Therefore, the quantum dots must be kept in an environment in which they will not be exposed to such elements. Encasing the quantum dots in a high-quality oxygen/moisture-barrier film does just that.

The ideal barrier film for QDEF must prevent degradation from oxygen and moisture in a package that is optically clear to let light pass through, flexible for rolling and thin to allow a slim device profile. The authors' company used a film from 3M that had been developed for solar, display, and lighting applications, which fit this ideal profile.

QDEF's barrier, based on a clear plastic material called polyethylene terephthalate (PET), is coated with a thin oxide/polymer barrier on the inside-facing side. This proprietary barrier provides the dots with oxygen and moisture protection that is orders of magnitude better than conventional barrier films, improving the lifetime and reliability of QDEF without impeding light transmission.

The result is a simple, ready-to-use product that manufacturers can directly integrate into existing processes. By adding QDEF, the display maker can immediately begin producing LCD panels with color and efficiency performance beyond OLEDs, without making any changes to established processes.

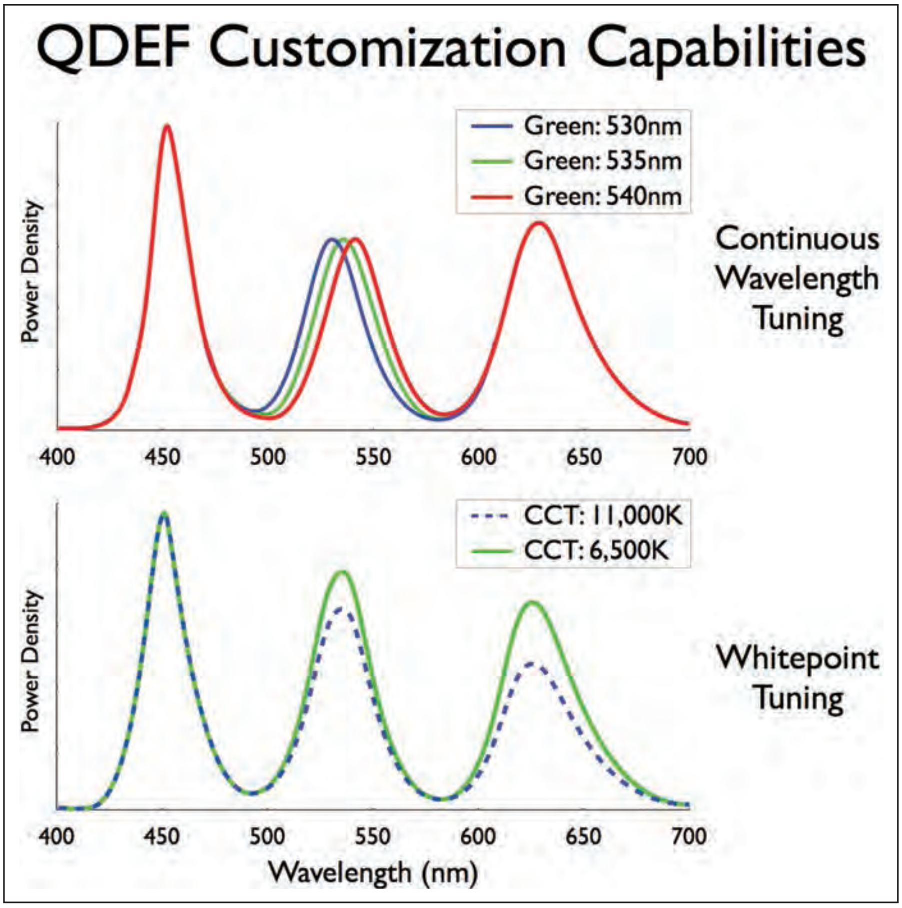

Fig. 5: *Various quantum-dot backlight customization possibilities exist. Top: Continuous-wavelength tuning enables display designers to target different color gamuts and/or optimize backlight emission for a given color-filter spectrum. Bottom: By changing the ratio of red to green and overall loading of dots in the film, different white points can be achieved to match the requirements of different display applications, i.e., mobile devices, tablets, and TVs.*

Customization

Using the size-dependent emission properties of quantum dots, QDEF can be custom formulated for different display applications – some for wide color gamut and some for energy/light efficiency. This allows display designers to tune the backlight spectrum to meet exact performance goals. For example, a display maker may want to target the Adobe RGB gamut and a D65 white point for a particular device. Each system is unique, and a number of variables, such as color-filter cutoff frequencies, optical path length, and the amount of light recycling in the film stack, can affect the light as it passes through the LCD. Nanosys can design a sheet of QDEF with the precise color wavelengths and ratio of red to green to blue to account for each one of these variables to meet the designer's goals.

Figure 5 demonstrates the customization capabilities of QDEF. Matching red and green wavelengths to color filters enables precise reproduction of color-gamut standards and high efficiency. In the example shown in Fig. 5, the three green wavelengths represent the difference between hitting the sRGB, DCI-P3, and Adobe RGB color gamuts. Additionally, by controlling the ratio of red and green to blue by loading more or fewer dots into the film, QDEF can create any desired white point. More red and green makes a warmer white, while more blue creates a cooler white point.

The results can be seen in Fig. 6, wherein a sheet of QDEF was matched to a CF72 color filter that was designed to create the sRGB gamut when paired with a white LED. By using QDEF, this display can now generate over 100% coverage of the much larger Adobe 1998 color gamut with high power efficiency.

Commercial Viability

Reliability is a concern for any new technology. Quantum-dot R&D efforts are focused on creating products that will meet the increasing demands of product applications. Display products are getting brighter and larger and are now expected to last beyond 30,000–50,000 hours of operation.

To address these reliability demands, QDEF has been tested for tens of thousands of hours of operation under a variety of conditions, including high temperature, high humidity, and high light flux. In every case, QDEF has met or exceeded industry expectations. Because TVs are expected to last for many years and tend to be used in harsh environments, TV lifetime standards are one of the toughest tests for a new display component. Using accelerated lifecycle testing, QDEF is expected to surpass the 30,000-hour lifetime specification expected by TV makers, which translates to approximately 10 years of typical television-set usage (8 hours per day) (Fig. 7).

Quantum dots also face a challenge for mass adoption from competitive products based on OLED and other RG phosphor technologies that are likely to arrive in the future. QDEF's ability to leverage the existing infrastructure of the LCD industry provides an advantage against these other entrants.

Color is the Next Big Differentiator

Since the days of the first color TVs, a

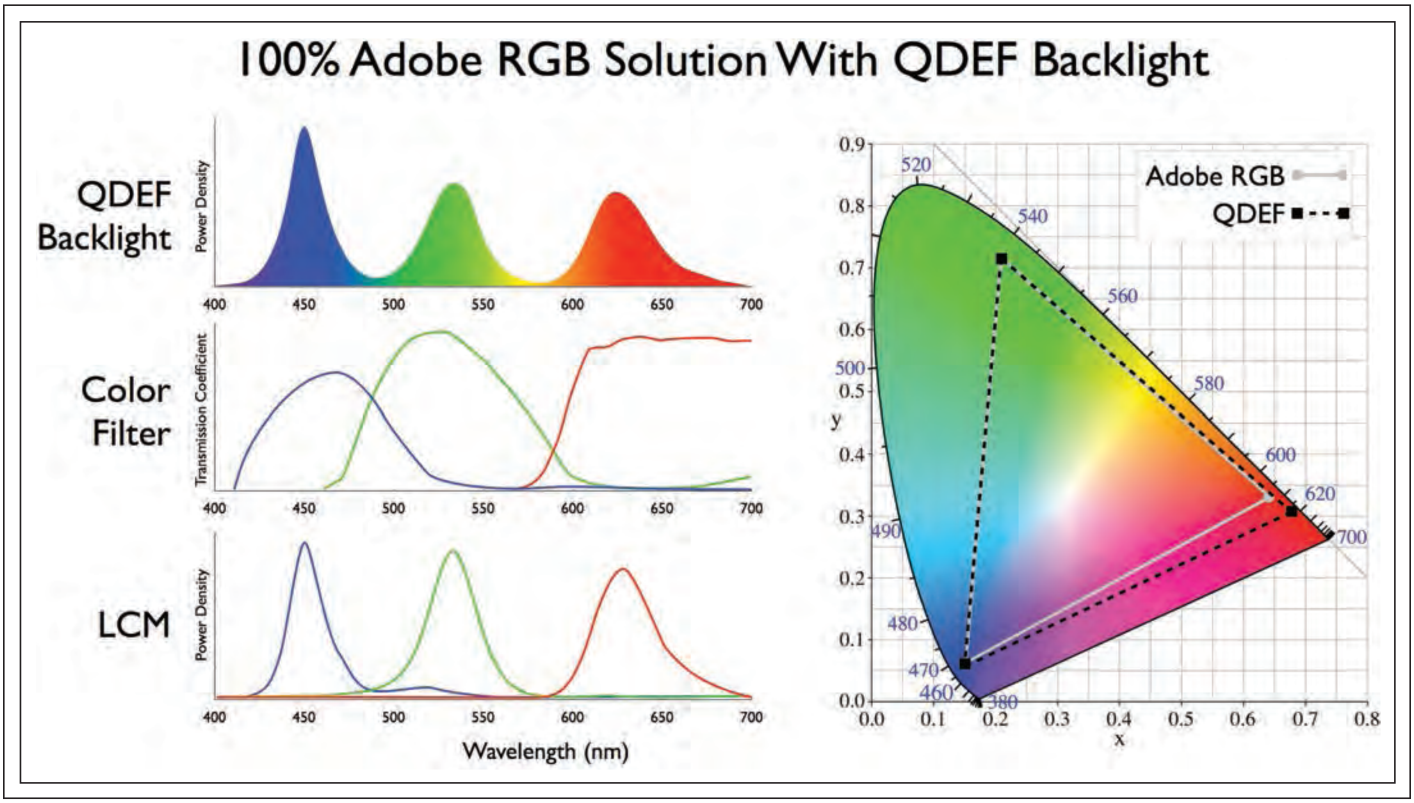

Fig. 6: A QDEF backlight using an off-the-shelf CF72 color filter is able to generate 100% coverage of the Adobe 1998 color gamut.

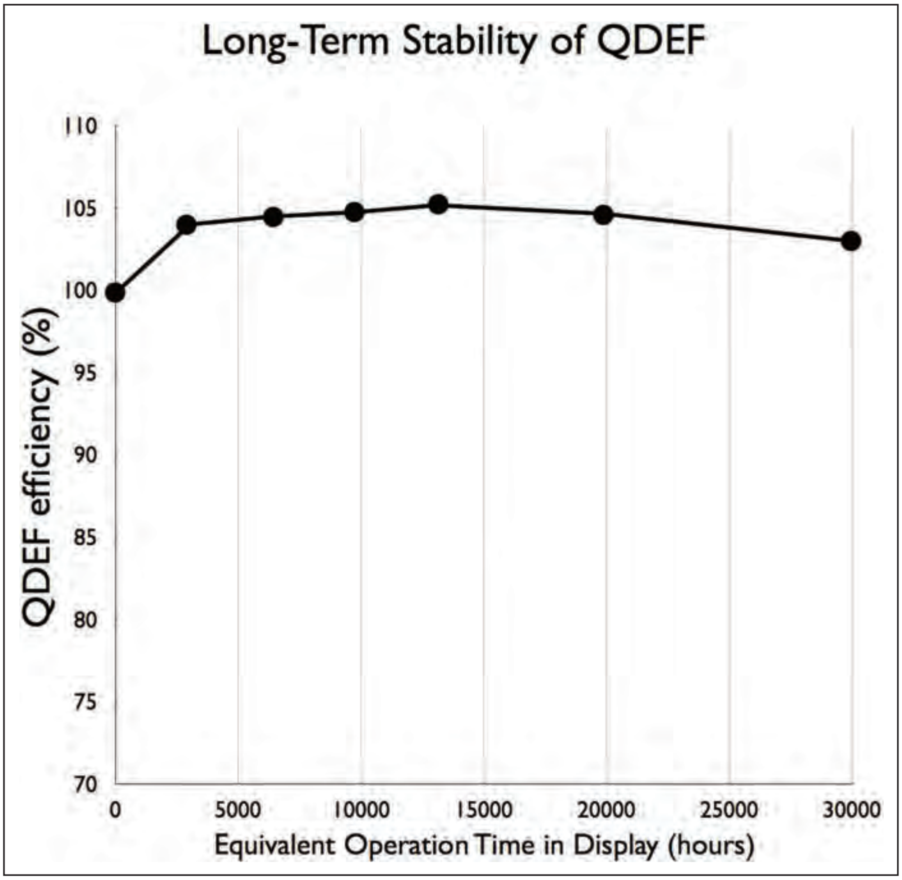

Fig. 7: Shown is 10x accelerated reliability data. The authors have tested QDEF at conditions that are 10x harsher than what a typical TV operates at, with a combination of more intense light and higher temperature. No degradation has been seen in this testing after 3000 hours of operation, which may be considered equivalent to normal operation after 30,000 hours.

chicken and egg problem has prevented wide gamut from gaining mass-market appeal. Content creators have avoided wide gamut because devices that support it are typically expensive and not widely available – niche products at best. Likewise, display makers have historically felt that a lack of wide-gamut content limits the appeal of hardware.

QDEF is cost-effective, process-ready, reliable, and efficient enough to bring wide-color-gamut performance to all of the screens in our lives, from the smallest mobile device to the biggest TV. None of the wide-gamut technologies that preceded QDEF could claim to pull all four of these critical attributes together in one package. With broader availability of wide-color-gamut hardware enabled by QDEF, content creators can begin to take wide gamut seriously. This opens the door for Hollywood to create a stunning new visual experience for consumers, actually bringing a full cinematic viewing experience to our living rooms.

Color is the next big differentiator in the increasingly competitive consumer display market. Display makers that can bring the user experience closer to reality with lifelike colors, without sacrificing efficiency or cost, will establish a dominant market position. It may have taken several decades, but quantum-dot displays will finally deliver on the wide-color-gamut promise of the 60-year-old 1953 NTSC TV color specification. ■

Making Color in LCDs

Color filters play a key role in the balance between image quality and power consumption in LCDs. With high resolution a key performance feature, and LCDs facing competition from OLEDs with superior color gamut, color-filter designs will need to continue to evolve.

by Paul Semenza

LIQUID-CRYSTAL DISPLAYS (LCDs) modulate the polarization of white light to produce gray levels, and thus require a way to create color. The color-filter process adds a red, green, or blue dye or pigment to each subpixel so that by mixing the three primary colors, almost any color can be generated. Like TFT arrays, color filters are typically manufactured by a photolithography process on a glass substrate. Unlike TFTs, color filters are passive optical components.

In addition to the RGB elements, the color-filter plate also carries a black matrix and may have patterned column spacers and protrusions for vertical-alignment LCDs, as well as ITO for the common electrode to provide the voltage reference for the liquid-crystal control from the TFT array. In combination with the TFT array, which is deposited on the lower glass substrate, the color-filter plate deposited on the upper glass substrate serves to contain the liquid-crystal material. In an approach called color filter on array, the color filter, possibly including the black matrix, is deposited on top of the TFT array on the lower glass substrate, which means that all of the complex deposition can occur on a single substrate.

Color filters need to have a high degree of color purity, optical transmittance, and optical tolerance (meaning that the spacing of the filters with pixels, and from pixel to pixel, must be strictly controlled), with no discoloration or fading over time, as well as high thermal stability and chemical resistance. The production process must not result in surface irregularities such as unwanted protrusions, bumps, or other defects. Most color filters use pigment-diffused resist to form color features. Through Gen 4, many color-filter processes formed the black matrix from a chrome film, patterned with positive resist and then etched. From Gen 5 on, most manufacturers adopted photo-definable resin resist because it can be coated on and patterned directly, eliminating the need for sputter and etch tools. This also reduces electrical interference on some wide-viewing-angle-type displays and has lower reflectivity. There are typically 4–6 layers coated and patterned, including the black matrix; red, green, and blue subpixels; vertical-alignment protrusions; and photospacers (Fig. 1).

The black matrix is a pattern of black lines on the color filter that shields bus lines and TFTs from the viewable area of the display, and which distinguish RGB subpixels to prevent color mixing and light leakage, thus improving contrast. The black matrix is a

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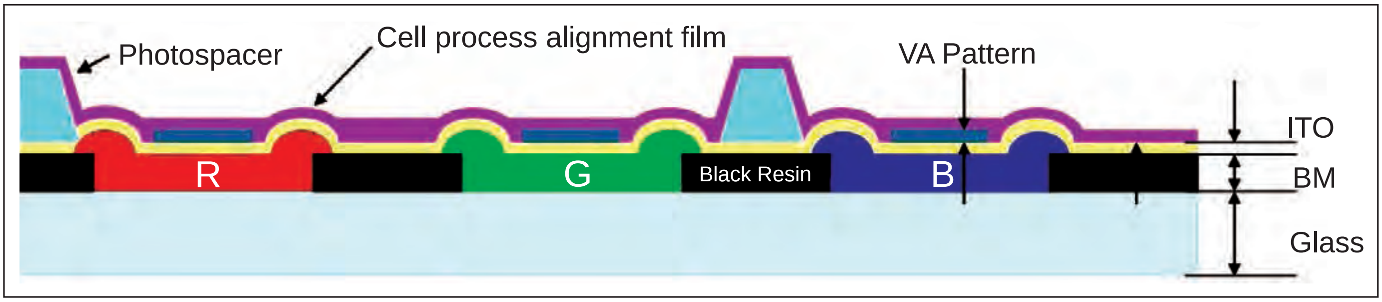

Fig. 1: *This typical six-mask vertical-alignment color-filter architecture employs photospacers, shown here as high bumps, to maintain the liquid-crystal cell gap, and protrusions to create domains within the liquid-crystal layer for the vertical-alignment mode. Source: DisplaySeach TFT LCD Process Roadmap Report.*

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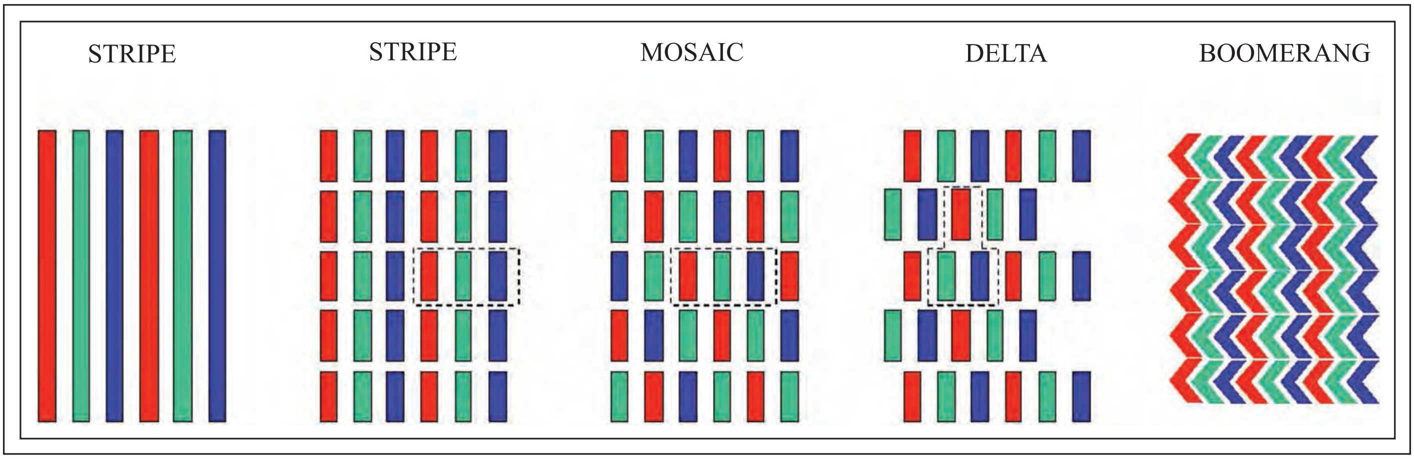


Fig. 2: Color-filter patterns vary a great deal in terms of subpixel arrangement.

layer only a few microns thick, but it covers electrical lines as well as spacers so they do not reduce the aperture ratio. Over the past few years, reduction in the width of the black-matrix lines has become an important way to increase aperture ratio and transmission. Leading-edge TV designs are moving to less than 10 µm in width, while small-to-medium designs can be as narrow as 5 µm, and the target for high-resolution small-to-medium displays is 3 µm.

While the RGB stripe is the most common arrangement, subpixels can be arranged and shaped in a variety of ways (Fig. 2).

In the PenTile approach, the subpixel arrangement is matched to human visual sensitivity, using fewer subpixels by having adjacent pixels sharing a blue subpixel or by adding a white subpixel (Fig. 3). The RGBW approach also adds a white subpixel, but the PenTile approach reduces the number of subpixels, while RGBW increases them. Both approaches substantially increase transmission, increasing brightness and/or reducing power consumption.

To date, the PenTile architecture has found the greatest use in the subpixel arrangement in RGB OLEDs, which do not use color filters, but which are limited in pixel density by the current process technology for depositing organic materials. PenTile allows higher "apparent" resolution with fewer (and thus larger) subpixels, which allows OLEDs to compete with LCDs in high-resolution applications. OLED makers are also developing WOLED, which combine a white emissive layer with color filters.

The PenTile and RGBW approaches trade off an increase in transmission versus image quality. RGBY is a compromise approach that adds one or more primary colors instead of white (Fig. 4).

By adopting a five-color multi-primary such as RGBYC, extremely accurate color production can be achieved. However, the extra colors and complicated driving (due to the addition of the fourth color) add substantial costs and have prevented commercial adoption to date.

The growth of high-resolution mobile displays has led to tradeoffs between color depth and power consumption. The low aperture ratio has led panel makers to use thinner color-filter layers to improve the transmittance, thus reducing power consumption. However, as the color-filter layer becomes thinner, its ability to filter the light spectrum is also reduced, which allows a broader spectrum of light energy through each filter. This results in a smaller total color gamut. While LCDs have had advantages in higher

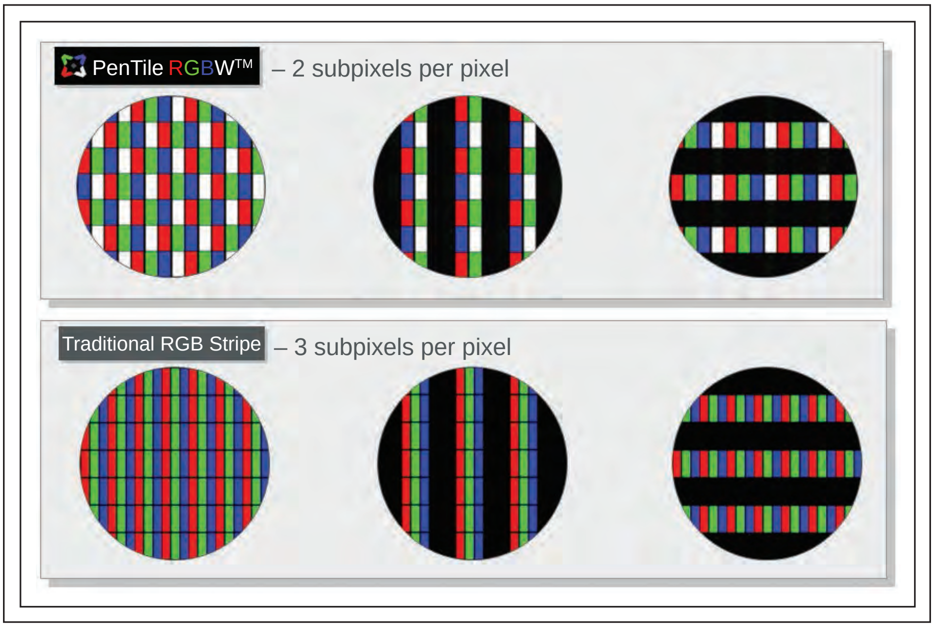


Fig. 3: In one PenTile approach, four RGB subpixels are converted to two RGB and two white subpixels. Source: NOUVOYANCE.

Fig. 4: Sharp's RGBY Quattron Pixel technology adds yellow to RGB

resolution, OLEDs have demonstrated wide color gamut, in excess of 100% of the sRGB standard. (sRGB stands for standard RGB and is a color space created by HP and Microsoft in 1996.) This is because OLEDs can emit pure primary colors directly, while color filters are devices that transmit a range of wavelengths that, depending on material and thickness, can be rather broad. The broader the range of wavelengths around each color, the more limited the overall gamut is. By using a thicker color-filter layer, LCDs can increase color gamut, but at the cost of higher power. In the new iPad display, the combination of doubling the resolution and increasing the color gamut from 65% to 100% of sRGB required more white LEDs in the backlight.

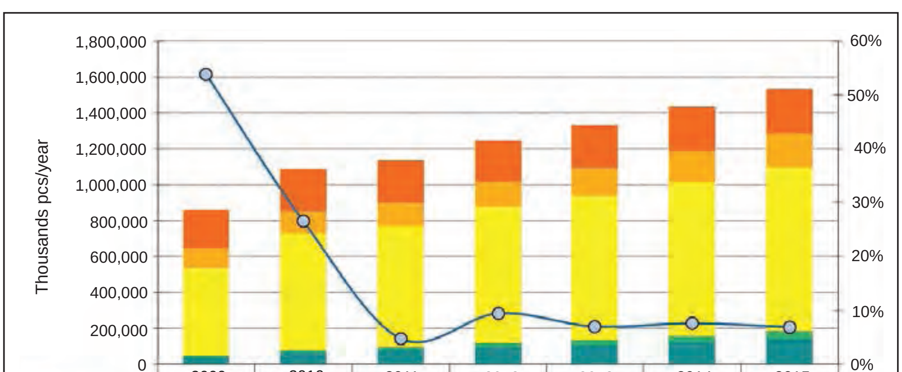
There are other ways to increase color gamut, particularly through the choice of LED phosphor and luminance. Quantum dots can enable high-efficiency color conversion by absorbing broadband light and emitting narrow spectra, which can be tuned to the color-filter bandwidth. 3M is working with Nanosys to make quantum-dot enhancement film. (See the article "Quantum Dot Displays: Giving LCDs a Competitive Edge Through Color" in this issue.)

Color-Filter Manufacturing

Color filters are produced in-house by panel manufacturers as well as by dedicated merchant manufacturers, who purchase glass substrates, deposit the color-filter layer, and sell the coated sheet to panel makers. While older-generation lines tend to use merchant suppliers, Gen 7 and larger color filters are produced in-house or nearby due to high transportation costs. Since 2005, the largest panel makers have also been the leading color-filter manufacturers. In 2013, in-house production is expected to account for 83% of color filters. Korean and Taiwanese panel makers are almost completely self-sufficient in color-filter production, whereas Japanese panel makers rely heavily on DNP and Toppan for their color filters. Japanese color-filter makers DNP and Toppan have historically been the leading merchant suppliers; for the past several years, they have focused on supplying Japanese panel makers, particularly for small-to-medium display production. They have also been supplying several Chinese panel makers, who use a mix of in-house and merchant suppliers, including some domestic suppliers. Taiwanese color-filter makers have mostly exited the business or converted capacity to touch-sensor production.

The biggest challenge for color-filter development has been the limited growth of the LCD market that drives demand (Fig. 5). There have also been threats to the concept of the color filter, mainly in the form of field-sequential-color approaches, in which rather than arranging the primary colors spatially, across each pixel, colors are presented temporally, through the use of sequential firing of RGB backlights, for example. This allows for elimination of the color filter, although it requires very fast-switching liquid-crystal materials because the frame rate is tripled; this also tends to cause optical effects, often perceived as a rainbow in the peripheral vision. One potential way to deal with the problem of needing fast-switching liquid-crystal material is to eliminate it and use a faster material; this approach has been developed by Pixtronix (now part of Qualcomm), which uses MEMS, and demonstrated by several panel makers.

For now, the biggest challenge for color-filter makers is that, for panel makers, the color filter is a cost element to be controlled, which exerts constant pressure on pricing and revenues. However, color filters will remain a critical component in LCDs and are likely to be increasingly important as panel makers struggle to balance high resolution, wide color gamut, and power consumption. ■



	2009	2010	2011	2012	2013	2014	2015
Desktop Monitor	214,707	239,364	243,359	230,152	239,072	245,628	250,409
Notebook PC	111,123	121,507	129,163	141,495	158,989	174,076	187,060
LCD TV	484,532	649,196	669,238	756,201	802,128	856,686	912,038
LA Others	9,524	11,982	16,516	20,975	25,644	33,142	43,707
Small&Medium	38,865	64,600	80,274	97,355	107,801	125,635	141,116
Total	858,751	1,086,648	1,138,550	1,246,179	1,333,633	1,435,166	1,534,331
Growth	54%	27%	5%	9%	7%	8%	7%

Fig. 5: Slow growth in most LCD applications limits the growth for color filters, shown here in 19-in. equivalents. However, rapid growth in smartphones, tablets, and other small-to-medium applications is leading to a doubling of its share of color-filter demand. Source: DisplaySearch Quarterly Color Filter Report.

Characterization of 3-D Gray-to-Gray Crosstalk with a Matrix of Lightness Differences

Stereoscopic televisions, which are mainly striped-retarder displays with passive glasses or time-sequential displays with active glasses, are emerging in the consumer market. 3-D crosstalk is an important characteristic that defines the quality of these displays. A new crosstalk metric is proposed that uses an intuitive matrix representation with perceptually relevant lightness-difference values instead of the single percentage value that is often used.

by Hans Van Parys, Kees Teunissen, and Aleksandar Ševo

STEREOSCOPIC TVs are becoming commonplace in the consumer market. Available models are usually striped-retarder displays with passive glasses or time-sequential displays with active glasses. The most important characteristic in defining the quality of 3-D image perception, and therefore the quality of the user experience, is inter-ocular crosstalk. The use of a good characterization method for crosstalk is crucial to enable direct comparison of the performance of 3-D TVs and technologies. This means a characterization method that is well-defined and easy to measure, calculate, and interpret. Only with a good characterization method can the performance of different stereoscopic displays be compared and insight be gained as to the source and nature of crosstalk, which will, in turn, lead to improvements in 3-D performance.

Different 3-D crosstalk formulas are proposed in the literature.[1-3] A commonly used crosstalk definition is discussed in more detail in the next paragraph. The shortcomings of this characterization are shown, and a better characterization method is derived in the following paragraphs.

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Commonly Used 3-D Crosstalk Characterization

A 3-D crosstalk characterization commonly used in the industry today is provided in the equation below. It is based on the combination of white and black test images for the left and right views (see Fig. 1) when the luminance is measured through, for instance, the left lens of the 3-D glasses.[4] The equation below assumes "identical" behavior for left and right views.

$$X = \frac{L_{B,W} - L_{B,B}}{L_{W,B} - L_{B,B}} \times 100\%$$

in which $L_{M,N}$ is the measured luminance with M in the observed and N in the unobserved image. M and N can be white (W) or black (B).

However, this formula has several severe drawbacks, especially for the characterization of time-sequential 3-D LCDs. First of all, the characterization of 3-D crosstalk with only one number does not make sense for many 3-D display types: 3-D crosstalk can be heavily dependent on the applied gray levels, and, as such, also on the image content. This has already been noticed and concluded by, for instance, Shestak *et al.*[3] and Barkowsky *et al.*[5]

A second drawback is that white-to-black and black-to-white crosstalk are mixed into one formula. This makes the interpretation of the result less than obvious. Moreover, it becomes problematic when $L_{W,B}$ is higher than $L_{W,W}$ – this is possible in time-sequential 3-D displays: with $L_{W,B}$ in the nominator, the crosstalk will decrease with higher $L_{W,B}$, although more crosstalk will be visible. An improvement can be made here by replacing $L_{W,B}$ with $L_{W,W}$.

Finally, Xia *et al.*[6] found a poor correlation between perceived crosstalk and crosstalk as determined by several crosstalk equations. In particular, the white-to-black crosstalk (see, *e.g.*, Fig. 2) is much more visible than the black-to-white crosstalk, although the crosstalk percentage values could be identical. This clearly demonstrates the necessity for a perceptually relevant characterization method.

A New Method for 3-D Crosstalk Characterization

A proposed measurement setup is shown in Fig. 3. A luminance meter is directed perpendicularly toward the center on the display surface. The 3-D glasses are mounted in front of the luminance meter with the meter measuring through one of the lenses. The glasses should be mounted in a position similar to what their position would be if a person was wearing them to watch the 3-D display.

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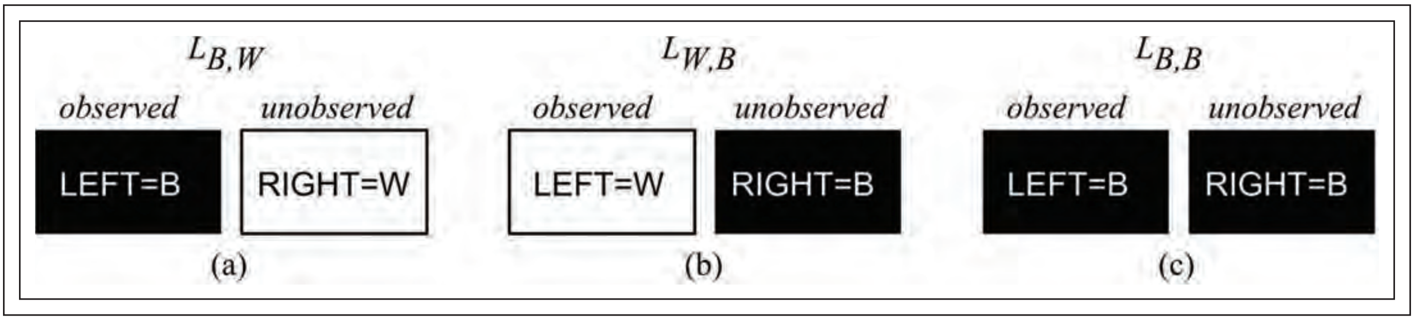

***Fig. 1:** A combination of left and right images while measured through the left-eye lens of 3-D glasses.*

During the measurement, a range of test patterns are rendered on the display and for each test pattern, the luminance is measured through the glasses. These test patterns are generated with different combinations of two gray levels for the left- and the right-eye image as shown in Fig. 4 (left).

Conventionally, only the four combinations of full black (B) and full white (W) are measured. Especially for the time-sequential 3-D LCDs, this leads to an incomplete characterization. For these displays, the crosstalk is strongly dependent on the particular combination of gray levels for both eyes, due to intrinsic properties of LCDs and response-time compensation technologies. Thorough characterization of time-sequential 3-D displays may require as many as 17 gray values per view. This leads to a 17 × 17 measurement grid containing 289 cells. However, for convenience, we will restrict the examples in this paper to a 9 × 9 measurement grid.

Interpretation of the Measurement Grid

The measurement grid in Fig. 4 (right) shows the luminance values as recorded by the luminance meter. In this example, the applied gray values (in the gamma-corrected domain) on an 8-bit scale are 0, 32, 64, 96, 128, 160, 192, 224, and 255. The value of 0 corresponds to full black and 255 to full white. In the grid, the rows correspond to the values of the unobserved right-eye image and the columns to the values of the observed left-eye image. Obviously, the measurement grid could also have been measured for the right-eye image as the observed image and the left-eye image as the unobserved image. For most stereoscopic systems, however, the obtained measurement grid would be the same.

In the upper left corner, we find the level when full black is applied to both images (left and right view), so this number could be called the "black offset," and it can have multiple origins in the display as well as in the measurement setup. In the lower right corner, we find the full-white level.

On the diagonal, we find the luminance values for the observed left-eye image when the left and right images have equal gray levels. So, on the diagonal we find per definition the crosstalk-free luminance values for the applied gray levels, or in other words, the "target luminance levels."

When the system is crosstalk free, *i.e.*, when the observed image is not influenced by the unobserved image, the luminance values should be constant down every column because in theory the gray level of the unobserved image (right eye in this example) should have no impact on the gray-level measured from the observed image (left eye in this example). That would represent a case of no crosstalk at all. In this example, this is apparently not the case; in some cells, the luminance is higher than the luminance on the diagonal. In other cells, it is lower.

Conversion to a Lightness Value

Instead of calculating crosstalk numbers by subtracting and dividing luminance values, we will first perform a conversion to a "lightness value." This step will make the resulting crosstalk figure more perceptually uniform.

To do this, we first subtract the "black offset" and normalize on the full-white luminance level. Then we apply the lightness

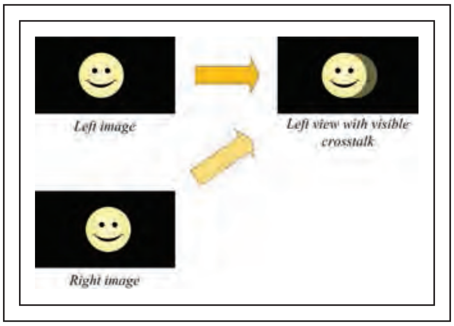

***Fig. 2:** The image at the far right shows the effect of visible crosstalk.*

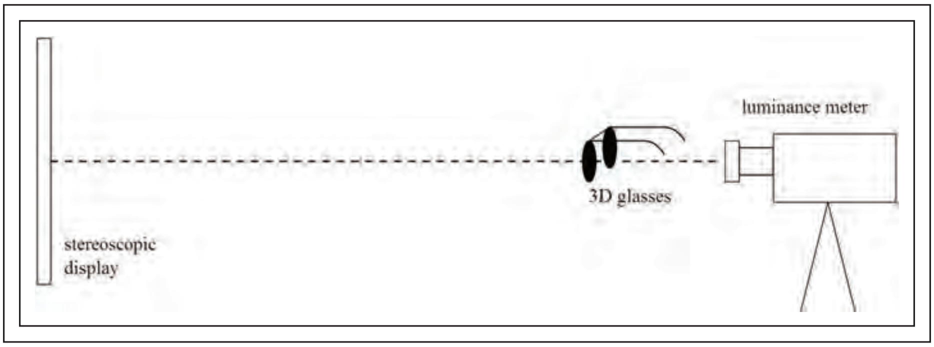

***Fig. 3:** This measurement setup includes a stereoscopic display, 3-D glasses, and a luminance meter directed perpendicularly toward the display and measuring through one of the lenses of the glasses.*

unobserved image \ observed image	G0	G1	G2	G3	G4	G5	G6	G7	G8
G0	0.22	0.31	1.4	3.5	8.1	14	23	35	50
G1	0.23	0.42	1.9	4	9.1	14	23	35	50
G2	0.24	0.51	1.5	4.1	8.6	15	25	38	51
G3	0.26	0.47	1.8	3.8	8.3	15	27	37	50
G4	0.32	0.57	1.6	3.8	8.2	15	24	37	50
G5	0.43	0.51	1.3	4.2	8.1	14	23	34	48
G6	0.59	0.62	1.5	4.6	8.3	14	23	34	46
G7	0.9	0.87	1.5	3.2	9	14	23	33	46
G8	1.4	1.4	1.8	3.4	8.7	15	23	33	46

***Fig. 4:** At left are test images for the left eye (observed image) and the right eye (unobserved image); at right is a measurement grid for the combination of left-eye (observed image) and right-eye (unobserved image) gray levels.*

formula from the CIELab colorspace.[7] We propose to use a scale factor of 255 (8-bit equivalent) instead of 100, as this makes the formula more intuitive for engineers working with image processing: the results can be interpreted as 8-bit (gamma-corrected) gray values. Besides, the scale factor of 255 better suits the rounding used in the last step of the procedure.

For any cell on coordinate *r,c* (where *r* is unobserved image and *c* is observed image) on the measurement grid, the conversion from luminance to 8-bit normalized lightness values (0..255) is expressed by the following formula:

$$L_{r,c} = \frac{255}{100}\cdot\left(116\cdot f\left(\frac{Y_{r,c}-Y_{0,0}}{Y_{N,N}-Y_{0,0}}\right)-16\right)$$

$$f(x)=\begin{cases} x^{1/3}, & x>\left(\frac{6}{29}\right)^3 \\ \frac{1}{3}\left(\frac{29}{6}\right)^2 x+\frac{4}{29}, & otherwise \end{cases}$$

where $Y_{r,c}$ is the luminance in each cell as measured by the luminance meter, $L_{r,c}$ is the corresponding lightness, $Y_{0,0}$ is the "black offset," and $Y_{N,N}$ is the full-white level. As an alternative, a simplified formula with a pure power law could also be used:

$$L_{r,c} = 255\left(\frac{Y_{r,c}-Y_{0,0}}{Y_{N,N}-Y_{0,0}}\right)^{1/\gamma}.$$

The exponent 1/γ can be discussed. We propose to use 1/2.2 because, although 1/2.4 is a closer match to the overall CIELab function, 1/2.2 is a better match where it matters most, *i.e.*, for low light values.

The conversion of the luminance grid to a lightness grid is shown in Fig. 5 (left). This conversion can be interpreted as follows. The numbers show what lightness is perceived for any combination of gray-level values for the observed and unobserved image. Again, on the diagonal we find the "target lightness" for the columns. The difference between a cell's lightness and the target lightness of its column can be qualified as the visible crosstalk. Therefore, to construct the final crosstalk grid, we subtract from the value in every cell the value on the diagonal in the same column and round the result to the nearest integer.

As a consequence, the result will show zeros on the diagonal, and this fits with our previous observation that there is no visible crosstalk for combinations on the diagonal, per definition. Please notice that with our 8-bit representation, rounding leaves enough precision for practical applications and makes interpretation faster.

An additional enrichment is a small modification on the sign: for all cells above the diagonal, we will invert the sign. This will give a consistent relationship between the sign of the crosstalk number and the direction of crosstalk: a positive number will always denote a type of crosstalk that has its luminance level between the observed and unobserved luminance levels (see the equation below).

$$XT_{r,c} = \mathrm{sgn}(r-c)\cdot \mathrm{rnd}(L_{r,c}-L_{c,c})$$

Finally, the crosstalk grid can be made even more intuitive by applying a bipolar color map. For example, in Fig. 5 (right), crosstalk with a positive number obtains a blue color, crosstalk with a negative number obtains a red color, and crosstalk-free cells are black. The more crosstalk, the more saturated the color. The result is a gray-to-gray crosstalk grid in a perceptually uniform lightness domain that can be interpreted quickly, without the necessity for a three-dimensional graph.

The bipolar color map in Table 1 is inspired by a submission in the Matlab Central File Exchange[8] and describes the exact color mapping. In Table 1, a color value of one is the maximum value for that color. Outside the range of [-64, 64] colors are clipped to the values for -64 or 64. The colors for crosstalk numbers in between those mentioned in the table are linearly interpolated.

Interpretation of the Crosstalk Grid

Contrary to crosstalk percentages, the lightness-difference-based crosstalk numbers have a more perceptually intuitive meaning. The conversion to lightness makes the result an approximation for perceptual uniformity. The absolute value of the crosstalk number is a

Table 1: This bipolar color map allows a quick interpretation of the crosstalk matrix.

Crosstalk number	red	green	blue	Color
–64	1	1	0	(yellow)
–32	1	0	0	(red)
0	0	0	0	(black)
32	0	0	1	(blue)
64	0	1	1	(cyan)

observed image (columns) / unobserved image (rows)

	G0	G1	G2	G3	G4	G5	G6	G7	G8
G0	0	4.77	47.6	82.1	123	158	194	229	263
G1	0.552	10.1	57.8	87.8	130	158	194	229	263
G2	1.1	14.7	50	89.4	127	160	201	235	265
G3	1.96	12.8	54.5	85.9	125	164	205	234	264
G4	5.37	17.8	52.2	85.9	124	160	198	233	263
G5	10.7	15	44.7	89.8	124	159	194	227	258
G6	18.7	20.1	49	94.5	125	158	193	225	256
G7	32.1	31	50.1	77.9	129	158	193	225	255
G8	45.8	45.4	56	80.8	128	161	192	225	255

observed image (columns) / unobserved image (rows)

	G0	G1	G2	G3	G4	G5	G6	G7	G8
G0	0	5	2	4	1	1	0	-5	-8
G1	1	0	-8	-2	-6	2	0	-5	-8
G2	1	5	0	-4	-3	-1	-8	-11	-10
G3	2	3	4	0	-1	-4	-12	-10	-9
G4	5	8	2	0	0	-1	-5	-9	-8
G5	11	5	-5	4	0	0	-1	-3	-3
G6	19	10	-1	9	1	-2	0	-1	-1
G7	32	21	0	-8	5	-1	0	0	0
G8	46	35	6	-5	4	2	-1	0	0

Fig. 5: At left is a measurement grid converted to lightness. A final crosstalk representation as a grid of lightness differences appears at right.

measure of the visibility of the crosstalk – it denotes how many "gamma-corrected gray-level values" (on an 8-bit scale) the crosstalk is away from the target level.

In the lower left corner of the grid, we find the white-to-black crosstalk, generally the most dominant crosstalk factor in the display, and in many other 3-D characterization methods the only crosstalk number that is focused upon.

The sign of a crosstalk number denotes the direction of crosstalk. Striped-retarder stereoscopic displays will generally only show positive crosstalk numbers. This type of crosstalk is due to leakage of the light intended for one view into the other view. In time-sequential stereoscopic displays, however, crosstalk with a negative number is also present. The origin of this is "overcompensated" crosstalk or so-called "overshoots".

This method could be seen as a simplification of the method using the DICOM standard and the concept of just-noticeable differences (JNDs) as proposed by Teunissen *et al.*[9] This is shown in Fig. 6, where a comparison is made between the two methods. The middle grid shows the ΔJNDs calculated from the same luminance measurements and adapted with the sign and color conventions as proposed here. In the right grid, the ΔJNDs are scaled for equal numbers on white-to-black crosstalk. The similarity between lightness differences and (scaled) ΔJNDs is clearly visible. This observation supports the corre-

Left – observed image (columns) / unobserved image (rows)

	G0	G1	G2	G3	G4	G5	G6	G7	G8
G0	0	5	2	4	1	1	0	-5	-8
G1	1	0	-8	-2	-6	2	0	-5	-8
G2	1	5	0	-4	-3	-1	-8	-11	-10
G3	2	3	4	0	-1	-4	-12	-10	-9
G4	5	8	2	0	0	-1	-5	-9	-8
G5	11	5	-5	4	0	0	-1	-3	-3
G6	19	10	-1	9	1	-2	0	-1	-1
G7	32	21	0	-8	5	-1	0	0	0
G8	46	35	6	-5	4	2	-1	0	0

Middle – observed image (columns) / unobserved image (rows)

	G0	G1	G2	G3	G4	G5	G6	G7	G8
G0	0	8	3	6	1	2	-0	-6	-10
G1	1	0	-11	-3	-9	2	-0	-6	-10
G2	2	6	0	-5	-4	-2	-11	-14	-13
G3	4	4	6	0	-2	-6	-16	-12	-11
G4	10	10	3	-0	0	-1	-7	-11	-9
G5	18	6	-7	6	-0	0	-1	-3	-4
G6	27	12	-1	13	2	-2	0	-1	-1
G7	43	25	0	-12	8	-1	-0	0	-0
G8	[illegible]	43	8	-8	5	3	-1	-0	0

Right – observed image (columns) / unobserved image (rows)

	G0	G1	G2	G3	G4	G5	G6	G7	G8
G0	0	6	2	4	1	1	-0	-5	-8
G1	1	0	-8	-2	-7	2	-0	-4	-8
G2	2	5	0	-4	-3	-1	-8	-10	-9
G3	3	3	5	0	-1	-5	-12	-9	-8
G4	7	7	2	-0	0	-1	-5	-8	-7
G5	13	5	-5	4	-0	0	-1	-3	-3
G6	21	9	-1	10	1	-2	0	-1	-1
G7	32	19	0	-9	6	-1	-0	0	-0
G8	46	33	6	-6	4	2	-1	-0	0

Fig. 6: Above are comparisons of the lightness differences (left) with ΔJNDs (middle) and scaled ΔJNDs (right).

spondence between our measured crosstalk values (Fig. 6, left) and the (relative) severity of the perceived crosstalk.

The relationship between the level of measured crosstalk and acceptability is not straightforward. The concept of JND, as introduced by Teunissen *et al.*,[9] does provide an answer if crosstalk is just visible (JND = 1), perceptible (JND ≥ 3), or easily visible (JND ≥ 10). However, this is calculated for the most critical case, *e.g.*, a white bar on a black background. For natural images, this critical pattern may not occur or if it occurs, may even be unnoticed. Also, motion in the image may draw attention away from crosstalk. Finally, some image impairments remain unnoticed until someone points them out. After that, those impairments may become unacceptable, while they initially were unnoticed.

A New Way of Looking at Crosstalk

We presented a new method of crosstalk characterization that is suited for all types of stereoscopic displays and is particularly useful for time-sequential stereoscopic displays. The result is a matrix of gray-to-gray crosstalk numbers to be interpreted as corresponding gray-level offset or lightness-based difference values. This representation is a good approximation for perceptual uniformity and clearly shows visibility differences in perceived crosstalk for different gray-level transitions. It allows a quick calculation and analysis of the complete crosstalk behavior of a stereoscopic display device. Although there are no clear guidelines for crosstalk in terms of acceptability, system developers may strive for lightness difference values less than 5.

References

[1]A. J. Woods, "Understanding Crosstalk in Stereoscopic Displays," Keynote Presentation at the 3DSA (Three-Dimensional Systems and Applications) Conference, Tokyo, Japan, May 2010.

[2]A. Abileah, "3-D Displays: Technologies and Testing Methods," *J. Soc. Info. Display* **19**/11, 749–763 (2011).

[3]S. Shestak, *et al.*, "Measuring the Gray-to-Gray Crosstalk in a LCD Based Time-Sequential Stereoscopic Displays," *SID Symposium Digest Tech Papers* **41**, 132–135 (2010).

[4]J.-C. Liou, K. Lee, F.-G. Tseng, J.-F. Huang, W.-T. Yen, and W.-L. Hsu, "Shutter Glasses Stereo LCD with a Dynamic Backlight," *Proc. SPIE, Stereoscopic Displays and Applications XX* **7237**, 72370X (2009).

[5]M. Barkowsky *et al.*, "Crosstalk Measurements of Shutter Glasses 3-D Displays," *SID Symposium Digest Tech. Papers* **42**, 812–815 (2011).

[6]Z. Xia, X. Li, Y Cui, L Chen, and K. Teunissen, "Perceptual Correspondence of Gray-to-Gray Crosstalk Equations for Stereoscopic Displays," *Proc. IDW/AD '12*, 581–584 (2012).

[7]*Colorimetry*, 3rd edition. CIE 15:2004. ISBN 978-3-901906-33-6.

[8]G. Ridgway, "Bipolar Colormap," submission in the Matlab Central File Exchange, 04 Dec 2009.

[9]K. Teunissen *et al.*, "Perceptually Relevant Characterization of Stereoscopic Displays," *SID Symposium Digest Tech Papers* **42**, 994–997 (2011). ■

Q&A: ICMD

Q&A: A Conversation with the People Behind the IDMS

The Information Display Measurements Standard (IDMS) represents years of work by many individuals in the display industry who form the International Committee for Display Metrology (ICDM). The standard would not exist in its present form, however, without the contributions of ICDM committee chair Joe Miseli and IDMS Editor Ed Kelley. Both Miseli and Kelley recently described the challenges and highlights of the process.

Compiled by Jenny Donelan

THE International Committee for Display Metrology (ICDM) standards project began in 2007 as a replacement for the VESA Flat Panel Display Measurement (FPDM) standard, which the same authors wrote. It became a monumental effort that redefined the standards for the optical metrology of displays. In June of 2012, the Information Display Measurements Standard (IDMS), containing approximately 140 different display measurements, was released as both a free download and a hardcopy for purchase (see sidebar for availability).

In the words of the ICDM literature: "The IDMS is the "Go-To" document for standard measurement procedures to quantify electronic-display characteristics and qualities. It is the culmination of years of effort by engineers and scientists across dozens of organizations to codify the science of display measurement, explain some of the difficulties associated with making measurements, and offer solutions to help make the measurements properly. The IDMS has benefited from the expertise of the ICDM, consisting of display metrologists, electrical, mechanical, software, and optical engineers, physicists, vision scientists, and many other display-related disciplines."

IDMS Editor
Ed Kelley

Hundreds of individuals in the field of displays contributed to the project. Key among them were ICDM committee chair Joe Miseli and Editor Ed Kelley. *Information Display* recently spoke with Miseli and Kelley about the process and how the IDMS will evolve in the future.

ID: What were the biggest technical and scientific challenges that needed to be addressed to complete the IDMS?

Kelley: The biggest challenges were mostly editorial in nature. I found that I had to rewrite quite a bit of the material to keep it within the style and philosophy of the document.

Miseli: Some of the technical difficulties we encountered had to do with the mass of this project. There are so many measurements and many of them are detailed to the point where other standards organizations might take one of them and turn it into a full-blown standard on their own. In addition, technically we had plenty of resources within our group, but it was sometimes tough for everyone to find the time to work on the project due to the level of detail and time required to produce the quality of metrology per the ICDM's exacting standards.

ICDM Committee Chair
Joe Miseli

ID: What's new in the document, as compared to its former iteration as the FPDM?

Kelley: Of course, there was a lot of material to add to keep pace with industry progress. Stereoscopic 3-D displays were a big addition. We also added front projection and front-projector screens, and a chapter on motion artifacts. Another new chapter is on touch-screen and surface displays. Gray and color scales have been greatly expanded, with more ways to analyze the gamma or tone curves. The uniformity chapter was expanded

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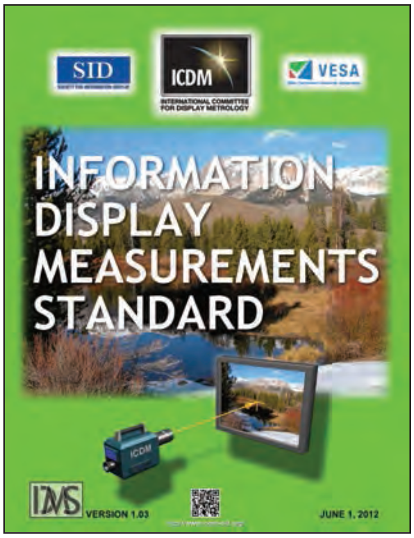

The ICDM license and download of the latest version is available at the ICDM home page http://www.icdm-sid.org, under Downloads or by clicking on the image of the IDMS book. To buy the printed version ($140.00), visit the SID bookstore at http://www.sid.org/Publications/kstore/tabid/836/c/book/p/idms2/Default.aspx

to include the use of tristimulus imaging cameras. Viewing-angle measurements received additions, with emphasis on perception, color, and providing single-number metrics. The temporal-measurements section was improved, and many additions were made to the reflection chapter. A great deal of reflection research had been accomplished since the FPDM and this was included in the new document.

***ID:* What has been the feedback/industry reaction so far?**

Kelley: A number of people have mentioned that it was a monumental task and that they appreciated it.

Miseli: Reactions have been extremely positive. We've had thousands and thousands of downloads. As you know, we made it for free, which was part of our charter coming into SID. The download is free – there is a charge for the printed copy. I will say there's plenty of merit to having a printed copy. It's the kind of document that lends itself to being held in your hand, where you can actually refer to the pieces that you want. It's printed in full color.

***ID:* For companies looking to adopt the IDMS, what kind of investment is needed and how accessible are the methods contained in the standard?**

Kelley: I have a fully functional laboratory in my basement. My total investment is around $200K, which doesn't include $45K for the spectroradiometer. If one were to limit acquisitions to only what is absolutely needed, you could get started for much less. That is the intent of the document, to keep everything as simple as possible.

Miseli: We offer various ways to make luminous measurements, for example, that a person could do with virtually any piece of professional equipment so that they do not need to invest in a specific type of equipment that can be pretty pricey.

***ID:* So, people do not need to build an entire lab?**

Miseli: No, but there are things that people need to have in place, like a darkroom. They don't necessarily have to have extraordinary XY stages and moving devices and so forth. It can be as simple as a luminous measurement device on a tripod for many of the basic measurements. We even have some very fundamental assessments that can be done visually, just to give people an overview of what's going on with their displays, even if they do not have equipment. However, to maximize the value of the standard, one would require more sophisticated and higher- end equipment and software support, which could become rather pricey, depending on the amount of sophistication and automation that one chose to utilize.

***ID:* Once you've caught your breath, what's in store for the next version of the IDMS?**

Kelley: We can expect that there will be additions to all the chapters. Head-mounted and near-to-eye (NTE) displays will likely be added as a chapter, as will transmissive displays. Flexible displays need to be added, especially in the reflection chapter. Reflective displays may also be added as a separate chapter with connections to the reflection chapter. We can expect some contributions in the way of creating composite metrics based upon the existing metrology in the document; such metrics could be useful to those who consider the vision impaired. That could end up being a separate chapter as well.

Miseli: The next version should be ready a couple of years from now. It should have at least 10–25 new measurements in it.

***ID:* What aspect of the document are you most pleased with?**

Kelley: The graphics are by and large improved. The color and gray scales section in particular is rather nicely detailed. I'm pleased with how the document looks overall. This is an example of how to not waste paper by getting everything into a small space that's easy to read and easy to understand. It's not a spaghetti document: You do not have to search here and there to find everything you need to know. The downloadable version is a PDF that's searchable; it's really nice.

Miseli: The document is a complete standard, with all measurements and expanded reference materials within a single cover. The task for getting a document of this scope completed was very challenging, and there were a number of skeptics who doubted that it would ever be completed, as well as others who often suggested making compromises. Yet we persisted and got it done – properly and to our expectations. I'm pleased that we were able to get so many tests and metrology chapters done which address the needs of today's displays, such as for motion artifacts, 3D stereo, projection, touch screens, reflection, temporal measurements, viewing angle, *etc*. Yet, we maintain high quality and clear and concise presentation of the standards methods as well as possible. We have nearly every measurement needed to evaluate displays today in a full color, very-high-quality document, all within a single cover, due to the tremendous expertise and effort of many, many experts who contributed. This document is a great work which is a worthy representative of the first standard from SID and the ICDM. ■

SID Celebrates Its 50th Anniversary

by Larry Weber

On September 29, 2012, the Society for Information Display celebrated its 50th anniversary at the site of the original organizing meeting. SID was founded in Room 3400, Boelter Hall, UCLA, on September 29, 1962, by Dr. Harold R. Luxenberg and 39 attendees who represented major high-tech firms. Three of those 39 attendees attended the 50th anniversary celebration (sponsored by the SID LA chapter): Phil Damon, Dail D. Douchette, and Robert C. Knepper.

3400 Boelter Hall is a large room that has for more than 50 years been used as a lecture hall. A special commemorative plaque has been prepared that will be placed at the entrance of this room, commemorating the founding of SID. SID President Brian Berkeley presented this plaque to UCLA Dean Vijay K. Dhir of the UCLA Henry Samueli School of Engineering and Applied Science. In accepting the plaque, Dean Dhir remarked that most of the current students who attend lectures in 3400 Boelter Hall are now using the display devices in class that were developed by the members of SID.

Preceding the formal anniversary ceremonies, the attendees were treated to a series of excellent lectures by six prominent display experts. Larry Tannas of Tannas Electronics kicked things off by discussing the evolution of SID. He explained how in June of 1961 Dr. Harold R. Luxenberg initiated a UCLA Extension class entitled Information Display Systems. This class drew attention to the need for an international society for displays. In a little over a year after this first class, Luxenberg led the organizational meeting that formed SID 50 years ago and he became SID's first President. In 1963, SID's second President, Rudolf L. Kuehn, inaugurated the "SID Journal," which is now known as *Information Display* magazine.

Tannas then reviewed the history of the rise of LCDs to become the dominant display technology of today. This story included the early dynamic-scattering displays, the invention of twisted-nematic LCDs, the super-twisted-nematic (STN) development, the introduction of the amorphous-silicon thin-film-transistor AMLCDs, and the ultimate dominance of AMLCDs as large-area TV displays.

Next, Professor Ching Tang of the University of Rochester, well-known inventor of the OLED, discussed the OLED and its history. In the '60s, electroluminescence was observed in anthracene, but the devices were very thick and the voltages much too high. The big breakthrough was first published in 1987 by Ching Tang and Steve VanSlyke. This described the fundamental OLED structure that is so familiar today. OLEDs succeeded because (1) highly emissive molecular RGB emitters can be designed and synthesized, (2) the charge-transport problem in organics is manageable, (3) robust desiccant/encapsulation technology is available, and (4) they can piggyback on LCD backplane technology. To develop the very beautiful and practical OLEDs of today, other breakthroughs were achieved, such as high-efficiency phosphorescent materials, solutions to life problems in both organic materials and thin-film transistors, and the discovery of manufacturable lithography methods.

Prof. Ho Kyoon Chung of Sungkyunkwan University, best known for his pioneering R&D of OLEDs at Samsung SDI, discussed AMOLED TV challenges. He first reviewed the current business status, then cited four key issues of AMOLED TV manufacturing:

- The TFT backplane: polysilicon or oxide semiconductor?
- R/G/B side by side or white OLED plus color filters?
- When will printed OLEDs be practical?
- How to differentiate from LCD (LED-backlit) TV?

Regarding the fourth issue, he stated that OLEDs could differentiate themselves from LCDs through innovations such as transparent OLEDs and plastic-substrate OLEDs. After covering the many advantages and challenges of plastic OLEDs, he stated his dream of having practical roll-to-roll AMOLEDs by 2019.

Prof. Shuji Nakamura of the University of California Santa Barbara, who is well known for developing practical commercial GaN blue LEDs, was not able to attend, but his Ph.D. student Yuji Zhao did an excellent job explaining their research on improved LEDs. One exciting area is the development of LEDs

Shown along with the 50th anniversary commemorative plaque are, left to right, Past-President Erv Ulbrich, Past-President Larry Tannas, current SID President Brian Berkeley, UCLA Dean Vijay K. Dhir of the UCLA Henry Samueli School of Engineering and Applied Science, and Carol Tannas. The Carol and Lawrence E. Tannas, Jr., Endowed Chair in Engineering at UCLA is the first engineering chair in the world devoted to electronic information displays.

that emit polarized light. This could potentially increase the power efficiency of LED-backlit LCDs by reducing light lost in the LCD polarizer. An added benefit of their new process is LEDs with reduced droop in light output as drive current is increased. The researchers are also developing high-efficiency green LEDs that fill the notorious green gap by using methods that allow a greater amount of soluble indium in the crystals of InGaN.

Prof. Shin-Tson Wu of the University of Central Florida described how the LCDs of the future will require three times less backlight power by eliminating color filters through the use of the color-field-sequential approach with LED backlights and microsecond-response-time blue-phase liquid crystals. He detailed two new approaches for solving one of the key problems with blue phase by reducing the typically high 50 V drive voltage to only 10 V. This reduction will allow practical a-Si TFT addressing. Prof. Wu then presented possible approaches to achieving an additional factor-of-two power reduction by eliminating the LCD polarizers.

David Barnes of BizWitz made the business case for the future of OLEDs. AMOLEDs are exciting because they are emissive displays. They can be used to re-purpose existing AMLCD assets and create a better cost structure with less materials cost. Materials have been just under two thirds of cost for AMLCDs, and the inability to reduce this ratio as production ramped up is a major reason why many AMLCD manufacturers have recently experienced significant losses. AMOLED manufacturers are seeking an advantage through technology, but the differing choices, such as RGB *vs.* color by white, made by different manufacturers will slow overall industry development. In the end, AMOLED displays have the potential to become the next new display commodity.

SID has had a glorious past 50 years, but, more importantly, the attendees of the 50th Anniversary Celebration walked away with the sense that display technology continues to have a very exciting future. ■

Larry Weber *is a Past-President of SID. He can be reached at larryweber@ieee.org.*

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this new class of semiconductor materials. Parts of this article have also appeared in the *Journal of SID*, but we thought it was such an important foundation topic we persuaded the authors to work with us to produce an ID-friendly version. We are very grateful for their patience and support. While editing this article, I was impressed not only by how versatile these new TFTs could be when used in traditional OLED and TFT applications, but by the many different ways that oxide TFTs might enable future inter-active displays. This is an area that has already seen a great deal of infrastructure investment since it appeared just a few years ago and now shows even more promise.

Next, we hear from authors Jian Chen, Veeral Hardev, and Jeff Yurek, all with Nanosys, in an article titled "Quantum Dot Displays: Giving LCDs a Competitive Edge Through Color." Quantum-dot technology is not new by itself; in fact, we've covered it a couple times previously, but Nanosys has made new strides in packaging its proprietary chemistry into a practical lightguide film it calls "Quantum Dot Enhancement Film (QDEF)." This QDEF film produces a secondary emission in conjunction with a blue LED backlight to produce a finely tuned palette of R-G-B light for optimizing the color performance of LCDs. SID presented Nanosys with the Display Component of the Year award in 2012 for this new material, and now you can read about the details behind its development.

Paul Semenza is a contributing editor of *ID* magazine, and we always enjoy his objective and very insightful analysis of specific technology topics. Therefore, we were pleased when Paul agreed to take a look at the topic of color filters for this month's Display Marketplace feature. This is a topic we have often touched on peripherally, such as in articles about multi-primary displays or different color-filter patterning schemes (*i.e.*, PenTile), but not something we have covered from the top down in the way Paul has done it for us this month. I was, for example, very surprised to learn about the degree of vertical integration of color-filter manufacturing among Asian panel makers and the degree of technological diversity in this field. I'm sure you will enjoy it as well, and thanks to Paul for his effort on this topic.

Although the 3-D TV buzz has died down somewhat, there are still a lot of opportunities for performance improvements and some very dedicated metrologists are working on better ways to measure that performance. One effort in this area that is addressed this month is a proposal of a new method for "Characterization of 3-D Gray-to-Gray Crosstalk with a Matrix of Lightness Differences," by authors Hans Van Parys, Kees Teunissen, and Aleksandar Ševo. In this very detailed piece we learn about the complexities of crosstalk performance when the analysis includes the intermediate gray-to-gray transitions between left- and right-eye images. The authors use their new approach to illustrate how crosstalk performance can be highly dependent on the specific gray levels chosen for each eye and how this varies from the typical black-white measurements currently used in most cases. To make their data-collection process easier to understand, they provide an interpretation method involving just-noticeable lightness differences in a simple color-coded matrix. A basic computer program can be used to generate this data from a standard set of measurements, providing a much richer profile of a display's true stereoscopic image performance. While reading their article, I was reminded of earlier work on LCD pixel response times, when we all quickly realized that in order to fully understand motion-blur performance on a subject panel, we needed to characterize the response time between all intermediate gray levels, not just black to full white or vice versa.

In another article, we take a look behind the scenes of what is incontestably the most important document in display metrology: the Information Display Measurements Standard (IDMS). This monumental effort, released in June of 2012, redefined the standards for the optical metrology of displays. *ID* recently interviewed IDMS committee chair Joe Miseli and IDMS Editor Ed Kelley, and they were pleased to share some of the details behind the creation of the document, as well as how the IDMS will evolve in the future.

At the beginning of this editorial, I mentioned SID's 50th Anniversary meeting held in Los Angeles in late September. SID Past-President and good friend Larry Weber was there, and he filed our SID News feature this month on the highlights of the celebration, which by all measures appeared to be a great success. I was there in spirit, and you can be as well when you read his submission. Also, mark your calendars for Display Week in Vancouver in 2013, which will include the 50th SID Symposium and Exhibition. A lot has happened in the past 50 years and a lot more will be happening in the next 50.

Intel's co-founder Gordon Moore coined a phrase known as "Moore's Law" based on his predictions that the number of transistors on integrated circuits would double approximately every 2 years. Others have helped that expression evolve into various exponential predictions of technological growth doubling in various periods of time. There is no doubt that many aspects of display technology have followed this type of function, at least for a significant number of years. Consider, for example, the growth of resolution and content in both physical devices as well as content streams. While changing very slowly before the 1960s, it started to expand in the '70s and '80s and then "went vertical" as they say in the '90s and '00s as we watched LCDs, computers, and digital broadcasting all become pixel rich. The trend is continuing at an exponential pace through the '10s, as we talked about extensively in the last issue of *ID* (November/December 2012). Pretty soon we might be buying giga-pixel cameras and watching movies on our UHDTV stereoscopic tablet computers where even a magnifying glass would not reveal the matrix. In whatever field of display technology you work, I'm sure you can express a similar example based on what you have seen. As we look ahead to the next 50 years I'm sure we will see these growth trends continue, and even branch into new discoveries we can't even imagine today.

And so, while the snow continues to fly and spring remains a few months away, enjoy this issue of *ID* and think about your own hopes, dreams, and ambitions for 2013 and beyond. Happy New Year! ■

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SID 2012 include Sharp's 500-ppi-resolution mobile LCD panel and 31.5-in. UHD LCD panel, each of which use IGZO TFT backplanes.

The next article, by Dr. Jian Chen, Veeral Hardev, and Jeff Yurek from Nanosys, describes the use of semiconductor quantum dots to both enhance the color performance of LCD panels and to enable their image quality to compete with OLEDs. While the basic size-dependent photoluminescence property of this class of nanomaterials has been known since the early 1990s, when the synthesis and study of these materials exploded, it took the confluence of a few factors to identify breakthrough opportunities in display applications. The Nanosys team describes the development of a quantum-dot enhanced film (QDEF) to be used as a drop-in solution in minimally modified LCD backlights for improving the spectrum emitted by LCDs. The minimal modification consists of employing blue LEDs instead of the regular white LEDs, with the QDEF acting as a downstream color-conversion layer that produces red and green colors from a portion of the blue light emitted from the edgelit lightguide. The LCD color improvement is so noticeable, with a measured gamut in excess of 100% NTSC, that it garnered this technology the SID 2012 Display Component of the Year Gold Award.

Next, in our Display Marketplace article, Paul Semenza from NPD DisplaySearch gives an overview of LCD color-filter materials, architectures, and manufacturing topics. The key role played by these materials in LCD image quality and power consumption is described, as well as current manufacturing trends across various panel makers.

We would like to thank all the authors for sharing with us their expert opinions on these important developments in display materials and applications. The undersigned never ceases to be fascinated by the contributions of materials science and engineering that enable the visually rewarding experience working with displays and hopes that you will also enjoy reading the articles in this issue. ■

***Ion Bita** is Senior Staff Engineer at Qualcomm MEMS Technologies, San Jose, CA. He can be reached at ibita@qmt.qualcomm.com. The opinions expressed in this article are his own and do not reflect the opinions of his employer.*

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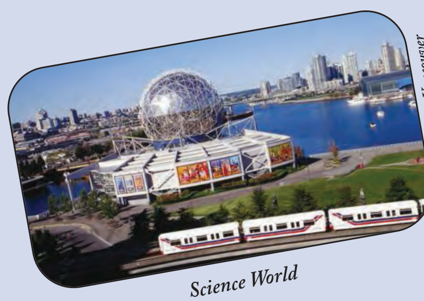
Display Week 2013

SID International Symposium, Seminar & Exhibition

Vancouver Convention Centre
Vancouver, British Columbia, Canada
May 19–24, 2013

Tourism Vancouver

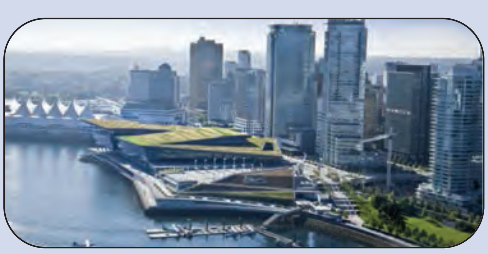
Grouse Mountain's Skyride Gondola



Tourism Vancouver

Science World

Display Week will be held May 19–24 at the Vancouver Convention Centre, with the exhibition open from May 21–23. Display Week is the once-a-year, can't-miss event for the electronic information display industry. The exhibition is the premier showcase for global information-display companies and researchers to unveil cutting-edge developments in display technology. More display innovations are introduced year after year at Display Week than at any other display event in the world. Display Week is where the world got its first look at technologies that have shaped the display industry into what it is today; that is, liquid crystal display (LCD) technology, plasma display panel (PDP) technology, organic light emitting diode (OLED) technology, and high definition TV, just to name a few. Display Week is also where emerging industry trends such as 3D, touch and interactivity, flexible and e-paper displays, solid state lighting, oxide TFTs, and OLED TV are being brought to the forefront of the display industry. First looks like these are why over 6500 attendees will flock to Vancouver, Canada, for Display Week 2013. Display Week 2013 will cover the hottest technologies in the display marketplace.



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The I-Zone will give attendees a glimpse of cutting-edge live demonstrations and prototypes of the display products of tomorrow. Researchers from companies, startups, universities, government labs, and independent research labs will demonstrate their prototypes or other hardware demo units for two days in a dedicated space in the main Exhibit Hall. The "Best Prototype at Display Week," to be selected by the I-Zone Committee, will be announced at the Awards Luncheon.

SID DISPLAY WEEK

Vancouver 2013

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