DIGITAL SIGNAGE AND DISPLAY MATERIALS

Information DISPLAY

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New Directions for Digital Signage

EVOLUTION OF DIGITAL SIGNAGE

MARKET DYNAMICS OF PUBLIC DISPLAYS

OXIDE-TFT PROGRESS REPORT

AMORPHOUS METAL FILMS ENABLE NOVEL BACKPLANES

Plus:

Optimizing Color Rendering Across Platforms

China's Expanding Display Industry

WILEY

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ON THE COVER: The growth in digital signage remains significant for the foreseeable future. Increasing market demand, which is being met with an aggressive push to develop new products, are enabling improvements in all current technologies, especially those that are LED based. Many new applications are emerging based on these new innovations. The ever-widening availability of content is also driving the need for more displays.

Cover Design: Jodi Buckley

In the Next Issue of *Information Display*

Display Week Preview and Flexible Technology

- 2016 SID Honors and Awards
- Display Week 2016 Symposium Preview
- Rollable AMOLEDs
- Flexible TFT Enables Novel Applications
- Highlights from CES 2016

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contents

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editorial

Sign of the Times

by Stephen P. Atwood

We have probably all seen them, even if we did not realize what we were looking at – the newest generation of electronic signs and interactive displays that are popping up everywhere in new form factors and innovative designs. This latest generation is enabled by the impressive work from digital-sign display manufacturers. New and really unique capabilities are finally becoming affordable thanks in part to recent commercial developments in LEDs and LCDs, along with the imaginations of marketers and retailers. An example appears on our cover this month from my region of the world. This is in the Hall of Fame at Gillette Stadium in Foxboro, Massachusetts, where the New England Patriots play football. These futuristic looking kiosks, set against a backdrop of direct-view high-resolution LED displays from NanoLumens showing full-motion video, create a very exciting visitor space. These displays are made from high-density R-G-B LED building blocks the company calls "nixels" that can be assembled in a wide variety of shapes and form factors. These displays are part of the overall recent renovation of the venue and typical of what designers are looking to do in public spaces these days.

When I think about this marketplace, my first thoughts are not the numbers (although we will see later that they are trending well) but the ways in which digital signage can change how we interact with the world around us. We all respond better to things that are pleasing and entertaining. Whether we are in sports venues, shopping malls, restaurants, or other public areas, our experiences are greatly enhanced by good design and pleasing sights and sounds. Previous generations of electronic displays in these places might have been described as clunky or even in some cases, garish. They usually did not fit well into the environment and frequently presented disappointing image quality. Remember the days of CRT TVs or early generation flat panels hanging from the ceilings in retail stores? Yes, me too, and they were not very attractive.

Well, those days are gone, and we are witnessing the next generation just coming to life. As you will see in some of the illustrations and descriptions in this issue, digital-signage displays are becoming part of the architecture and ambiance of the environment, frequently making a positive and even artistic contribution to the overall visitor experience. New form factors in packaging combined with amazing improvements in resolution, color gamut, and luminance are opening up new ways to design interactive spaces such as the one at Gillette Stadium. These innovations now include advanced content, as these displays stand ready to show high-definition streams at amazingly high luminance levels to stand out in even the brightest indoor and outdoor environments. These new screens are much more advanced than your local sports bar's big-screen TVs. They can be mega-sized screens in large public areas that look really good even from just a few feet away. They can also be draped attractively around the sides of buildings to form unique visual effects that enhance the entire landscape as easily as they can facilitate a more rewarding shopping experience at a countertop or entry-way location. And, of course, they need to do this 24 hours a day, 7 days per week for years upon years, with high asset up times to achieve the investment and return on investment targets set by the owner-operators.

To cover all this, we are extremely grateful to have as our guest editor this month Gary Feather (Chief Technology Officer at NanoLumens and a highly experienced

(continued on page 42)

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Sharp to Complete Sale of North American TV Business to Hisense

Last summer, Sharp announced that it would be exiting the TV business in North America, selling its brand name and its LCD production plant in Mexico to Chinese manufacturing giant Hisense.[1] At press time, the transaction was scheduled for completion on January 6, 2016, for a total of $23.7 million.[2]

Consumers may notice little difference, as Sharp's name will live on, and at least some of the TVs labeled Sharp will be made in Sharp's former facilities. A spokesperson for Hisense said that Sharp and Hisense brand-name TVs will be available in North America in both the premium and the mid-range, while the Hisense name will continue to represent the low end of the market.[2] According to an article in *Forbes* earlier this year, Sharp will continue to sell TVs in Japan, as well as continue to make panels for a wide variety of devices.[1]

[1]http://www.forbes.com/sites/johnarcher/2015/08/01/sharp-exits-us-tv-business/
[2]http://www.twice.com/hisense-outlines-plans-sharp-tv-brand/58474

NEC Introduces Two New Monitors for Professional Applications

NEC Display Solutions of America recently announced new 30- and 27-in. displays (the EA305WMi and EA275WMi, respectively) in its MultiSync line. Designed for dual-monitor configurations, these wide-screen models feature IPS panel technology with wide viewing angles (178° horizontal/vertical), DisplayPort 1.2 inputs and outputs, and NEC's ControlSync technology.

ControlSync allows users to control up to six displays in a multi-monitor configuration. Upon establishing one unit as the master, users are able to control most settings of the multi-monitor setup in unison through the primary monitor. The models also offer "smart sensing" technology, which automatically detects work conditions to determine the proper display brightness with ambient light and human sensors. A comprehensive input panel, including HDMI 2.0, DisplayPort 1.2 out, DVI-D, and 3-port USB hub, connects users to the necessary devices.

According to the company, the wide-color-gamut EA305WMi (Fig. 1), with a resolution of 2560 × 1600, is a cost-effective option for photography, video production, and print, while the sRGB gamut EA275WMi, with a resolution of 2560 × 1440, is ideal for online content development.

***Fig. 1:** The 30-in. NEC MultiSync EA305WMi is a high-resolution LCD designed for multiple-monitor configurations.*

Instrument Systems Now Offers Stray-Light Correction

Instrument Systems GmbH, a developer and manufacturer of high-precision light-measurement systems, is now offering stray-light correction as a calibration feature in its array spectrometers. Stray light can now be suppressed during measurements by an order of magnitude down to 10^{-5}. A 10% higher sensitivity in the UV range after stray-light-corrected calibration leads to about 3–4% higher accuracy in radiometric measurements.

According to the company, this new feature will enable more accurate measurements of UV-LEDs. More accurate determination of the radiometric values of UV LEDs facilitates their characterization and development and supports the various applications of these radiation sources in, for example, the fields of coating, curing, disinfection, and biomedicine.

Osram Plans to Invest Approximately €3 Billion by 2020

Osram, a leading lighting manufacturer based in Germany, has announced that it will invest approximately €3 billion in new technologies and applications by 2020. Recent shifts in the lighting market toward semiconductor-based technologies are creating new opportunities in that area, according to the company, which says that approximately €2 billion will be spent on research and development in the new markets. Additionally, Osram has planned another €1 billion for the construction of a new LED chip plant in Malaysia. ■

M&A BRIEFS

Leyard American Corp Buys Planar Systems

Display maker and designer Planar Systems, Inc., announced that it has recently closed its sale to Leyard American Corp., a subsidiary of Leyard Optoelectronic Co., Ltd., which designs and distributes LED-based display products. In August 2015, Planar and Leyard entered into a merger agreement in which Leyard American Corp. agreed to acquire all of the common stock of Planar for a purchase price of $6.58 per share.

* * * * *

Apple Purchases Faceshift

TechCrunch has confirmed that Apple has bought Faceshift, a motion-capture startup based in Switzerland with technology that captures a person's facial expressions in real time. Faceshift technology was used in the making of the latest Star Wars movie. Apple does not usually make official announcements of its acquisitions (somewhere between 6 and 9 of them are said to have been made in 2015), but this announcement has been widely confirmed.[3] The reasons behind the acquisition can only be speculated upon, but several industry bloggers have suggested gaming and TV-related applications.

[3]http://techcrunch.com/2015/11/24/apple-faceshift/

guest editorial

Amorphous? Again??

by John F. Wager

In the beginning, there was amorphous hydrogenated silicon. That is the gospel; at least with respect to the materials aspects of flat-panel-display backplane technology. More recently, there are amorphous-oxide semiconductors. The article I have contributed to this issue's special coverage of materials, "Oxide TFT: A Progress Report," is essentially a report card on the above-mentioned materials. They form the basis of oxide thin-film-transistor (TFT) or indium gallium zinc oxide (IGZO) technology. Oxide-TFT or IGZO technology is vital to what is going on with backplanes today. The other materials-related article in this issue, "Amorphous-Metal Thin Films Enable UHD Display Backplanes," by Sean Muir, Jim Meyer, and John Brewer from Amorphyx, Inc., proposes that the future is the amorphous-metal non-linear resistor (AMNR). What gives with this obsession with amorphous?

It comes down to scalability. Amorphous thin films are homogenous in two dimensions. Amorphous thin films do not possess grain boundaries. This is important – very important! Impurities and defects tend to originate from and/or segregate to grain boundaries. Grain boundaries introduce bulk and surface morphological inhomogeneities to a thin film. Thus, compared to an amorphous thin film, a polycrystalline thin film with grain boundaries is harder to manufacture and integrate into a product, tends to be less stable and reliable, and is much more challenging to scale to the large-area meter-sized dimensions required for high-volume flat-panel-display commercial applications. Bottom line: amorphous thin films scale.

OK. But why an amorphous *metal*? Answering this question requires a bit of explaining. The starting point is to employ a thin-film diode (TFD) as a flat-panel-display backplane switch instead of using a TFT. However, Amorphyx does not want to use a conventional TFD, *i.e.*, a metal-insulator-metal (MIM) device in which the insulator possesses a large density of traps so that electronic conduction through the insulator occurs by trap-assisted thermal emission. (This is often referred to as Poole–Frenkel emission.) Poole–Frenkel-based TFDs do not have the manufacturability, performance, or reliability required for next-generation commercial flat-panel displays (relying on a material filled with traps is usually a dicey proposition). Instead, the Amorphyx approach is to use a new type of MIM device in which electronic conduction through the insulator occurs by quantum-mechanical tunneling, often referred to as Fowler–Nordheim tunneling. Fowler–Nordheim TFDs appear to be much better suited to meet the commercial challenges associated with future flat-panel-display products. In order to fabricate a Fowler–Nordheim TFD, Amorphyx employs an amorphous-metal bottom contact because it has an atomically smooth surface. Thus, an amorphous metal is required for its atomically smooth surface, allowing for control of the uniformity of the electric field across the TFD insulator, thereby facilitating the realization of a TFD based on Fowler–Nordheim tunneling.

That is why an amorphous metal is used. However, there is a bit more to this story. Even with the availability of higher-performance Fowler–Nordheim MIM diodes, a conventional single-TFD switch backplane architecture is unlikely to be able to compete with alternative state-of-the-art TFT-based flat-panel-display backplane technologies. Instead, a dual-select diode strategy is required. Basically, a dual-select diode pixel consists of two identical TFDs that are biased across two select lines.

(continued on page 43)

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Elemental Evolution of Digital-Signage Components

The strong market growth of digital signage over the past 10 years will be outshone by the expanded performance and applications made possible through recent display and system advances.

by Gary Feather

DIGITAL SIGNAGE can be defined as a wide range of unique out-of-home experiences created with large-area display systems. These public displays can be used separately or tiled together to enable merged images, supporting any size and any resolution by extension. Digital-signage systems are generally commercial/industrial in nature and include both indoor and outdoor varieties. Large heterogeneous audiences experience these displays in many different venues for many different purposes (Fig. 1).

The digital-signage market has grown impressively in recent years. According to a recent report from research firm IHS, shipments of public displays 26 in. or larger are forecast to approach 3 million units in 2015 and close to 4.5 million units in 2019. (For more discussion of the digital-signage market, see the article "New Directions for Digital Signage" in this issue.) While there are a number of technologies that have contributed to this growth, this article will focus on those technologies that are contributing to the evolution and future of direct-view digital signage in particular. (For the purposes of this article, "direct view" refers to digital signage that is not based on projection technology.)

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Market-Growth Opportunities

As mentioned previously, the market for digital signage has been demonstrating profound growth, as the desires of companies to place digital imagery in front of a public audience grows on a global basis. Also, the exponential growth of and increased availability of high-quality HD content has created a need for more displays, larger displays, and displays with increased resolution. Segmentation in

Fig. 1: LED digital signage is used to enhance the environment outside the elevators of the World Trade Center Freedom Tower.

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this market includes solutions for permanent digital-signage installations supporting sports (professional to high school), corporate (internal and public), transportation (airports, trains), casino gaming (statistics and entertainment), retail (advertising and promotion), and government and municipalities.

Group entertainment is another growth segment, as digital-signage image-quality performance now competes to replace or substitute for DLP and LCOS projection in digital-cinema applications. Over 1500 sq. ft. of three existing entertainment projection displays were replaced by Station Casinos at Red Rock Resort in Las Vegas, Nevada, this year with fine-pitch LED displays. Last year, Telstra installed a new LED HD theater in Australia. This wide range of applications (Fig. 2) requires a correspondingly wide range of technology advances and innovations in order to ensure competitiveness and ROI to the owner of the digital sign.

Fig. 2: Digital-signage solutions include, from top to bottom: a Holt Renfrew LED flat window display, an Estee Lauder LED and transparent display in Detroit, and an LED sign at a mall in Australia.

Key Trend: The Transition from Static Signage to Video Displays

One key requirement across all but street/highway-level outdoor signage is the trend toward increasing image quality and video performance. Digital-signage application focus was initially on bright images promoting products and services. These were designed to capture many views and, subsequently, mindshare. Current displays have clear requirements for image quality, true 8-bit color, consistent color points, linear gray scale, higher contrast ratio, HD and UHD resolution (depending on size), and uniformity of image with no visible seams. Even a still image has increased viewer impact if the visual quality is more lifelike. And a large percentage of application spaces for digital signage are now showing video (except for roadside signs). All the market segments highlighted earlier require improved full-frame video quality. While video was initially a significant leap for the industry, this transition is well under way, as digital signs are providing compelling video in all market segments.

In the smallest sizes, early LCD signage has already met or exceeded the video and resolution requirements. LCD-backlight modifications have been able to support the brightness requirements. Tiling and uniformity over large areas are still challenges. The requirements for LED signage indoors and outdoors continue to become more demanding (Table 1).

Digital-Signage Development Progress

Three major categories exist for the display modules that make up large direct-view digital signage:

- LCD flat panels (single panel or multiple panels tiled with seams) adapted for commercial/industrial environments.
- Custom-tiled surface-mounted-device (SMD) RGB LED displays; curved and flat displays (indoor and outdoor). Each tile (~0.5 ft.^{2} in area) is designed to create a seamless display product.
- Flat, seamless, and tiled module arrays of discrete LEDs (one for each color in a pixel) for outdoor usage.

The use of LCD flat panels takes advantage of economies of scale. While a customized ruggedized design is generally required by the digital-signage supplier, the provider is often able to use the flat-panel products already available on the market. Flat panels also have significant advantages in providing the greatest dpi density with existing panel manufacturing (Fig. 3). LEDs, for their part, provide fully adaptable pitch, resolution, and size. The past and current use of the LEDs (discrete and SMD) allows designs that can meet a customer's exact requirements. However, every separate tiled LED display module must be custom designed and then built by manufacturers to satisfy the full seamless display solution. For all applications, a display system design can be either front or rear installable and serviceable (Table 2).

Flat Panels

Flat-panel solutions for large-area digital signage have been provided by both plasma and LCD for many decades. Emissive plasma

Table 1: These requirements for outdoor and indoor LEDs will no doubt continue to increase.

Typical Requirements	Outdoor (LED)	Indoor (LED/LCD)	Comments
Pixel Pitch	25mm–4mm	10mm–1.2mm	Application Dependent
Luminance	5,000 nits–12,000nits	750nits–5000 nits	Application Dependent
Color (8bit/color)	24 bit	24 bit	Delivered to Viewer
Contrast Ratio	2000:1–10:1 (sunlight)	1000:1–10:000:1	Use Dependent
Lifetimes to 70% bright	50,000–100,000 hours	50,000–100,000 hours	Driven by LED/BLU

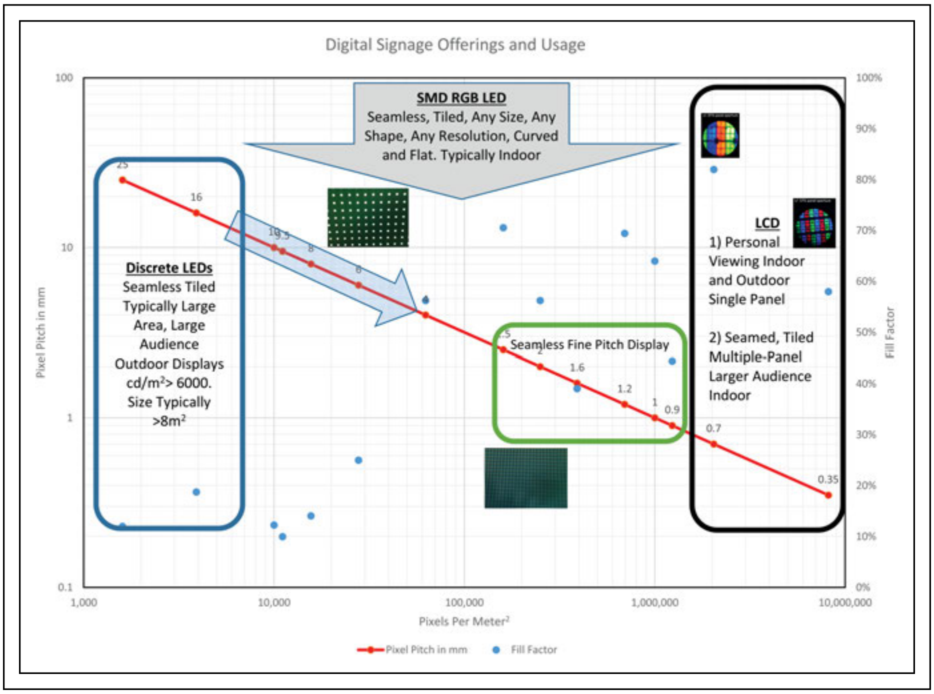

Fig. 3: Three major categories for display modules include discrete LEDs, SMD RGB LEDs, and LCD flat panels.

panels showed great promise in the 1990–2010 time frame, as the size and the luminance (in nits) allowed for the largest single display solutions for indoors and outdoors. Plasma's limited lifespan compared to that of LCD was a significant deficiency. With the monotonic technology and performance increases of LCD panels and the improvements in luminance and ruggedization, the LCD became a real competitor to plasma 5 years ago. From 2010 to today, the LCD has surpassed the plasma panel in a number of areas in both the consumer as well as the commercial market spaces. Those areas include efficacy, resolution cost, and lifetime. As a result, plasma panels as a digital-signage solution have been displaced.

The LCD panel is used in both indoor and outdoor markets. For the outdoor market in a single-panel system, the manufacturer can choose almost any size display that is currently in standard production. Current products support common single displays as large as 90 in., and high-brightness applications >6000 nits for outdoor to indoor common luminance solutions <1000 nits. These implementations can support power and cooling to assure luminance and resolution in keeping with the specified environmental application requirements. The designs are rugged for outdoor and interactive spaces. The methods and processes for meeting the environmental requirements have matured so that high-brightness, reliable, readable, and ruggedized LCDs can be deployed effectively.

For larger-area displays, the large LCD panels can be tiled. In this implementation, the single-panel requirements must be satisfied in addition to the LCD tile-element alignment, calibration, and implementation. Tiled LCDs support larger areas by incorporating an array of displays carefully aligned and calibrated to support a full-screen image. The results are effective, but the image tiling "lines" can be easily seen and are not acceptable in applications in which the customer is looking for a continuous (no lines/seamless) display solution. Current LCD technical approaches do not currently provide for a tiled seamless display, due to both the core pixel layout and the difficulty in expanding the image portion to the very edge of the panel. If visible lines are acceptable, tiled LCDs can create very acceptable large-area displays.

Power requirements are a function of the total luminance requirements, but in general the LCD offers ~5 cd/W at 400 nits and half that at the highest luminance. These compelling HD and 4K displays satisfy nearly all resolution (and dpi) requirements. Resolution capabilities are usually greater than the viewing-distance requirements, resulting in no limitations or design changes. While the panel lifetimes and quality for application are robust in basic performance, the implementation can have a major impact in limiting the lifetime and the quality of the display. For indoor displays, temperature variations across the display can create visual inconsistencies. For outdoor displays, dirt/dust, high temperatures, and UV from sunlight can cause life-limiting effects to the display.

Elemental Technology Drivers For Discrete and SMD LED Displays

The core building blocks for each of these digital-signage solutions have enabled the evolution of the market. Existing unsatisfied needs appear largely from new markets,

Table 2: Digital-signage panel types are listed along with some of the applications for which they are most often used.

Display Type	LCD Single Indoor	LCD Tiled Indoor	LCD Single Outdoor	LED Outdoor Discrete	LED SMD Outdoor Flat and Curved	LED Indoor Flat and Curved
Applications	POS, Retail Advertising, Food menus, Electronic directories	TV Production Studios, Trade Shows, Corporate Lobbies	Drive through window, Direction finding	Large Roadside Billboards, Stadium scoreboards, Advertising	Open Mezzanine areas, Video Entertainment	Malls, Airports, Casinos, Corporate Corporate, Retail, Sports Stadium

enabling advantages for those companies with innovative solutions and leading to new market growth. Each element will be discussed to identify the changes over the past that are leading to future opportunities for both integrated flat panels as well as emissive discrete display solutions based on LEDs. These building blocks are:

- Display Elements and Pixels (size, luminance, design)
- Pixel Pitch (pixel-to-pixel spacing and characteristics for effective seamless tiling)
- Mechanical (weight lbs./ft.^{2}, thickness)
- Power (W/ft.^{2}) and Efficacy (nits/W)
- Resolution/Size Capabilities
- Lifetimes/Quality

Display Elements

The discrete outdoor LED package (Fig. 4) in red, green, or blue allows solutions from 50- to ~10-mm pixel pitch in the outdoors, which is now standard. However, closer viewing in outdoor situations demands a smaller pixel pitch. By employing SMD RGB technology, outdoor displays are now being installed at 8- and 6-mm pixel pitches in flat formats and in one Miami venue, at over 1000 ft.^{2} in a 4-mm pixel pitch on a curved display. The discrete pixel underpins the ability to leverage pixel patterns for better display imagery. Wide spacing and low fill factors provide a number of solutions for tiling and seamlessly creating nearly any size and any resolution. Maturation of the outdoor discrete LED has made possible solutions with wide color gamut and robust mechanical electrical assembly.

The discrete LED as a percentage of all outdoor usage will likely decline as more outdoor panels transition to tighter pixel pitches at 10 mm and lower. Outdoor SMD LED packages have an RGB in each SMD package. Sizes range from 4.5 to ~2.8 mm on a side. These packages are robust to provide package integrity even in the worst environments.

LED solutions for the indoor markets are generally those in which the user is much closer to the display. The technology uses surface-mounted devices, typically with a tighter pitch than 10 mm (per RGB SMD LED). To achieve this, the SMD LED assembly is packaged with one each of a single red, green, and blue LED together. The package size is a function of the die size and the thermal performance as well as the pitch requirement on the SMD-to-SMD spacing. SMD indoor packages are rectangular, with the largest geometries ~3.5 mm on a side. Solutions also exist at 3.0, 2.1, 1.5, and 1.0 mm with 0.8 and 0.6 mm emerging for the finest pixel pitches (1 and 0.9 mm).

Pixel Pitch, Resolution, and Size

LED digital-signage pixel pitches are selected to optimize the expected viewing distance with the greatest pixel pitch to create the optimal image. How much detail you can effectively perceive depends not on how many pixels there are (each with an RGB), but on the pixel density of display (pixels per inch), your visual acuity, and how far away you are from the screen. In addition, there needs to be a sufficient number of pixels on the smallest character or icons so that viewers can discern the character fonts and minimal lines in the input image for the various viewing distances. Factoring in the characteristics of the human eye (limited to no more than 1/60th of one degree), the standard display content and the operating environments, minimal viewing distances can be calculated. In general, the minimal viewing distances to mitigate pixilation in the image for various pixel pitches are ~1000 times the mm pixel spacing. Therefore, a 3-m pixel pitch is nominally best viewed at no closer than a viewing distance of ~3 m. Typical indoor displays will range up to a 10-mm pitch.

The LED indoor and outdoor digital-signage displays have already demonstrated dramatic capabilities in both resolution and total size (m^2 of display). Indoor displays of 150 m^2 and resolutions of over 11 million pixels have recently been installed in the US. As pixel pitch tightens, higher resolutions will be achieved in a number of emerging projects.

Mechanics

In outdoor LED displays, the development emphasis is currently on reducing weight that is caused by the large sizes and the sign structure. Outdoor displays must prioritize and apply a disproportionate amount of the display system's weight to satisfy the environmental requirements and constraints of outdoor events such as wind, rain, extreme temperatures, *etc*. LED displays for indoor applications do not experience these challenges and are being continuously improved in size, weight, and depth. Typical industrial single-sided displays are currently in the 100-mm thickness range with all power and mounting and wiring included. Double-sided displays are usually two times thicker. Display weight is a major factor for competitiveness. Current indoor LED displays range from about 25–30 kg/m^2. Outdoor displays require significantly more construction support for wind and weather and can range from 45 to 60 kg/m^2. There exists significant headroom for future reductions in kg/m^2 in both indoor and outdoor varieties. The use of polycarbonate materials for frames, lighter-weight power supplies, and thinner designs can reduce the mass.

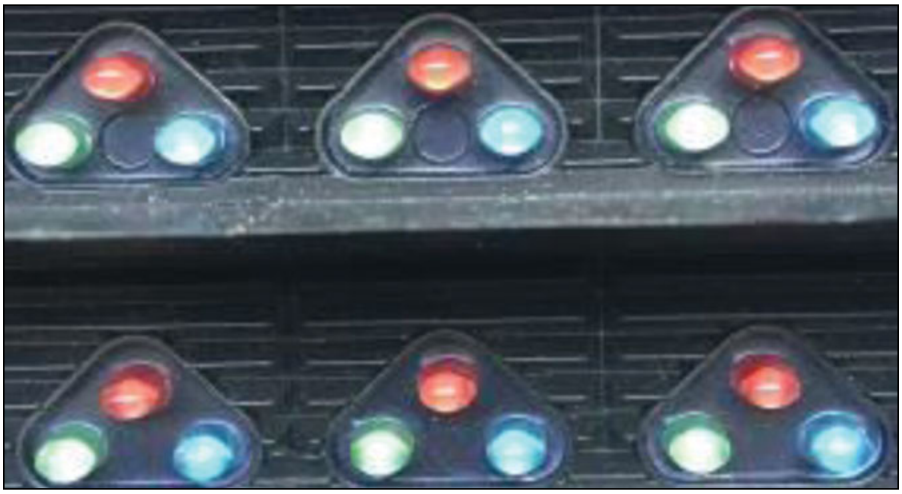

Fig. 4: *Discrete red, green, and blue LEDs are deployed in an outdoor panel.*

Power and Efficacy

Total power consumed by an LED digital sign is a direct result of luminance, display contrast ratio, optical efficacy, pitch, power system, and image calibration losses. White levels are set at D65 (6500K) for consistency across various types of display viewing. Industry efficacy for power input to full-white light output (full end to end) has a wide range across the industry, based upon specific performance requirements. One example is a 6-mm pitch with the nominal contrast ratio at ~7 cd/W. High-contrast 4-mm displays can be at ~4 cd/W and fine-pitch 2-mm displays at ~2.5 cd/W. Future emphasis in this area is for increasing luminous efficacy. Solutions here relate to different distributed power and managing the drive circuits to minimize image off-state power.

Lifetimes/Quality

LED displays, when assembled in adherence with application notes and operated in a fashion consistent with the manufacturer's recommendations, have a lifetime equal to that of the LED. Common LED lifetimes are often specified with a 70% brightness number of 100,000 hours. Derating operating points will exceed that nominal lifetime. Most LED manufacturers follow JEITA (Japan Electronics and Information Technology Industries Association) and JEDEC (Joint Electron Device Engineering Council) standards for accelerated life testing and evaluation to predict relative lifetime advantages of new LED designs. Maintaining a low ambient temperature by properly managing the thermal system design can provide extended lifetimes. In addition, meeting rigorous requirements in die, package, mounting, bonding, sealing, and testing will assure that a device meets its quality requirements and will not be degraded by the environment.

5-Year Vision for Digital Signage

Large-area digital signage for LEDs is entering into a faster adoption and faster performance improvement rate than seen in the last 5 years. Improvements in each area are helping expand the market through new and improved offerings. LCDs have already met most performance requirements. Here is the future direction for these technologies:

• ***LCD Panels***:

The application of LCD panels in digital signage will remain strong based on the technology's firm foundation in the greater LCD panel infrastructure. Solutions are currently fully compliant and the innovation lies in increased reliability and potentially lower cost. More automated calibration will be a benefit to performance over time. Outdoor LCDs (high luminance) need to continue to improve in the areas of reliability and performance to meet the exacting requirements of harsher outdoor environments.

• ***LED Displays***

Outdoor: The revolution in technology (increasing frame rates and bit depth) will focus on non-roadside applications. Outdoor LED-based displays are being used in more open public spaces at close proximity to the audience. As a result, expectations are for the current SMD 10-mm pixel-pitch category to grow rapidly, but, in parallel, for a much faster market growth in 8, 6, and 4 mm. Should the average public-space viewing distances decrease below 3 m, we can expect the pitches to go even smaller.

Shape and size are also differentiators. While in the past, the largest percentage of outdoor displays were rectilinear, expectations would be for concave and convex designs to be used in an increasing number of applications. Large-area seamless continuous displays will still require the same strict tiling requirements for uniformity; smaller pitches and curved will be addressed with successful approaches.

Success in improving efficacy will also continue. Current compelling efficacy numbers for outdoor installations will improve by 30% in the next 2 years and 50% in the next 5 years. Emphasis on the efficacy of the smaller outdoor pixel pitches has the greatest impact to market growth. The current size capabilities of outdoor displays are almost overwhelming, and few improvements are needed to maintain that size. Longer life and increased MTBF will continue at a measured pace, as most market requirements are being met. Improvements to the LED efficacy will impact the greatest percentage of gain.

Indoor: Indoor LED RGB SMD digital signage will show the greatest percentage of revenue growth of all categories in the next 5 years. Current discrete LED packages have already provided for prototype solutions that can be implemented down to 1-mm pitch. The RGB-packaged SMD LED innovations are a solid growth engine for indoor digital signage. Emerging solutions in LED microelectronic packaging and LED arrays in a module will continue to push growth in the finer pitch (<1.9 mm) categories and to support moving to submillimeter pitch (0.9 mm).

In addition, those making finer pitch (<1.9 mm) displays can now begin to consider organic devices such as OLEDs and other integrated solutions over discrete RGB LEDs. Organic devices will need to minimally maintain the best-of-class achieved efficacy and the luminous flux (cd/m^2) while driving down manufacturing times and technology limiting inorganic LED costs. The challenges for digital signage with OLEDs are different from those of television. In addition, there are unique innovations in the interfaces and edges that will allow robust seamless solutions with consistent dimensional requirements approaching control to less than 100 µm.

An Ocean of Opportunity

Digital-signage growth remains significant for the foreseeable future. Increasing market demand, which is being met with an aggressive push to develop new products, are enabling improvements in all current technologies, especially those that are LED based. Many new applications are emerging based on these new innovations. The ever-widening availability of content is also driving the need for more displays. Digital-signage innovation is a blue ocean of opportunities in each segment, and many developers can contribute. ■

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Innovation Zone (I-Zone)

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The prototypes on display in the Innovation Zone at Display Week 2016 will be among the most exciting things you see at this year's show. These exhibits were chosen by the Society for Information Display's I-Zone Committee for their novelty, quality, and potential to enhance and even transform the display industry. Programmable shoes, interactive holograms, the latest head-up displays, and much more will not only fire your imagination, but provide an advance look at many of the commercial products you'll be using a few years from now.

SID created the I-Zone as a forum for live demonstrations of emerging information-display technologies. This special exhibit offers researchers space to demonstrate their prototypes or other hardware demos during Display Week, and encourages participation by small companies, startups, universities, government labs, and independent research labs.

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Ubiquitous Energy

New Directions for Digital Signage and Public Displays

Part one of our two-part series on the market dynamics of digital-signage applications for commercial (or public) displays looks at the growth of the industry and the technologies that are helping shape that growth into the future.

by Todd Fender

NOW that unit shipments of public displays[a] have rebounded from 2012 lows caused by the global recession of 2008–2010 and are showing signs of longer-term sustainability, companies in the digital-signage ecosystem are searching for ways to best position themselves to take advantage of this growth. However, as might be expected, the display landscape has changed in the meantime. New display technologies, resolutions, product features, and form factors are now available. In order to determine their future direction, many display companies are asking themselves which of the above will be the driving forces behind this growth and which vertical markets or applications hold the most promise.

Market Dynamics

After an 18% decline in 2012 and a relatively flat 2013, the global large-screen public-display market rebounded in 2014 by 14.6%. It was up 10% in the first half of 2015 and is forecast to grow through 2019 (Fig. 1).

In 2009, global shipments of public displays 26 in. and larger totaled 1.6 million units. Shipments are forecast to approach 3 million units in 2015 and near 4.5 million units in 2019, according to the most recent Quarterly Public Display Tracker Report from IHS. In Q2 '15, shipments were just over 650,000 units; an increase of 1% Y/Y and –5% Q/Q.

Revenues have grown in a similar fashion. In 2009, global revenues were $1.7 billion. In 2015, revenues will more than double that of 2009 to reach $3.6 billion. In 2019, those revenues are forecast to more than double and exceed $8 billion.

The 60–99-in. size category is forecast to increase at a 33% CAGR from 2014 through 2019, as the 85-in. variety in particular will grow at a 135% CAGR in the same time period. However, 70-in. public displays will show the largest unit volume increase – more than 325,000 units.

Although displays with ultra-high-definition (UHD) resolution will lead on a percentage growth basis, increasing at almost 80% CAGR through 2019, unit growth is only expected to be 330,000 units. Shipments of

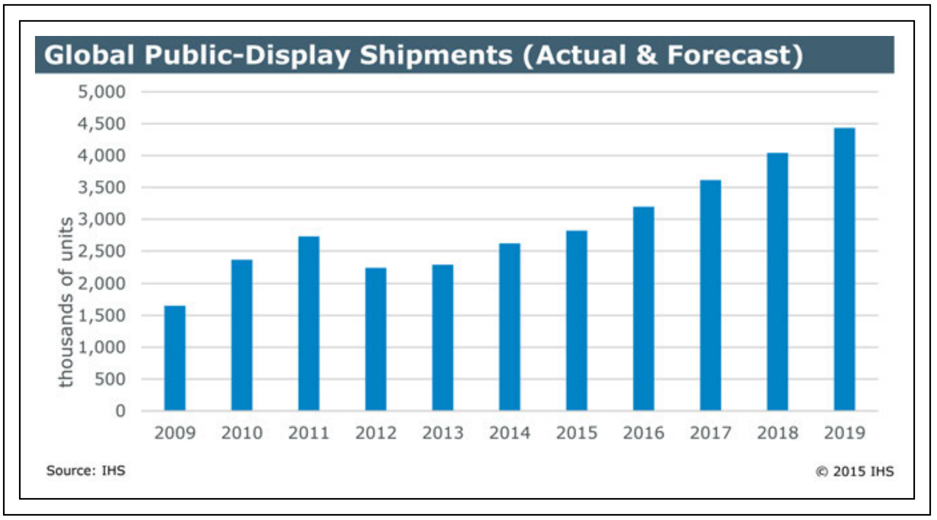

Fig. 1: *Global public-display shipments (actual and forecast) show sustained growth from 2013 through at least 2019.*

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displays with full-high-definition (FHD) resolution are expected to increase by over 2 million units in the same time period.

Digital-Signage Market Technologies

Now that commercial plasma displays are no longer being manufactured, liquid crystals are the dominant technology used for public displays. This direct-view flat-panel technology has become relatively affordable and readily available, due to the significant price erosion that has occurred over the last several years and to rapid adoption by the consumer television market. (Although there are slight differences in the build of a television LCD panel *vs.* a public-display LCD panel, there tends to be a direct relationship between the sizes and resolutions that sell well in the consumer market and those that are eventually developed into public-display panels.) In addition to LCDs, a number of "up-and-coming" technologies are possibilities for the future direction of digital signage. These include OLEDs, which will be discussed in part 2 of this series later this year. The most prominent such technology, however, is direct-view LED technology.

Direct-View LED Technology

Historically, direct-view LED technology was limited to the outdoor realm (sports stadiums, sides of buildings in major cities, billboards, *etc*.), due in part to wide pixel pitches (low resolution) and high cost. Mitsubishi, with its Diamond Vision LED display systems, and Daktronics have been industry stalwarts for many years.

The modular design of direct-view LED displays makes it easy to scale to very large sizes and allows for non-typical shapes and sizes. According to the latest IHS Signage and Professional Displays Market Tracker, 83% of all direct-view LEDs shipped globally in Q1 '15 had pixel pitches of 10 mm or greater. This percentage was down from 90% 2 years ago. (For more about professional displays, see part 2 of this article.)

In 2013, shipments exceeded 180,000 units globally (one square meter of viewable area equals one unit). In 2015, shipments are forecast to approach 240,000 units and will near 400,000 units in 2019. Revenues will grow from $1.22 billion in 2013 to $1.96 billion in 2019.

However, in just the last 2–3 years, the industry has seen an explosion of small-pixel-pitch direct-view LED samples shown at the major industry exhibitions, most of which have been introduced by Asian-based companies (mainly China and Taiwan).

At InfoComm in June 2015, major brands Christie, Daktronics, Leyard, NanoLumens, and Panasonic all showed narrow-pixel-pitch LED video displays ranging from 1.2 to 2.6 mm pixel pitches. SiliconCore Technology, an innovator and manufacturer of LED displays and laser-diode controls, showed an array of ultra-narrow-pixel-pitch direct-view LED displays, including 1.2-, 1.5-, and 2.6-mm offerings.

Planar Systems, known more for its mosaic architecture LCD-based commercial displays, showed similar direct-view LED modules at InfoComm, and in August 2015 was acquired by Leyard. Prior to this acquisition, in March 2015, Samsung acquired YESCO to gain access to its wider-pixel-pitched products to augment its newly released indoor smaller-pixel-pitched direct-view LED modules.

Today, these narrow-pixel-pitched products are very expensive compared to direct-view LCD products. Therefore, they are competing more directly with laser-projection technologies and in niche, unique, or customized applications and installations.

Larger Screen Sizes, Smaller Bezels

A key trend in digital signage is increasing size. Each year, larger direct-view LCDs are announced, shipped, and sold. In 2013, Sharp briefly shipped a 108-in. FHD public display. In 2014, 98-in. UHD models began shipping from several companies (LG Electronics, NEC Display Solutions, Planar, and Panasonic). In 2015, Samsung began shipping its 105-in. 5K-resolution display.

However, as the size of the display approaches and passes the 100-in. mark, the viability of shipping it effectively, efficiently, and with minimal damage is questionable.

As an alternative to a single large display, with the continued improvements in super-narrow-bezel (SNB) technology, it is becoming easier and more acceptable to tile smaller-sized displays together to form larger video walls.

Not too long ago, a public display or any display for that matter that had a single-side bezel measurement of 10 mm (equivalent to a 20-mm bezel-to-bezel (BtoB) measurement) or less was considered by some as a "narrow" bezel display. In the last 3 years, LG Electronics has shown LCDs at the annual InfoComm Exhibition measuring 4.9 mm (BtoB) (2013), 3.5 mm BtoB (2014), and less than 2 mm BtoB (2015). A bezel-to-bezel measurement is the sum of two bezel measurements (one bezel from one display and another bezel from an adjoining display).

Although the viewer can still see lines between the individual displays (a.k.a. window-pane effect), at smaller than 2 mm it becomes less of a distraction. It is expected that bezel-size reductions will continue to be made, and the bezel gap will narrow either mechanically or optically. Manufacturers and integrators are therefore finding it easier to manipulate multiple 40-, 50-, and even 60-in. displays to create large video walls. Mount manufacturers have also made it easier to tile the displays in a uniform configuration and many now allow easy removal of a single screen for service.

Luminance and color uniformity for the tiled displays is still a challenge for some makers, and definitely for televisions (more on this later); however, most major brands include solutions (hardware and software) to combat these issues.

High-Bright and Half-Height

Panel manufacturers are always looking for new ways to recoup the billions of dollars they have invested in manufacturing facilities. In order to do this, revenues alone are not enough. They need to focus some of their resources on products that have higher profit margins or, more precisely, products that generate more margin dollars.

For the last several years, the profit generators have been narrow- and super-narrow bezel panels. In addition, some panel manufacturers are beginning to focus more attention on the development of high-brightness panels (700+ nits) than in the past. These panels are used in developing outdoor or semi-outdoor displays, such as for quick-service restaurants (QSRs) drive-thrus, street-side kiosks, outdoor retail, or public walkway areas at sports stadiums, *etc.*

There are currently high-bright solutions in the marketplace. However, the price points are at significant premiums. As more high-bright panels are manufactured, yields will improve and economies of scale will be realized, which generally equate to lower prices.

LG Display is working on a high-bright panel it refers to as M+ technology, which allows the company to produce high-bright panels with lower power consumption than typical high-bright LCD panels; however, the acquisition price is much higher than for those typical high-luminance panels. We expect the price to come down as more panels are produced.

Another product area a few panel makers have circled back to are half-height, stretched, bar-type, or transportation panels. Whatever name they go by, they are the same thing; very-wide-aspect-ratio displays, designed mainly to replace bus and train signage. A few years back, displays utilizing these types of panels were introduced to less than ecstatic response. According to the IHS Public Display Market Tracker, approximately 2,000 units of these half-height displays were shipped globally since 2012.

It is possible these panels were launched before their time and will have better sales success now. AU Optronics has introduced 28- and 38-in. models, which have been picked up by BenQ and made into displays. Samsung has launched a 24-in. panel, and recently even larger sizes, such as 16:3 and 16:4.7 have been planned by a major panel manufacturer.

Televisions and Public-Display TVs[b]

As IHS has mentioned in the past, the biggest threat to the public-display market remains televisions. Although much can and has already been said about the ideal performance and potential lower total cost of ownership of public displays, the industry is realizing that not everyone needs a commercial display. There are tradeoffs, and price is usually king.

IHS tracks shipment of public displays and public-display TVs in the IHS Public Display Market Tracker. Public-display TVs are more of a hybrid category, which is usually identified by a lower warranty (2 years instead of the standard 3 years), features like RS-232C (for remote control and monitoring), and button and I/R lockout. Sometimes they include a tuner and digital-signage content software. These displays are intended for usage up to 16 hours a day. Several major brands are targeting the small-to-medium business (SMB) market with these types of displays and have shown some recent success. Examples of this market include "mom and pop" stores, non-franchised fast food shops, laundromats, boutiques, *etc.*

However, there are some end users that are using consumer televisions for their public displays. What they give up in performance, longevity, and warranty, they gain in price. The quality of consumer televisions has increased significantly over the past several years and the quality gap between a consumer television and commercial displays has narrowed considerably.

When the price of a large television falls below the $1000 and even $500 mark, more customers have been willing to take the risk. In some scenarios they are pleasantly surprised that the television did the job they needed. In others, the television usually performs well for a year or two. When it fails, the loss is not catastrophic. The low acquisition price puts it in a "throw-away" category and the customer ends up buying a larger screen, with better technology for a lower price.

This is not to say that the market for true public displays is not healthy or growing. There are still many solutions that need 24/7 performance and all of the advanced features of a commercial public display. However, the low end is clearly limited in terms of growth potential.

UHD and HDR

The overall display industry has continued to move to higher-resolution displays based on the perceived need by the end user to be able to see images better and in more detail. On the consumer side, the latest transition (to UHD) has performed fairly well, since price premiums have been reduced significantly, especially by third-tier brands. By the end of 2015, 15% of television shipments will be generated by televisions with UHD resolution. By 2019, this percentage will climb to 40%, according to the latest IHS TV Sets (Emerging Technologies) Market Tracker Report. However, for public displays, this transition has not occurred as rapidly and is not forecast to ramp up aggressively.

First, the price premium for a UHD display *vs*. an FHD is greater for public displays than for consumer televisions due to production and manufacturing variables in addition to the limited volumes. This premium may be reduced in the future as some brands introduce common public-display sizes that will compete head-to-head with their FHD counterparts.

Second, most public-display solutions are intended to reach audiences that have far greater viewing distances than those of at-home consumers. As the viewing distance increases, the perceived image quality or difference between FHD and UHD lessens. There are many different screen size *vs*. viewing-distance calculators on the Internet that provide a good indication of where perceived image-quality difference does and does not exist. At a recent USFPD IHS Conference in Santa Clara, California, it was stated that the minimum size of a display in order for viewers to see the difference between FHD and 4K is 50 in.

There is also some speculation that to deliver networked high-resolution content to these displays will require many customers to upgrade their infrastructures. This may be very costly for some or may just be another roadblock that has them questioning if it is needed or just wanted. Customers will definitely be considering ROI in this context.

With all of this, add to the mix that 8K is already being talked about and it seems some want it available sooner than later. The Japanese 2020 Olympic committee is already stating that the games will be televised in 8K.

It is for these reasons that IHS analysts believe shipments and sales will be initially limited to niche vertical markets such as high-end retail where the audience will be within 2 m of a 50-in. or larger display and where the company believes that higher resolution plays into its brand messaging of quality.

High dynamic range (HDR) is the second of the one-two-three punch the television industry is counting on to spark a new replacement cycle. (The first punch was UHD resolution.) HDR refers to a combination of higher luminance capability for whites and more selectable levels of gray scale (higher bit range) for the R-G-B channels. This wider range produces more realistic images and is said to be able to produce images the eye actually sees *vs*. what the camera sees.

HDR is not new; in fact, the photography industry has been using it for years. In laymen's terms, three pictures are merged together to produce one "realistic" photo. However, in the display industry, HDR is relatively new. One of the main reasons is in order to take full advantage of the improved image results, HDR content is required.

Among others, Dolby has been working diligently in the HDR space and has developed a relationship with several television brands, including Vizio, for Dolby Vision licensing processing software. However, it works best on high-bright displays (800 nits+), which are typically uncommon in the television marketplace today.

HDR alone is not enough to complete the replacement cycle; however, paired with wide-color-gamut display capabilities, whether created through the use of phosphor-coated LEDs or quantum dots or other solutions, offering more colors in the color palette makes the user experience that much more dynamic.

It will take some time for these technologies to trickle down to the benefit of the digital-signage marketplace, but when they do, it will help digital-signage networks charge a premium or give them the ability to secure the upper echelon of advertisers who demand more control over the imagery.

Opportunities and Threats

The public-display market is poised to grow over the next several years as economic and market conditions have stabilized or improved and as emerging countries begin to invest. The majority of the growth will be derived from an increase in sales of larger-sized displays (50 in. +). One of the biggest threats to the growth of public-display shipments will be the continued acceptance and shift by end users of using consumer televisions or public-display TVs for 16/7 (or less) operation.

LCD technology will continue to be the dominant volume and revenue technology for the next few years in standard aspect ratios. For larger panels, LEDs provide nearly any size and nearly any resolution. In parallel, "newer" technologies will begin to enter the space, first as niche solutions and then, as prices decrease, in greater volumes. On a percentage basis, LCDs with UHD resolution will grow the most; however, this growth stems from relatively small unit shipments. Shipments of FHD displays will grow by 1.5 million units between 2015 and 2019. Talk of HDR and wide-color-gamut displays will begin to enter conversations; however, the price premiums will force these displays to remain niche for the time being.

The top five digital-signage brands in terms of signage as of Q2 '15 (LG Electronics, NEC Display Solutions of America, Philips, Samsung, and Sharp) have positioned themselves well to continue to dominate the marketplace, although their individual rankings may change over time. There still appears to be room for smaller manufacturers and integrators to grow their businesses by focusing on niche vertical markets by utilizing products such as high-bright outdoor displays, half-height transportation displays, and other specialty displays.

The quest for larger public images will continue to fuel the video-wall market along with the increase in ultra-narrow-bezel panel and display production. Small-pixel-pitch direct-view LED displays will start to compete for more volume as the average selling prices erode. Until then, their usage will be niche or custom.

Footnotes

[a]The term Public Displays is a general term used to describe displays that have been designed for commercial usage (or commercial displays). These displays contain components that allow them to perform 24/7 for a minimum of 3 years. They are most commonly used for digital signage, which actually describes digital advertising. There are some "hybrid" displays or "public-display TVs" that are marketed as public displays but are only designed for 16/7 (16 hours a day, seven days a week) operation (2–3 year warranties). Lastly, some digital-signage customers purchase consumer TVs built to perform 4–8 hours a day that carry a 1-year warranty.

[b]Here, televisions refer to consumer televisions (the same ones people buy at local retailers and use at home). They are not designed for 24/7 operation and have 90-day to 1-year warranties at most. Many also come with disclaimers that say the warranty is voided if used outside the home. ■

Oxide TFTs: A Progress Report

For flat-panel-display backplane applications, oxide-TFT technology is the new kid on the block – recently conceived and in its early stages of commercialization. How is it going for oxide-TFT technology as it attempts to match up with a-Si:H and LTPS technology?

by John F. Wager

OXIDE thin-film-transistor (TFT) products are a recent development. The path toward commercialization began in the spring of 2012, with Sharp's announcement that Gen 8 Kameyama Plant No. 2 would be retrofitted to the production of indium gallium zinc oxide (IGZO) LCD panels for tablets, high-resolution notebook PCs, and monitors. Sharp's first IGZO product was the Aquos Phone Zeta SH-02E, appearing (in Japan) in the fall of 2012. In early 2013, LG Display began taking pre-orders (in South Korea) for its 55-in. OLED TV, which employed an IGZO-TFT backplane.

In retrospect, the period of early commercialization of oxide TFTs that occurred between spring 2012 and fall 2014 can be characterized as a time of high expectations, over-promising while under-delivering, skepticism, hype, over-optimistic timelines, misinformation, excitement, apprehension, giddiness, and confusion. Thus, in all respects the introduction of oxide-TFT technology was a "situation normal" rollout.

Oxide-TFT early commercialization drama centered on four main questions. First, did Sharp know something that no one else did? Did it possess a manufacturing "secret sauce" that would preclude other companies from duplicating its oxide-TFT success? Was CAAC (c-axis-aligned crystallinity) the secret? Second, was oxide-TFT technology just another flash-in-the-pan technology that would either elude being tamed by high-volume manufacturing or would underperform when eventually productized? Third, many observers questioned whether oxide-TFT technology could really compete with low-temperature polysilicon (LTPS), especially given LTPS's multi-decade head start, commercial entrenchment, and perceived performance advantages.[1] Fourth, rumors about Apple were flying in all directions. Was Apple *really* moving toward the use of oxide TFTs? If so, what was holding it up?

To a large extent, this era of oxide-TFT confusion and uncertainty ended mid-October 2014 with Apple's launch of its iMac with its 5K Retina display. This product had an IGZO-TFT backplane.

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Oxide TFTs or IGZO

Some readers may be confused: If this article pertains to oxide TFTs, why is IGZO the only oxide being discussed? Aren't there any other oxides of relevance out there? Good question.

Oxides are an attractive class of materials for commercialization for several reasons. First, from an anion classification perspective, oxides are the most numerous compounds on the planet, by far. Thus, oxides offer a rich palette of possibilities. Second, oxides tend to be thermodynamically stable. This attribute often leads to excellent product lifetime and reliability. Third, oxides are air processable. This fortuitous property offers a possible path toward lower manufacturing costs.

Oxides are not a materials panacea, however. For an oxide to be useful, it must possess requisite attributes for the application of interest. For flat-panel-display backplane applications, a candidate oxide should have (at least) the following properties: (1) possess an electron mobility significantly greater than that of hydrogenated amorphous silicon (a-Si:H), *i.e.*, $\mu_n >> 0.5$ cm^2/V-sec, (2) exhibit superior TFT stability compared to that of an a-Si:H TFT, and (3) be capable of scaling to large areas (Gen 10+) at a price competitive to that of a-Si:H.

IGZO meets all of these flat-panel-display backplane requirements. Currently, IGZO is the only oxide that can. Thus, at this time, oxide TFTs and IGZO can be considered to be synonymous and interchangeable terms, at least from the perspective of commercialization.

Oxide-TFT Products

Product assessment is one approach for answering the question of whether oxide-TFT technology is "real." Table 1 is a list of IGZO-based products that were either available (**blue**) or had been announced (**red**) as of mid-October 2015.

Table 1 is surprising, and very encouraging. Adopting the usual perspective that oxide-TFT technology is in its infancy, the number of IGZO products already available via a simple Internet search seems astonishing, especially given IGZO's current lack of manufacturing capacity, as discussed in the next section of this article. Additionally, the product breadth found in Table 1 is auspicious – phones, monitors, tablets, laptops (even gaming laptops), desktops, and TVs, *i.e.*, products with small, medium, large, and very

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large areas. These considerations argue against the assertion that IGZO is a one-trick-pony technology, capable of addressing only a limited and perhaps even a niche market.

Oxide-TFT Manufacturing

As alluded to in the discussion of Table 1, it appears likely that the oxide-TFT product market is currently limited by the lack of high-volume manufacturing capacity, as well as by the newness of the technology itself. Table 2 is an attempt to estimate current and near-term oxide-TFT production activities.

The primary take-away from Table 2 is that three companies appear to be actively shipping oxide-TFT panels, *i.e.*, Sharp, Samsung, and LG Display. All three companies have announced their intention to ramp up their oxide-TFT production volume in 2016, although Sharp has not yet specified this quantitatively. Note that the sheets per month unit used in Table 1 is only part of the production volume story, given areal differences associated with fab size. For example, a Gen 5 sheet of glass has dimensions of 680 × 880 mm (0.6 m^2), whereas a Gen 8 sheet of glass is 1870 × 2200 mm (4.1 m^2). The three other players listed in Table 2, *i.e.*, BOE, CPT, and CEC Panda, have publicly announced that they expect to be shipping oxide-TFT products soon. However, it is not yet clear if they will be able to hit their late-2015 timelines, or if product introduction will be delayed until sometime in 2016.

Total worldwide oxide-TFT capacity was estimated as ~65M m^2 in 2014 and is projected to be ~125M m^2 (2015) and ~195M m^2 in 2016.[3] This same flat-panel-display production capacity assessment predicts that 2016 oxide-TFT capacity will overtake that of LTPS, which is projected to be ~180M m^2 in 2016.

Commercial adoption of oxide-TFT technology requires the availability of appropriate equipment for large-area high-volume manu-

Table 1: Oxide-TFT products are in **blue** and products that have been announced are in **red**.

Product	Maker	Display
Phone		
Aquos Compact SH-02	Sharp	4.7", 1080 × 1920, 469 ppi
Aquos Xx2 mini	Sharp	4.7", 1080 × 1920, 469 ppi
Aquos Xx2 (502SH)	Sharp	5.3", 1080 × 1920, 415 ppi
Aquos Zeta SH-01	Sharp	5.5", 1080 × 1920, 401 ppi
Aquos Zeta SH-02	Sharp	4.7", 720 × 1280, 300 ppi
Aquos Zeta SH-03	Sharp	5.5", 1080 × 1920, 401 ppi
Aquos Zeta SH-04	Sharp	5.4", 1080 × 1920, 408 ppi
Aquos Zeta SH-06	Sharp	4.8", 1080 × 1920, 459 ppi
Infobar A03	Kyocera	4.5", 1080 × 1920, 490 ppi
m1 note	Meizu	5.5", 1080 × 1920, 401 ppi
m2 note	Meizu	5.5", 1080 × 1920, 401 ppi
MX5	Meizu	5.5", 1080 × 1920, 401 ppi
Nubia Z5S	ZTE	5", 1080 × 1920, 441 ppi
Nubia Z5S mini	ZTE	4.7", 720 × 1280, 312 ppi
Readmi 2 Prime	Xiaomi	4.7", 720 × 1280, 312 ppi
Torque G02	Kyocera	4.7", 720 × 1280, 312 ppi
Monitor		
LQ-101R1SX03	Sharp	10.1", 2560 × 1600, 299 ppi
PN-K322B	Sharp	31.5", 3840 × 2160, 140 ppi
PN-321Q	Sharp	31.5", 3840 × 2160, 140 ppi
UltraSharp UP3214Q	Dell	31.5", 3840 × 2160, 140 ppi
UltraSharp UP3216Q	Dell	31.5", 3840 × 2160, 140 ppi
PA322UHD-BK-SV	NEC	31.5", 3840 × 2160, 140 ppi
Tablet		
i6 Air	Cube	9.7", 2048 × 1536, 264 ppi
iPad Pro	Apple	12.9", 2732 × 2048, 264 ppi
LaVie Z	Lenovo	13.3", 2560 × 1440, 221 ppi
Lifebook S935	Fujitsu	13.3", 1920 × 1280, 221 ppi
Lifebook T935	Fujitsu	13.3", 2560 × 1440, 221 ppi
Lifebook T904	Fujitsu	13.3", 2560 × 1440, 221 ppi
Lifebook U904	Fujitsu	14", 4300 × 1800, 262 ppi
P98 Air	Teclast	9.7", 2048 × 1536, 264 ppi
V919 Air	Onda	9.7", 2048 × 1536, 264 ppi
Laptop		
Radius 12	Toshiba	12.5", 3840 × 2160, 352 ppi
Satellite P55t-B5262	Toshiba	15.6", 3840 × 2160, 282 ppi
Skylake NS850	NEC	15.6", 3840 × 2160, 282 ppi
VersaPro Type VG	NEC	13.3", 2560 × 1440, 221 ppi
XPS 12 (option)	Dell	12.5", 1920 × 1080, 176 ppi
XPS 15 (option)	Dell	15.6", 3840 × 2160, 282 ppi
Gaming Laptop		
Alienware 13 (option)	Alienware	13.3", 3200 × 1800, 276 ppi
Alienware 17 (option)	Alienware	17.3", 3840 × 2160, 255 ppi
Razor 14" Blade	Razor	14", 3200 × 1800, 262 ppi
X3 Plux v3	Aorus	13.3", 3200 × 1800, 276 ppi
X3 Plus v4	Aorus	13.9", 3200 × 1800, 264 ppi
Desktop		
iMac with 5K Retina display	Apple	27", 5120 × 2880, 218 ppi
21.5" iMac with 5K Retina display	Apple	21.5", 4096 × 2304, 218 ppi
TV		
LV-85001	Sharp	85", 7680 × 4320, 104 ppi
Smart OLED TV 55EG9100	LG Display	54.6", 1920 × 1080, 40 ppi
Smart 3D Curved OLED TV 55EC9300	LG Display	54.6", 1920 × 1080, 40 ppi
Smart 3D OLED TV 55EF9500	LG Display	54.6", 3840 × 2160, 81 ppi
Smart 3D OLED TV 65EF9500	LG Display	64.5", 3840 × 2160, 68 ppi
Smart 3D Curved OLED TV 55EG9600	LG Display	54.6", 3840 × 2160, 81 ppi
Smart 3D Curved OLED TV 65EG9600	LG Display	64.5", 3840 × 2160, 68 ppi
Smart 3D Curved OLED TV 65EG9700	LG Display	64.5", 3840 × 2160, 68 ppi
Smart 3D Curved OLED TV 77EG9700	LG Display	76.7", 3840 × 2160, 57 ppi

Table 2: Oxide-TFT manufacturing activity is in blue and announced activity is in green.[2-6]

Company	Year	Production Volume (sheets per month)	Fab Size
Sharp[2]	2015	30,000	Gen 8
”	2016	30,000 + ?	Gen 8 + ?
Samsung[2]	2015	40,000	Gen 5
”	2016	100,000	Gen 5
LG Display[3]	2014	9,000	Gen 8
”	2015	30,000	Gen 8
”	2016	60,000	Gen 8
BOE[4]	~2015–2016	90,000	Gen 8.5
CPT[5]	2015 Q4	?	Gen 4
”	2016	?	Gen 4 + Gen 6
CEC Panda[6]	~2015–2016	?	Gen 8.5

facturing. Figure 1 is an example of the type of tool innovation that is required before a new technology such as IGZO is indeed ready for commercialization. The large-area coater shown in Fig. 1 is capable of producing uniform IGZO films over a 2200 × 2500 mm (Gen 8.5) substrate. The use of rotary targets improves target lifetime and production yield, reduces particle generation, and lowers manufacturing costs compared to that obtainable using planar targets.[7] (For more about this system, see the article, “A Process for Using Oxide-TFTs over LTPS-TFTs for Better OLED-TV Manufacturing” in the November/December 2015 issue.)

Tools such as the one discussed in Fig. 1 are capable of fabricating IGZO TFTs with excellent properties and with acceptable uniformity even over Gen 8.5 dimensions. Figure 2 summarizes typical IGZO-TFT performance results. Note that a mobility of 12 cm^2/V-sec is 24 times larger than that typically obtained for an a-Si:H TFT. Also notable is the large drain current on-to-off ratio of 10^8. This is several orders of magnitude better than that obtainable using a-Si:H or LTPS TFTs. This translates into a lower power advantage for IGZO TFTs, an important and potentially game-changing distinction.[1,8] Finally, the IGZO-TFT stability specs reported in Fig. 2 in terms of positive- and negative-bias temperature stress (PBTS and NBTS) and negative-bias illumination stress (NBIS) are all quite encouraging, especially when it is realized that this result is obtained using Gen 8.5 tools.

NBIS is a topic that has been extensively discussed in the literature. It was originally considered to be a possible show-stopper for the commercialization of IGZO technology. It appears that the industrial solution to circumventing the deleterious effects of NBIS often involves the use of light shielding.[9]

Oxides Other Than IGZO

As mentioned previously, IGZO and oxide TFTs are different terms used to refer to essentially one and the same thing, at least in the context of products, since IGZO is the only oxide currently being commercialized for flat-panel-display backplane applications. This does not mean that IGZO is the only oxide that will or can ever be employed in a future display or non-display product.

Then why is IGZO the only oxide currently being marketed? In a word, it comes down to *standardization*. For a market as large as that of the flat-panel-display industry, panel manufacturers have to work closely with tool vendors, materials suppliers, and others in order to successfully implement a new technology. This is a vast undertaking. Many different partners, as well as competitors, have to agree to cooperatively explore a new technology in order for innovation relevant to high-volume manufacturing to occur. These

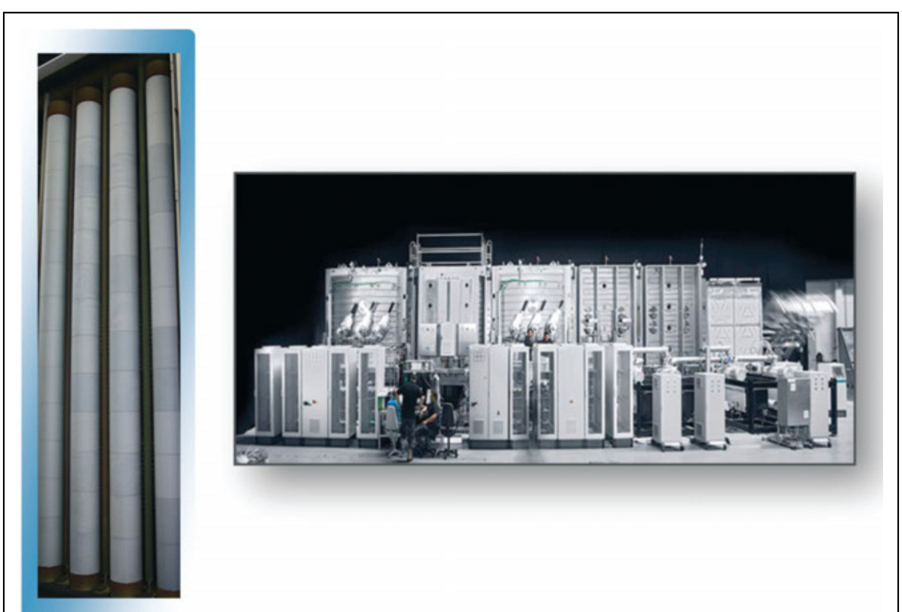


Fig. 1: *This rotary target array consists of 12 Gen 8.5 IGZO sputter targets (a subset is pictured at left) installed in an Applied Materials PIVOT®-sputtering system. (For a sense of scale, note the person standing in front of the system.) Image courtesy Applied Materials, Inc.*

kinds of co-operative undertakings occur all the time in the semiconductor integrated-circuit industry, giving rise to the formulation of roadmaps that are useful for guiding R&D activities.

Cooperation leads to *standardization*. About 5 years ago, IGZO was informally selected as a consensus best-of-class candidate oxide for the pursuit of commercialization. Many other oxides were being investigated 5–10 years ago for display applications. Although oxide-TFT technology then looked like an attractive flat-panel-display backplane option, panel manufacturers, tool vendors, and materials suppliers were unwilling to seriously devote their time and resources to an unproven oxide-TFT technology until a viable contender material was identified. IGZO was chosen. Recent oxide-TFT technology trends indicate that IGZO was an excellent choice.

Which oxides other than IGZO are likely to emerge in future applications? The answer to this question is not entirely obvious. Here are some thoughts. First, a viable candidate oxide should have an amorphous microstructure. a-Si:H and IGZO are scalable to Gen 8.5+ sizes for one primary reason; they are amorphous. Second, an IGZO replacement must offer some sort of compelling manufacturing and/or performance advantage. Consider two examples. I think that it is highly likely that a future oxide-TFT material will contain tin as a constituent element, since incorporation of tin will allow oxide wet etchability to be dramatically engineered over a broad range of selectivity.[10] In this respect, recent industrial R&D involving ITZO[11] and IGZTO[12,13] is intriguing. Next, and most importantly, the flat-panel-display industry seems to have an insatiable desire for ever-increasing TFT-channel-layer electron mobility (as well as hole mobility, if it could only get it). Alternative channel layers such as ITZO[11] may prove capable of satisfying next-generation oxide-TFT electron-mobility requirements.

An alternative approach for improving TFT-channel-layer electron mobility is to employ a dual-layer stack. Typically, amorphous oxides with the highest mobilities also possess very high electron-carrier concentrations. This makes it difficult to fabricate enhancement-mode TFTs with turn-on voltages near zero. Rather, a negative gate voltage is required to deplete electrons in the channel in order to turn off the current. This results in depletion-mode TFT behavior. A dual-layer channel TFT employs a very thin high-mobility oxide at the interface to the gate insulator, which is covered by a thicker more insulating oxide. This approach allows for concomitant optimization of mobility and threshold voltage.

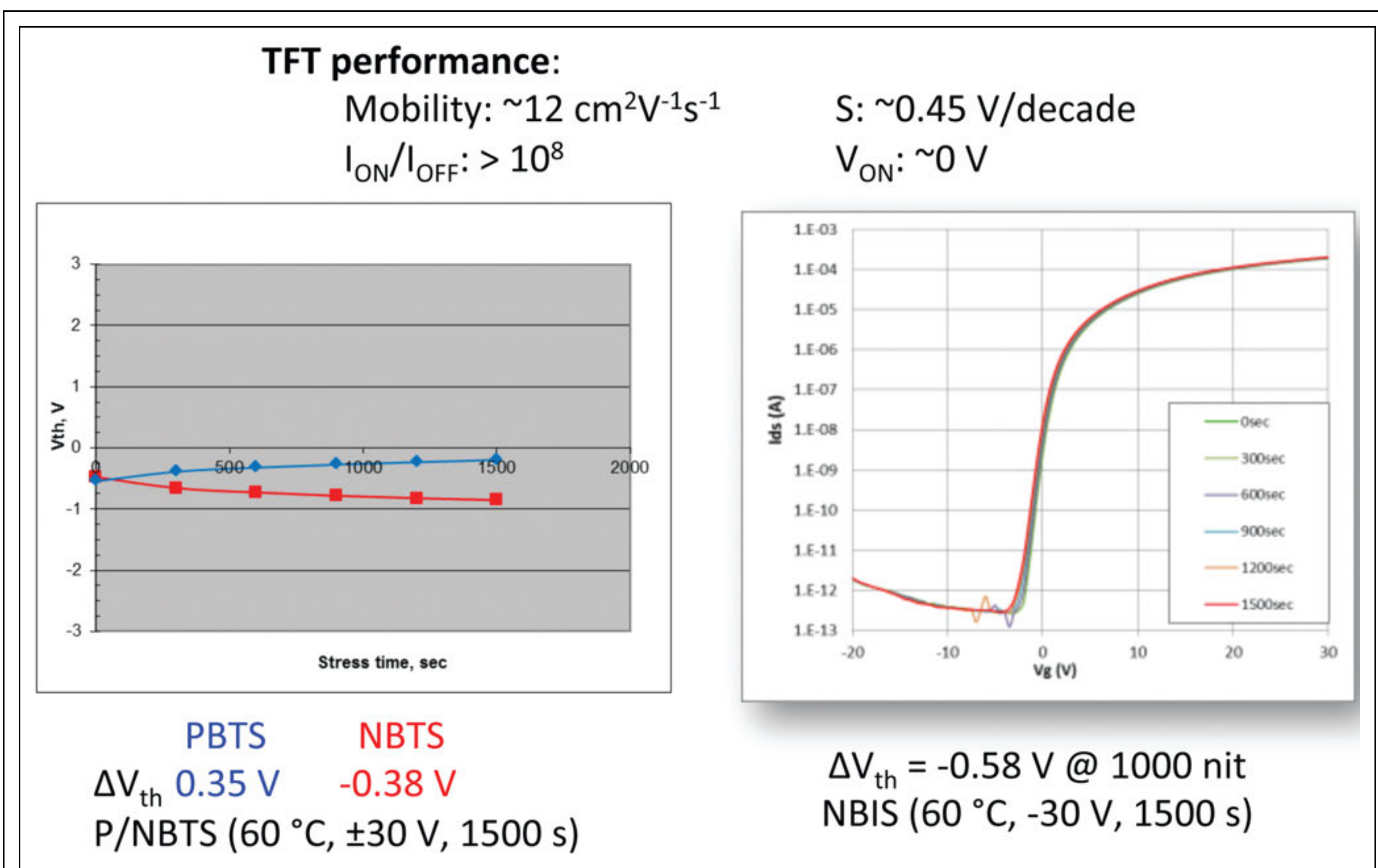


Fig. 2: *IGZO-TFT performance obtained using Gen 8.5 manufacturing tools is shown at left and right. Image courtesy Applied Materials, Inc. PBTS = Positive-Bias Temperature Stress. NBTS = Negative-Bias Temperature Stress. NBIS = Negative-Bias Illumination Stress.*

Figure 3 illustrates results achieved using the dual-layer TFT approach for an IZO/IGZO TFT. The 62 cm^2/V-sec mobility reported in Fig. 3 for a 10-nm-thick IZO TFT suggests that oxide TFTs with mobilities 100 times greater than that of a-Si:H are likely to be a commercial reality in the not too distant future. Note also that preliminary TFT stability data is very encouraging for these dual-layer IZO/IGZO TFTs.

Right Material, Wrong Reason

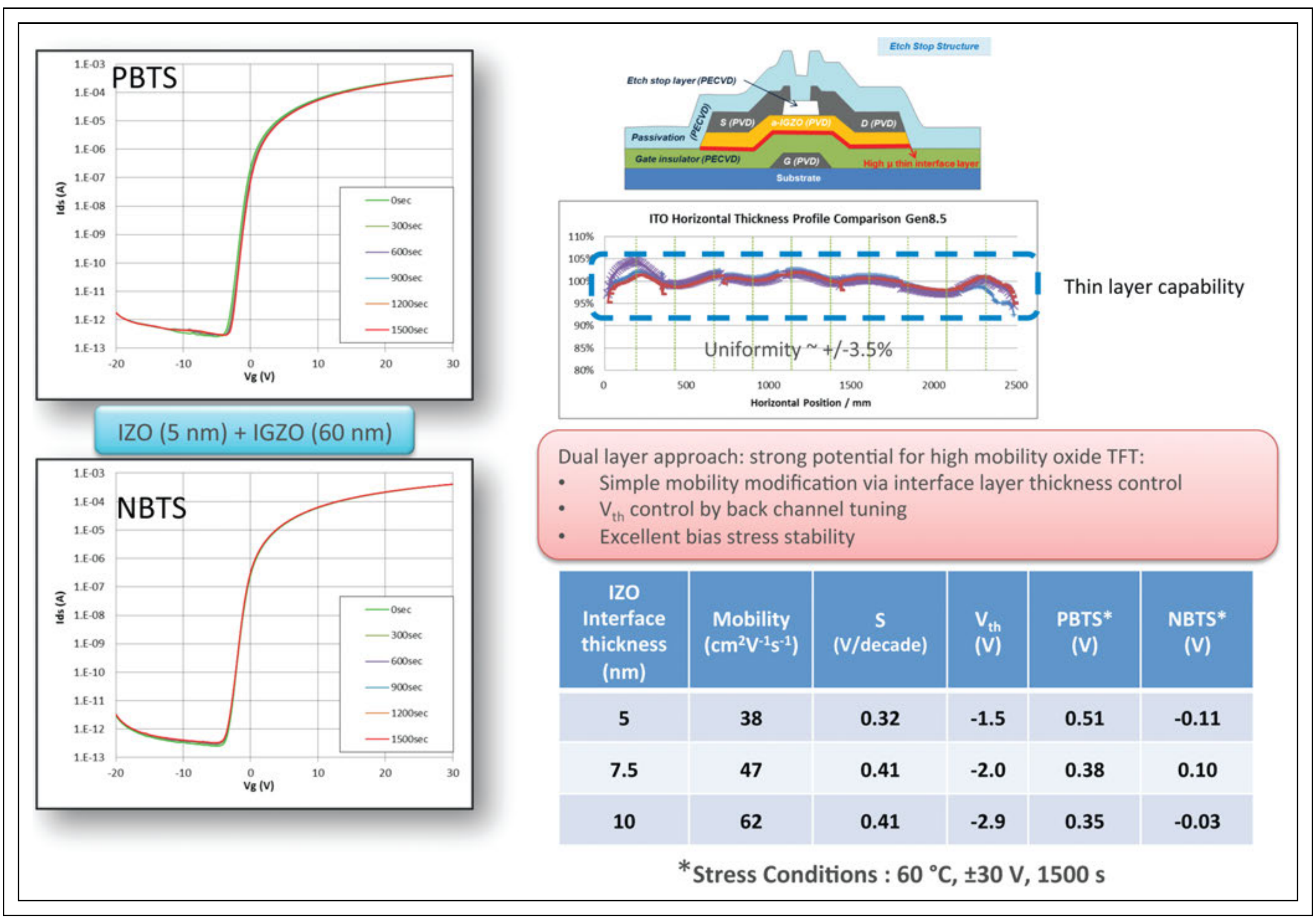
The scientific rationale for exploring amorphous-oxide semiconductors, such as IGZO, was first articulated by Hosono and co-workers, way back in 1996.[14] They pointed out that large ionic radius, spherically symmetric s-orbitals that form the conduction bands in an amorphous oxide semiconductor offer the potential for higher mobility than that obtainable in a-Si:H. More simply, a larger orbital overlap promotes better electronic exchange between atoms, leading to higher mobility. Although this simple picture has been universally adopted and promulgated, by me, among many others, I no longer believe it to be true.

To see this, consider the following simple equation[15]:

$$\mu_{drift} = [n/(n+n_T)]\mu_0. \qquad (1)$$

This equation says that the drift mobility, μ_{drift}, *i.e.*, the relevant mobility responsible for channel current in a TFT, is equal to a trap-free mobility, μ_0, times the fraction of electrons in the channel that are free, not trapped, where n is the free-electron carrier concentration and n_T is the trapped electron concentration. Formulation of a physics-based model for carrier mobility in an amorphous semiconductor then is used to demonstrate that the trap-free mobilities for a-Si:H and IGZO are rather similar.[15] Thus, differences in mobility between a-Si:H and IGZO are found to be a consequence of dissimilar trapping tendencies. Electron trapping is more pronounced in a-Si:H than in IGZO. In turn, these electron-trapping tendencies are found to be related to the nature of disorder in each material, *i.e.*, bond-angle variability for a-Si:H and cation-sublattice disorder for IGZO.

Without getting any more deeply enmeshed in details associated with the chemistry and physics of amorphous semiconductors, here is the point. If the picture proposed by Hosono and co-workers is accurate, mobility differences between a-Si:H and IGZO should arise



IZO Interface thickness (nm)	Mobility ($cm^2V^{-1}s^{-1}$)	S (V/decade)	V_{th} (V)	PBTS* (V)	NBTS* (V)
5	38	0.32	-1.5	0.51	-0.11
7.5	47	0.41	-2.0	0.38	0.10
10	62	0.41	-2.9	0.35	-0.03

*Stress Conditions : 60 °C, ±30 V, 1500 s

Fig. 3: *The above charts reveal high-mobility IZO/IGZO dual-layer TFT performance. Image courtesy Applied Materials, Inc.*

from differences in μ_0 in Eq. (1). However, this is not found to be the case. This new perspective is perhaps somewhat disappointing since the chemical insight inherent in the Hosono picture provided a very compelling motivation for the development of amorphous-oxide semiconductors as a new class of materials.

Perhaps it really does not matter at this point. In any event, I think that it is better that my good friend Professor Hosono got the right answer, although perhaps for the wrong reason, than if he had gotten the wrong answer, but for the right reason. So with regard to the question of how's it going with all that oxide-TFT stuff, the answer is: "Great! Thanks for asking."

Acknowledgments

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Amorphous-Metal Thin Films Enable Ultra-High-Definition Display Backplanes

Amorphous-metal thin films can enable a new generation of TFT-free display backplanes for ultra-high-definition (UHD) LCD TVs. This technology builds upon previous efforts to commercialize dual-select thin-film-diode backplanes and addresses issues faced by TFTs in UHD-TV applications through use of the amorphous-metal non-linear resistor. Demonstrating the reliability of amorphous-metal-based tunneling electronics and the scalability of these materials to panel-size processing tools are now the key challenges for this technology.

by Sean Muir, Jim Meyer, and John Brewer

THERE is no one-size-fits-all solution for flat-panel-display backplanes. Many backplane technologies exist and each has its pros and cons. To a large extent, choosing a backplane technology depends on the display type and/or application, *e.g.*, liquid crystal or organic light-emitting diode, smart phone or television, home or industrial use, *etc*.

One area of rapid growth for the display market has been ultra-high-definition (UHD) LCD TVs. Since 2012, the UHD-LCD-TV market has steadily grown from fewer than 100K panels shipped to well over 10 million in 2014.[1] Estimates for 2015 UHD-LCD shipments are now at 40 million, indicating that strong growth for this market segment continues.[2]

The increasing demand for UHD-LCD TVs 50-in. or larger has already put pressure on well-established backplane technologies. Hydrogenated amorphous-silicon (a-Si:H) thin-film-transistor (TFT) UHD-LCD backplanes are fundamentally limited by the low mobility of a-Si:H. Low-temperature polycrystalline silicon (LTPS) TFTs have higher mobility, but their application to UHD-LCD-TV backplanes is hindered by grain-boundary-related large-area uniformity issues, which result in difficulties in scaling to large areas and high-production costs inherent to the use of ion implantation and excimer-laser annealing.

Undesirable attributes associated with a-Si:H and LTPS have stimulated the development of newer technologies such as oxide TFTs for UHD-LCD TVs.[3] Oxide TFTs offer improved large-area uniformity compared to LTPS, due to their amorphous structure and higher performance compared to a-Si:H from their increased mobility. However, with these improvements comes an increase in backplane complexity. Oxide TFTs in production typically use an etch-stop-type architecture which requires additional process and photolithography steps.[4] These additional process steps can negatively impact production costs and yields.[5]

The common feature of all of these UHD-TV backplane technologies, as well as of all other (that we are aware of) emerging small- and medium-format backplane technologies, is the use of a TFT. TFT-based backplane performance is primarily defined by TFT channel width (W), length (L), and mobility (μ). Optimizing displays for higher resolution, lower power consumption, and faster refresh rates involves (to a large extent) optimizing TFTs within the "transistor box" defined by $W \times L \times \mu$. The demands of UHD TV are shrinking the "transistor box" even further as channel W and L must be reduced to maintain decent aperture ratios at higher resolution, *i.e.*, panel light efficiency. However, short-channel effects from this size reduction are significant and can potentially have adverse effects on performance, such as mobility reduction at high gate-source voltages.[3]

The question as to whether there are alternatives to using TFTs in backplane technology has been asked for some time.[6] From the early 1990s to the mid-2000s, metal-insulator-metal thin-film-diode (MIM-TFD) and dual-select-diode (DSD) backplane technologies were developed as low-cost alternatives to TFT backplanes.[7–14]

The Case for Amorphous Metals

Our team at Amorphyx is developing a new generation of dual-select (DS) backplanes using amorphous-metal thin films. The device enabling these backplanes is the

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amorphous-metal non-linear resistor (AMNR). In our discussion, we will first introduce the AMNR device and then describe how it is utilized in an AMNR-DS backplane for UHD LCD TVs. We also present a high-level 2016–2017 roadmap for AMNR technology.

An amorphous-metal thin film generally provides a much smoother surface than that of a normal polycrystalline metal thin film. The reason is simple. An amorphous-metal thin film does not possess grain boundaries. The lack of grain boundaries in an amorphous-metal electrode can smooth out the local work function and enable better control of the electric field in a transistor or a MIM tunneling device.[15–18] Figure 1 details a schematic of the atomic arrangement in a crystalline metal compared to that for an amorphous metal, as well as a representative atomic-force micrograph (AFM) for each. Typical amorphous metals can achieve a surface roughness root-mean-square (RMS) of less than 1 nm, whereas typical crystalline metals have an RMS greater (usually much greater) than 1 nm.

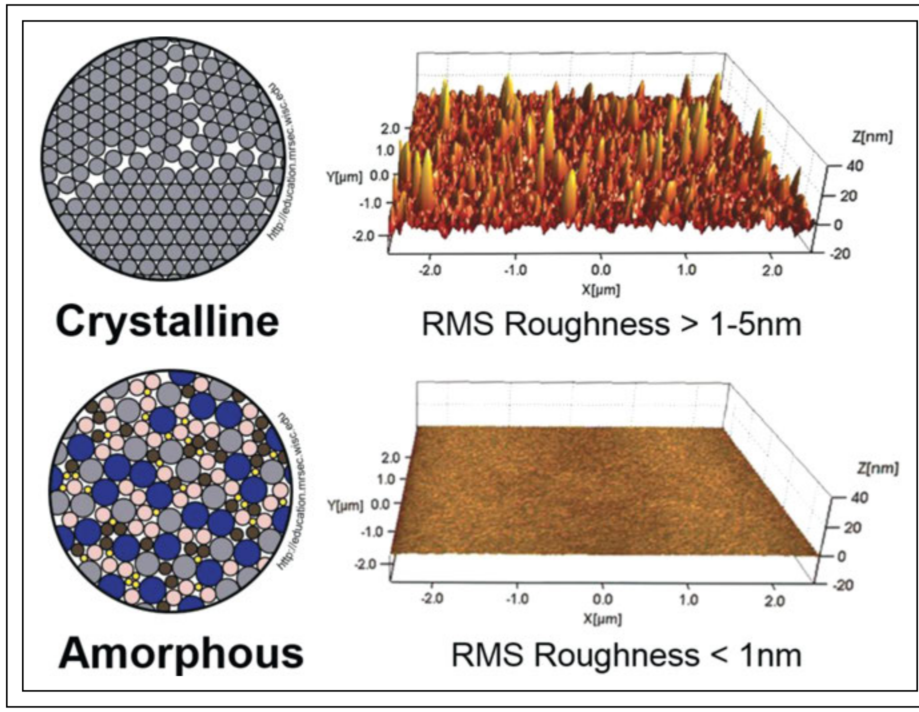

***Fig. 1:** At left are schematic atomic arrangements of a crystalline metal and an amorphous metal, as well as, at right, a representative atomic-force micrograph for each, highlighting typical differences in surface roughness root-mean-square (RMS).*

Introducing the Amorphous-Metal Non-Linear Resistor

The amorphous-metal non-linear resistor (AMNR) is a two-terminal device that employs amorphous-metal thin films to create highly uniform tunnel junctions for regulating current–voltage performance.[19] AMNR electrical performance is similar to that of an amorphous-metal-based MIM diode. However, an AMNR exhibits a symmetrical current–voltage curve. This is accomplished through the use of opposing tunnel junctions. Figure 2 shows a cross-sectional view of an AMNR, as well as a top-down view of one possible layout of an AMNR.

As shown in Fig. 2, an AMNR is a three-layered electronic device that can be fabricated using only two photolithography masks. Reduced mask count and process simplicity can potentially have a tremendous impact on device yield and cost. This is precisely why manufacturers invested in MIM-TFD technology throughout the 1990s.[7,8] Single-select MIM-TFD technologies struggled with poor gray-scale control and large-area uniformity issues so that they could not compete with a-Si:H TFT backplane technology. The uniformity issues can be solved by moving to a dual-select drive circuit.[20] However, the dual-select backplane prototypes produced using SiN_x-based MIM-TFDs were leaky in the off-state and only demonstrated 6-bit color resolution.[14]

We believe that the availability of an AMNR is a game-changer for dual-select TFD backplane technology. Table 1 highlights how AMNR technology differs from that of previous technology based on a MIM TFD, as well as oxide-TFT backplane technology (using an etch-stop TFT architecture).

Amorphous-metal lower electrodes allow for thin high-K dielectrics, such as Al_2O_3, to be used as a tunneling insulator in an AMNR, while maintaining low leakage current in the off-state. The use of a thick SiN_x dielectric for previous-generation dual-select backplanes led to Poole–Frenkel trap-assisted emission as the dominant conduction mechanism. Poole–Frenkel emission is difficult to

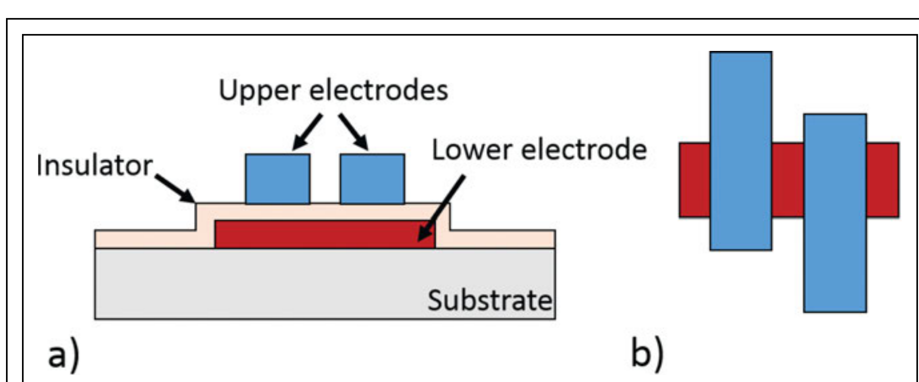

***Fig. 2:** (a) A cross-sectional schematic of an AMNR device and (b) a top-down view of one possible AMNR layout.*

Table 1: AMNR, SiN_x MIM-TFD, and oxide-TFT technologies are compared in terms of temperature sensitivity, number of lithography steps, and other characteristics and requirements.

Feature or process step	AMNR	MIM-TFD	Oxide-TFT
Conduction Mechanism	Fowler-Nordheim	Poole-Frenkel	Channel
Active Material	Al_2O_3	SiN_x	InGaZnO
Light Sensitive	No	Yes	Yes
Temperature Sensitivity	~ –10 mV/K	~ –30 mV/K[10]	~ –12–17 mV/K[21,22]
Lithography Steps (pattern, etch)	2	2	5*
Sputter Depositions (metals, oxide)	2	2	3
PECVD Depositions (Insulators, passivation, etch stops)	1	1	3*
Total Thickness	<200 nm	>400 nm	>500 nm
Registration Tolerance	>5 µm	>5 µm	1-2 µm

*For an etch-stop TFT architecture.

control since it depends on the nature and density of traps present in the insulator. Also, Poole–Frenkel emission leads to I–V curves that are non-abrupt and temperature-dependent. In contrast, use of a thin Al_2O_3 insulator leads to electron conduction *via* Fowler–Nordheim tunneling in an AMNR.

An AMNR is an electronic device without a semiconductor. This is an important point. In fact, it is hard to overemphasize its importance. Since an AMNR is a semiconductor-free device that employs Fowler–Nordheim tunneling as its operative mechanism, an AMNR has low temperature and light sensitivity compared to that of Poole–Frenkel or channel-conduction-dependent devices. Fowler–Nordheim tunneling yields I–V curves that are abrupt and nearly temperature independent. Fowler–Nordheim tunneling is the mechanism used in flash memory. By utilizing Fowler–Nordheim conduction, the leakage current of an AMNR is reduced, leading to less shift of the subpixel data voltage between each frame refresh and the potential to eliminate subpixel storage capacitors. Figures 3(a)–3(f) show example I–V curves for an AMNR, a SiN_x-based non-linear resistor used in prior-generation dual-select backplanes[10] and a typical metal-oxide IGZO-TFT.[23]

Figures 3(a)–3(c) highlight a key difference between AMNRs and other technologies. The AMNR is not as leaky as a SiN_x-based device. Compared to a SiN_x device, the AMNR conducts much less in the low-field region. Additionally, it has a more abrupt turn-on.

The AMNR is bi-directional. Bi-directionality allows the select voltage for an AMNR-based subpixel to be either negative or positive. However, the use of a bi-directional current has implications for AMNR device reliability. By changing the polarity of the select voltage with each subpixel activation, the AMNR

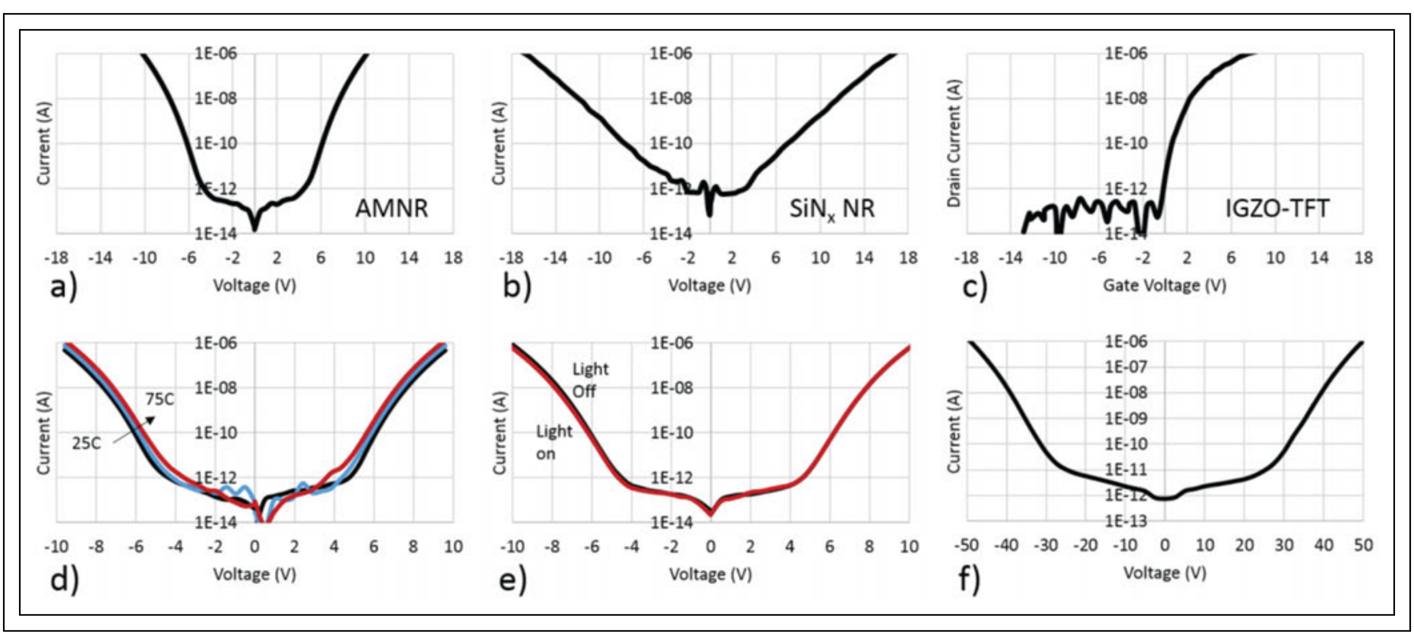

Fig. 3: *(a) Examples of room I–V curves are shown for an AMNR, (b) a SiN_x-based non-linear resistor, (c) an IGZO-based TFT, (d) an AMNR at elevated temperatures, (e) an AMNR under illumination, and (f) a high-field AMNR. The SiN_x non-linear resistor curve is adapted from Ref. 10, whereas the IGZO-TFT curve is adapted from Ref. 23.*

experiences a symmetrical voltage waveform. Use of a symmetrical voltage waveform improves threshold-voltage stability and device reliability.

The AMNR does not conduct at 0 V. Since it does not conduct at 0 V, the AMNR does not need to be negatively biased to transition to a fully off-state unlike most TFTs.

Figures 3(d)–3(f) demonstrate that the AMNR has a wide operating range. It can operate at elevated temperatures and under direct illumination with only a minor shift of its I–V curve. One way to shift the threshold voltage of an AMNR is simply to change the thickness of its insulator; however, this will also alter the dominant conduction mechanism. If the insulator is too thin, device operation is dominated by direct tunneling with a high leakage current. If the insulator is too thick, phonon-assisted tunneling or another more complicated and thermally activated conduction mechanism becomes operative. To maintain Fowler–Nordheim conduction as the dominant mechanism, while increasing the threshold voltage, the number of AMNR tunnel junctions can be increased. This allows for a more flexible design in which both low- and high-operating voltage Fowler–Nordheim- based AMNRs are used, as shown in Fig. 3(f).

Using the AMNR in a Dual-Select Backplane

As the name implies, a dual-select backplane requires the use of two select lines in addition to a data voltage line. A typical TFT backplane for a LCD has one select line and one data line. Circuit schematics for a dual-select subpixel and for a typical 1-TFT 1-capacitor (1T1C) liquid-crystal subpixel are shown in Figs 4(a) and 4(b).[20]

A key difference between the dual-select TFD circuit and the 1T1C circuit is that the liquid-crystal capacitor (CLC) for each subpixel is not tied to a common ground. The dual-select circuit is driven differentially, essentially creating a virtual ground for each subpixel when the two AMNRs become activated. The data voltage for each subpixel is set relative to this virtual ground during the AMNR "on" period. The use of a differential circuit effectively cancels out AMNR variations across the display area and over time. The cancellation provided by this configuration makes the AMNR-DS backplane well-suited to large-area-display applications.

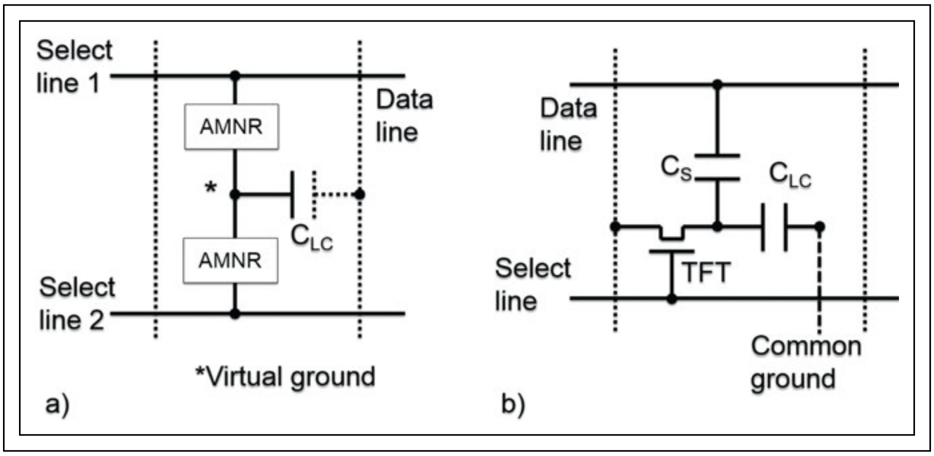

Fig. 4: Circuit schematics for (a) a dual-select AMNR subpixel and (b) a typical 1T-1C subpixel. The schematics are adapted from Ref 20.

Early dual-select display prototypes produced using SiN_x-based non-linear resistors showed crosstalk between subpixels due to the large capacitance of these devices. To eliminate crosstalk, the offset, scan, and hold (OSH) drive scheme was developed.[9,11] Figure 5 shows schematic select and data voltage waveforms for the standard and OHS dual-select drive schemes.

The OSH drive scheme puts the virtual ground at a non-zero but sub-threshold "offset" value between frame refresh cycles. This reduces the total voltage swing on CLC between data voltage inversions, allowing for the use of 5-V data drivers and thereby reducing the voltage that the AMNR experiences in the off-state. The OSH drive scheme therefore reduces the sensitivity of the data voltage to AMNR leakage current non-uniformities and improves high-temperature operation.

The low leakage current of the AMNR combined with the use of an OSH drive scheme can eliminate the need for a storage capacitor. Furthermore, an AMNR for an UHD LCD has a small footprint, estimated at 1–5% of the total subpixel area for 50–100-in.-diagonal displays with UHD (4K) and FUHD

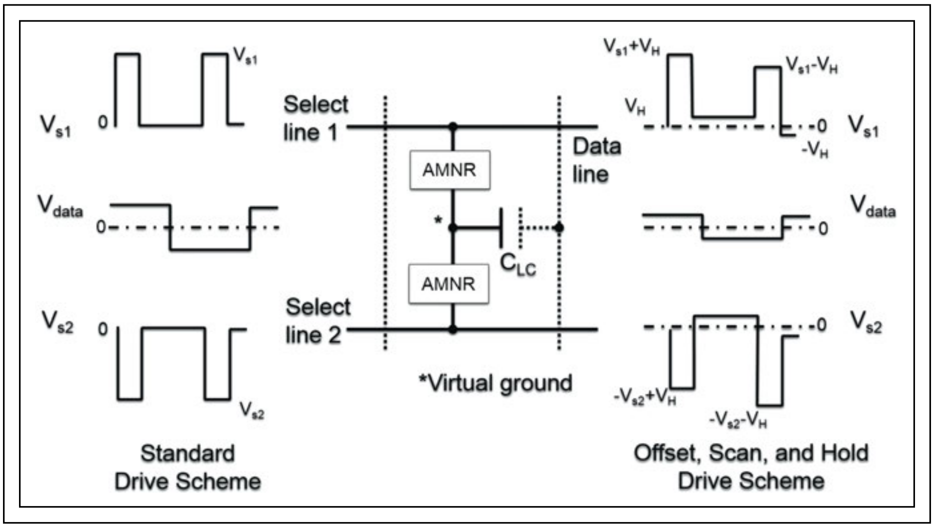

Fig. 5: Schematic select and data voltage waveforms for the standard and OSH dual-select drive schemes are shown left and right, respectively. Drive scheme waveforms adapted from Ref. 9.

(8K) pixel densities. Because of the compact nature of the AMNR and its ability to eliminate the need for a storage capacitor, AMNR backplanes for UHD and FUHD are expected to provide aperture ratios in excess of 50%, despite the need for an additional AMNR select line.

The Future for AMNR Backplane Technology

To firmly establish the AMNR as a backplane contender, future AMNR technology development will be focused on reliability, scalability, and flexibility, as shown in Fig. 6.

Reliability

Accelerated lifetime testing of AMNR devices at 100% duty cycle has shown "champion" devices that last well beyond 50,000 hours at a 100-nA current when scaled to high-resolution duty cycles (*e.g.*, UHD = 0.046% duty cycle, so that 24 hours @100% equals 52,174 hours @ 0.046%). While these results are very encouraging, a complete display-backplane package requires the availability of appropriate models for predicting AMNR performance and reliability. AMNR studies involving variable stress, temperature, duty cycle, frequency, and storage conditions are all under way in order to formulate robust physically based models. The techniques available for evaluating the performance and reliability of thin-gate dielectrics for transistors are generally identical to those needed to evaluate AMNR performance. AMNR reliability analysis therefore draws on the same standards used for transistor reliability analysis, such as the JEDEC (Joint Electron Device Engineering Council) standards, JESD35-A, and JESD92.24–26.

Scalability

AMNR research and development is now focused on the use of 6-in. wafers. Each wafer contains a large number of test devices for statistical process control assessment, as well as a wide variety of devices to facilitate process optimization. The exercise of scaling from a 1-in. substrate toolset to a 6-in. toolset has revealed that amorphous-metal thin-film quality can vary from toolset to toolset, as one might expect. However, once basic differences in configuration, environmental baselines, and sputter conditions have been taken into account, it is possible to port AMNR technology from one toolset (and location) to another. AMNR technology assessment is now transitioning to a Gen 2.5 prototype line.

Flexibility

Flexible backplanes are another application in which AMNR technology is a possible game-changer. Amorphous metals are flexible. For example, amorphous-metal thin films have been commercialized as hinges for digital micromirror devices.[27] An AMNR is thin. As shown in Table 1, the total thickness of a typical AMNR is less than 200 nm. Use of a thinner layer tends to reduce film stress, thereby leading to a backplane device that is more robust and flexible. An AMNR offers wide registration tolerance. AMNR performance is defined by the total tunneling area and insulator thickness, not by channel dimensions, as in a TFT. Thus, AMNR registration tolerance can be 3× or more than that of a TFT, as shown in Table 1. Wide registration tolerance make an AMNR well suited to roll-to-roll processing, which has the potential to completely redefine backplane manufacturing processes and cost structures. The flexibility of an amorphous metal and the thinness and wide process registration tolerance of an AMNR bode well for the use of AMNRs in future flexible-display products.

AMNR technology is now being commercialized through the Amorphyx AMNR Consortium. This technology consortium is similar to those created to accelerate the development of flexible electronics or OLED technologies.[28–30] The key focus of the AMNR Consortium is to address critical device and panel level issues so that members are better positioned to translate AMNR technology into production. Amorphyx has partnered with the Industrial Technology Research Institute in Taiwan to host the AMNR Consortium beginning in 2016. High-level goals for the AMNR Consortium include (1) verifying reliability and scalability, (2) developing device models, drive schemes, and subpixel layouts to maximize display performance, and (3) building prototype AMNR-based displays to evaluate crosstalk and subpixel bit resolution.

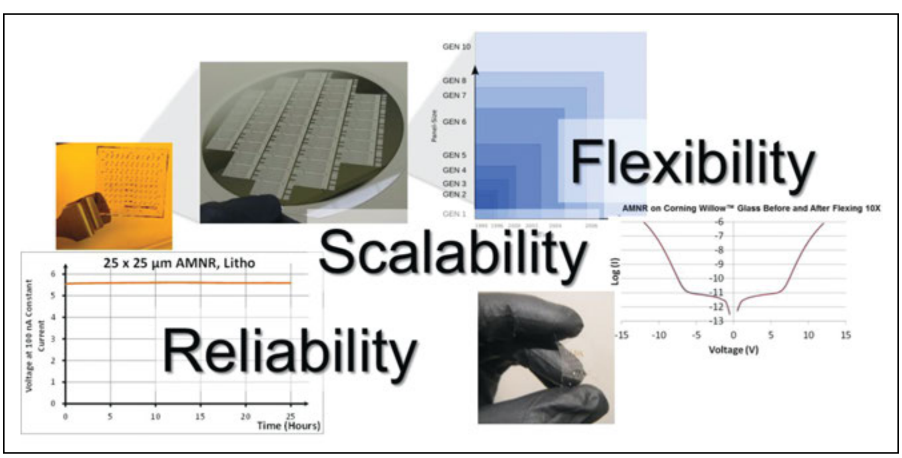

Fig. 6: The future development of the AMNR is focused on three main areas: reliability, scalability, and flexibility. The lower left insert shows a reliability stress-test plot for a "champion" AMNR device that did not fail after 24 hours of continuous stress at 100 nA. The upper insets depict how the AMNR has already been scaled from 1- to 6-in. substrates and is now being scaled to Gen 2.5 "prototype" sizes. The lower right insets show a Corning Willow glass substrate with AMNR devices being flexed as well as I–V plots for an AMNR device before and after flexing of its substrate.

Acknowledgment

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China Continues to Expand Display Operations

The country's recent economic setbacks have done little to slow the progress of new fabs in China.

by Jenny Donelan

ONE of the biggest trends from Display Week 2015 was how the Chinese panel makers stole the show in terms of big TVs. In our review of last year's event, we wrote: "This was the first year at Display Week ...that products from China made such a strong appearance at the show. These companies have made real progress in recent years in terms of innovation. Among the many worthy Chinese firms in the exhibit hall (including the Innovation Zone) were certain standouts, including BOE, CCDL, CSOT, and SuperD."

Since that time, the Chinese economy, until recently one of the most rapidly growing in the world, has faltered. According to a recent article in *The Wall Street Journal*, at the end of 2015, China was preparing to report its slowest annual economic growth rate in 25 years. Two of the major factors behind the slowdown are industrial overcapacity, especially in terms of commodities such as steel and glass, and also an oversupply of unsold homes in less economically developed cities.[1]

The overall economy might be expected to affect the display industry in China in at least two ways. First, a country struggling with industrial overcapacity might shelve plans for previously announced fabs. Second, in an economic downturn, consumers would be expected to spend less than previously on items such as TVs and cell phones.

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In fact, as of this writing, local governments in China were continuing with those plans to build new fabs. And Chinese citizens were still the primary customers for TVs made in China. It sounds puzzling, but here is what's going on, according to a number of experts both inside and outside the display industry.

Fab Stats

According to David Hsieh, Director of Analysis and Research for research firm IHS Technology Group, Chinese flat-panel makers have been ambitiously expanding their capacity for several years now, and the pace is not slacking. In a December 2015 blog post titled "China to have 28 flat-panel-display fabs in 2018. Long-term oversupply?", Hsieh writes: "Panel makers such as BOE, China Star, CEC-Panda, Samsung Display, and LG Display are investing in Gen 8 fabs in China. Newcomers such as HKC are also investing in Gen 8, as this is currently the best generation line for TFT-LCDs. Although Gen 10 is the biggest line, both the Chinese government and makers have recognized the huge risk and narrow product mix available from Gen 10. Therefore, the focus has been primarily on Gen 8 investment ...The majority have been a-Si TFT-LCD fabs, especially for Gen 8 (2250 × 2500 mm), which is also called Gen 8.5 in China."

Hsieh also notes that based on current investment plans and existing facilities under construction, there should be at least 28 fabs in China by 2018. About half of those are Gen 5.5 and 6, and the other half are Gen 8 or larger, as shown in Fig. 1.[2]

At least one exception to the 8.5 trend is BOE, which recently announced that it was partnering with Corning to build a Gen 10.5 LCD fab in Hefei, about 2 hours from Nanking. According to a recent report in *Tech News*, BOE plans to allocate the production of 65- and 75-in. super-large TV panels to this Gen 10.5 fab. The report adds that the investment is being made to take advantage of the rising market acceptance of large-sized TVs in China and will help the company gain market share in this segment.[3]

A Part of the Solution

Dr. Qun (Frank) Yan, Committee Chair of SID's Display Training School, Chief Technology Advisor for Changhong Electric Group, and expert on China, notes that although it seems surprising that Chinese companies are investing so heavily in display fabs during the economic downturn, the factories are considered part of the solution to the downturn. "Local government policies support this activity and funding is already allocated," says Yan. Building TFT fabs is considered a way to help the local economy, he explains. Economic development is not very balanced across China, and some regional local governments are competing to host next-generation large TFT-LCD fabs, so this development is unlikely to be curtailed.

Hsieh's blog explains in more detail why provincial Chinese governments are so eager

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Status of Gen 8 and Larger Fabs in China

Gen 8+	BOE	ChinaStar	CEC	HKC	Samsung	LG Display
MP	Beijing B4 Hefei B4 Chongqing B8	Shenzhen T1 Shenzhen T2	Panda Nanjing		Suzhou Fab	Quangzhou Fab
Under Construction	Fuqing B10 Hefei B9			Chongqing HKC		
Planning	Mianyang B11 Dalian B12	Wuhan T4	Panda Chengdu IRICO Xianyang			

Source: IHS

Fig. 1: *BOE, China Star, CEC, HKC, LG Display, and Samsung (the last two are Korean companies) all have Gen 8 and larger fabs in China that that are either built, under construction, or in planning stages. BOE is currently on track to have seven Gen 8+ fabs in China.*

to support LCD fabs built in their cities. One reason is stock growth: Panel makers' share prices generally increase from new investments, which in turn helps the local government or capital fund under the government's surveillance gain profits. Another is tax gains: Revenue from a new fab equates to tax gains on revenue tax or the VAT (Value Added Tax) for local governments. Real estate is another motivator. The government is the biggest owner of land resources in China, and land does not generate profit unless it is used productively. With new fabs built on that land, not only do employment and business activities create prosperity, but higher land value represents a better tax income for the local government. GDP growth is important, explains Hsieh, because China is "a special economic entity in which investment accounts for a large share of the GDP, rather than consumption. In fact, local government performance is judged by GDP growth because the central government values the nation-wide GDP as an important index for the country's development. Government officials are rewarded for their efforts in growing the GDP of their cities." Big LCD investments can stimulate that GDP growth.

According to Robin Wu, Principal Analyst with IHS DisplaySearch China, while the country's current TFT-LCD capacity is certainly growing, it is important to realize that it is already enormous. "The China mainland now boasts the #3 capacity in the world after Korea and Taiwan and will soon overtake Taiwan to become the second largest region with TFT-LCD capacities," he says.

Consumer Side

What helps make the display economy so interesting in China is that it is a huge market for buying displays, not just making them. "China is the #1 market in the world for LCD TVs, LCD monitors, and smart phones," Wu says, adding that despite recent setbacks, "there is still steady economic development and a growing population with the ability to spend money in China."

A recent article in the *Financial Times*, "China slowdown belies consumer market health," acknowledges that consumers are still spending, but that many analysts are skeptical of recent government reports that retail sales were growing at an annualized 10% in mid-2015. The article noted that succeeding in China's consumer economy is not as easy as it once was. Companies need to work harder and smarter, whether by offering less-expensive products to less-affluent customers or by improving the products and services they offer to high-end customers. Displays obviously can be targeted to both ends of the market.[4]

Says Yan, "Domestic supplies of panels still cannot meet the full demand in China. Most products made in China target the domestic market, and current fab capacities are not yet large enough to feed ongoing consumer-product demands. Currently, some of the highest-end TVs (4K) come from Korea and Taiwan. But that is going to change very quickly."

Of course, at some point the Chinese consumer market will become saturated with TVs, mobile phones, and other devices, much as markets have in North America and Europe – just not quite yet, it seems.

Display Talent from China

This relative affluence affects the Chinese display industry from an additional angle – academic research. Shin-Tson (ST) Wu, a professor with the College of Optics and Photonics at the University of Florida, notes that his college receives more than 100 Ph.D. applications each year from China alone. "In the early 2000s," he says, "the Chinese economy was still developing. So, if we offered a student admission without a scholarship, that was equivalent to rejecting the applicant." Now, however, many admitted Chinese students attend without financial support.

Another trend, he adds, is an increase in visiting scholars, including graduate students and faculty, who come with Chinese government funding. These visits can span from 6 months to 2 years. The trained display scientists who return to China to work will strengthen the R&D side of the industry.

Show Products

It is intriguing to wonder what kinds of products the Chinese companies that brought the big TVs to Display Week 2015 will offer the show this year. A look at CES 2016, only a few weeks away at press time, may offer hints. Show previews mentioned pending announcements from Chinese display companies such as Lenovo (monitors, device touch panels), Huawei (smartphones), and Hisense (TVs). To read more about Hisense's recent acquisition of Sharp's North American LCD-TV business, see Industry News in this issue.) According to CNBC, CES 2014 had 871 tech firms from China, a 34% jump from 2012, when there were 648 Chinese companies.[5]

Nothing is certain, of course, when it comes to any country's economy, and China's is unique in terms of size, scope, and recent acceleration (the current downturn notwithstanding). It is exciting, however, to see that the pace of display development has continued, despite stumbles from the overall economy. The editors at *Information Display* think there is a very good chance that we will be standing in front of more big, beautiful displays from China at this year's show in San Francisco.

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True Color: The Road to Better Front-of-Screen Performance

The authors have created an architecture that optimizes image processing across a complex display ecosystem, including smartphones, tablets, and desktop panels.

by Stefan Peana and Jim Sullivan

IN a race to win customers, manufacturers are bringing high-resolution displays to market with the message that more pixels per inch equal premium image quality. While focusing on a single performance measure such as resolution may come across as a sensible way to market display quality, it does not serve as a sufficient means to achieving superior front-of-screen performance. That is a complex process involving numerous elements that include environmental conditions, system requirements, user preferences, and the mapping of input to output images as well as optimizing multiple display-performance parameters – resolution, color, brightness, contrast – all working together in real time.

This article presents an architecture that optimizes image processing across a complex display ecosystem such as a smartphone, tablet, or desktop. The architecture leverages a mathematical model that enables color expansion to produce a brighter and more vibrant image output with superior front-of-screen performance.

Improved Display Performance Is a Game Changer

The rapid market adoption of high-resolution displays indicates consumers' desire for better front-of-screen performance. Manufacturers are working to define new display categories and features – streaming media content optimization, wider-color-gamut capability for gaming and rendered content, greater dynamic range to support greater flexibility of artistic intent – all in order to win new customers. This recent trend represents a shift from the previous generation of computing products that were designed and optimized for total system performance (*i.e.*, size, weight, cost, battery life, *etc.*), in which displays were deemed sufficient if usable for applications such as Word, Excel, and PowerPoint. Display functionality kept pace with product needs and stayed in line with display technology development.

The importance of improved display performance in the latest devices tracks the rise of use of smartphones and social media for mass communication. A brilliant and vivid display is the face of computing products. As previously mentioned, smartphone and computer makers promote improved display resolution or brightness as competitive differentiators.[1] In the absence of a display front-of-screen performance standard, such promotions have proven successful.

Strides in Color Design

Several industry leaders have developed design elements to enhance front-of-screen performance. Dolby, a forerunner in the theater viewing market, has made a compelling argument to pair high-definition resolution with wider color gamut as an improved approach to image quality.[2] A wider color gamut is delivered in the company of high-dynamic-range (HDR) input content, metadata encoded with the content characteristics, and multi-zone backlight control as the critical elements of how Dolby improves display images. Dolby's work is most suitable for television and difficult to realize in mobile devices because of product form factors such as size and configuration as well as battery-life limitations.

Technicolor has created a color-certification process in partnership with Portrait Displays to guarantee color quality on any computer or mobile device.[3] The primary focus of color certification is to eliminate variation in color performance across a multitude of display products. For example, a consumer may not see a correct representation of product color on a shopping Website and decide to return the merchandise at a reseller's expense. Instances such as these are a major challenge in the context of today's portable products. A user who expects to acquire, share, and view images across multiple devices is often frustrated by the difficulty of maintaining visual consistency in a complex ecosystem.

J. F. Schumacher *et al.*[4] developed a perceptual quality metric as a predictive measure of image quality rather than a measure of image fidelity rendered by the display. (See "PQM: A Quantitative Tool for Evaluating Decisions in Display Design" in the May/June 2013 issue of *Information Display*.) A change

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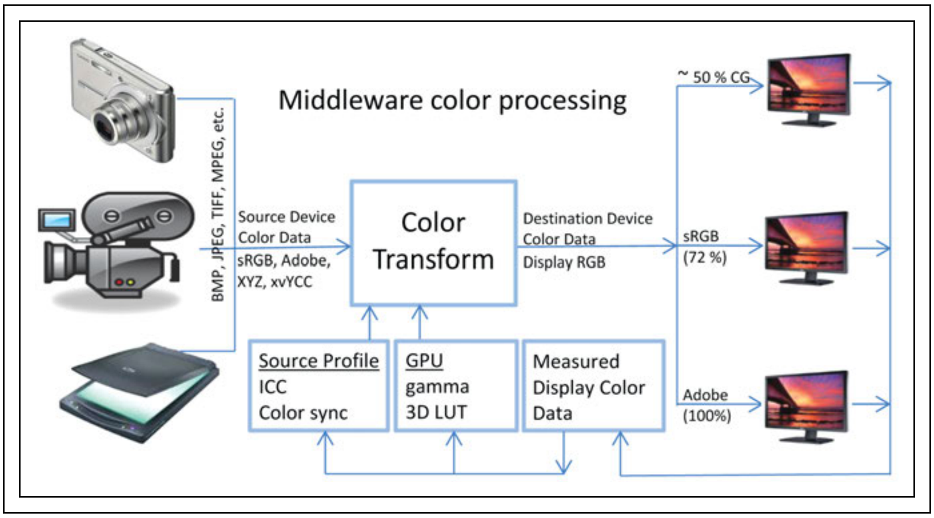


Fig. 1: The above schematic outlines a color-mapping workflow for multi-sourced input and destination output.

in display specifications alters the quality of the image; the measure provides a single metric to detect this improvement. Display makers can use this metric to make design choices across multiple specifications, improving user perception of the display. Nonetheless, technical focus of this metric on its own will not lead to the best visual experience.

Manufacturers of timing controllers offer a built-in color-management engine that uses simple one-dimensional color corrections to modify display color. These color-management solutions tend to be specific to a particular display and its timing controller. As a result, manufacturers such as Dell who source multiple display vendors for the same platform are unable to deliver consistent visual performance across all manufacturing builds.

Other companies have developed hardware solutions located between the GPU output and display input, converting images using proprietary algorithms.[5,6] The centerpiece of these solutions is a video-display-processor IC, which handles various input and output protocols, manages and buffers images, and performs high-speed processing for most display resolutions. While offering compelling display-performance capability, these intermediate hardware solutions duplicate existing GPU and timing-controller capability, impacting product size and cost.

An Innovative Architecture for Optimal Display Front-of-Screen Performance

Optimizing display front-of-screen performance requires a new architecture that consists of multiple elements working together. The most complex element of this architecture is the color-processing algorithm, which manages multiple color transformations while factoring in various input variables and user preferences under diverging viewing environments. The algorithm must be flexible, expandable, and capable of processing large data with the ability to maximize the visual experience of any display. It must also be able to distinguish between skin tones and non-skin-tone objects for independent processing. Moreover, the algorithm must manage the input-to-output mapping, identifying the need to compress or expand the input image relative to the output display device capability as illustrated by Fig 1.

During the image compression or expansion from one color space to another, preserving the original location of colors is challenging and requires transform functions that map the image from input device color space to output device color space. Running each image through the transform function requires hardware overhead, which can be power demanding and slow moving.

sRGB color space, used almost exclusively nowadays to represent color, may prove ineffective during expansion as it cannot preserve color accuracy, particularly in reds and blues. In the sRGB color space, if blue is expanded to be more colorful, it can become purple. Additionally, expanding color using sRGB adversely affects other elements such as skin tones, gray tones, white points, environmental illumination, and color temperature, as they increase at different magnitudes.

In 2011, Rodney Heckaman[7] developed an algorithm to achieve brighter and more vibrant colors during color expansion, realizing a

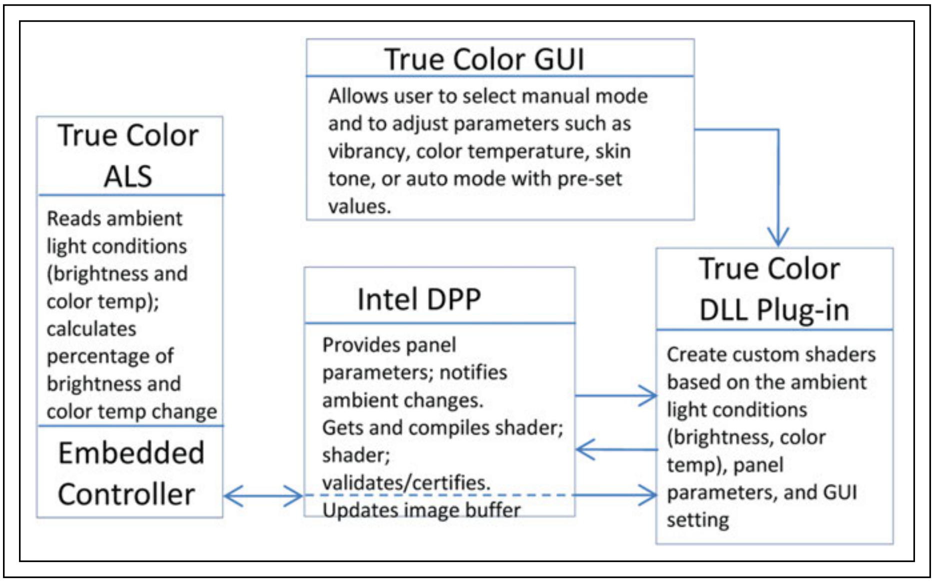
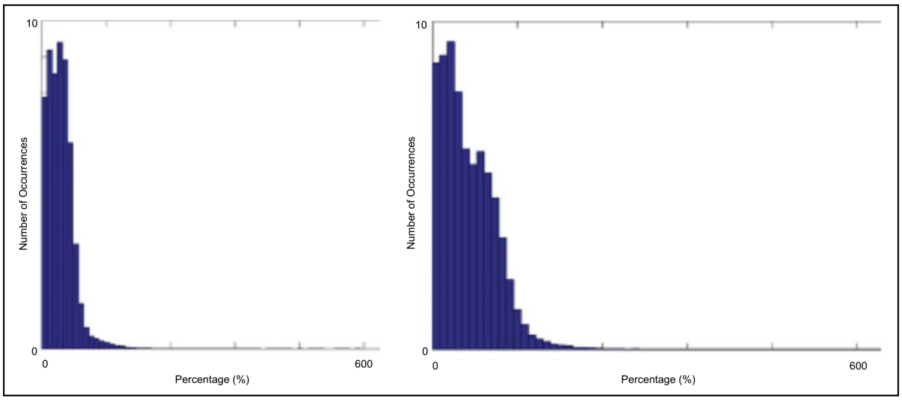


Fig. 2: The True Color high-level architecture incorporates three functional elements (ALS, DPP, and DLL), the True Color software, and a GUI.

(a) (b)

Fig. 3: (a) Original image. (b) Enhanced image using highest boost setting.

richer visual experience. The algorithm involves a sigmoidal function that isolates colors and the IPT color space to identify planes of constant hue for a particular display at a given luminance. Yang Xue describes the IPT color space in his graduate thesis, "Uniform Color Spaces Based on CIECAM02 and IPT Color Differences," paragraph 2.1.[8] Identifying and rendering specific colors independently (green grass, blue sky, purple flowers) maximizes display-gamut potential while maintaining memory colors (skin tone, *etc.*) to their original intent. The algorithm detects the input color values of each object type and uses selected color preferences for those objects to produce the chosen output object colors for just those objects, independent of the other colors that are processed to boost color to compensate for color losses in poor lighting. This results in larger display gamut utilization and an expanded image output containing memory colors that are identified and maintained to their original intent as well as independently rendering secondary colors. Building on Heckaman's work, Jim Sullivan of Entertainment Experience[9] has developed a model to improve the overall visual quality of color displays using IPT color space to convert to RGB while preserving input color, hue, and brightness.



(a) (b)

Fig. 4: (a) Mean and 95% increase in colorfulness for medium boost setting. (b) Mean and 95% increase in colorfullness for highest boost setting.

Look-Up Tables

Leveraging Heckaman's algorithm and Sullivan's model, our research team at Dell has co-developed an improved approach to achieving superior front-of-screen performance without compromising processing limitations. This approach involves creating a library of 3D Look-Up Tables (LUTs), which cover RGB to IPT color-space transformations that can be easily accessed and implemented. The IPT color space includes both environmental illumination and color temperature.

Using the environmental inputs, we set the P and T to zero, which defines the white point based on the viewer; all colors then adjust relative to white. Expanding a data point proportionally on the T axis saturates the environmental brightness and sets the desired saturation level. If the data-point color needs to change, it shifts to the desired color direction, selected from the appropriate 3D LUT. For example, shifting skin tone to warmer moves the data point toward yellow, progressing toward the higher-T positive direction in the IPT color space. For a lighter skin tone, color moves toward the negative in the blue direction. Skin tone is color specific and easily identifiable; therefore, it can be differentially expanded.

The IPT color-space data points also expand proportionally to the amount of color loss in brighter light. Blues and greens do not lose as much color as reds and yellows; consequently, reds and yellows expand more when the environmental light is brighter. As a result, unequal expansion must be considered. Similarly, uneven compensation is applied for shadows and highlights where the color of the brighter area expands more than for shadows.

Several notebook systems have recently been released with Dell's True Color software, which optimizes display color output by factoring in environmental conditions to make images appear as if in real life. True Color software also performs one-to-one image input to output color mapping and expand-maps the input image to a wider display gamut, making the output image appear more colorful. The True Color software is ideal for products with smaller color gamuts, such as computers and mobile devices, especially when used under a variety of environmental viewing conditions, or by the new generation of wide-color-gamut displays where the accuracy of color remapping is critical. The product of the software is a front-of-screen image true to the artistic intent of the creator.

True Color Architecture

True Color architecture, depicted in Fig. 2, is composed of three functional elements (ALS, DPP, and DLL), as well as True Color software and GUI. A True Color Ambient Light Sensor (ALS) is a sensor that responds to ambient brightness and color-temperature events. It filters the ambient light events to control the rate of change and interacts with True Color DLL through the Intel DPP to communicate ambient-light changes.

The Intel Driver Post-Processing (DPP) is a component of the Intel Display Driver, which supports True Color functionality. The DPP accepts the pixel shaders and associated parameters from the True Color DLL and uses these parameters to transform the image to be displayed. The new image is placed on the display buffer and then pushed to the display. The True Color Dynamic Link Library (DLL) is a plug-in loaded by the Intel DPP that receives the environmental brightness and color temperature values to create custom shades, which provide ambient light compensation using color boost and white-point adjustment. The interface lets the user interact with the True Color application settings through simple graphical icons and visual sliders.

The process starts with the True Color ALS reading the environmental illumination and color temperature, then passing the data to the embedded controller for processing. When the input data falls outside the preset ranges, the embedded controller notifies the Intel DPP *via* an API. The new data triggers the selection of a new 3D LUT from the library to change the color saturation and white point based on the environmental conditions. The Intel DPP requests new custom shaders from the True Color DLL based on the environmental input and the interface setting. The shaders are generated by averaging values in a maximum of four tables from a set of 16 tables that covers four light levels and four color temperatures. Once the image to be displayed is adjusted, it is placed on the display buffer and then pushed to the display.

True Color Software

The True Color software generates the 3D LUTs using display-measured data of the white and primary colors at various brightness

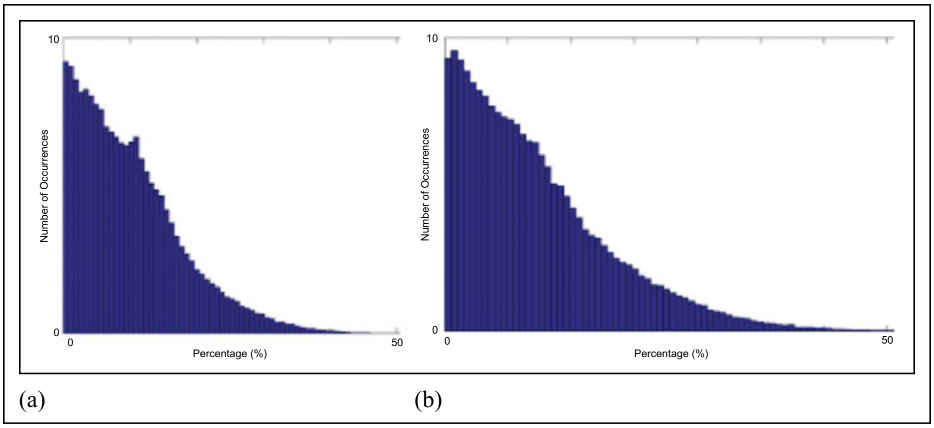


Fig. 5: (a) Mean and 95% image gamut increase for medium boost setting. (b) Mean and 95% image gamut increase for highest boost setting.

	Medium		Highest boost	
	Mean	95%	Mean	95%
Image Gamut	5.08	12.00	7.40	17.97
Colorfulness	29.07	67.85	42.71	101.04

Fig. 6: Both the mean and 95% measurement data are shown for image gamut and colorfulness enhancement.

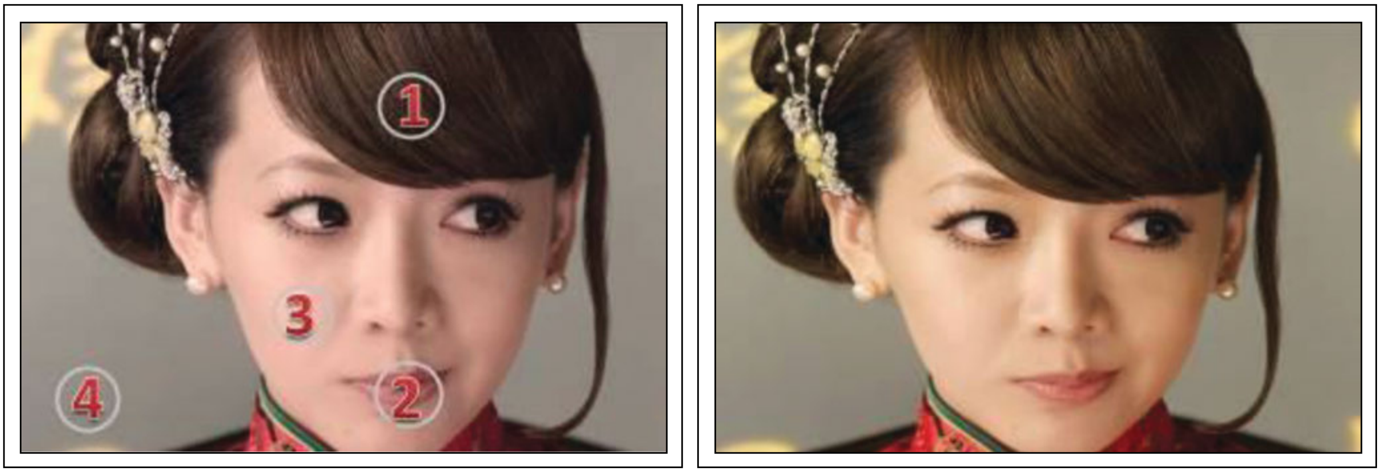


Fig. 7: (a) Original image with measurement locations. (b) Enhanced image using maximum skin tone and warm illumination.

levels and four different environmental illuminations (dark, dim, bright, and extra bright) and four color temperatures (incandescent, fluorescent, D50, and D65).

The software either automatically or manually sets the degree of expansion, also referred to as the boost level, which is always maximum-bounded by the display color-gamut capability. The maximum boost possible is defined as the outside edges of the display color volume calculated using the display color primaries and the white brightness, so the boost "knows" how far it can expand to stay in gamut in all directions in the color space.

The sigmoidal function is replaced by a nested formula that contains a set of inter-dependent factors managing the percentage of color boost, the magnitude of skin enhancement, the display color gamut, the gamma level, and the white-point management. The True Color algorithm uses these factors, along with user presets, to interpret the input image and map out the new display image.

The True Color Interface

The True Color interface set-up features two primary modes:

Manual Mode: The user can adjust display settings by selecting vibrancy level, color temperature setting, and flesh-tone enhancement. The user uses the vibrancy slide to adjust the color boost from minimum, normally used for dark ambient lighting or to maximum for brighter lighting. Typical manual mode features may not include an ambient-light sensor; therefore, the user can select color temperature by moving the slider from left to right – incandescent to fluorescent. Skin-tone settings can be varied from no flesh to maximum flesh enhancement by moving the slider from normal to warm. Manual mode trumps all presets as the user chooses to optimize all settings.

Auto Mode: Factory pre-set; the auto mode features an integrated ambient-light sensor to enable auto selection of 3D LUTs that produce color saturation and color white-point changes to accommodate the user's environmental lighting.

	CIE_x	CIE_y
1	0.4007	0.3757
1'	0.4546	0.375
Δ	0.0539	-0.0007
2	0.4037	0.3597
2'	0.4482	0.3575
Δ	0.0445	-0.0022
3	0.3712	0.37
3'	0.397	0.3707
Δ	0.0258	0.0007
4	0.3378	0.3682
4'	0.3658	0.3719
Δ	0.028	0.0037

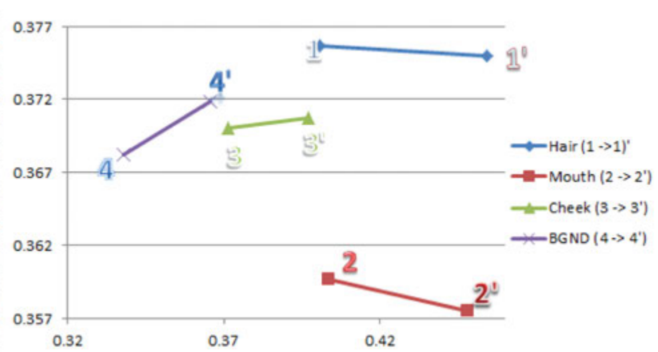


Fig. 8: Optical data of the enhanced image using maximum skin tone and warm illumination settings.

System Demonstrations

To validate our solution, we selected two images and tested them on two different systems using True Color. We created 3D LUTs for display based on the color primaries and white point. The first image [Fig. 3(a)] and the True Color application were loaded onto a Dell AIO Inspiron Series 5000 FHD desktop and enhanced using two boost settings – the medium and highest levels [Fig. 3(b)]. Using colorfulness, defined as the color volume in IPT color space, we created histograms of the enhanced images, illustrating the mean [Fig. 4(a)] and the 95% [Fig. 4(b)] increase of colorfulness *vs*. frequency of occurrence. Similar histograms were created for image gamut *vs*. occurrence [Figs. 5(a) and 5(b)]. The mean and 95% measurements of the image gamut and colorfulness are summarized in Fig. 6.

Measurement data show that 95% of the input-image data points are mapped to a new location, which expands by 7.40 and 17.97, respectively, for the highest boost setting. By using a similar setting, the color increases to 42.71 and 101.04, respectively. The True Color highest boost setting produces the best visually noticeable image enhancement. The new image features higher color saturation and a brighter background, as observed in the surrounding foliage. The barn in the enhanced image stands out, looking more vivid, as if it were being viewed in a brighter sunlight.

Similarly, we loaded the second system, a Dell Inspiron 15 7000, with the 3D LUTs and the True Color application. The image was tested using maximum skin-tone adjustment and warm-illumination setting; these images were measured using Minolta Model C210 U-Probe color-processing equipment with a large-measurement spot size. Four measurements points were taken as indicated in Fig. 7(a) and then plotted showing the change in magnitude and directional shift (Fig. 8).

As observed in Fig. 8, the four points move away from the white point toward higher saturation. The non-linear data transformation of the conversion equation impacts the magnitude and directional change of each point differently. The skin boost is set to warm while the background is brightened and adjusted for the user's color-temperature environment. As a result, image Fig. 7(b) boosts to a warmer skin tone over a brighter gray background, appearing vivid and more colorful.

Better Display Quality through Color

True Color improves front-of-screen performance by targeting the colorfulness of output images. The main purpose of this work on color improvement was the design of a robust system architecture at the system level, flexible to the complex tasks of color management (*i.e.*, transform, correct, boost) and controlled by a graphical user interface for individual customization. Developers can access the pixel data using the SDK specification and True Color enabled Intel chipsets to build innovative applications that lead to the next level of display performance (*e.g.*, color-accuracy adjustments, and new accessibility tools for color-blind users using look-up tables). Future development will focus on intermediate steps where the input image is sharpened and contrast enhanced so as to, along with color management, enable a superior front-of-screen experience.

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Event Date	Event Description	Closing Date
January/February	**Digital Signage, Materials** **Special Features:** Digital Signage Technology Overview, Digital Signage Market Trends, Oxide TFT Progress Report, Alternate Display Materials, Top 10 Display Trends from CES, Chinese Business Environment **Markets:** Large-area digital signage, in-store electronic labeling, advertising and entertainment, market research, consumer products, deposition equipment manufacturers, fabs	**December 28**
March/April	**Display Week Preview, Flexible Technology** **Special Features:** SID Honors and Awards, Symposium Preview, Display Week at a Glance, Flexible Technology Overview, Wearables Update **Markets:** Research and academic institutions, OLED process and materials manufacturers, consumer products (electronic watches, exercise monitors, biosensors), medical equipment manufacturers	**February 29**
May/June	**Display Week Special, Automotive Displays** **Special Features:** Display Industry Awards, Products on Display, Key Trends in Automotive Displays, Insider's Guide to the Automotive Display Industry **Markets:** Consumer products (TV makers, mobile phone companies), OEMs, research institutes, auto makers, display module manufacturers, marine and aeronautical companies	**April 21**
July/August	**Light Fields and Advanced Displays** **Special Features:** Overview of Light-field Display Technology, Next-generation Displays, Market Outlook for Commercial Light-field Applications **Markets:** Research institutions, market analysts, game developers, camera manufacturers, software developers	**June 20**
September/ October	**Display Week Wrap-up, Emissive Technologies** **Special Features:** Display Week Technology Reviews, Best in Show and Innovation Awards, Quantum Dot Update, A Look Forward at Micro-LEDs **Markets:** OEMs, panel makers, component makers, TV and mobile phone companies	**August 25**
November/ December	**Applied Vision** **Special Features:** Advanced Imaging Technology Overview, Current Key Issues in Applied Vision, Real-World Applied Vision Applications **Markets:** Medical equipment manufacturers, game developers, research institutions, OEMs, software developers	**October 24**

Mark Your Calendars for These Upcoming SID Events

April 7–8, 2016: SID Mid-Europe Spring Meeting

The next Society for Information Display Mid-Europe Meeting will take place in Berlin, Germany. A €1500 award will be granted to the best student contribution to the spring meeting. The winner of last year's student award was Mohammed Mohammadimasoudi from Ghent University for his paper, "Thin-film polarized liquid-crystal backlight." According to Mid-Europe Director Herbert DeSmet, "The Mid-Europe Spring Meeting is the best way to find out about the latest display developments from European companies, particularly because EuroDisplay, held every other year, does not take place until 2017."

More information about dates, location, and agenda will be available soon at www.sid.org/chapters/europe/mideurope.aspx.

For information, Contact the Mid-Europe Director, Herbert De Smet, at Herbert.DeSmet@elis.UGent.be.

Notes: The proceedings from the 2015 EuroDisplay Conference in Ghent, Belgium, are available to all logged-in SID members as a special issue of the SID Digest, at http://online library.wiley.com/doi/10.1002/sdtp.10580/abstract.

The 18th century Brandenburg Gate in Berlin is one of the most iconic structures in Germany.

May 22–27: Display Week 2016

In 2016, the biggest, can't-miss event of the year for the display industry comes to one of the most exciting destination cities in North America – San Francisco. People from all over the world travel to this truly international destination for its architecture, food, history, and culture.

The next issue of *Information Display* will feature a show preview, including information about the schedule and highlights from the technical program. In the meantime, check out www.displayweek.org for more information.

August 23–26: iMID

Jeju City is located on the volcanic island of Jejudo, a World Natural Heritage Site known for its warm climate and unique culture.

The next International Meeting on Information Display will take place in Jeju City, Korea. Jeju City is a resort destination located on an island off the Korean Peninsula. IMID is a premier display conference with more than 1,800 attendees every year, a venue in which many academic, industry, and business leaders meet, publish R&D results, and share knowledge of information displays.

The conference includes keynote presentations (Professor Hideo Hosono of the Tokyo Institute of Technology was recently announced as a speaker), technical oral and poster presentations, tutorials, workshops, and special display exhibitions.

Visit http://www.imid.or.kr for more information.

continued from page 2

industry veteran). Gary developed his own Frontline Technology article titled, "Elemental Evolution of Digital-Signage Components," to give us a clear picture (pun intended) of the trends and recent technical innovations making this recent wave of digital signs possible, along with some of the most interesting new embodiments in this space.

We also have a Display Marketplace feature from Todd Fender with IHS Technology Group, titled "New Directions for Digital Signage and Public Displays," to help fill in the story from the business side. As I said earlier, the numbers are worth talking about, as the total global sales forecast for public displays is forecasted to grow from 3 million units in 2015 to near 4.5 million units in 2019. Now, if this does not sound like very much volume, just consider that this translates to a market size near US$10 billion, made up mainly by large-sized LCD panels and even larger-sized direct-view LED displays. This market is big enough that major LCD manufacturers are taking notice and developing special industrial-grade high-performance panels just to support this application. Many parts of the supporting eco-system are growing rapidly as well to deliver content and to provide new materials and methods for packaging, installation, maintenance services, *etc*. It is clear why the SID Symposium program committee identified digital signage as a special topical area for Display Week 2016. This is a business and technology market poised for a lot of growth in the coming years.

Our other important technical focus area this month is Display Materials, and specifically we are talking about ways to make active-matrix backplanes either from oxide TFTs or possibly from a new type of switching device called an amorphous-metal non-linear resistor (AMNR), which is described as "… a two-terminal device that employs amorphous-metal thin films to create highly uniform tunnel junctions for regulating current–voltage performance." Guest Editor and SID Fellow John Wager (Professor at the School of EECS at Oregon State University) joins us again this month first to update us on the latest advances in oxide-TFT research with his Frontline Technology article, "Oxide TFTs: A Progress Report." This is a great update to a technology gaining wide-ranging acceptance that we have been covering with John's help for several years now.

But next, we hear from authors Sean Muir, Jim Meyer, and John Brewer, all with a new entrant company called Amorphyx, describing their development of AMNR devices in their Frontline Technology article, "Amorphous-Metal Thin Films Enable Ultra-High-Definition Display Backplanes." A common theme in both articles is the emphasis on making switching devices from amorphous rather than polycrystalline thin films for several critical reasons, including stability, uniformity, and ultimately scalability to very-large panel sizes including those needed to make some of the incredibly large (> 80-in.) LCD panels being sold now for TVs and digital signs. John Wager explains all the details about this as well in his Guest Editorial, "Amorphous? Again??" I hope you will find it as helpful as I did in putting all this new activity around oxide-film research into the proper context.

Our Business of Displays coverage continues this month with an update on the Chinese economy and its impact on display manufacturing in China. Not long ago we heard impressive stats about plans for new display-manufacturing capacity. We have also heard a lot this past year about the Chinese stock market and the slowing of the company's overall domestic economy, and we wanted to know what impact that was having on those aggressive plans. Our own Jenny Donelan did a great job assembling this feature, titled "China Continues to Expand Display Operations," and she explains that despite the recent news, things remain very positive for new investment and capacity expansion. We'll be keeping an eye on this throughout 2016 and bringing you updates as we dig deeper into some of the plot lines she uncovered while developing this article.

For as long as I can remember, people have looked for ways to make multiple-color displays appear the same and optimize the available color gamut of each one for the best user experience. It used to be relatively hard just to get two displays next to each other to look the same. Various calibration techniques were developed to address this issue, and today you can assemble entire walls of flat-panel displays and, with the right software, make them all track the same in terms of luminance and chrominance. You can also manipulate the source content to make them look more vivid and utilize as much available display color gamut as possible. This latter desire becomes more interesting as we see LED and quantum-dot (QD) backlights become widely available. However, now consider trying to do the same kind of thing between a tablet display and a laptop, or develop content that looks as vivid on a smartphone as it does on your home TV screen. Well, authors Stefan Peana from Dell and Jim Sullivan from eeColor take on this challenge by describing a new platform for display color optimization they call "True Color." In this issue's installment of Making Displays Work for You, titled "True Color: The Road to Better Front-of-Screen Performance," we hear about a sophisticated set of hardware and software tools built on the Intel graphics processor platform to transform the color space of content sources to optimize their appearance on a variety of known target displays. I will not try to explain it all to you in this short introduction – that is what their article does – but what I will say is that this kind of capability has far-reaching possibilities, if used properly, to enhance the user experience as advertised. I applaud the people who worked on this project for giving due consideration to the importance of realism and including the impact of the viewer's ambient environment in the methodology to optimize color performance.

Of course, before we end, let me offer a truly heartfelt wish for your good health, success, and prosperity in this New Year. We all have our individual hopes for 2016 and beyond. Mine include spending more time with my family and making important memories at home as well as at work. I hope you too have similar ambitions and as I have said many times, a better work-life balance actually makes you more productive and more prosperous than endless working hours ever will. May we all find our own form of peace in the New Year. ■

continued from page 4

Essentially, an AMNR is an elegant realization of a dual-select diode pixel. That is the basic idea. A more complete introduction to AMNR technology is presented in the article in this issue by Muir, Meyer, and Brewer.

What are the commercial prospects of AMNR backplane technology? Here is my take.

Advantages:
- A simple 2–3 mask process using only three thin-film layers.
- Temperature-independent operation expected for Fowler–Nordheim-based TFDs.
- Light insensitivity anticipated due to absence of a semiconductor.

Challenges:
- Insulator fabrication *via* plasma-enhanced chemical vapor deposition, or is atomic layer deposition required?
- Performance/Stability/Reliability/Scalability?

The Amorphyx vision is "Simple" – for a change. Whether or not the company's undoubtedly simple backplane approach can satisfy the extraordinarily demanding requirements associated with flat-panel-display commercialization will require (i) validation of the technology via prototype fabrication and testing and (ii) feasibility scaling to ensure that expectations associated with amorphous thin-film scaling are indeed warranted for this new case of an amorphous metal.

So, regardless of whether you speak about the past (amorphous hydrogenated silicon), the present (amorphous oxide semiconductors), or the Amorphyx-envisioned future (amorphous-metal non-linear resistors) of flat-panel-display backplane technology, I suspect that "amorphous" will be a useful adjective.

John F. Wager *holds the Michael and Judith Gaulke Endowed Chair in the School of EECS at Oregon State University and is a SID Fellow. He can be reached at jfw@eecs.oregonstate.edu.* ■

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