IMAGING TECHNOLOGIES AND LIGHTING ISSUE

Information DISPLAY

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Advances in Depth Imaging Enable Innovative and Creative User Interfaces

UNDERSTANDING THE MECHANISMS THAT LINK LIGHTING AND HEALTH

IMPROVING MANUFACTURING YIELDS FOR OLED TVs

ADVANCES IN LIGHT-FIELD PHOTOGRAPHY

Information Display Magazine - The First 50 Years

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ON THE COVER: Recent developments in depth-imaging technologies and 3D computer-vision algorithms are enabling an array of new applications based on life-like machine vision.

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- Market Dynamics for Public Displays
- Outdoor Digital Signage
- Sensor Architecture for Interactive Displays
- A Progress Report for Oxide TFTs
- Amorphous-Metal Thin Films

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editorial

A Look Back at 2015 – and Even Further

by Stephen Atwood

Welcome to the final 2015 issue of *Information Display*. It's been an amazing year for both our own display industry and the wider world of electronics, computers, and technology in general. We've experienced some amazing paradigm shifts involving communications, personal devices, entertainment, and so much more. Wearable devices made amazing strides this year, going from novelties to must-have accessories. Data speeds for both wired and wireless networks expanded dramatically as streaming media seemed to take over the entertainment landscape. It seems like I watched more original content from non-broadcast sources (Amazon, Netflix, *etc*.) than broadcast this year for the first time. Fitbits, Apple Watches, and other wearable devices were everywhere at my workplace, and the typical tablet display had more pixels and better image quality than my best television did just 5 years ago. Smartphones with unique display shapes also came to market, giving us a hint of how flexible displays may be implemented in the future. I finally achieved a paperless office with not a single printout or paper form to sign all year No, I'm just kidding about that one! I doubt that will ever happen. The digital dashboards in new cars were simply amazing, though it felt like they were about 10 years behind schedule – at least compared to when we were expecting them to appear. I saw my first true light-field projection-display demo and heard promises about a $3000 OLED TV. I also saw an amazing demonstration of the Dolby Vision HDR technology now available through TV maker Vizio (read more about it in this issue's Industry News).

Display Week 2015 revealed a dizzying week of new discoveries and proof that our industry is experiencing more creativity than ever before. On top of all this, I now actually own a laptop that stays alive on battery longer than my flights between Boston and California – and the display is great! The variety of creative product ideas that are enabled by the latest generation of displays and related electronics are simply endless. This is a great time to be part of our wonderful industry and also the best time ever to be a member of SID. There is no other organization that can put you on the inside of this industry like SID can – whether through the wide variety of local chapter activities or through the great international events such as Display Week or the recently announced Display Training School (DTS) courses being organized all over the world (find out more in this month's SID News.) Joining SID is the best step you can make to further your career skills and technical knowledge in this very dynamic field.

Our issue theme for this month is "Lighting and Imaging Technologies," two very active areas of research and development that have the potential to change our lives in significant ways. Advanced lighting systems, as I'll explain shortly, have the potential to literally improve our health and productivity while imaging technology, specifically real-time 3D depth imaging of live scenes, will change the way we interact with all our electronic devices in the future. I'm placing emphasis on the term "will" because I have no doubt that the future of human interaction with computers will include voice, gesture, face, and identity recognition. It may someday go as far as emotional interaction and real personality identification but even without that latter dynamic, we're very soon going to start seeing platforms capable of complex gesture and facial recognition. Even more exciting is that the same technology that enables these capabilities also enables endless new ways of creating augmented-reality applications such as merging real-life scenes with animation and virtual-reality platforms bringing users directly into the digital world. I've learned this in part by following the work at Intel being widely publicized recently and brought to us this month by our Guest Editor Achin Bhowmik, who also co-authored our cover story "Advances in 3D Sensing Technologies and Applications" written by Achin and his research team at Intel. Their work includes solving a number of very specific problems related

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Executive Editor: Stephen P. Atwood
617/306-9729, satwood@azonix.com

Editor-in-Chief: Jay Morreale
212/460-9700, jmorreale@pcm411.com

Managing Editor: Jenny Donelan
603/924-9628, jdonelan@pcm411.com

Global Advertising Director:
Stephen Jezzard, sjezzard@wiley.com

Senior Account Manager
Print & E Advertising:
Roland Espinosa
201-748-6819, respinosa@wiley.com

industry news

VIZIO Announces TVs with Dolby Vision High-Dynamic-Range Support

VIZIO and Dolby Laboratories recently announced VIZIO's new Reference Series televisions, which incorporate high dynamic range with Dolby Vision playback technology. At a suggested retail price of $6,000 for the 65-in. model and $130,000 for the 120-in. one, these sets – particularly the 120 in. – are aimed at cinephiles with very deep pockets.

Both models feature VIZIO's Ultra Color Spectrum for a wide color gamut and an 800-nit full-array local-dimming LED backlight with 384 zones for what the companies describe as a "stunningly vivid UHD picture." The 65-in. model comes with a quantum-dot-enhanced LCD panel. Customers will receive immediate access to certain Warner Bros. Home Entertainment 4K UHD Dolby Vision mastered titles (such as *The Lego Movie* and *Man of Steel*) via the video-on-demand streaming service VUDU. Additional Dolby Vision titles from other content providers will soon be available through Netflix, according to VIZIO.

The Lego Movie *will be one of the first titles to be made available in 4K UHD Dolby Vision, which is supported by VIZIO's new Reference Series TVs.*

Mitsubishi Electric Releases New Tough Series Module

For display users looking for attributes such as vibration-resistance and extreme-temperature operation rather than the UHD imagery described above, Mitsubishi Electric has announced the launch of the Tough Series 10.4-in. XGA TFT-LCD module. This product is designed for industrial applications that will severely test a display's ruggedness, such as construction, agriculture, factory automation, and industrial weaving. The module offers 6.8G vibration-resistant acceleration seven times greater than that of conventional modules, as well as an operating temperature range of –40 to 85°C and 1200-cd/m^2 super-high brightness and high contrast ratios.

DisplayMate Reports Viewing-Angle Weakness in PVA LCD TV with Quantum Dots

Reluctantly, because he describes himself as an enthusiastic supporter of quantum dots, DisplayMate President Ray Soneira recently reported some disappointing viewing-angle results in a patterned-vertical-alignment (PVA) LCD TV he tested.[1] Specifically, there was a "tremendous" loss of color saturation with viewing angle resulting from using PVA, wrote Soneira. Although the September report, "Flagship OLED and LCD TV Display Technology Shoot-Out," revealed many positive attributes of the quantum-dot-enhanced LCD, the viewing-angle issue, based on extensive lab test and measurements, was significant.

(continued on page 41)

M&A BRIEFS

Tianma Group Merges U.S. Sales Subsidiaries to Create New Company

The Tianma Group, Shenzhen, China, a leading global manufacturer of LCDs since 1983, has decided to merge its two U.S.-based subsidiaries – Tianma NLT America and Tianma Microelectronics USA – to form Tianma NLT USA, Inc. The merger is designed to strengthen Tianma's presence in the Americas and to provide customers with a single source for the two subsidiaries' complementary LCD products and services. These include a broad lineup of LCDs for industrial, medical, and other professional applications as well as technologies like LTPS-TFT, oxide-TFT, AMOLED, flexible, transparent, 3D, and touch displays for consumer, industrial, and automotive applications.

Tianma NLT USA will be headquartered in Chino, CA, and will continue sales, marketing, and engineering activities out of both Chino and its Northern California office in Santa Clara.

* * * * *

Lotte Group Acquires Samsung's Chemical Business

In October, the Lotte Group, a Korean conglomerate comprising more than 60 business entities, announced that it would buy the chemical businesses of Samsung Group for about 3 trillion Korean won ($2.6 billion).[3]

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[3] http://economictimes.indiatimes.com/articles how/49590187.cms?utm_source=contentof interest&utm_medium=text&utm_campaign =cppst.

guest editorial

A New Look at Lighting

by Mike Lu

It is often said that we do not appreciate what we have until it's gone. The adage seems fitting when it comes to lighting – reliable and pervasive, luminaires once installed are then forgotten for the next 20 years. Lighting is simple and works, most of the time. About the only time lighting enters our mind is when there is a burnt-out or faulty lamp.

The advent of solid-state lighting (SSL) is breathing new life and opportunity into that staid landscape. The initial focus has been the energy-saving potential of light-emitting diodes (LEDs). More recently, the "connected" nature of both lamps and luminaires is allowing a new degree of control over the built environment. It has propelled lighting to the forefront of another revolution known as the Internet of things (IoT).

The Society for Information Display (SID) has long recognized the interest in lighting among its members. Lighting has been a special topic at Display Week for several years running. Moreover, SID entered into a friendship agreement with the Illuminating Engineering Society of North America (IESNA) last year. Very broadly speaking, both display and lighting are about the generation of light and its subsequent manipulation. More specifically, we have seen the LED-powered backlight units for liquid-crystal displays (LCDs) morph into edge-lit flat panels for illumination and organic light-emitting diodes (OLEDs) designed for emissive displays enabling both white and color tunable panels for lighting. While improvements in both LED and OLED performance remain a hotly pursued topic, finding new applications for connected lighting draws ever more companies, large and small, into this renewed enterprise.

This issue highlights another emerging and major trend in lighting research, the impact of lighting on health. Dr. Jennifer Veitch from the National Research Council of Canada has contributed an article for this special topic with an overview of the medical research centered on intrinsically photosensitive retinal ganglion cells (ipRGCs). These cells are a separate class of photoreceptors, different from the retinal rods and cones responsible for vision. Reports of a fifth opsin or photosensitive material in the retina, melanopsin, began to appear as early as 1998.[1] Evidence clearly linking this opsin, the ipRGCs, and sleep, as well as potentially other biological regulatory functions with light, began appearing shortly thereafter in 2002.[2] A flurry of activity has ensued as the anatomical and physiological links from the ipRGCs to the super-chiasmatic nuclei were established, and with these discoveries a mechanism for light to regulate the human circadian rhythm, including levels of melatonin.[3] Blue light at night has been shown to suppress melatonin secretion, which can lead to sleep disorders, and there are even suggestions in the literature that this may be related to a higher incidence of breast cancer.[4]

Reducing the putative hazards posed by blue-light exposure at night or during inappropriate times within an individual's diurnal cycle was the key motivation behind the work described in the second lighting article, by Professor Jou *et al.* from the National Tsing Hua University in Taiwan. His group has made candle-like (CCT $\leq$ 2000K) OLEDs with minimal blue spectral content. Unlike typical OLED lighting panels with red, green, and blue emitters, these candle-like OLEDs employ four, five, or even six emitters to best approximate the continuous spectrum of a black-body radiator of low correlated color temperatures.

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Advances in 3D-Sensing Technologies and Applications

3D sensing enabled by depth-imaging technologies allows immersive user interfaces and life-like interactive experiences via real-time understanding of the 3D environment, people, and objects in real-world scenes. Advances in this area are being made possible through several key technologies, including sensors, algorithms, and system integration.

by Achintya K. Bhowmik, Selim BenHimane, Gershom Kutliroff, Chaim Rand, and Hon Pong Ho

RECENT developments in depth-imaging technologies and 3D computer-vision algorithms are allowing efficient and real-time acquisition, reconstruction, and understanding of the 3D environment, which in turn are enabling an array of new applications based on life-like machine vision. These applications include immersive and interactive gaming, video conferencing with custom backgrounds and synthetic environments, education and training, virtual home and office decoration, virtual clothes fitting, autonomous machines, and numerous other entertainment and productivity usages that incorporate natural and intuitive interactions.

This article discusses the advances in key technologies, including sensors, algorithms, and system integration, that are fueling the recent proliferation of 3D-sensing applications. Specific topics include depth-sensing and tracking technologies, 3D imaging and reconstruction, 3D gestural interactions with hand skeleton tracking, background segmentation, and collaborative augmented reality.

***Achintya K. Bhowmik**, **Selim BenHimane**, **Gershom Kutliroff**, **Chaim Rand**, and **Hon Pong Ho** are with Intel Corp. in Santa Clara, California. Achin Bhowmik can be reached at achintya.k.bhowmik@intel.com.*

Depth Sensing and Tracking Technologies

The recent availability of small form factor, low power, and real-time depth-image-capture technologies is a key enabler for mainstream devices and systems with 3D-sensing capabilities and interactive applications. Conventionally, vision-based applications have used 2D image sensors, utilizing the cameras that are already part of mobile devices such as smartphones, tablets, and laptops. These conventional image-acquisition devices are able to convert the visual information in a 3D scene into a projection of 2D arrays of discrete numbers. As a result of this transformation process, the 3D information cannot be accurately recovered from the captured 2D images because the pixels in the images preserve only partial information about the original 3D space.

Reconstruction of 3D surfaces from single-intensity images is a widely researched subject. However, recovering 3D spatial information from 2D projections possesses inherent ambiguities. Moreover, this type of approach is generally computing intensive and often requires manual user inputs; hence, it is not suitable for applications that require real-time and unaided understanding of the 3D environment and interactive usages.

In contrast, the human visual system incorporates a binocular imaging scheme and is capable of depth perception. These capabilities allow us to understand, navigate, and interact in our 3D environment with ease. Similarly, natural and interactive experiences with vision-based schemes are better accomplished using 3D image-sensing devices, which can capture depth or range information in addition to the color values for a pixel, thereby allowing fast and accurate reconstruction and understanding of the 3D world. Interactive devices and applications utilizing real-time 3D sensing are rapidly gaining adoption and popularity.[1] Examples include personal computers and mobile devices using Intel's RealSense cameras, and gaming console systems such as Microsoft Kinect in living rooms. Figure 1 shows a pair of depth and color images captured with the RealSense 3D Camera.

Besides the advances in image sensing, vision-based tracking and mapping techniques have progressed significantly with the advent of visual simultaneous localization and mapping approaches or visual SLAM,[2–4] which allow real-time construction and updating of a spatial map while simultaneously tracking features within the environment. This is often built on top of standard 2D imaging devices to allow real-time camera pose estimation and a sparse reconstruction of the environment. In

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Fig. 1: *Shown at left is the output from a 3D imaging device, with depth mapping that shows nearer points as brighter. At right is the corresponding color image.*

this type of representation, the object and scene surfaces are not recovered. These approaches provide limited applications because they only open up the possibility of restricting interactions to the knowledge of the camera pose.

Other visual SLAM approaches built on top of standard 2D imaging devices have been proposed and achieve denser reconstruction, but require high-end desktop computers because of high computational demand[5] or provide low-density reconstruction.[6] Using 3D-imaging cameras allows real-time camera pose estimation and a dense reconstruction of the environment. With 3D-imaging cameras, simultaneous localization and dense mapping have already been shown on high-end desktop computers using rather large-form-factor RGB-D camera systems such as the Microsoft Kinect and where the implementations were processed on powerful discrete graphics processing units.[7] Note that these cameras, in the best cases, require a special mount in order to be fitted on tablet form factors.[8] This can result in additional costs, calibration, and grip/handling limitations that also restrict the application experiences. In contrast, the RealSense camera system provides RGB and depth data that can be embedded into a mobile device such as a tablet or a phone. Having a small form factor and low-power 3D-imaging camera system integrated in a mobile device such as a laptop, tablet, 2-in-1 device, or smartphone allows new interaction experiences (Fig. 2).

In conjunction with the small-form-factor computing devices incorporating 3D-sensing technologies, the Intel RealSense platform provides frameworks for algorithm implementations including scene perception based on real-time pose estimation and dense 3D reconstruction of the environment, which can be used across heterogeneous platforms (CPU/GPU) running in OpenCL kernels. These frameworks open up new types of applications that increase the interactivity between the users and the environment. For example, augmented-reality applications, among others, can make use of virtual content seamlessly added to the live camera input at an interactive rate, and occlusions of the augmentations by real objects can be correctly handled. The motion estimation is correctly scaled and the metric measurements of the scene are possible as well. Also, the parallel dense reconstruction allows an increase in the realism of the experience, thanks to physics and lighting simulation.

3D Imaging and Reconstruction

3D imaging and reconstruction are classic topics in computer vision. Early work focused on inferring 3D models from lines and corners, followed by work on stereo matching and multi-view stereo.[9] As digital-imaging hardware progressed, it made it possible to create dense 3D depth maps in real time, which led to advancements in robotics, computer graphics, and image analysis. A natural question that emerged was whether the depth images could be fused together to form a 3D model, provided there was a way of determining the pose of the camera for each image. Early methods focused on space carving and point-cloud representations because the devices were either tethered, low frame rate, or low resolution. Therefore, only thousands of depth measurements could be used to construct a model. However, approaches for 3D reconstruction have been revisited in recent years to address bandwidth challenges of dense high-frame-rate 3D-imaging devices mounted on handheld devices. Intel's RealSense camera is capable of capturing millions of depth samples per second in an unrestricted workspace.

To efficiently process and use as much of the depth data as possible to form a 3D model, voxel representations are popular because the voxel grid data structure is very efficient for accumulating information in 3D space. It also allows multiple accumulations to occur in parallel without memory contention in different regions of space, which is amenable for GPU or multicore CPU processing.[7] The drawback to voxel representations is that the workspace has to be known in advance to enable real-time reconstruction, and the amount of memory needed to reconstruct an object scales cubically with resolution, even though the surface area of the object scales quadratically (two dimensionally). For instance, a 1-m cubed space that is to be reconstructed at 2-mm resolution requires a memory block for 125 Mvoxels, even though for a closed object, the surface of the object will occupy ~1 Mvoxels, which means 99.2% of the memory will go unused (wasted). To address

Fig. 2: *The RealSense camera can be integrated within a phablet.*

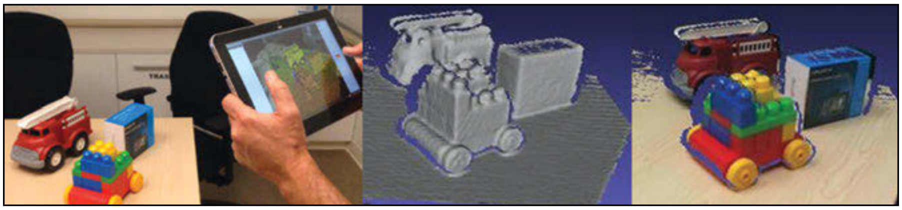

Fig. 3: Real-time 3D scanning and reconstruction are demonstrated with (left) a tablet equipped with an embedded RealSense camera used to scan a real-world scene. The middle image is the 3D scanned version. At right is the same image including texture mapping and color information.

the data space inefficiency of voxel grids, hierarchical techniques have been developed to increase the grid resolution where there are more samples,[10] along with variants that are more appropriate for GPU architectures.[11]

These methods reduce the memory requirements to be quadratic and in line with the amount needed to represent the surface as a triangle mesh. Figure 3 shows a real-time 3D reconstruction using the RealSense technology.

Hand Skeleton Tracking

Real-time hand skeleton tracking capability is necessary for implementing 3D user interfaces supporting fine-grain manipulation of virtual objects with finger-level gestural articulations. This is a challenging problem, due to its high dimensionality, the prevalence of self-occlusions, the rapid movements of the fingers, and the limited viewpoint of a single camera. Moreover, in the case where skeleton tracking enables gesture control for interactive applications, user expectations of robustness and continuity of experience place high demands on the quality of the solution. False positives and unpredictable behavior due to erratic tracking are liable to quickly exhaust the user's patience.

One approach with the potential to handle the complexities of human-hand articulations is known as synthesis-analysis. In this technique, the skeleton joints of a 3D articulated hand model are transformed according to a search optimization algorithm, and then the hand model is rendered and compared to the data captured by the camera. The process is repeated for as long as the rendered data do not match the camera data or until there is convergence. When there is a match, the pose of the model is assumed to be correct and the skeleton's articulation to be found.

Synthesis-analysis approaches have been applied to various problems in computer vision, such as tracking facial expressions[12] and object recognition.[13] However, there is a clear benefit in applying this technique to 3D camera data as opposed to 2D images. In particular, with 2D images, the effects of shadows, lights, and varying materials all must be factored into the synthesized render. Figure 4 displays an RGB image as captured, adjacent to an unshaded render of a 3D hand model. With some effort, multiple layers of effects can be added to the rendering pipeline in order to produce a rendered 3D model that more accurately resembles the image captured by the camera. In Fig. 4, we see that the end result is reasonably close to the image captured by the camera. However, the complexity of this pipeline means it is difficult to design texture maps and shading scales sufficiently general to handle the full range of users' skin colors and characteristics. Moreover, appropriate lighting models must be extracted from general scenes, and the entire pipeline must run in real time, through several iterations per frame.

By contrast, when displaying a depth map of the hand as captured by a 3D camera adjacent to a single pass of a depth map as rendered from the same 3D hand model, the resemblance between these two images is quite strong. Moreover, rendering a depth map can be easily performed on the GPU to accelerate the real-time performance of the algorithm.

In this way, the availability of real-time depth data allows for the implementation of a synthesis-analysis technique that enables real-time robust hand skeleton tracking, providing the level of tracking required to drive intuitive, immersive, and natural experiences. The hand skeleton tracking solution available in the RealSense SDK relies on a synthesis-analysis approach to derive the full articulation of the skeleton and runs at 30% of an Intel 5th Generation Core i5 CPU, at over 30 frames per second (fps).

Background Segmentation

The identification of object boundaries has long been a core research topic in computer vision. Classical color or intensity-based

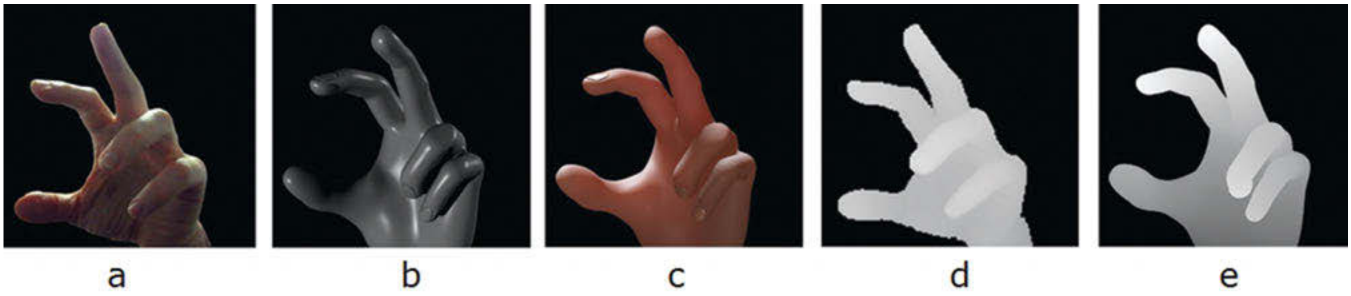

Fig. 4: The 2D image data appears in (a); (b) is the unshaded rendered model; and (c) the model with texture, shading, treatment for fingernails, and lighting. The depth map appears in (d) and (e) shows the rendered depth map.

segmentation techniques spanning from edge detection, pixel classification, shape/texture modeling, combinations of the above, and others have been proposed.[14,15] The distortion introduced during image formulation makes boundary delineation from color data difficult. Small differences make general-purpose edge detection very challenging and that is without considering lighting and motion distortion. Region-based techniques such as texture analysis could be less sensitive to subtle capturing variations; however, they often rely on expensive or restrictive prior knowledge, and it is difficult to cover a wide range of targets robustly in one system.

With RGB-D sensing technology such as RealSense on a system such as a laptop computer, we can reformulate the intrinsically ill-posed segmentation problem in a robust and practical way. First, the additional depth information provides an excellent engineering prior knowledge, as we can easily obtain a good initial estimate of foreground and background pixels in real time. Second, an integrated camera system allows efficient alignment between color and depth image that brings the initial estimate to the color image for the segmentation process. Third, with enhanced 3D face detection enabled by real-time depth-sensing technology, the recovery of relatively problematic target structures, *e.g.*, hair, can be achieved by a new formulation incorporating color, depth, and position relative to the face.

As an illustration of practical usage of background segmentation, we show a background replacement example in Fig. 5.

Fig. 5: Left: Real-time user segmentation of integrated RGB-D data stream enables enhanced video-collaboration experiences. In the center image, a boy is pictured in front of the original background, and, at right, against a synthetic background.

Collaborative Augmented Reality and Other Applications

Collaborative augmented reality (AR), with a host of possible real-world uses, is one of the most immediately appealing applications that can be realized through the latest depth-imaging technology. Figure 6 depicts two AR usages. The left image shows a virtual decoration of a room in which real-world objects (*e.g.*, the sofa) are intermingled with digitally rendered objects (*e.g.*, the lamp). Note the geometric correctness of the perspectives and consistent shadows and shades. The right image shows an immersive gaming application in which a virtual car is rendered on a physical table that interacts with other real-world objects.

When workers collaborate on projects, they often find it useful to share, visualize, and interact with the same digital information. Similarly, outside of work, many people relax by playing collaborative or competitive games with others. Collaborative AR builds on scene perception to enable and enrich such interactions. Users can enter an environment with depth-camera-enabled devices, automatically discover fellow workers or players, and seamlessly connect to them to enter a shared physical-digital interaction space. Each device reconstructs the environment around it, and all devices in the interaction space initially calculate then track their pose relative to the same origin in 3D space by using natural features of the scene and putting them into the same coordinate system. This enables any rendered graphical content to appear to be placed in exactly the same physical location for all users.

One example of a collaborative AR application is room re-decoration. Two users start the application, see each other on the network, and connect. As they move the devices around to look at different areas of the room, they reconstruct a digital representation that is shared across both devices. The users can drag and drop 3D furniture models (such as a sofas, tables, and lamps) into the scene, then move and re-orient the models. The furniture appears realistically integrated with the real-world camera view, with correct occlusion of real-world objects and with shadows. As they interact, users see each other's changes reflected on their devices; hence, they can discuss and collaboratively arrange the furniture until both are happy with the layout (see Fig. 7).

Head-mounted displays (HMDs) are another possible application. While depth cameras enable sensing, tracking, reconstruction, and interaction in 3D, conventional display devices such as monitors, tablets, phones, or projectors are limited to 2D image displays. We can enable a matching output fidelity and have users be more immersed in virtual content by making use of HMDs in both virtual-reality (VR) and AR scenarios.

Depth data also opens the door to a world of new and enhanced photography and videography capabilities. This data enables features such as changing the depth of field of a captured image, applying artistic filters to specific portions of the picture such as the foreground or background, enhanced editing based on depth information, applying motion effects such as parallax, and more.

The Future of 3D Imaging

The low power and small form factor of the 3D depth imaging provided by RealSense

Fig. 6: Examples of augmented-reality applications include virtual room arranging at left and gaming with a virtual car at right.

Fig. 7: In this example of collaborative AR, users move virtual furniture to decorate a room together.

technology allows a 3D sensing camera to be nearly anywhere – on handheld, wearable, and mobile computing systems ranging from HMDs, laptops, 2-in-1 devices, tablets, or even phablets, in addition to desktop and stationary computing systems and kiosks. The immersive applications that benefit from it include interactive or collaborative usages such as gaming, virtual home and office decoration, video conferencing with custom backgrounds and synthetic environments, virtual clothes fitting and shopping, 3D scanning, *etc*. In addition to these, real-time 3D sensing and visual understanding will also enable autonomous machines that can interact with humans naturally and navigate in the 3D environment.

We believe that a trend of moving from 2D imaging to depth imaging and 3D sensing using RealSense will allow original equipment manufacturers to differentiate their products. In addition, the free Intel RealSense Software Development Kit (SDK) will encourage independent software vendors to develop various applications in gaming, education, and training, providing novel and innovative experiences.[16] Mobile computers with integrated RealSense technology are already available in the marketplace from a number of system makers.[17] Interactive and immersive software applications built using the RealSense SDK are also increasingly becoming available from an array of application developers.[18] Beyond the conventional computing devices, autonomous machines such as robots and drones have also been demonstrated that have the ability to understand and navigate in the 3D world with RealSense technology.[19,20]

The future of interactive and immersive computing enabled by 3D visual sensing and intelligence is exciting, and that future is already here!

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LumiCam 1300 Advanced
New 6-filter technology

Light-Field Imaging Approaches Commercial Viability

Recent advances in light-field imaging suggest that light-field photography can increasingly displace traditional 2D photography.

by Kurt Akeley

LIGHT-FIELD technology adds an exciting new dimension to traditional still or moving-picture photography. Whereas traditional 2D cameras can only capture the scene from one observation point perspective, light-field cameras can capture an array of observation points along with the associated features of the scene that users would expect to see in real life, including variable depth of field, occlusion, and depth perception. The ability to capture the light field of a scene and then render that scene from multiple points of view is truly exciting and innovative. With today's state of the art in electronics, image detection, and optics, we have finally reached a point where electronic light-field photography is a practical pursuit of science and engineering. This article summarizes the development of light-field photography over the past century, briefly addresses issues such as depth of field and final-image resolution, and identifies future photographic and imaging opportunities based on experimental and research work to date.

Integral Imaging

Both intuitively and in actual practice, the light passing across a plane may be characterized as a function of four geometric dimensions: the spectral flow at each angle (two geometric dimensions) through each point on the plane (two additional geometric dimensions). This geometric function may be referred to as the 4D light field or as just the light field.

Early in the 20th century, physicist and inventor Gabriel Lippmann of Luxembourg developed integral imaging: the capture and re-display of the 4D light field at a bounded planar region. As depicted on the left side of Fig. 1, an array of micro-cameras, each comprising a lens and a sensor, captures the 4D light field, each camera capturing two angular dimensions at its 2D position in the array. The captured light field is recreated by an array of micro-projectors, as depicted on the right side of the same figure. The method used to store and transfer the 4D light field depends on the camera and projection technology: Lippmann used photographic film, which was developed in place and then re-projected through the same micro-lens array, while contemporary systems utilize digital sensors

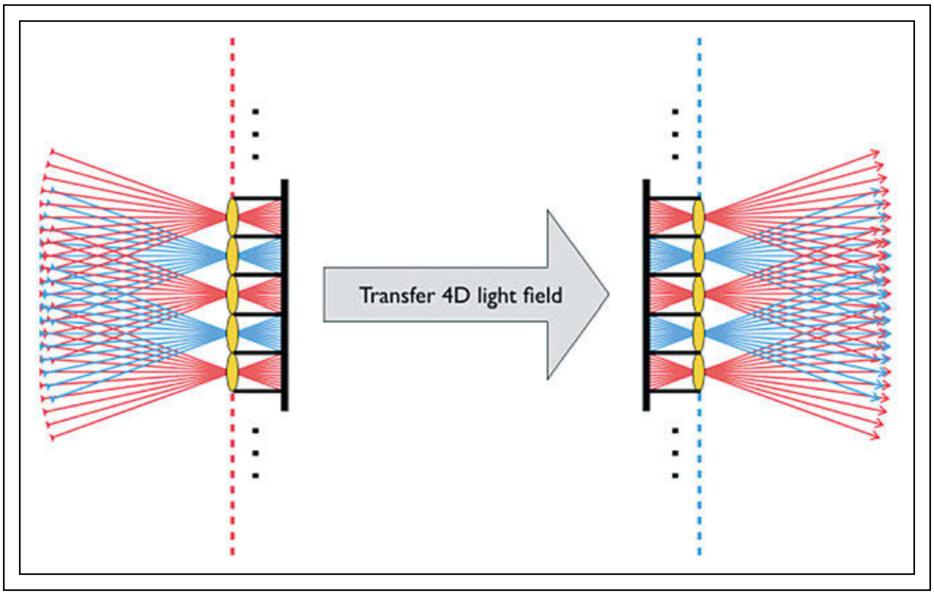

***Fig. 1:** In this example of integral imaging, an array of micro-cameras captures the 4D light-field imagery on the left, which is recreated by an array of micro-projectors on the right.*

***Kurt Akeley** is with Lytro, Inc., in Mountain View, CA. He can be reached at kakeley@lytro.com.*

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and displays, whose data are stored and transferred using computing technology.

In principle, the experience of viewing the recreated light field is equivalent to viewing the original scene. In practice, constrained sampling and spectral resolution limit the fidelity of the recreation, and hence of the viewing experience. At very low resolution, head-motion parallax may be experienced as discrete views and binocular parallax may be experienced intermittently or not at all (because both eyes see the same discrete view position). As resolution is increased, motion parallax becomes continuous, and correct binocular parallax (*i.e.,* stereo vision) is achieved. With still further increase in resolution, parallax is accurately developed across the human pupil, stimulating correct accommodation (focus response) in a human viewer and depicting correct blur cues on the viewer's retinas. Achieving such resolution is challenging; however, in part due to the confounding of both capture and reconstruction by diffraction, which result from the small device geometries required for high spatial and angular sampling rates.

Light-Field Photography

A simple thought experiment illustrates the leap from integral imaging to light-field photography: store the captured 4D light field as the light-field picture then create 2D photographs from it by imaging the recreated light field using a conventional camera. The traditional camera may be positioned arbitrarily within the light field to adjust center of perspective and tilt, and the camera's focus distance, focal length, and aperture may be adjusted to control the properties of blur in the resulting 2D image. Thus, critical photographic aspects that are unchangeable in traditional photographs may be varied freely, within the constraints of the captured light field, after the capture of the 4D light-field picture. While direct realization of the thought experiment is impractical, modern computing technology replaces physical recreation of the light field, as well as the physical camera used to reimage it, with software simulation, leaving only the light-field capture unit (light-field camera) to be implemented in hardware (Fig. 2).

The light-field camera depicted in Fig. 2 differs from that in Fig. 1 by including an objective lens through which the micro-lens array images the scene.^{2} Such lenslet light-field cameras adopt the form of conventional cameras, allowing adjustments to focal length and focus of the single lens to adapt the field of view and depth of field of the captured light-field picture. Because 4D capture is very demanding of sensor resolution, such adaptation may be critical to successful light-field photography.

Multi-camera arrays, whose micro-cameras image the scene directly rather than through an additional objective lens, may also be used to capture light-field pictures. While multi-camera arrays with adjustable lenses on each camera have been implemented as research projects, the expense and complexity of assembling and calibrating tens or hundreds of lenses make such systems impractical as consumer products. Thus, multi-camera arrays may be practical only for applications that do not require adjustments to the focus distance or field of view, such as in mobile devices, where the absence of an objective lens may also reduce the thickness of the camera.

Multi-camera arrays also serve a pedagogical purpose – their construction clearly illustrates the dimensions of spatial light-field resolution (the grid of cameras) and angular light-field resolution (the pixel resolution of each camera) of the captured light-field picture. The optics of the lenslet light-field camera are indirect; they are best understood as they relate to an equivalent multi-camera array. The equivalence is a simple duality, as illustrated in Fig. 3. Light-field spatial resolution – the grid of cameras of a multi-camera array – corresponds to the pixel resolution behind each micro-lens in the lenslet light-field camera. And light-field angular resolution – the grid of pixels in each camera of the multi-camera array – corresponds to the number of micro-lenses in the lenslet light-field camera.

Light fields may also be captured using a traditional 2D camera by taking multiple exposures at different times and positions. This has the advantage of utilizing readily available equipment, but the resulting data are inherently corrupted if the scene changes during the capture period. Light fields may also be inferred from 2D images, rather than sampled directly as in lenslet light-field cameras and multi-camera arrays. While this approach has been demonstrated in research systems, the author knows of no products that utilize it.

Depth of Field

While the angular and spatial dimensions of the captured light-field relate more directly to the mechanism of the multi-camera array, other properties of the captured light field, in particular its depth of field, are more readily grasped by considering the optics of the lenslet light-field camera. And because depth of field is inherently non-linear, it is convenient to do as photographers do and use *f*/# as its proxy.

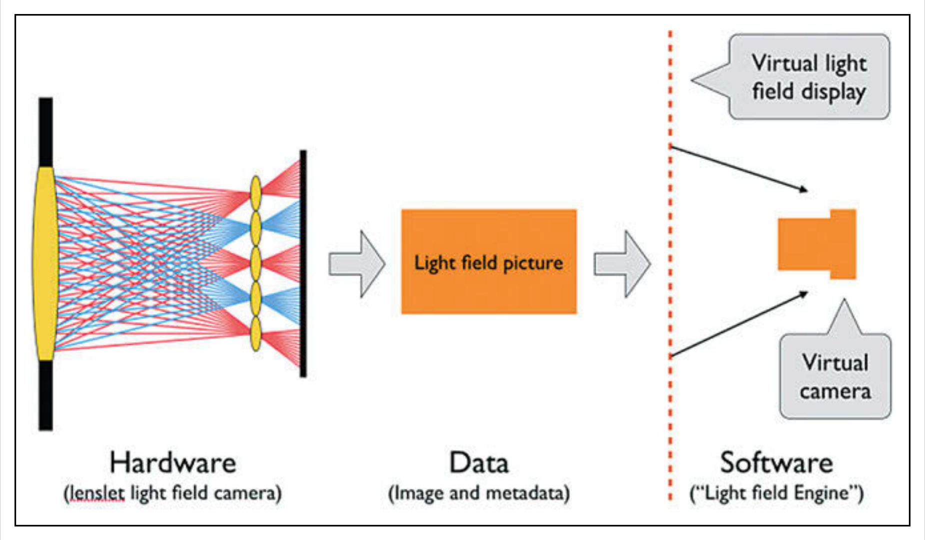

Fig. 2: *An illustration of light-field photography includes a camera (at left) with a micro-lens array that images the scene.*

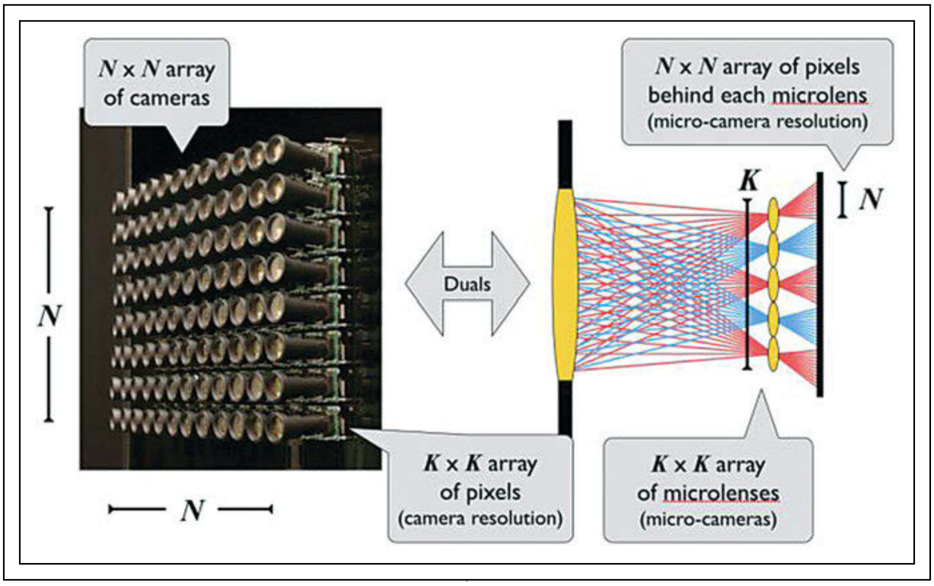

Fig. 3: Light-field-camera duality is illustrated above. The grid of cameras in a multi-camera array (upper left) – corresponds to the pixel resolution behind each micro-lens in the lenslet light-field camera (upper right). And light-field angular resolution — the grid of pixels in each camera of the multi-camera array (lower left) – corresponds to the number of micro-lenses in the lenslet light-field camera (lower right).

The f/# of the image cast on the light-field sensor of the camera depicted in Fig. 4 is the ratio of the focal length of the objective lens to its diameter.[a] But the light that reaches a single pixel on the camera's light-field sensor surface passes through only one Nth of the objective lens, so its effective f/# is N times greater: $f/(a/N)$. Here, we may ignore light spread due to the micro-lenses because

1. The micro-lenses are understood to be "in focus" (meaning that they are separated from the sensor surface by a distance equal to their focal lengths), and
2. The micro-lenses are tiny relative to the objective lens.

Thus, the bundle of all rays that pass through a micro-lens and reach a single pixel is only slightly larger at the objective lens than the depicted bundles, whose rays pass through only the centers of the micro-lenses.

The depth of field of the light-field camera is equivalent to the depth of field of the ray bundles it captures and is therefore also N times that of a conventional camera with the same optics. While this is a substantial improvement, it does not obviate the need to adjust the focus of the light-field camera. For example, only scene objects that are within the depth of field of the light-field camera can be sharply refocused in images that are reconstructed from the captured light-field picture. And the captured depth of field may be shallow relative to the range of depths in the scene, especially when the objective lens has a long focal length.

Light-field-camera depth of field also collapses quickly as the micro-lens array is defocused by positioning it either nearer or farther from the sensor surface than its focal length. The reason is that the bundle of rays traced from a single sensor pixel quickly spreads to cover a significant fraction of the objective-lens aperture, reducing the f/# advantage from N back toward unity.

Final Image Resolution

The "natural" pixel dimensions of the 2D images reconstructed from a captured light-field picture are equal to the pixel dimensions of each camera in the capturing multi-camera array, which from duality (Fig. 3) correspond to the dimensions of the micro-lens array in a lenslet light-field camera. Unless care is taken, reconstruction of an image with greater pixel dimensions results in more pixel data, but no increase in the true resolution of the image. While the sensor pixel dimensions of cameras in a multi-camera array may be readily increased to the current limits of individual sensors, the micro-lens array dimensions of a lenslet light-field camera are not so easily increased because the micro-lenses typically share a single image sensor. But multi-camera arrays are often impractical, due to their need for multiple complex objective lenses, and N values in the range of 10–15 mean that the final image dimensions of a lenslet light-field camera may be a factor of several hundred (N^2) less than the pixel count of the camera's sensor. So final-image resolution is a significant challenge for light-field photography.

There are many ways to increase final image resolution. Here, we list methods appropriate for a lenslet light-field camera, following each with a short discussion of its limitations:

- ***Improve the reconstruction algorithm***. Micro-lens-array resolution is achievable with simple back projection. Using approaches outlined in Ramamoorthi and Liang,[3] so-called super-resolution, as much as a factor of two in each dimension, may be achieved with more complex back-projection algorithms, which typically compute a depth map of the scene. Even more complex algorithms, such as algebraic reconstruction, increase computation load dramatically, with final image improvement limited to an asymptote that remains far below sensor resolution.
- ***Reduce micro-lens diameter***. As micro-lens diameter is decreased, the number of micro-lenses increases, raising final image resolution linearly. But each micro-lens "covers" fewer sensor pixels, reducing N and consequently the depth of field of the light-field camera.
- ***Reduce micro-lens diameter and sensor pixel pitch.*** As both micro-lens diameter and pixel pitch are reduced in lock step, final image resolution increases with no corresponding decrease in depth of field. But the range of wavelengths in the visible spectrum remains constant, and sensor pixels are already near diffraction limits, so this approach does not define

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[a] Formally, f/# is the ratio of focal length to entrance-pupil diameter. In the depicted single-element lens, they are the same.

an obvious path to significant improvement in final image resolution.

- ***Increase sensor size***. Increasing the dimensions of the light-field sensor, while holding the micro-lens diameter and sensor pixel pitch constant, increases final image resolution linearly and without physical limit. But large sensors are expensive, and linear increases in sensor dimensions correspond to cubic increases in camera (especially objective lens) volume, which both increases cost and decreases utility (due to increased size and weight).
- ***Defocus the micro-lens array***. As discussed in Ng,[1] reducing the gap between the micro-lens array and the sensor surface below the focal length of the micro-lenses yields a substantial increase in final image resolution, asymptotically approaching sensor pixel resolution as the gap approaches zero. (Increasing the gap also has the effect, though with additional complexity.) But defocusing the micro-lens array also reduces the depth-of-field advantage of the lenslet light-field camera. And it interacts badly with other opportunities of light-field photography that are described next.

Opportunities

While the most familiar advantage of light-field photography is its ability to reconstruct images with arbitrary parallax effects (focus distance, depth of field, center of perspective, *etc*.) from a single exposure, there are other opportunities that may, over time, prove more important. These include:

1. Improve the tradeoff between depth of field and amount of light captured. In traditional photography, depth of field is increased by reducing the aperture of the objective lens, which causes less light to reach the sensor. Subject to limitations due to diffraction, a lenslet light-field camera with the same optics and sensor size of a conventional camera can achieve N times its depth of field (f/#) with no reduction in captured light.
2. Create a depth map from a single exposure. Traditional photography supports depth-map creation only with multiple exposures, using either a single camera (which is sequential and inherently risks data corruption in dynamic scenes) or multiple cameras in parallel (which avoids data corruption, but quickly becomes impractical as the number of cameras is increased). Lenslet light-field cameras capture the necessary information in a single exposure (avoiding data corruption) and do so without emitting any radiation of their own (avoiding detection and operating without distance constraints due to limits in emission intensity).

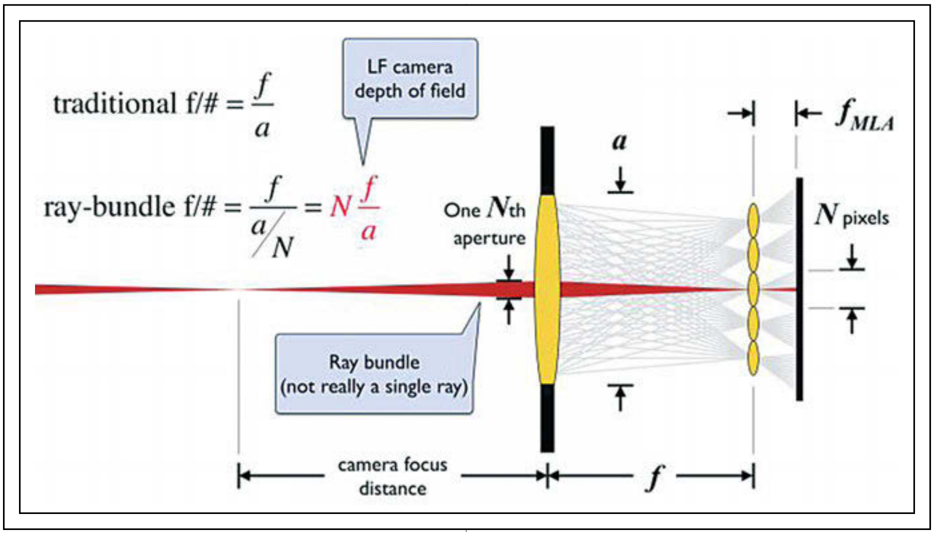

Fig. 4: The above schematic depicts the depth of field of a focused lenslet light-field camera.

3. Correct for aberrations in the objective lens. The objective lens of a lenslet light-field camera need not form an image – it must only facilitate a tight sampling of the scene's light field. As discussed in Ng,[1] eliminating the need for image formation greatly reduces time-honored constraints on lens design, opening the possibility of lenses with dramatically improved performance and/or reductions in cost. Indeed, replacing optics hardware with computation may become the most consequential aspect of light-field photography.[b]

As these opportunities are explored, and others are discovered, light-field photography may increasingly displace traditional 2D photography.

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[b] Both aberration correction and improvements in the tradeoff between depth of field and light capture are seriously compromised when the micro-lens array is defocused.

Light for Life: Emerging Opportunities and Challenges for Using Light to Influence Well-Being

Both lighting technology and our understanding of the relationship between light and human health have advanced rapidly in recent years. The latter needs to be carefully evaluated, particularly as longer-lasting light sources enter the market.

by Jennifer A. Veitch

ADVANCES in science and technology, occurring separately but in parallel, have brought new life to all aspects of lighting research and application. With this has also come tension between those who argue in favor of rapid adoption of practical applications based on the scientific advances and those who favor a slower approach that waits for deeper understanding of related human physiological issues.

Readers of *Information Display* need hardly be reminded of the solid-state-lighting (SSL) revolution. It has rendered the old cathode-ray-tube monitor obsolete and is partly responsible for the portable computing we now enjoy. Most industrialized countries have now enacted energy-efficiency regulation for light sources that have resulted in common incandescent lamps being withdrawn from the market. Although compact fluorescent lamps generally fulfill the new light-source efficacy requirements, it is light-emitting-diode (LED) sources that are projected to dominate the market in the coming years, with organic LEDs (OLEDs) lagging a little behind.[1] Whereas most household lighting formerly delivered, at best, 20 lm/W, and commercial fluorescent systems delivered 70–80 lm/W, inexpensive LED replacement lamps now deliver ~100 lm/W. The U.S. Department of Energy predicts that 200 lm/W will be achieved before 2020.[1] If that goal is met, that would be a 10× increase in energy performance for common light sources used in homes (LEDs *vs.* incandescent lamps) and a ~3× increase for common commercial light sources (LEDs *vs.* electronically ballasted fluorescent systems) in under two decades.

The scientific revolution is no less marvelous. In 2002, in the culmination of several decades of investigation and debate, we learned conclusively that there is a class of photo-receptive cells in the retina that is separate from the rod and cone cells that transduce visual signals.[2,3] Thus, the eye–brain connection is far more complex than previously thought, and the more we learn the more complex we find it to be.[4] These findings have captured the attention of many labs in the intervening years: a search of the Scopus database using the terms (light AND (health OR circadian OR melatonin)) for the periods 1996–2001, 2002–2007, and 2008–2013, returned, respectively, 8172, 12,886, and 20,692 records.

Not long after the identification of what are now known as intrinsically photoreceptive retinal ganglion cells (ipRGCs), some authors began to advocate for changes to lighting practice to take advantage of the burgeoning research in the field.[5] Others argued in favor of a slower pace of adoption, citing the risks of applying only partial knowledge and possibly causing unintentional effects.[6] Ten years later, this debate continues. In late June 2015, the International Commission on Illumination (known as CIE for its French name, Commission Internationale d'Eclairage) issued a statement on "Recommending the proper light at the proper time,"[7] outlining its cautious step-by-step approach to applying the findings of this burgeoning area of investigation.

One reason for caution is that lighting installations serve many functions, and recommendations need to reflect this complexity. Lighting quality exists at the nexus of the needs of individuals, the environmental and economic context, and architectural considerations (Fig. 1). New technologies offer new opportunities to use light to influence well-being, and research is providing new (but still emerging) understanding of how light can influence well-being – but there exist many challenges as we seek to blend these opportunities into coherent guidance or practice in balance with the other considerations.

***Jennifer Veitch** is a Principal Research Officer at the National Research Council of Canada and Director of Division 3 (Interior Environment and Lighting Design) of the International Commission on Illumination (CIE). She can be reached at jennifer.veitch@nrc-cnrc.gc.ca.*

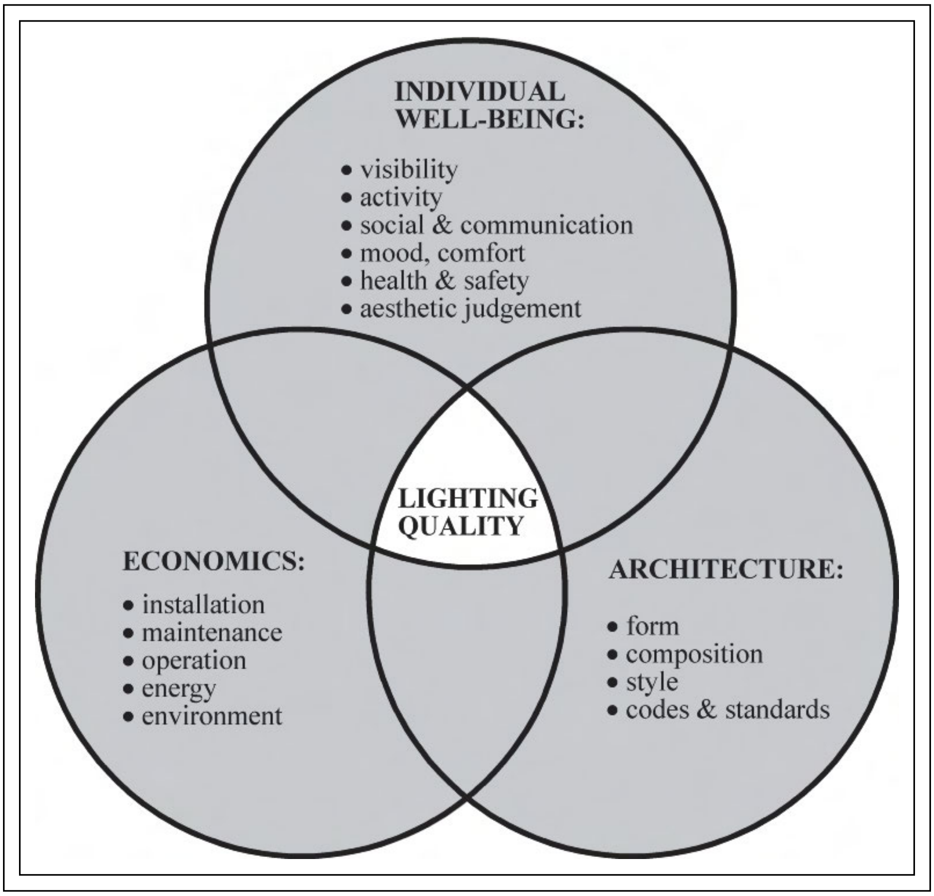

Fig. 1: *Good lighting quality requires balancing the individual needs of people who will experience the installation, its economic and environmental context, and the architectural setting. From Veitch.*[8]

The remainder of this article will expand upon the state of knowledge and the possible guidance for its application.

Eye–Brain Pathways

Extensive investigations by photobiologists have revealed to us that the connections between the eye and brain are far more extensive than are needed for vision alone. Figure 2 provides a schematic guide to some of these connections. The connections through the retino-hypothalamic tract leading to the control of melatonin secretion are the best understood. Melatonin is an important marker of circadian rhythms. Melatonin is a hormone that is secreted in high levels at night, but not by day, in all vertebrate species that have been studied.[9] In some species (*e.g.*, rats), melatonin signals waking and activity, whereas in others (including humans) it signals sleep and rest. The secretion profile of this hormone helps the organism to match activity levels and internal processes to the external cues of day and night, a process called entrainment.

In a healthy person with a regular schedule of daytime activity and nighttime sleep, melatonin secretion begins to rise in the evening, reaching its peak in the middle of the night before falling abruptly around dawn. Its level remains very low throughout the daytime hours before rising again the following evening. Other processes rise and fall in response to this signal. As melatonin rises, we become less alert and more sleepy, and digestive and immune processes alter, for example, by increasing infection-fighting processes while the organism is at rest.[9] As melatonin levels fall in the morning, we become more alert; the hormone cortisol increases in level, signaling a period of activity.

The observation that nighttime melatonin secretion by humans is acutely suppressed by nighttime light exposure[10] was an important step in understanding how light entrains our daily rhythms of waking and sleeping. After early missteps that led to the development of tight experimental controls, this paradigm has been the foundation of much that is currently known colloquially as "light and health." Melatonin is relatively easy to measure (in either blood or saliva samples), making it a practical starting point for understanding these effects. Consequently, our understanding of how light exposure regulates circadian rhythm, although not complete, far exceeds our understanding of light's influences on other behavioral and physiological processes.

In the 1980s and 1990s, researchers focused attention on the physiology of circadian regulation and on identifying the photoreceptive mechanism. Extensive discussion (and some heated debate) concerned whether or not the signals to the suprachiasmatic nucleus began with the classic photoreceptors – the rods and cones well known from vision research – or with a different cell type. Evidence that the spectral sensitivity of the melatonin suppression response to nighttime light differs from any of the then-known photoreceptors[11,12] was part of the process leading to the identification of ipRGCs.[2,3] The curves reported by various researchers all differed slightly, but were consistent in showing peak sensitivity for radiation between 460 and 490 nm in the blue range.

Among the important consequences of this finding is the need for new quantities to characterize the intensity of light exposures that are intended to trigger effects other than vision. Light is unique in the International System of Weights and Measures (Système Internationale, SI) in that its definition is tied to a human biological response, the photopic spectral luminous efficacy function,[13] commonly known as $V(\lambda)$. This function is a combination of the spectral responses of the medium- and long-wavelength cones at the fovea; the response is strongest for radiation of 555 nm (green). Once it was established that ipRGCs are responsible for light detection that leads to parts of the brain not responsible for visual processing, it became clear that if investigations report light exposures in illuminance or luminance units, they would be a poor indicator of the stimulus strength for these other processes.

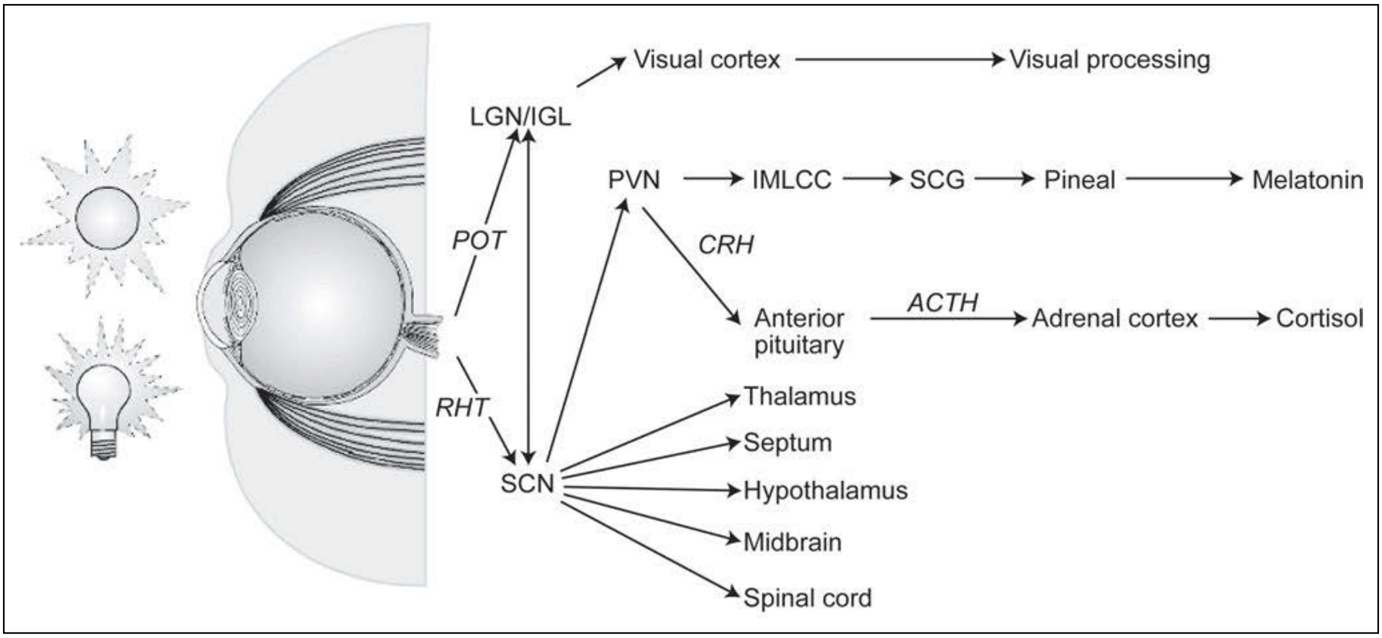

Fig. 2: *This simplified schematic diagram of two eye–brain pathways is taken from CIE 158:2009. The light received by the eye is converted to neural signals that pass via the optic nerve to these. © CIE, 2009. Used by permission.*

Although the need for a new quantity has been known for many years, only with the publication of CIE Technical Note TN 003:2015 have we taken the first step toward the goal of appropriate SI-compliant units to characterize the stimulus strength for processes other than vision, including circadian regulation. TN 003 is an extensive report of a consensus workshop held in 2013 to establish the action spectrum for ipRGC stimulation, first reported by Lucas *et al.*[4] Figure 3 displays the spectral efficiency functions for the five photoreceptors. TN 003:2015 is a free document, which also comes with an Excel toolkit for calculating light exposures using the weighting functions for the five photoreceptors. Note that the functions published in TC 003:2015 and in Lucas[4] do not have the status of international standards. CIE has formed a technical committee to translate the consensus expressed in TN 003 into the first international standard on quantifying irradiance with respect to stimulation of all ocular photoreceptors.

Since the identification of ipRGCs, and the awareness that their action spectrum shows greater sensitivity to short-wavelength radiation, there has been a desire among many in the lighting industry to use this knowledge in practical applications. This is challenging, however, because of growing awareness that the pathways shown schematically in Fig. 2 are very complex. The photoreceptors interact. For example, it now appears that pupil size is regulated by different photoreceptors at different times. The immediate pupillary light reflex response to light exposure occurs because of rod and cone responses, but the sustained response occurs because of ipRGC stimulation.[4,14]

Moving from science to application is further complicated by the fact that in addition to the light-source spectrum, four other parameters also influence our physiological and behavioral responses to light exposure: light intensity, duration, timing, and pattern. Some of these are better understood than others. For example, we know how to influence circadian rhythm by changing the timing of light exposure in relation to the nadir of the cycle. Light exposure before this point (*e.g.*, late in the evening, after melatonin secretion has begun) tends to delay the cycle – it slows down melatonin secretion. Light exposure after this point (*e.g.*, around dawn) tends to advance the cycle – melatonin secretion will begin again at an earlier clock time than on the previous day. This knowledge is the basis for recommendations for shift-work adaptation and the avoidance of jet lag.[15]

Principles of Healthy Lighting Redux

One way to think about how light might influence human health is in the expression of principles of healthy lighting. The first consensus report in this field was CIE publication 158, first published in 2004 (re-issued in 2009 with errata corrected). Although based on the knowledge available at that time, subsequent evidence has not displaced these principles; rather, it has emphasized their importance, as will be shown briefly here. Each bullet point below is a principle of healthy lighting as articulated in CIE 158:2004/2009.

- ***The daily light dose received by people in Western [industrialized] countries might be too low.***

Since 2004, evidence for this has mounted. Several investigations show that people who experience increases in light exposure during daytime show beneficial effects.[16,17] Time-use studies consistently show that people spend ~90% of the day indoors, which raises the possibility that interior light-level recommendations might need to be higher than is currently the case. This could be controversial because of the need to reduce lighting energy use. Even with smart lighting systems using solid-state lighting and advanced controls, providing higher light exposures without increasing lighting energy use will demand careful design and planning.

- ***Healthy light is inextricably linked to healthy darkness.***

Although circadian regulation is not the only function influenced by ipRGC stimulation, it is an important one. There need to be signals for both light and dark. Without a period in darkness each day, nighttime melatonin is suppressed. Growing evidence links this to serious health consequences from cancer to metabolic disorders.[18]

The importance of a regular rhythm of bright light and darkness (the first two principles) leads to a conclusion that healthy lighting is not only an architectural issue: It is a public-health matter, and individuals will need to take responsibility for their own light hygiene. Most people do not spend all of their time in one place lit with one set of lights. There are notable exceptions, which demand special attention, such as care homes, hospitals, and prisons, where a single authority is largely responsible for establishing and maintaining the light pattern. For most of us, however, our personal behaviors will largely determine the amplitude of the daily light–dark pattern to which our bodies respond. Even relatively low-intensity ambient illumination (200 lx) late in the evening can influence melatonin levels at night.[19]

- ***Light for biological action should be rich in the regions of the spectrum to which the nonvisual system is most sensitive.***

Even in 2004, when there was no consensus concerning the action spectrum for ipRGCs, it was clear that short-wavelength radiation had a greater effect on circadian regulation. This evidence has led to the introduction of many products designed to increase short-wavelength light exposure by day, such as fluorescent lamps with high correlated color temperatures and dynamic color-changing lighting systems that can vary the spectral content of the light source and its intensity over time. As we learn more about the complexity of these processes, the limitation of this principle becomes clear: We need to think carefully about what biological action we wish to influence in order to choose the correct spectrum (and intensity, duration, timing, and pattern) of light exposure.

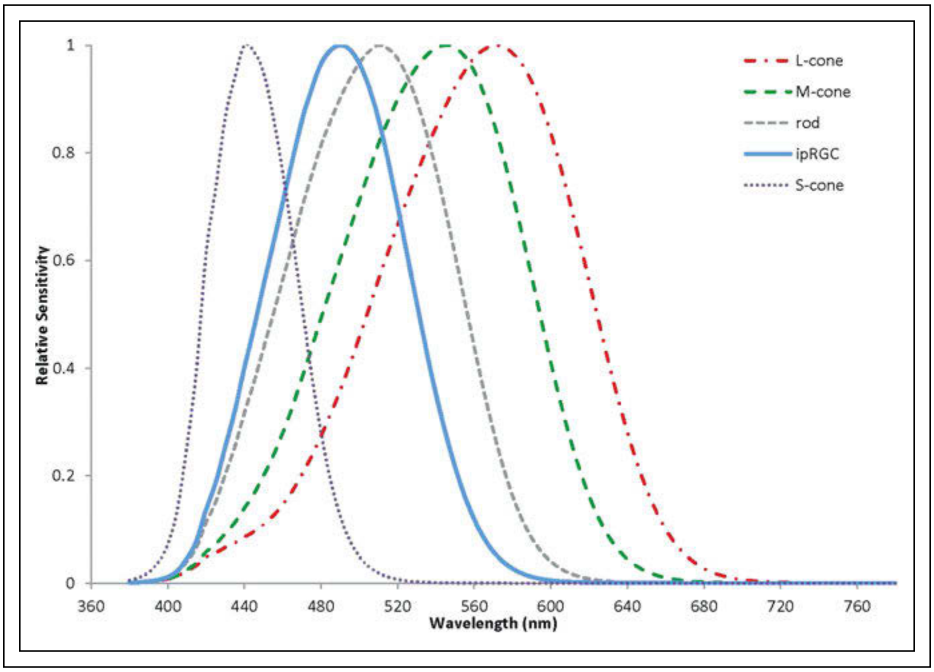

Fig. 3: *There are five known photoreceptive cells in the human retina, each with a different action spectrum, shown here as relative sensitivity normalized to their peaks. The three cone types are responsible for color vision and fine-detail detection and are present primarily in the fovea. Rods are present across the retina and are primarily responsible for vision at low light levels; their activity is suppressed at daytime and indoor light levels. The ipRGCs are irradiance detectors, sending signals to the brain through the retino-hypothalamic tract (see Fig. 2). Data used to prepare this figure are from CIE.*[14]

- ***The important consideration in determining light dose is the light received at the eye, both directly from the light source and reflected off surrounding surfaces.***

This principle remains true for circadian regulation and processes mediated by eye–brain pathways. Anyone developing a lighting system needs to be aware that the effects are not determined by the technology alone but by how it is used. For architectural lighting, this means that the room surfaces are part of the lighting system. For display-screen devices, determining the light exposure will mean thinking about how the viewer holds the device, as well as the ambient environment in which it is used.

- ***The timing of light exposure influences the effects of the dose.***

System sensitivity has long been known to be time-dependent, but we are beginning to learn how complex the system can be. Evidence coming in now shows us that prior experiences influence subsequent responses: thus, when one experiences a day of lower light exposure, one shows a lower nighttime melatonin suppression response.[20] As we learn more about how pattern affects various physiological responses, we might become better able to deliver the greater peak light exposure referred to in the first principle but without increasing lighting energy use by employing information about duration, timing, and pattern to better effect.

Recent evidence has shown that illuminated-display-screen use in the evening, before bed, can influence subsequent sleep quality and disrupt circadian rhythms.[21] This has been attributed in part to the relatively high level of short-wavelength radiation emitted from many display screens[22] to which the ipRGCs are most sensitive, particularly at that time of day. Personal light hygiene and technology together can play a role in preventing problems. Altering the display properties in relation to the time of day is one possibility (*e.g.*, using software such as f.lux, https://justgetflux.com/). (That is, avoid using a light source with emissions in the most-sensitive region of the spectrum if one wishes to avoid biological effects.) Other options are to reduce the screen intensity or to reverse the text polarity (supported by many eReaders). A simple solution requiring no technology is to stop using a display screen late into the evening, just before bedtime.

Other Healthful Lighting Issues

The principles of healthy lighting set out above focus primarily on stimulating ipRGCs, but to use light to benefit well-being in all aspects of life – as would be required to achieve good-quality lighting – is more than this. There is more to learn about the non-visual processes because we do not yet have a clear understanding of the purposes of the links from the RHT to brain structures other than the hypothalamus. Some evidence suggests that there are acute effects on alertness separate from circadian regulation;[23,24] Whitehead[25] identified issues related to light-source properties as they can affect color vision. Well-being also includes environmental perception, such as evaluations of spaciousness and feelings of visual comfort.[26] Lighting for life demands an integration of many considerations.

One issue that many had thought was resolved with the advent of electronic ballasts for fluorescent lamps is light-source flicker. Electronic ballasts operate between 20 and 40 kHz, whereas the magnetic ballasts they replaced operated between 100 and 120 Hz (depending on the supply frequency). The change occurred in order to achieve energy efficiency but had the demonstrated benefit of reducing the incidence of headaches and eye strain.[27] LED drivers, however, show great diversity in their operating characteristics, which means that there is a vast range of diversity in the flicker properties of LED devices on the market.[28] Some of these operate in the ranges previously associated with adverse health effects. In an attempt to educate the industry about these issues and to provide guidance concerning the safe range of operating conditions, IEEE published a recommended practice for LED operation to mitigate health risks from flicker.[29] This is the first guidance of its kind and is likely to be revised as new information becomes available, particularly concerning parameters that have not previously been investigated (*e.g.*, duty cycle and waveform). It is a new document and not yet referenced in any legislated requirements (to my knowledge), but we can expect the issue to remain on the agenda for healthful lighting in the months and years to come.

What the Future Holds

Recent revolutions in both lighting technology and lighting research make this a very exciting time to be affiliated with these fields. With 2015 having been designated by UNESCO as the International Year of Light and Light-Based Technologies (www.light2015.org), this excitement is reflected in the popular press to a far greater extent than in previous years. People are hungry to know how to use light for living, and manufacturers are eager to provide them with the tools to do so.

Nonetheless, we are only at the beginning of understanding how light can affect us, and there may be surprises ahead as our understanding expands and strengthens. Choices made today about technology that might have a long operating lifetime need to be carefully weighed, lest we find ourselves unintentionally conducting a natural experiment with unwanted consequences. These important decisions about light sources, their operating properties, their use in devices, the installation of those devices in the environment, and our personal patterns of light and dark exposure, all require bodies of knowledge. One investigation ought not to be the basis of national, regional, or international standards or regulations; look for replications and extensions that provide consistent results that follow predictions based on a deep understanding of underlying anatomy, physiology, and psychology. When reading about exciting new lighting products that are said to deliver healthful lighting, we need to consider whether they provide a complete lighting quality solution.

In the coming months, CIE will issue a new technical report, "Research Roadmap for Healthful Interior Lighting Recommendations," outlining requirements for that body of knowledge. Among the challenges ahead is sustained interest (with research funding) to develop that knowledge so that future lighting systems fulfill the promises of delivering "light for life." Fortunately, the advances in technology, including controls and imaging, offer many new tools to build systems that take advantage of these research findings. Partnerships between industry and researchers will sustain progress for both.

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OLEDs with Candle-Like Emission

Candle-like organic light-emitting diodes (OLEDs) emit much less blue light than other non-incandescent light sources. This type of OLED is characterized by low correlated color temperature (CCT), chromaticity tunability, and low melatonin (MLT) suppression. The light evokes a sense of warmth and creates a pleasant and calming ambience with its high-quality diffuse orange-red emission.

by Jwo-Huei Jou, Meenu Singh, Yi-Fang Tsai, Hui-Huan Yu, Szu-Hao Chen, Sheng-Hsu Shih, and Shang-Chih Lin

THE medical community has been sounding alarms with increasing frequency about the health hazards of blue light. An International Energy Agency report from 2014 stated that blue and cool-white light-emitting diodes (LEDs) could damage light-sensitive tissues in eyes and even lead to blindness.[1,2] Numerous medical studies have also reported that intense blue or white light may cause circadian disruptions[3-5] and sleep disorders.[6] Notably, Stevens *et al*. discovered that electric light at night was at least in part a factor in causing breast cancer through the mechanism of suppressing the oncostatic hormone melatonin.[7,8] Specifically, the rate of breast-cancer occurrence was 73% higher in females in communities with the brightest light at night than those in the darkest comparative environments.[9] Outside the human sphere, the International Dark-Sky Association reports that light pollution at night disrupts the life-sustaining behavior of many nocturnal animals such as birds, amphibians, and insects, causing damage to the ecosystem.[10] Other potentially deleterious effects from short-wavelength light, especially that from LEDs, include the discoloration of oil paintings in museums, including works by Van Gogh and Cézanne, as reported in 2013.[11,12]

Jwo-Huei Jou *is a professor in the Department of Materials Science & Engineering at National Tsing Hua University, Taiwan, and the president of the Chinese Organic Electronics Association. He can be reached at jjou@mx.nthu.edu.tw.* ***Meenu Singh****,* ***Yi-Fang Tsai****,* ***Hui-Huan Yu****, and* ***Szu-Hao Chen*** *are Ph.D. students from Prof. Jou's group.* ***Shang-Chih Lin*** *is a Marketing Department Manager for WiseChip Semiconductor Inc. (www.wisechip.om.tw).*

A New Light-Quality Metric

It should now be clear that we need a light source that is reliably benign in terms of the health of both people and the environment while providing quality illumination. Even the U.S. Department of Energy, unwavering in its focus on energy-consumption reduction, has acknowledged the health effects of light and the need for new metrics that describe improvements in "health and productivity" in its 2013 Multi-Year Program Plan.[13] That said, no currently available lighting-quality metric measures the impact of lighting on human health; instead, they focus on the color point and color rendering of light sources (see the article, "Light for Life: Emerging Opportunities and Challenges for Using Light to Influence Well Being" in this issue).

One such well-known metric is the color-rendering index (CRI), which describes the color fidelity of various samples illuminated by said light source *vs*. a black-body radiator of the same correlated color temperature (CCT). It is worth noting that a black-body radiator will by definition have a CRI of 100, the maximum value. At CCTs of 2000K or lower, black-body radiation has very little spectral content in the blue region [*e.g.*, Fig. 3(a)]. Thus, a light source with a spectral power distribution (SPD) similar to that of a black-body radiator at low CCTs will simultaneously have high color rendering and very low emission of hazardous blue light.

The authors' group at National Tsing-Hua University in Taiwan developed the spectrum resemblance index (SRI) as a metric for the percentage similarity between a given light source and its corresponding black-body radiator at the same CCT[14]:

$$SRI \equiv \frac{\int L(\lambda,T)\,\mathrm{dy}}{\int L_{\mathrm{BR}}(\lambda,T)\,\mathrm{dy}} \times 100\%$$

where LBR(λ,T) is the luminance spectrum of the black-body radiator at the specific CCT and $L(\lambda,T)$ is the overlapping area between the luminance spectra of the light source under investigation and its corresponding black-body radiator.[14] Luminance instead of power spectra are used since they are more relevant to gauging human visual responses. SRI can be calculated for any light source and will range between 0 and 100 for total non-overlap or identity with the black-body radiator.

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Figure 1 shows the power and luminance spectra for various light sources as well as the calculated SRI. For high-intensity-discharge (HID) lamps with "spikey" spectra, the SRIs are in the 60s or even as low as the 30s. The cool fluorescent lamp is only slightly better with an SRI of 78. Thus far, SRI has done a good job summarizing the resemblance to black-body radiation in a single metric. In the modern white LEDs and OLEDs studied, the spectra are substantially more continuous. They arise in the LEDs due to the broad phosphor peak(s) and in OLEDs due to the intrinsically broad emission of the organic chromophores. The calculated SRIs are all in the 90s and thus enable much discrimination between the sources. There remains a need to develop a light quality more sensitive to the blue part of the spectrum. In particular, any such metric should also recognize the need for circadian stimulation (or the lack thereof) during different times of the day, which remains an active area of research.[15]

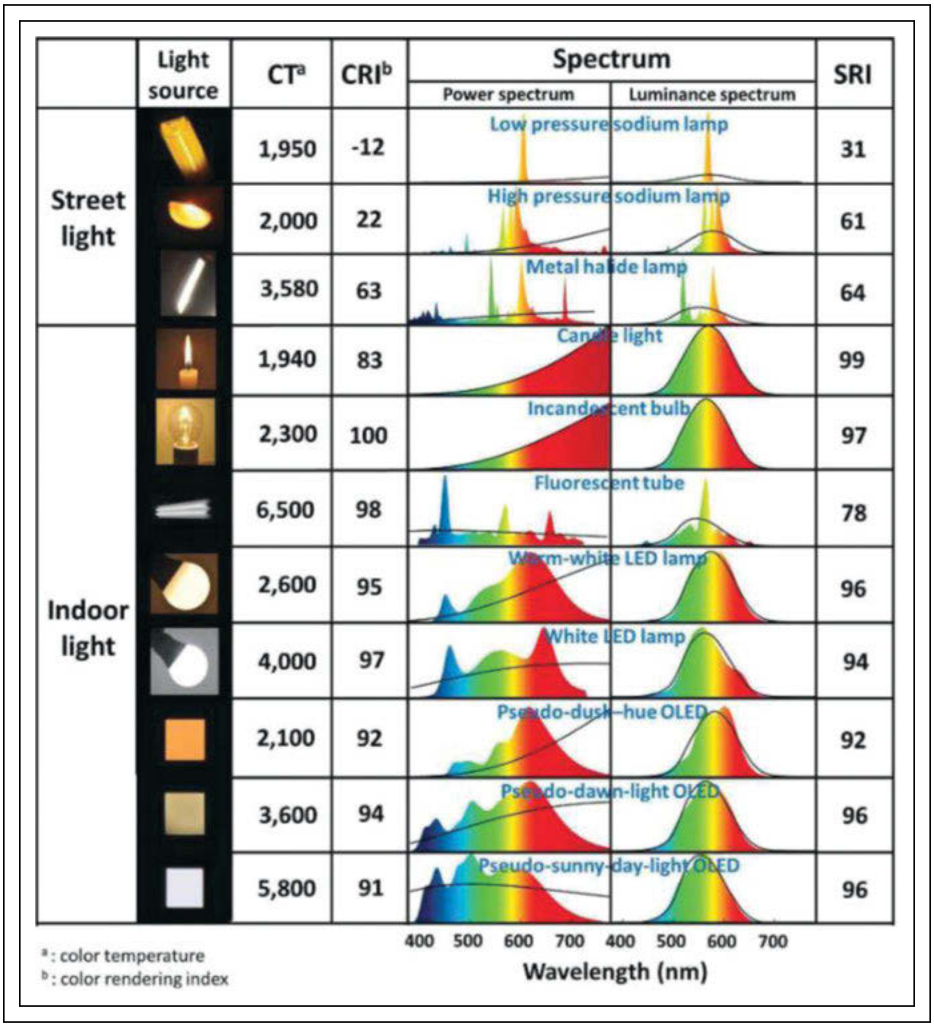
OLEDs with Candle-Like Emission

Candles were the main source of artificial illumination for mankind for thousands of years. Even today, candlelight evokes a sense of warmth and creates a pleasant and calming ambience. The flame itself is a complex source composed of regions of different color temperatures where we use the brightest spot at 1914K to represent the whole (Fig. 2).[17] The candle spectrum has inherent low blue-spectral content that minimizes MLT suppression in the evening. However, the natural candle is an extremely inefficient light source, with a total efficacy of 0.1–0.3 lm/W, not to mention the other shortcomings of a combustible source. On the other hand, a solid-state light source that matches the visible spectrum of a candle holds great promise.

Most white OLEDs for lighting contain three emitters: red, green, and blue (RGB), in either two-stack (RG,B) or three-stack (R,G,B) architectures. Over the years, our group fabricated a number of warm white OLEDs with two- or three-emitter systems.[18-22] However, even with three broad emitters, there can still be a sizable gap in the resulting spectrum. In 2012, our group was the first to develop a four-emitter OLED containing red, yellow, green, and sky-blue phosphorescent emitters (Fig. 3).[17] Adjusting device parameters allowed a CCT range of 1918–3000K to be accessed, at 1000 cd/m^2. An optimized device had a broad spectrum resembling that of a black-body emitter and achieved 19 lm/W, a higher CRI of 93 at a CCT of approximately 2000K (Fig. 4).[17] It can be seen from Fig. 4(b) that the device spectrum still deviated appreciably from that of a black-body radiator, which resulted in an SRI of 80.

Pseudo-Natural Light

We continue to develop OLEDs with many (>3) emitters with ever-increasing spectrum



	Light source	CT[a]	CRI[b]	Spectrum (Power spectrum / Luminance spectrum)	SRI
Street light		1,950	-12	Low pressure sodium lamp	31
		2,000	22	High pressure sodium lamp	61
		3,580	63	Metal halide lamp	64
Indoor light		1,940	83	Candle light	99
		2,300	100	Incandescent bulb	97
		6,500	98	Fluorescent tube	78
		2,600	95	Warm-white LED lamp	96
		4,000	97	White LED lamp	94
		2,100	92	Pseudo-dusk-hue OLED	92
		3,600	94	Pseudo-dawn-light OLED	96
		5,800	91	Pseudo-sunny-day-light OLED	96

[a]: color temperature
[b]: color rendering index

Fig. 1: Various light sources are shown along with their power and luminance spectra, SRI, CRI, and CCT.[16] The CRI reported here is compared with a 2860K reference rather than a black-body radiator of the same CCT.

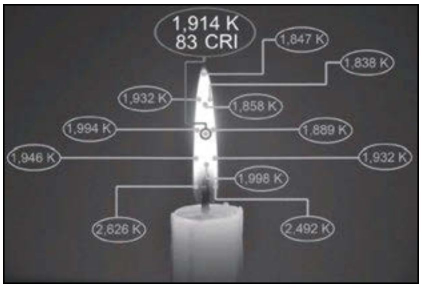


Fig. 2: *Different color temperatures are shown at different flame positions. The color temperatures vary from 1847 to 2626K, with the brightest spot at 1914K.[17] The CRI reported here is compared with a 2860K reference rather than a black-body radiator of the same CCT. Candlelight should have a CRI of 100 since it is a black-body radiator.*

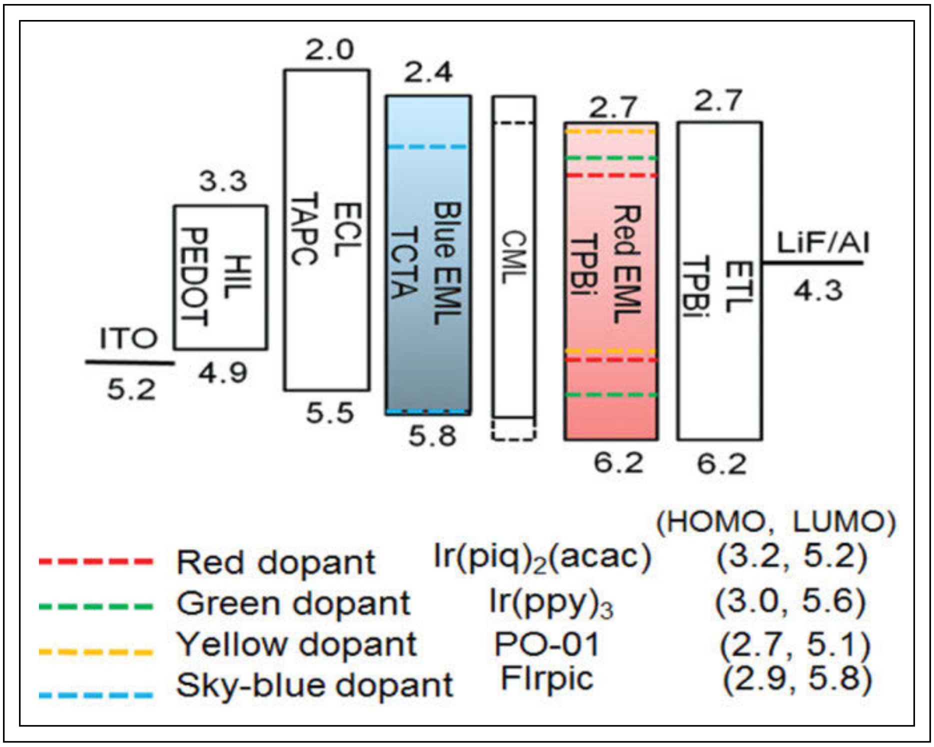


***Fig. 3:** This schematic illustration of the candlelight OLED composes four black-body-radiation complementary dyes; namely, red, yellow, green, and sky-blue, dispersed in two emissive layers separated by a nano-interlayer to harvest the ultimate color-rendering index and device efficacy.*[17]

tenability and CCT range, culminating in devices with as many as six emitters in three different emitter layers (EMLs) [Fig. 5(a)].[16,23,24] With so many emitters, the spectra are largely continuous such that we coined the term "pseudo-natural light" for these OLEDs (see bottom of Fig. 1). Figure 5(b) depicts the simulated and actual luminance spectra of devices at 2100, 3600, and 5800K. The SRI for these devices is well into the 90s, indicating a high resemblance to black-body radiation.

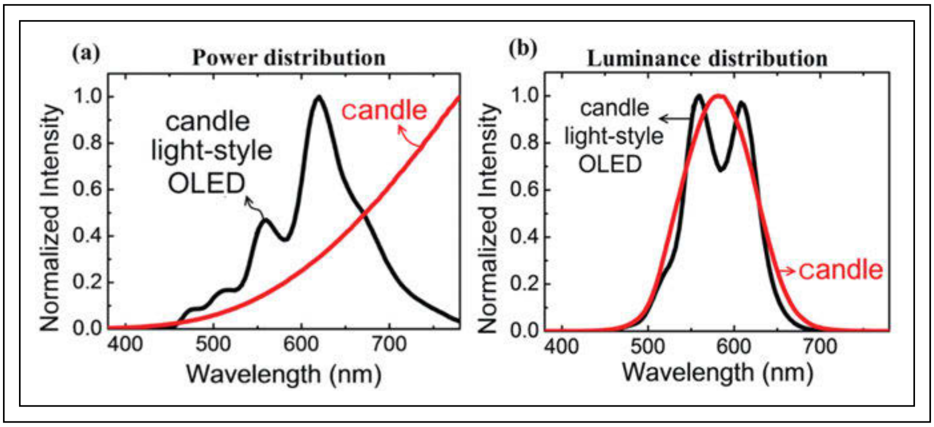


***Fig. 4:** These two charts compare the (a) spectral power and (b) luminosity distributions of a candlelight OLED with a CCT of 2000K with a candle.*[17]

With six emitters – deep-red, orange-red, yellow, green, sky-blue, and deep-blue – it is possible to produce white light and achieve good SRI along the Planckian locus from 1100K and higher. For a more-detailed discussion on color mixing, see "Pseudo-Natural Light for Displays and Lighting" in the journal of *Advanced Optical Materials*.[16]

Low MLT Suppression

Kozaki *et al*. reported that exposure to 200-lx illuminance from a 5000K fluorescent lamp for 90 minutes between 1:00 to 2:30 am suppressed MLT secretion by 78%. The suppression was 50% for 3000K and 17% for 2300K lamps.[25] According to this study, we expected exposure to the candlelight OLED of 1920K to result in a MLT suppression of less than 10% under similar conditions. However, in a recent study conducted by our own group, exposure to a candlelight OLED at 100 lx for 90 minutes from 2:00 to 3:30 am resulted in MLT suppression of 33% *vs*. 64% for a 5710K fluorescent lamp.[26] While the candlelight OLED led to significantly less-measurable MLT suppression, it is clear there is much work to be done to establish a qualitative understanding of the relationship and all the variables involved.

Commercialization

Commercialization of the candlelight OLED started at the end of 2014 by Wisechip Semiconductor of Taiwan.[27] The company is currently producing panels of 10 × 10 cm^2 in size. The first installation was in street lights for an aboriginal group – the Atayal Tribe in Smangus, Taiwan. The panels were deployed in lamp shades made of old wood (Fig. 6). The tribe required that the light sources be both human- and eco-friendly.

Our research team hopes that these multi-emitter candlelight OLEDs will eventually be used in a range of indoor and outdoor luminaires. These OLEDs have spectra that resemble low CCT black-body radiators characterized by good color rendering and much reduced blue spectral content, which in turn leads to reduced MLT suppression. It is reasonable to hope that such lighting will be conducive to human and ecological health.

Acknowledgment

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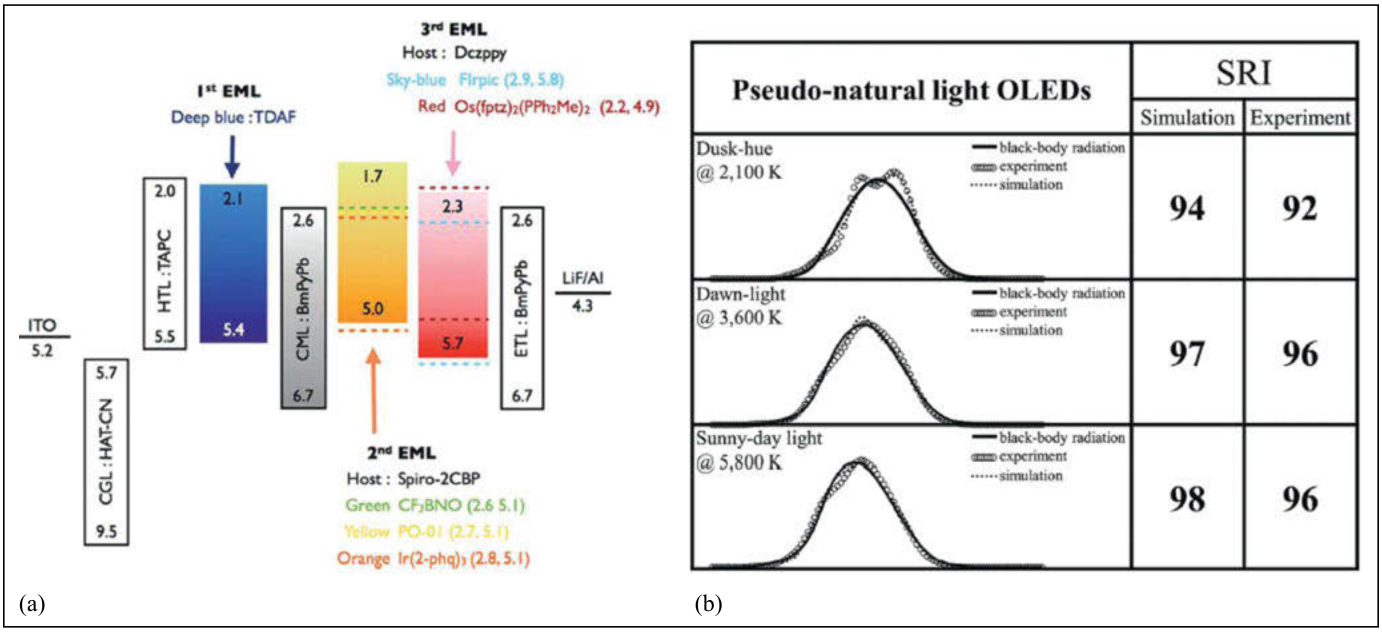

Fig. 5: *(a) At left are the energy-level diagram and layer structure of the six-emitter pseudo-natural-light OLED. (b) At right are the simulated and actual luminance spectra and SRI for the three different CCTs: dusk hue, 2100K; dawn light, 3600K; and sunny day light, 5800K.*

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Fig. 6: *These candlelight OLED panels were first produced for the Atayal Indigenous Taiwanese people who were without electricity until 1979. They had been using CFL-based street lights but rejected a suggestion by the government to install LED lights.*

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A Process for Using Oxide TFTs over LTPS TFTs for OLED-TV Manufacturing

Technical solutions for the fabrication of large-scale OLED displays include new manufacturing equipment and processes developed by Applied Materials.

by Kerry L. Cunningham

OLED TVs are compelling because they are lightweight and thin, requiring no backlight, and produce vivid color and true-black contrast ratios. Low manufacturing yields, however, have thus far held them back. According to Jae-Hak Choi, Senior Analyst for FPD Manufacturing at NPD DisplaySearch, "OLED TV has experienced various technical hurdles and roadblocks. The primary reason for the high cost of OLED TV is its low yield ratio. The organic-material evaporation process is a bottleneck for OLED-TV panels made using the RGB method, and oxide-TFT yields have not met expectations. NPD DisplaySearch's recent AMOLED Process Roadmap Report indicates that the manufacturing cost for a 55-in. OLED-TV panel is up to 10 times more than the manufacturing cost of that of a 55-in. LCD panel (Fig. 1).

Key opportunities for equipment manufacturers to reduce large-scale manufacturing costs for OLED-TV applications include (1) scaling processes to Gen 8.5 while maintaining high yields to reduce the manufacturing cost per area, (2) high material utilization, and (3) implementation of materials engineering to improve overall device performance. This article will discuss equipment and process solutions that Applied Materials has developed to reduce these costs.

Kerry L. Cunningham is the Product Marketing Manager for the Display Business Group of Applied Materials. He can be reached at Kerry_Cunningham@amat.com.

TFT and Backplane Performance

The OLED-display structure consists of a TFT backplane to control pixel driving, AMOLED layers to emit light, and encapsulation to protect the highly sensitive organic materials from exposure to moisture and air. The primary goal of many manufacturing technologies is to achieve uniformity and performance stability for both the backplane and OLED emission layers. The introduction of thin-film encapsulation (TFE) processes aims to support flexible OLED displays while providing key barrier protection. High electron mobility is also critical to backplane performance reliability and AMOLED display performance stability. AMOLED displays utilize a current-driving method so backplanes have to maintain a stable voltage. The use of LTPS TFTs is currently the best solution for driving the AMOLED device because of their

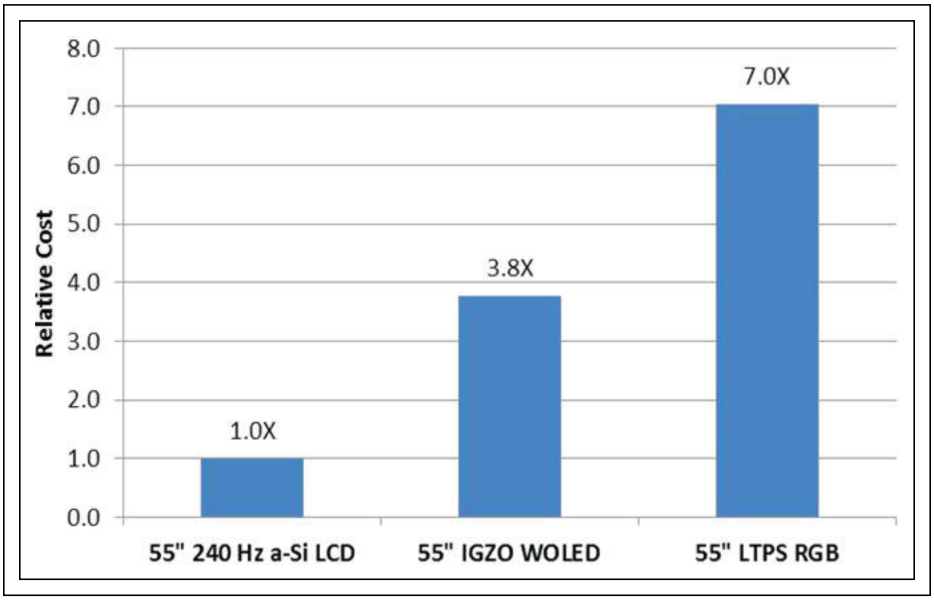

Fig. 1: The relative manufacturing costs of technologies for 55-in. TV panels are compared for LCDs (left) and two types of OLED panels, IGZO (middle) and LTPS (right). Source: IHS Technology, AMOLED Process Roadmap Report – July 2015 update.

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high electron mobility. However, the LTPS-TFT manufacturing process is more complicated and therefore more costly than the a-Si or MO_x TFT processes.

In order to drive an AMOLED pixel in a basic OLED circuit, each subpixel requires a minimum of two TFTs and a capacitor circuit to provide the current for the OLED light-emitting material. The first TFT controls the flow of electricity stimulating the OLED emitting material, while the second TFT controls the writing of the signal. LTPS is the best material to drive the device due to its high electron mobility (~50–100 cm^2/V-sec). However, because the semiconductor layer has uniformity and reliability issues, stability is insufficient without additional compensation circuits. Furthermore, the additional TFTs and capacitors increase the overall cost and have a negative impact on aperture ratio and brightness. More power is also required to maintain picture quality. The OLED pixel luminance is directly charged by the current; subtle variations in the TFT current result in brightness differences from pixel to pixel.

As a result, even the slightest non-uniformity in TFT performance can affect image quality. The inherent instability of the device is measured in variances in V_{th}, so a small variance of 0.1 V can cause image-quality problems, including mura. The large number of transistors required per pixel also has a big impact on manufacturing yield because a failure of any one transistor results in a complete malfunction of that pixel. The use of MO_x over LTPS (Fig. 2) has the potential to help reduce manufacturing costs by enabling simpler pixel-circuit designs, fewer masking steps, less capital-equipment intensity, and overall improved TFT uniformity.

The adoption of oxide TFTs in an AMOLED backplane requires high mobility and uniform TFT specifications. Electron mobility depends on oxide deposition using physical-vapor-deposition (PVD) technology. To efficiently drive OLED TV at >240 Hz, the mobility specification should be >30 cm^2/V-sec. The V_{th} shift (~2 V) is currently higher than that for LTPS. The target is 0.1 V or 1.0 V with compensation. To improve gate insulation, high-quality SiO_x reduces interface trapping and minimizes hydrogen content and boosts the etch-stopper layer performance that protects the IGZO layer during subsequent integration processes (source/drain, etch). Changing the passivation material to Al_2O_3 also improves the moisture barrier. Another issue is that submicron-sized particles can strongly affect the oxide-TFT yield, and some particles that are <1 µm create defects as black spots.

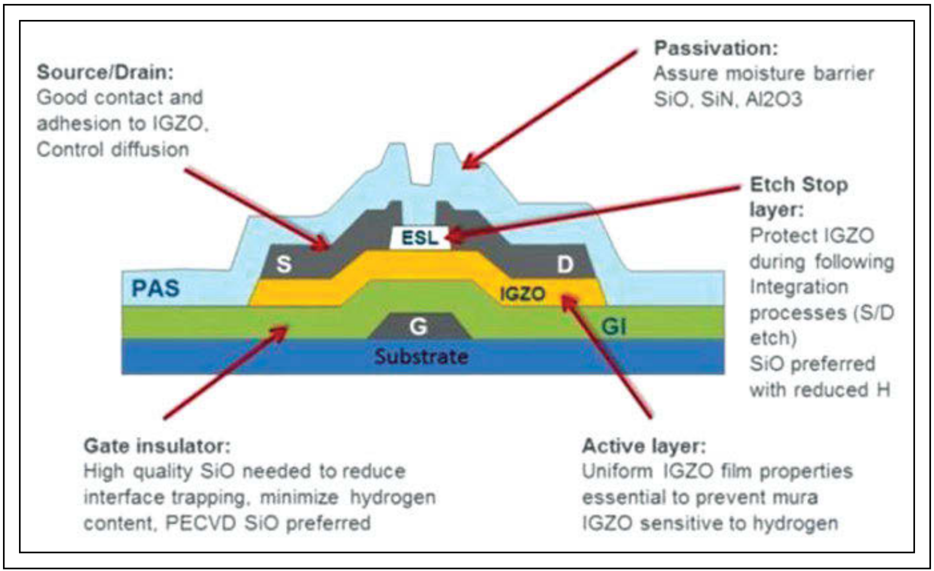


Fig. 2: *This metal-oxide (MO_x) device structure uses a six-mask process compared to the 10 masks typically needed for LTPS, thus reducing costs. Source: Display Business Group, Applied Materials.*

Scaling LTPS Films to Larger Substrates

The Applied Materials AKT– PiVot DT™ PVD system for fabricating a-Si, LTPS, or MO_x backplanes addresses the challenges outlined above, allowing panel makers to produce next-generation ultra-high-resolution displays and scale to larger substrates at lower costs than were previously possible (Fig. 3).

Using proprietary rotary target technology, the system deposits highly uniform homogeneous and low-defect materials such as ITO, IZO, TiN_x, Ti, MoW, Mo, and Al for use as interconnects and pixel electrodes and supports integrated passivation layers with LTPS films, IGZO, or Al_2O_3 for the active layer and passivation of MO_x on larger substrates. The system ultimately provides a wider process window with greater control of layer properties, higher productivity with faster TACT, and longer PM cycles with high target utilization. The equipment supports TFT-LCD and OLED flat-panel-display manufacturing, including TFT-array processes such as gate and source/drain metallization and the fabrication of color pixels and MO_x active layers.

To ensure a robust display product based on a-IGZO TFTs, it is essential to evaluate electrical stability. The reason is that OLED displays are current driven. If the current is changing, the amount of light generated in the OLED pixel is also changing. It is therefore essential that the current flowing through the TFT is stable over time. The threshold-voltage stability is a good measure for the

Fig. 3: *The AKT-PiVot 55K DT PVD system is designed for manufacturing large-area ultra-high-definition LCD and OLED panels.*

electrical stability of a TFT. Typically, the TFT stability is characterized at elevated temperatures by applying a voltage for a long time and by recording the response of the TFT. A bias-temperature stress (BTS) study (Fig. 4) shows that the a-IGZO TFT has stable electrical properties with a threshold-voltage shift (ΔV_{th}) much smaller (0.2 V) than the ΔV_{th} for an average a-Si:H TFT (>1.8 V) under similar AMOLED stress conditions.

The impact of uniformity and particles on yield is significantly magnified as TFTs get smaller and devices get larger (Fig. 5). Particles that were not problematic before can now become "killer defects" in smaller TFTs because they are relatively larger.

Equipment manufacturers must therefore reduce both the number (density) and size of particles when scaling to higher resolution and larger displays. The rotary target array in the AKT-PiVot system accomplishes this by providing less material re-deposition and nodule formation, which results in fewer and smaller particles, thereby enhancing device performance, yield, and product value.

This is accomplished by using a sophisticated magnet motion in the rotary target array to improve film uniformity, design rule, and glass-edge utilization, and also to deliver

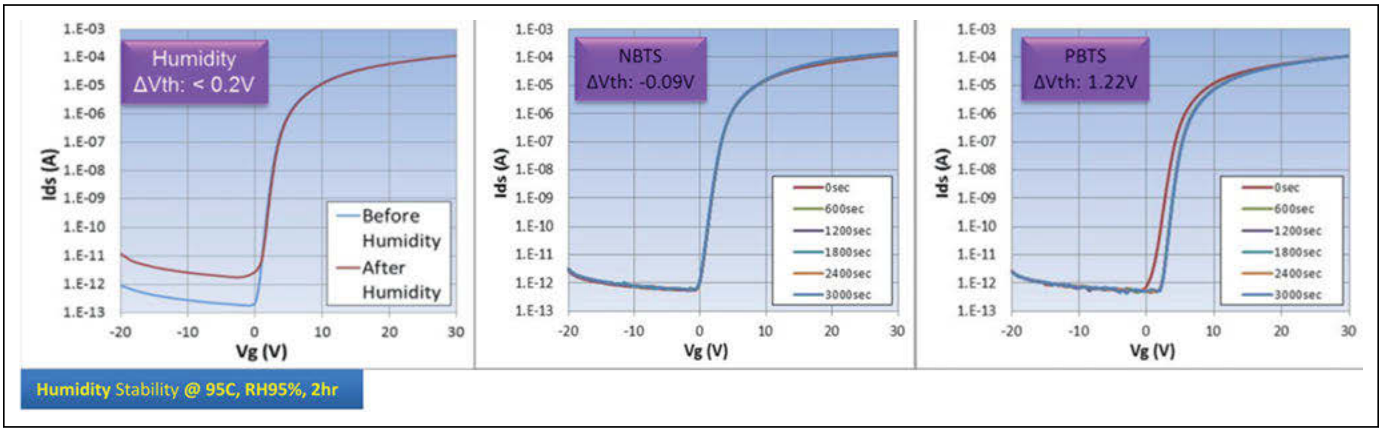


Fig. 4: Stress-test results show the TFT transfer curves after operating at elevated temperature and high humidity, with negative and positive bias stress. Humidity and negative voltage stress do show a very small influence on V_{th} ($\Delta V_{th} < 0.2$ V), while positive voltage leads to a drift of V_{th} on the order of 1.2 V.

Fig. 5: These optical microscope images show the potential of particles to become "killer defects" as TFTs shrink in size.

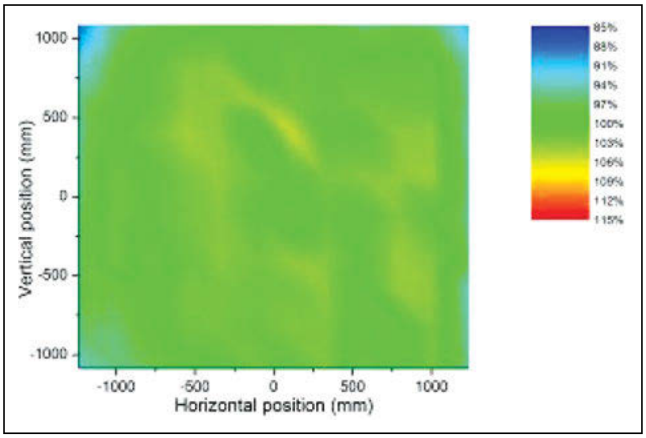


Fig. 6: This photograph of an LTPS film shows the high film uniformity achievable with the AKT-PiVot DT™ PVD systems on large substrates. Visible mura defects are eliminated. The surface plot shows that <10% sheet resistance (RS) uniformity is achievable with a thickness (THK) uniformity of <7%, along with a high deposition rate and low homogeneous stress levels.

mura-free devices (Fig. 6). In addition, the rotary target-array configuration enhances the post-etching process of pixel ITO, resulting in superior etching residue performance.

PECVD Technology: Improving Dielectrics and Barrier-Film Protection

Newly available plasma-enhanced chemical vapor deposition (PECVD) films provide an excellent dielectric-layer interface for MO_x transistors with exceptionally high-quality insulating films that minimize hydrogen impurities to deliver optimized performance.

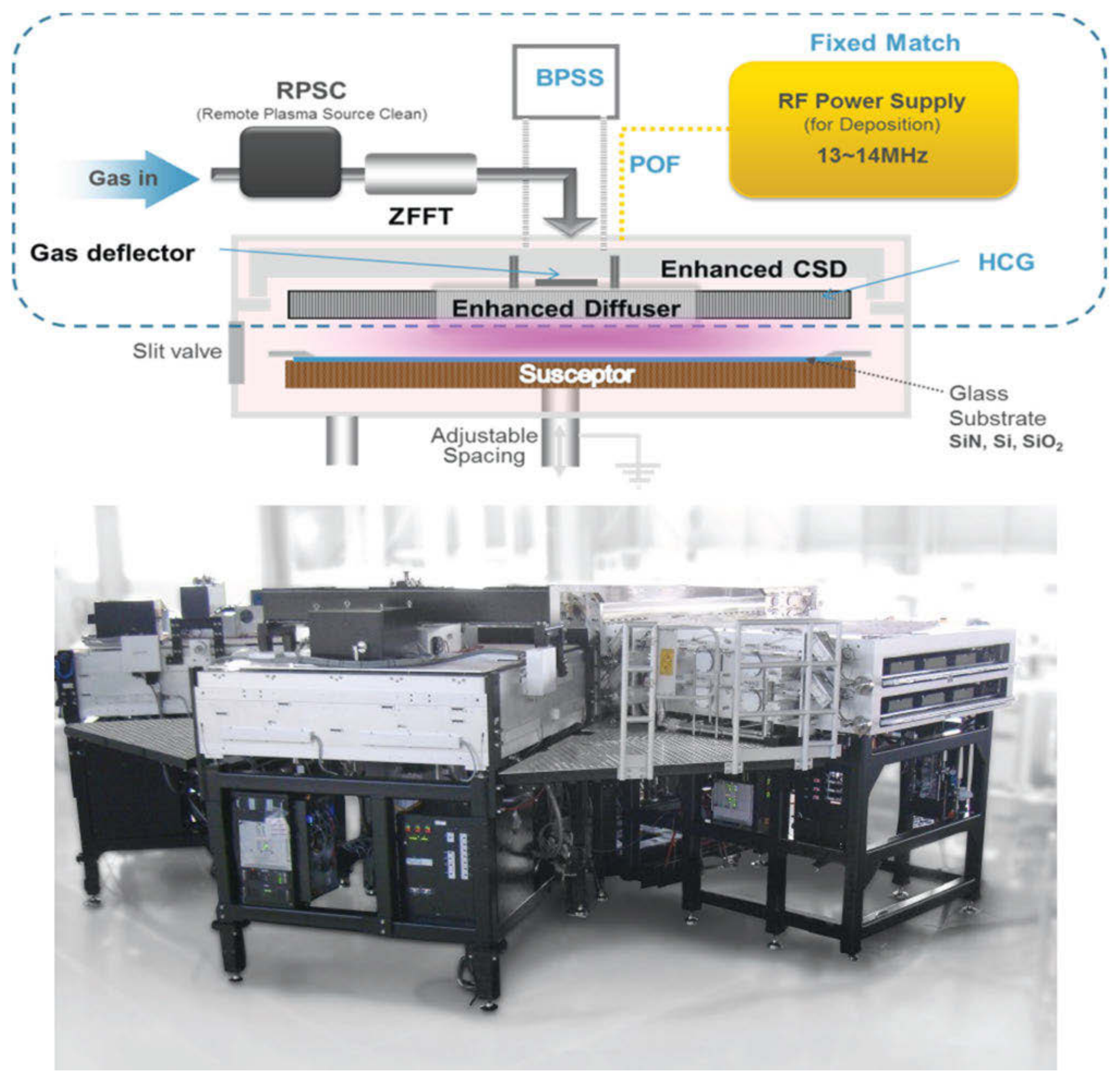


Fig. 7: Key process improvement features of the AKT-55KS PECVD (below) system that achieve IGZO-ready CVD are shown in the top image and include an enhanced hollow-cathode gradient (HCG) diffuser, (zero-field feed through (ZFFT), enhanced physical offset feed (POF), gas deflector, and enhanced center support diffuser (CSD).

Applied Materials' AKT-55KS PECVD system can deposit high-quality silicon-oxide (SiO_x) films with precise uniformity on sheets of glass up to 9 m^2 in size – a capability that is critical in achieving high production yields and low manufacturing costs. MO_x TFT requires low defect and hydrogen-free SiO_x dielectric material. The contact between the active IGZO layer and gate insulator is key to a stable TFT and requires a low defect hydrogen-free interface. Passivation is also required to protect against moisture and air, and process control is critical to ensuring superior film quality. Essential feature improvements have been applied to achieve these requirements in the process chamber of the system.

A closer look at the cross-view inside the process chamber (Fig. 7) shows the new features for IGZO-ready PECVD films, which provide advantages for both uniformity and low defects. The enhanced hollow-cathode gradient diffuser shapes diffuser holes to the plasma to improve deposition uniformity across the entire substrate. The gas deflector pre-distributes gas before it goes through the diffuser, and the enhanced center support diffuser provides improved flatness to the diffuser. Together they provide superior SiO_x film uniformity for MO_x applications. The top-down remote plasma source clean based on NF_3 plasma cleaning provides an efficient chamber clean resulting in fewer defect particles and disassociation of greenhouse gasses.

Thin-Film Encapsulation

Effective encapsulation is critical to preventing degradation of AMOLED materials by moisture and particles. Applied Materials' new AKT 40K™ TFE PECVD system deposits diffusion barrier films with very low water and oxygen penetration at low temperatures of <100°C. Encapsulation performance directly affects the lifespan and lighting performance of the AMOLED device. Frit encapsulation is currently the most common approach to enabling stronger, lighter, and more flexible AMOLED displays. The current standard for encapsulation lifetime (frit method) is approximately 2500 hours.

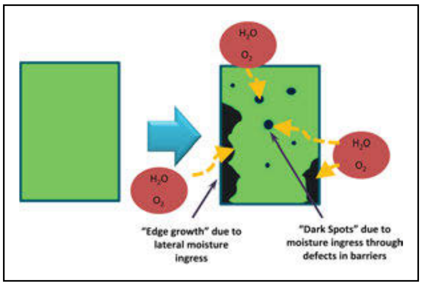


Fig. 8: *OLED device failures occur due to environmental factors including edge growth and dark spots.*

OLED devices are vulnerable to environmental factors such as moisture and oxygen. Particles are another major problem because they lead to dark spots and delamination issues (Fig. 8). High-quality encapsulation is required for lifetime and lighting performance and to enable the roadmap for flexible OLED displays.

The thin-film method depicted in Fig. 9 uses an alternating deposition of organic and inorganic materials. By alternating barrier SiN layers with SiCN inorganic buffer layers (for OLED TV applications), the multilayer concept reduces water permeation by decoupling defect sites in the barrier films and increasing the permeation channel length. The barrier-layer functions as a barrier to water and oxygen permeation, and the buffer layer releases stack film stress and covers unavoidable particles in upstream processes.

The SiCN buffer layer demonstrated high optical transmittance (>90% at 400 nm and above) and low stress. The samples passed a device lifetime test (SiN/SiCN, 7 layers) and passed a 100,000-cycle 1-in.-diameter bending test (Fig. 10). Without high stress points, this buffer layer provides excellent particle coverage without leaving any voids or diffusion channels. The architecture of the TFE tool is based on a cluster-tool design to facilitate high-throughput multilayer deposition without breaking vacuum.

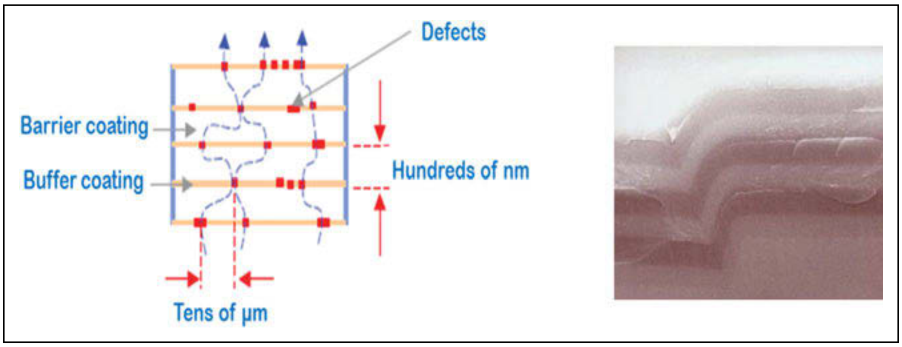
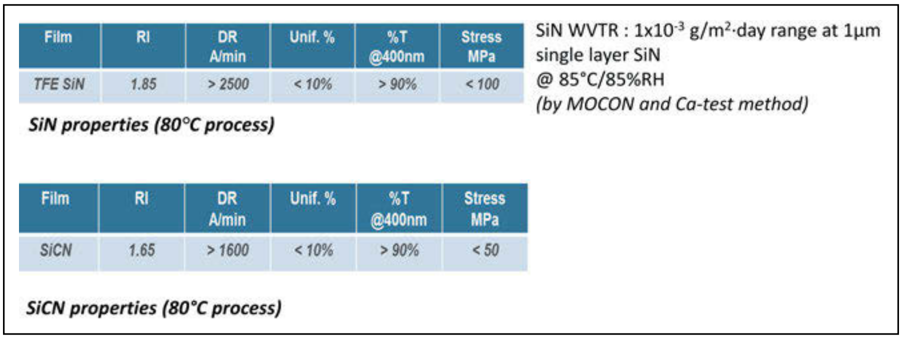


Fig. 9: *The multilayer thin-film encapsulation concept is shown at left with a 7-layer SiN/SiCN cross-section shown on the right.*



Film	RI	DR A/min	Unif. %	%T @400nm	Stress MPa
TFE SiN	1.85	> 2500	< 10%	> 90%	< 100

SiN properties (80°C process)

SiN WVTR : $1x10^{-3}$ g/m^2·day range at 1μm
single layer SiN
@ 85°C/85%RH
(by MOCON and Ca-test method)

Film	RI	DR A/min	Unif. %	%T @400nm	Stress MPa
SiCN	1.65	> 1600	< 10%	> 90%	< 50

SiCN properties (80°C process)

Fig. 10: *Film performance for PECVD SiN barrier (top) and SiCN (lower) buffer layers appears above. Results show promising WVTR barrier performance with high optical transmittance (>90% at 400 nm and above) at an excellent deposition rate. Buffer results show low stress in the stack and complete coverage without voids for good particle performance.*

Toward More Affordable OLED TVs
Applied Materials offers the backplane TFT and TFE manufacturing solutions described in this article to enable affordable OLED TVs. Specifically, MO_x backplanes have the potential to simplify pixel-circuit design, reduce masking steps and capital equipment intensity, and improve overall TFT uniformity. Film uniformity and particle control are where equipment manufacturers have the most impact in driving cost-effective manufacturing and increasing overall yield and device stability. Not only does TFE improve the lifetime of OLED TVs, it also supports the roadmap to flexible OLED displays, provides barrier protection, and reduces cost with the potential for eliminating glass encapsulation. These display-manufacturing solutions help make possible necessary cost reductions to boost OLED-TV adoption rates. ■

INFORMATION DISPLAY RETROSPECTIVE

Looking Back Over 50-Plus Years of Information Display

by Jenny Donelan

If you have ever wondered about the origins of *Information Display* magazine, you are not alone. When *ID* executive editor Steve Atwood came up with the idea to do a magazine retrospective, it seemed like it would be a straightforward matter to chronicle the complete history of *Information Display*. But it was harder than we expected. As it turns out, no one person set out with the intention of preserving a complete history when the magazine began and that history has proved difficult to unravel. There were years when the magazine came out more or less regularly and years when publishers, formats, and editorial staffs changed. There were even a couple of years (1971 and 1972) when the publishing rights to the magazine itself were under dispute. The Society for Information Display moved its headquarters several times, as did the editorial offices. As a result, there is no single complete repository of back issues.

Throughout the half-century of *ID*'s existence, its editors and publishers were doubtless more concerned about getting the next issue out on time than in preserving a record for posterity. (We, the editors of today, know from experience that this must be true.) But even though magazines are ephemera, some, including *ID*, contain invaluable records. Our searches through past issues have been filled with discovery – from the mundane (business attire in the early 1960s) to the awesome (articles on early plasma, LCD, and active-matrix technology). It's exciting to discover the seeds of a technology that went on to flourish and also to see that the scientists, and the editors who chose to publish their results so many years ago, were on track.

We will continue to find new pieces of history. One aspect of the retrospective process that has been particularly satisfying is the scanning of back issues prior to 2005, the date that *ID* began to be posted in digital format on the Web (the scanning was another idea from Steve Atwood). This is an ongoing process and issues are slowly being scanned and posted to the archives at www.informationdisplay.org. They date from 1965 to the early 1990s to right now and are being added to every couple of weeks. Take a look. It's a lot of fun. You might even recognize some names.

In the Beginning

ID was founded in 1964, 2 years after the Society for Information Display was established. There were only two issues that year, published in October and November/December. At that time, the Society already had a newsletter, which *Information Display* replaced. "Those first issues featured meetings, people, and activities. "It was a very informal publication," says Lawrence Tannas, an early member of SID and founder of Tannas Electric Displays.

Ambitions for *ID* were initially modest – there was no master plan for its future role. Today, we do have a mission statement, developed several years ago by the current editorial staff. "As the official magazine of the Society for Information Display (SID), *Information Display* serves the display industry through unbiased and objective reporting on the business and technologies related to displays. By serving the display industry, *ID* also serves the membership of the SID."

Even though the mission statement is recent, it seems clear that the *ID* magazine of the '60s and onwards did basically meet the goals that statement describes. Below is a timeline that shows the evolution of the publication and how it reflected that of the Society for Information Display and the display industry itself.

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ID TIMELINE

MAGAZINE HISTORY

DISPLAY INDUSTRY HISTORY & *ID* CONTENT

1962–1963

1962: The Society for Information Display is founded at UCLA and publishes a SID newsletter.

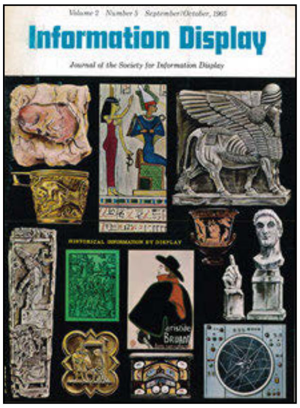
1963: SID publishes the *Journal of the Society for Information Display*, a peer-reviewed technical journal.

1964

The first issue of *Information Display* appears in October 1964, replacing the SID newsletter. There is only one more issue this year, November/December, which features three articles: "The JPL Space Flight Operations Facility Display and Control System" by Albert S. Goldstein, "1964 Voice-Response and Visual Display Techniques for On-Line Information Handling Systems" by Emik A. Avakian and Walter F. Jenison, and "Display Requirements of the Integrated Management Information System" by Donald L. Dittberner and Peter James.

The plasma display is invented at University of Illinois. Pioneering LC developments and active-matrix addressing are also going on at RCA.

1965



Volume 2, Number 5, September/October 1965

ID begins to publish six issues a year (its current format) and continues that way for more than a decade.

The editors and publishers are Martin H. Waldman and Hal Spector. The publishing company is Information Display Publications, located in Beverly Hills, California. This issue features a preview of the sixth SID Symposium and articles including "Energy Transfer from CRT to Photosensitive Media" by Leo Beiser. Note that the tagline under the masthead is "*Journal of the Society for Information Display*" even though a separate journal exists.

This advertisement from the 1965 September/October issue features a state-of-the-art display and, presumably, state-of-the-art business attire. Note the emphasis on accessing stored computer records instantly.

MAGAZINE HISTORY

DISPLAY INDUSTRY HISTORY & *ID* CONTENT

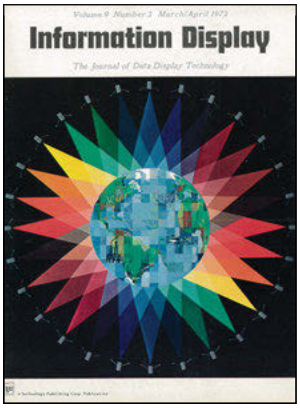
1970–1971

1971: This year marks the start of a 2-year legal battle between the publisher of the magazine and the Society over who had authorization to publish the magazine. According to former SID historian and founding SID member Bob Knepper, the issue below was one of several that were published without the permission of the Society. Note that the tagline is now: "*The Journal of Data Display Technology*."

1970: Twisted-nematic LC is developed.

1971: AC PDP 512 × 512 graphic terminal developed at Owens-Illinois.

1972–1974



Volume 9, Number 2, March/April 1972

1972: After this issue is published, and as a result of the aforementioned legal battle, *Information Display* is replaced by a similar magazine called the *SID Journal* for a period of about 2 years, from May/June of 1972 to September/October of 1974.

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1972: Cathode-ray tubes (CRTs) are a hot commodity in 1972. This ad, from the Special Purpose Tube Company of Van Nuys, California, is one of many for CRTs appearing in the May/June 1972 issue.

1974: First AMCLD prototype is developed at Westinghouse.

1975–1979

1975: *Information Display* begins to be published by SID out of its headquarters in Los Angeles. The publisher is Erwin Ulbrich (then SID Vice-President). Tom Curran is the publications chair. During this time, the magazine transitions from a bi-monthly to a more or less quarterly format. There are only two issues this year, June and September, and only one in 1976, in April.

1977: There are only three issues this year, and they are basically short newsletters.

1978: This year, Ted Lucas becomes the editor, and 10–12 issues are mailed out.

1979: a-Si TFTs are developed at the University of Dundee, Scotland.

1983–1985

1985: Publishing is turned over to a company called MetaData, based in New York City. Ted Lucas is an Editorial Consultant.

1983: The first commercial "pocket" LC TV, based on poly-Si, is sold by Seiko-Epson.

MAGAZINE HISTORY

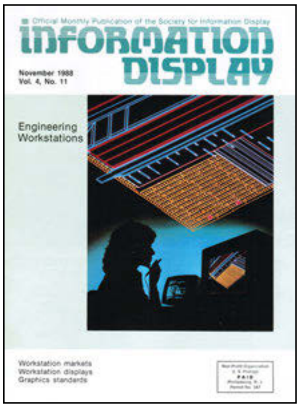
DISPLAY INDUSTRY HISTORY & *ID* CONTENT

1987

Palisades Institute for Research Services (now Palisades Convention Management) becomes publisher. Ken Werner is executive editor. Jay Morreale joins the magazine. Twenty-eight years later, he (left) is still with the magazine as editor-in-chief.

Low-voltage OLEDs are invented at Kodak.

1988



The November 1988 issue features articles on workstations. The CRT is still the mainstay of the display world.

A 21-in. color plasma display panel is introduced by Fujitsu.

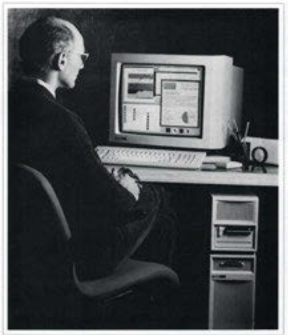
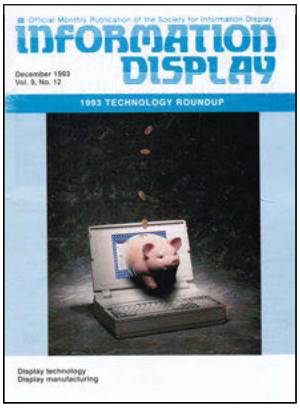


Photo: Sun Microsystems, Inc.

Fig. 1: Today's de facto standard workstation display is based on a 19-in.-diagonal full-color shadow-mask CRT and has sufficient resolution for an effective windowed user interface.

This image is from a November 1988 article simply titled "Displays for Workstations" by Hugh Masterson.

1993–1994



1993: The cover of the December 1993 issue sports a puzzling piece of conceptual art. It's a Technology Roundup issue and features stories on emissive technology and LCDs. Ken Werner's look at "Emissive Flat-Panel Display" highlights the following topics: "Fujitsu brought the first color plasma TV set to market, LEDs earned millions, and a full-color EL display earned respect." The issue also includes these two articles: "CRT-Based Data Display Technology: If CRTs are such a mature technology, why are they changing so quickly?" by Richard Trueman and "Liquid-Crystal Displays: The LCD is now challenging the CRT as the world's largest selling display – and will soon surpass it" by John L. West. The times are changing.

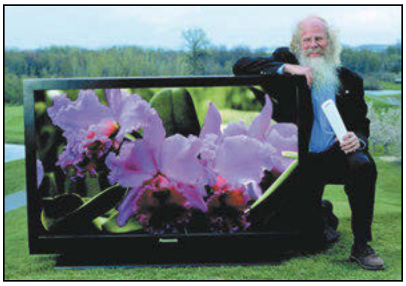
1994: Plasmaco, co-founded by plasma visionary and SID past-president Larry Weber, demonstrates a 21-in. color plasma display at Display Week in San Jose. Panasonic Corporation then forms a joint development project with Plasmaco, which leads in 1996 to the purchase by Panasonic of Plasmaco, its color AC technology, and its American factory.

MAGAZINE HISTORY

DISPLAY INDUSTRY HISTORY & *ID* CONTENT

1995–1999

1996: Ted Lucas retires as *Information Display*'s West Coast Advertising Representative at the age of 82.



1999: Larry Weber, a new member of the *ID* Editorial Board, poses next to one of the 60-in. plasma displays he helped develop for SID 1999 and the 1999 Japan Electronics Show. *(This photo is from a May 2009 article in* ID *on the history of Plasmaco. Photo courtesy Will Faller.)*

1995: Hitachi introduces an IPS TFT-LCD.

The U.S. National Institute of Standards and Technology announces the launch of its Video Processing and Display Meaurement laboratories, setting the stage for what is to become the seminal work in display measurement standards – the International Display Measurements Standard (IDMS) – now sponsored by SID.

During this timeframe, laptop PCs based on AMLCDs become affordable, which spearheads the subsequent domination of LCDs.

1998: The phosphorescent OLED is invented at Princeton and USC.

1999: Pioneer introduces the first commercial OLED panel.

2001–2005

2004: By this time, *ID* has more or less acquired its current logo. CRTs aren't mentioned. Topics in the January 2004 issue include LCD overdriving and AMOLEDs, with this feature by Koichi Miwa and Atsushi Tanaka: "Driving AMOLEDs with Amorphous-Silicon Backplanes: It had been believed that current-hungry OLEDs required expensive poly-Si TFTs, but now it seems that a-Si TFTs can do the job – and that means inexpensive AMOLEDs for TV sets are possible."

2005: *ID* Magazine's digitized pages begin to be posted on *Information Display*'s Web site.

2001: Samsung introduces a 40-in. TFT-LCD TV.

2003: The first color AMOLED product ships in cameras from Kodak and Sanyo.

2004: The article at left on AMOLEDs from the January 2004 issue features a 20-in. OLED display from IDTech, driven with super-amorphous-silicon TFTs.

2006

The June 2006 issue focuses on flexible displays and paper, with an article titled "Designing e-Books that Will Be Comfortable to Use" by Mark T. Johnson and Guofu Zhou. Its authors say: "Although documents can be read on computer screens, paper is still preferred. When will there be an e-Book that will be comfortable to read for hours at a time?"

In January of this year, Stephen Atwood, our current executive editor, takes the reins at *Information Display* and Allan Kmetz joins the Editorial Advisory Board as article reviewer.

Sony/Philips

Fig. 2: Sony's LIBRIé e-book reader is the first commercial product to use the Philips/E Ink Corp. active-matrix electrophoretic display. The 800 × 600 6-in. display exhibits four gray levels.

This early eReader is pictured in the June 2006 issue.

MAGAZINE HISTORY

DISPLAY INDUSTRY HISTORY & *ID* CONTENT

2007–2008

2008: The cover of the January 2008 issue reads – Has E-Paper Finally Arrived?

2007: The Amazon Kindle, though not the first commercially available eReader, is the most popular, selling out 4 hours after being introduced.

2008: Large-area AMOLED TV panels are demonstrated by Samsung and LG Display. Below is a 31-in. 1920 × 1080-pixel display from Samsung SDI that uses the company's super microcavity bottom-emission technology.

2013

Wiley takes on publishing responsibilities for *Information Display*. Palisades Convention Management and SID continue to provide editorial services.

2014

ID Magazine turns 50.

Samsung and LG announce that they will end production of plasma TVs this year, effectively ending the era of plasma displays.

2015

The best is yet to come!

Acknowledgments

Information Display is indebted to the following individuals and organizations who helped with the preparation of this timeline: Phil Heyman, Allan Kmetz, Bob Knepper, Larry Tannas, and Erv Ulbricht (who created the 50-Year SID History on which some of this timeline is based). ■

continued from page 2

to what we might have called "machine vision" in earlier times, as well as proposing a number of very intuitive and intriguing potential applications for the technology. Personally, I've been involved in this area of technology several times in my career and each time previously found the hardware and tools very limiting compared to my creative ambitions. Not so anymore! I hope, therefore, you find this article as inspiring as I did given my professional context.

Another area where 3D depth imaging is poised to change our lives is photography. We've covered light-field technology in several ID articles over the past couple of years, and one area that is taking advantage of the latest R&D is digital imaging. As author Kurt Akeley from Lytro explains in his Frontline Technology article, "Light-Field Imaging Approaches Commercial Viability," it is now possible to build cameras using arrays of micro-lenses to capture the light field of a scene for later post-processing and rendering in both 2D and 3D forms. Imagine being able to capture a complex scene and afterwards being able to digitally process the scene for varying depths of field, focal distance, and even viewpoint. Kurt's article describes the underlying optical science and the recent hardware and electronic advances that make this possible. You can bet I'm putting a light-field camera on my wish list for the near future.

Lighting is a subject that most of us take for granted most of the time – except when we can't find a flashlight or we need to change a light bulb. But, as Guest Editor Mike Lu explains in his editorial, this may all be about to change. We're learning that not only do our bodies respond to light through changes in our metabolism and circadian rhythms, the color of light is as much or more important than the intensity of the light. In the first of two articles Mike developed for us, author Jennifer A. Veitch explains how recently discovered photosensitive cells in our eyes appear to be directly linked to circadian regulation, and those cells are most sensitive to a region of blue light between 440 and 540 nm. These cells send signals to our brains that we are in daylight, or in night, in response to this light energy. In Jennifer's Frontline Technology article titled "Light for Life: Emerging Opportunities and Challenges for Using Light to Influence Well-Being," we also learn how most of us who work indoors are probably not being exposed to enough of the right blue light for full daytime cycles. At night, if we watch TVs or use our tablets, we are getting too much blue light and suppressing melatonin in our bodies that we need for proper sleep cycles. The consequences of decreased melatonin and proper sleep cycles over time have been widely studied and are very serious. Jennifer's article contains a great summary of the latest science, its implications for what she refers to as our "well-being," and some good advice for further areas of research.

One team that is working directly on lighting to control the amount of blue-light exposure is Professor Jwo-Huei Jou and his team from the National Tsing Hua University in Taiwan. His group has looked at fire, the dominant source of nighttime lighting for humans for at least the last 2000 years or so. Fire in the form of candlelight emits light exactly on the black-body-radiation locus and contains very little blue-color energy, making it ideal for indoor nighttime illumination. In contrast, other light sources such as compact fluorescent bulbs contain a lot of blue energy to give them a relatively high CCT rating. But at night, those CCFLs could be tricking your brain into thinking it is still daytime outside. In simple terms, if you were to use candles instead of CCFLs to light your home at night you might benefit from a more natural circadian rhythm and more productive sleep due to more natural melatonin cycles. In their Frontline Technology article, "OLEDs with Candle-Like Emission," the National Tsing Hua University team describes its development of an OLED luminary using six emitters specially tuned to produce a warm light spectrum that resembles a candle flame, which was shown to reduce melatonin suppression in test subjects.

OLED TVs hold a lot of promise, but so far, high yields and low manufacturing costs have not made the top of the list. The platform has gotten off to a slow start and could use some help in the form of advances in manufacturing equipment and processes. This may be coming, as explained in our applications segment this month titled "A Process for Using Oxide TFT over LTPS TFTs for OLED TV Manufacturing." In this article, author Kerry L. Cunningham from Applied Materials explains the work his company has done to improve several key process areas in OLED-display manufacturing, including uniformity/stability of oxide TFTs, dielectric deposition, and barrier-layer fabrication. These and other important improvements in process and manufacturing equipment will be important steps in bringing large-screen OLED TVs to the price points and quality levels that modern consumers demand.

I mentioned in September that if you looked closely at our masthead it would appear that *Information Display* magazine is in its 31st year of publication. But actually, we know now that *ID* is wrapping up its 51st year of publication. We were not sure of this until we began talking to people and attempting to unravel the history of this publication. I think to truly understand the depth of any human endeavor you need to know the history and appreciate the context. To understand the depth and scale of evolution in the display industry, you need to examine all the incremental steps that happened along the way, especially because the display industry is a unique convergence of many important fields of science.

Over the last 50 years, SID has been at the epicenter of this amazing development of technology, and *ID* magazine has been the chronicler of that remarkable progression. Therefore, *ID* magazine can be our window into the history of our industry. This is richly illustrated by our own Jenny Donelan in her retrospective article on the history of *Information Display* magazine, which we are proud to share with you. Our efforts to digitally archive back issues have resulted in a deeper understanding of just how much has transpired over these years, including an amazing view of people's visions for the future. One characteristic of many *ID* articles is the author's attempt to envision the future potential of the work and what it does or could mean for the associated products or applications. Looking at these articles years later gives you a deeper understanding of how people viewed the context of their work and the evolving potential of digital displays. Some got it right, and some did not, but it's fun to see what they were thinking. I hope you take the time to read Jenny's retrospective and then browse the on-line archive, which we will continue to update as we slowly locate and upload back issues – including the very first issue of ID from 1964!

Before I close this editor's note, the last one of 2015, I just want to thank everyone who worked so hard to put *ID* magazine together throughout the year. Our team of guest editors and contributing editors helped us create a great lineup of articles for 2015 and I cannot thank them enough for their hard work. Our editorial staff, consisting of Jenny Donelan and Jay Morreale, did an outstanding job managing the editorial and production processes and developing our in-house articles. Our cover designs this year continued to amaze, thanks to both Jody Robertson-Schramm and Jodi Buckley. I also want to thank our colleagues at Wiley publishing, including Simone Taylor and Roland Espinosa, who manage sales, final production, and distribution for *ID*. It is an honor to work with everyone on this team and I truly hope you enjoy reading the results as much as we enjoy producing them. As we all approach the holidays, I hope you find time to reflect on the many things that make your lives special, including family and friends that you hold dear. Life is much more than just the work we do in this industry. Cherish those things that are most important to you and nurture them so they enrich your life in return. I wish you all a healthy and prosperous New Year! ■

continued from page 3

Despite this, Soneira believes that both QD-enhanced LCDs (just not PVA LCDs) and OLEDs can provide superior enhanced display performance in commercial products. As he concluded in the shoot-out: “LCDs are a great display technology with lots of inherent native strengths that manufacturers should concentrate on and exploit instead of trying to pursue OLEDs on their native strengths. So LCD manufacturers should exploit very high image brightness, very large screens, and very wide color gamuts with quantum dots to improve picture quality in high ambient light. For wide-color-gamut displays and TVs using quantum dots, it is essential they use IPS, FFS, PLS, or equivalent LCD technologies with excellent viewing-angle performance to eliminate the large color shifts with angle that are produced by PVA (and other) LCD technologies. Finally, stick with flat screens – curved screens are especially challenging to implement for LCDs – leave those to OLEDs.”

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[1] http://www.displaymate.com/TV_OLED_LCD_ShootOut_1.htm#Quantum_Dots

Apple’s New Toys Are Being Bought by Older Men

In what is now a retail rite of fall, Apple announced its new product lineup in September. The lineup included more attractive Apple watches (there’s an Hermes collection now); an iPad Pro with 2732 × 2048 pixel resolution, an 8MP camera, and a claimed 10 hours of battery life; an iPad mini 4; Apple TV with a new interface (and operating system called tvOS) that works with Siri and offers touch-compatible remote; and, last but not least, the iPhone 6s and 6s Plus.

At press time, the new Apple TV had just shipped, with most critics saying that if you already have a lot of Apple products and like them, you will like this.

In terms of who likes Apple products, young people are widely assumed to be the company’s most eager consumers. However, according to a recent article in *Money* magazine (based on a report from Slice Intelligence, which tracks online shopping data), men aged 65 and older spent more on Apple devices than any other demographic group in the U.S. last year, spending, on average, $976 online, per person, annually.[2] Men aged 25–34 spent $838 annually and men outspent women in every age category by about $200–$300 per year. The reasons behind the popularity of Apple with the older set were not reported. They may be responding to ease of use, discovering the products for the first time, or, as the article’s author conjectured, simply be buying Apple products as gifts for children and grandchildren.

For a company known for its highly designed products, Apple has received low marks in the looks department for its watches. Presumably to address that, Apple is coming out with several new designs, including a collection by Hermes.

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[2] http://money.cnn.com/2015/10/29/technology/apple-customers/ ■

continued from page 4

Dr. Veitch's article further provides actionable advice – as useful as it is rare from an academician! There are gems for both luminaire manufacturers and ordinary consumers of light – everyone in the civilized word. Much of the research is on-going, but all signs indicate that in the not too distant future, we will develop a new appreciation for the value of lighting, not because it has stopped working, but rather due to its additional functionalities, which include making us healthier, more energized, and more productive.

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[1] I. Provencio *et al.*, "Melanopsin: An opsin in melanophores, brain, and eye," *Proc. Natl. Acad. Sci.* **95**, 340–345, (1998).

[2] M. Barinaga, "News Focus: How the Brain's Clock Gets Daily Enlightenment," *Science* **295**, 955–957 (2002); S. Hattar *et al.*, "Melanopsin-containing retinal ganglion cells: architecture, projections, and intrinsic photosensitivity," *Science* **295**. 1065–1070 (2002); D. M. Berson, F. A. Dunn, and M. Takao, "Phototransduction by retinal ganglion cells that set the circadian clock," *Science* **295**. 1070–1073 (2002).

[3] M. S. Rea *et al.*, "A model of phototransiduction by the human circadian system," *Brain Res. Rev.* **50**, 213–228 (2005) and M. G. Figueira, A. Bierman, and M. S. Rea, "Retinal mechanisms determine the subadditive response to polychromatic light by the human dircadian system," *Neuroscience Lett.* **438**, 242–245 (2008).

[4] R. G. Stevens *et al.*, "Breast cancer and circadian disruption from electric lighting in the modern world," *CA Cancer J. Clin.* **64**, 207–218 (2014).

__Mike Lu__ is currently Director, Innovation Engineering, at Acuity Brands Lighting, where he is responsible for developing new luminaire electronics and commercializing OLED lighting. He was previously a Senior Scientist at Universal Display Corp. He obtained his Ph.D. in electrical engineering from Princeton University. ■

DISPLAY WEEK
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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.

Don't miss the 2016 I-Zone, taking place on the show floor at Display Week, May 24–26.

I-Zone 2015 Best Prototype Award Winner:

Ubiquitous Energy

NOMINATE YOUR FAVORITE PRODUCTS FOR A DISPLAY INDUSTRY AWARD

If you've seen or used a new display product this year that you really like, let the rest of the industry know by nominating it for a Display Industry Award. The DIAs are the display industry's most prestigious honor, given annually by the Society for Information Display to recognize the year's best new display products or applications. There are three Awards categories: DISPLAY OF THE YEAR, DISPLAY APPLICATION OF THE YEAR, and DISPLAY COMPONENT OF THE YEAR. Winners are selected by the Display Industry Awards Committee based on nominations from SID members and non-members alike, and the awards are announced and presented at Display Week. Winning a DIA not only tells a company that it's doing a great job – it helps build brand recognition both inside and outside the industry.

To nominate a product, component, or application that was commercially available in 2015, send an email titled DIA 2016 Nomination to drocco@pcm411.com. The Display Awards Committee will review your suggestion.

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

ACT QUICKLY: THE DEADLINE FOR NOMINATIONS IS JANUARY 15, 2016.

SID's Display Training School Coaches the Next Generation

Less than 2 years ago, SID founded the Display Training School to prepare future members of the display industry. "Display training is designed to attract talented scientists and engineers who are learning display technology. It is also a great vehicle for serving SID members in building their careers," says Yan. As in any area of technology, the display industry needs a steady influx of new scientists in order to remain viable. The DTS, which is currently under the direction of DTS Committee Chair Qun (Frank) Yan, is designed to provide global outreach that will help prepare the next generation for the display industry. The program is starting out in China and will expand to other countries, including the U.S., in the future.

Fig. 1: Participants in the second DTS course learned about "Improving Production Yield of TFT-LCDs" in Hefei, China. About 43 students from nine different companies attended.

The first DTS course, on yield improvements for the TFT-LCD manufacturing process, took place in December 2014 in Nanjing. Forty-seven students attended the two-day event, which included a factory tour. Since then, the DTS has held three more classes in different areas of China, including Wuhan and Shanghai. Thus far, three of the classes have covered LCD technology and one has covered OLEDs.

The DTS works with both academic and business partners in the regional areas of concentration to provide a training program that combines fundamental science with practical display knowledge. Students come from both universities and companies involved in display manufacture and design. ■

NOMINATE YOUR FAVORITE PRODUCTS FOR A DISPLAY INDUSTRY AWARD

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To nominate a product, component, or application that was commercially available in 2015, send an email titled DIA 2016 Nomination to drocco@pcm411.com. The Display Awards Committee will review your suggestion.

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

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