OLED ISSUE

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A Bright Future for OLED Lighting

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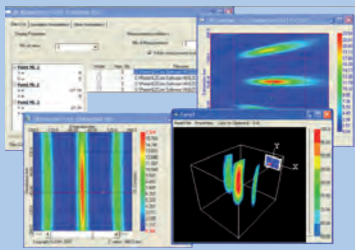

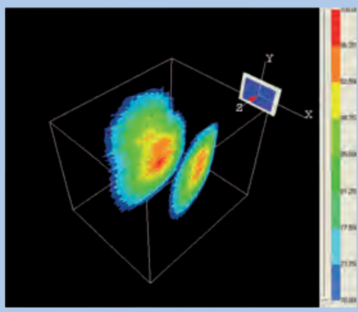

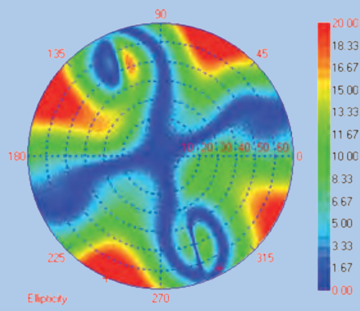

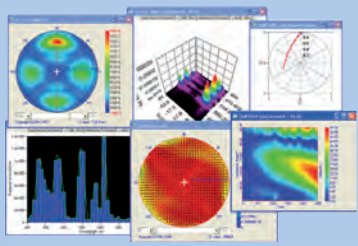

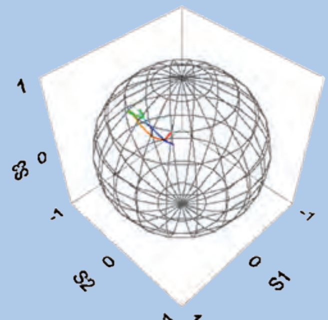

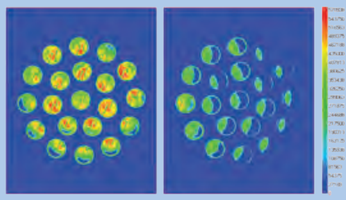

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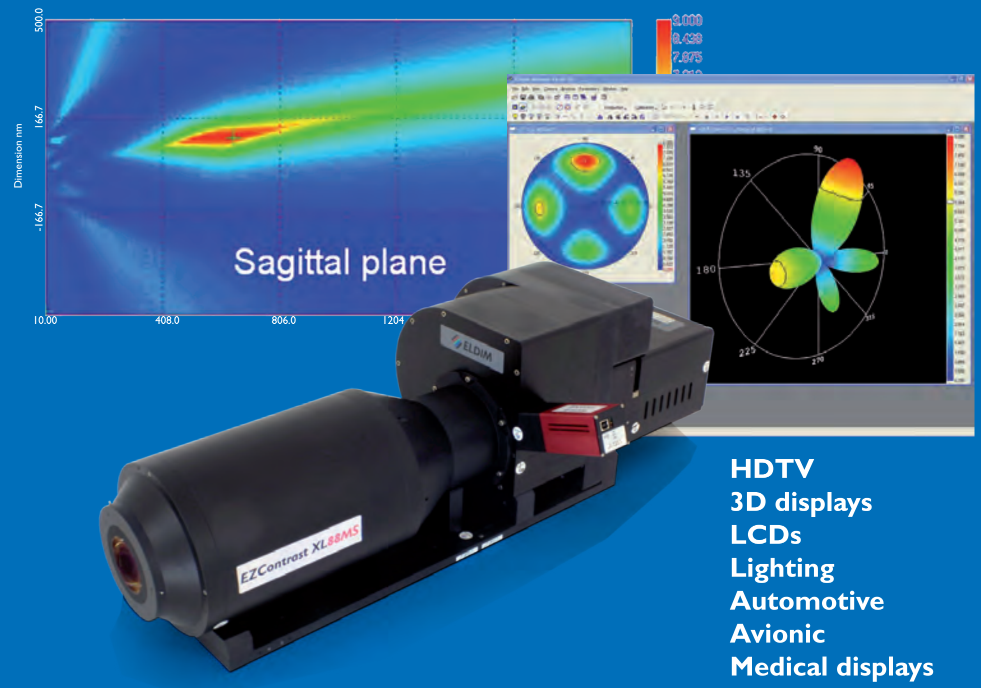

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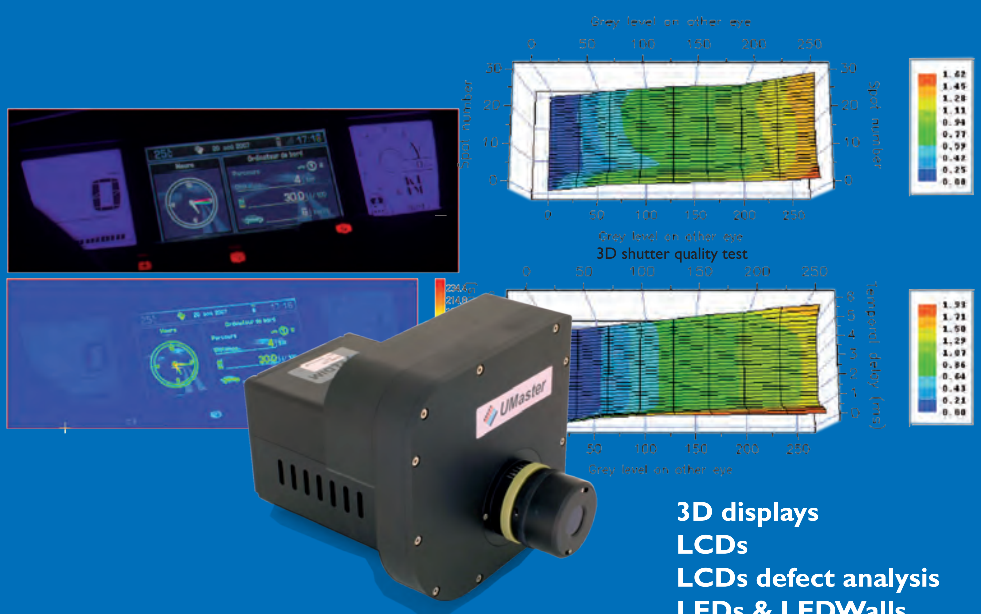

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COVER: Many companies have now expressed their interest in developing OLED lighting products, from panels to luminaires. Over the next few years, we will see a range of these products enter the marketplace, and it will be very exciting to see how consumer reaction shapes and drives this industry.

Cover design by Acapella Studios, Inc.

PHOTO CREDIT: Top left: OLED luminaire from Acuity Brands Lighting featuring OLED panels by LG Chemical. Image courtesy Acuity Brands Lighting. Lower left: A flexible white PHOLED panel designed and fabricated at UDC with a 15 cm x 15 cm metal foil substrate held in a flexed arrangement. Image courtesy UDC. Right: "Transparent Light Origami" designed by Emory Krall of Universal Display Corp. with transparent primary-color PHOLED lighting triangles mounted on adjustable hinges. Image courtesy UDC.

Next Month in *Information Display*

Green Manufacturing Issue

- Green Technology in LCDs
- Green TFT Technologies
- Eco-Designs for TV
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Living the *Star Trek* Life

Stephen Atwood

It is likely that most of you are familiar with the many episodes and storylines of the *Star Trek* science fiction franchise. Some 200 years into the future, the *Star Trek* personnel travel through the galaxy in technologically advanced spacecraft they call starships, encountering other civilizations that are also capable of space travel. One aspect of *Star Trek* that distinguishes it from many other Sci-Fi vehicles is the way the high-tech tools and seamless life-enriching technologies are liberally woven into each story.

A surprising number of these technologies, or at least their slightly less evolved versions, are already available to those of us who dwell in the 21st century. For example, people on *Star Trek* have small handheld devices they can use to contact any person they like, even over intergalactic distances. These "Communicators" as envisioned by series creator Gene Rodenberry, are what we all know now as cell phones. But in the 1960s when the first episodes aired, I doubt any of us realized what was coming. In later *Star Trek* episodes, the characters have hands-free communicators attached directly to their clothes, much like our Bluetooth devices today. Display technology is also richly portrayed in the 23rd century, from 3-D holograms the size of an entire room to huge, widescreen, high-resolution flat panels on almost every surface, to all manner of handheld devices with full-color video screens and touch interfaces. In fact, many of these futuristic portrayals are already becoming quite common. Also apparent is that the *Star Trek* characters do not view these display devices as exotic toys; they literally live with them and interact with them as part of their daily existence. They do not wear glasses to view 3-D displays, but they use the displays regularly for all the believable applications that 3-D enthusiasts have been talking about for so long, such as navigation and mapping, scientific imaging, and – unfortunately – even tactical warfare planning.

Something else that may not be obvious to most casual observers of the world as portrayed in *Star Trek* is that ambient lighting is a richly crafted element of the environment. Artificial light does not come from ceiling fixtures or point-source lamps. It comes from surfaces, walls, ceilings, and even furniture, and it somehow weaves a scene of peaceful and ergonomically perfect light around every conceivable circumstance. This lighting even simulates the natural rhythms of night and day to allow inhabitants to preserve their natural sleep cycles. It appears that people in the 23rd century seem to have conquered the challenges of aging vision – older people are rarely seen struggling to read or perform their work, even under the most incredibly stressful conditions. Visibility is never an issue during an attack by another starship, for example, or an impending explosion of the ship's engines. In any case, task lighting and ergonomic workstations will certainly be highly evolved in 200 years' time. A great many of these whimsical-seeming ideas are becoming real even today.

Could it happen that OLED technology will help enable the types of ideal lighting environments depicted in the *Star Trek* future? I think the answer is yes. Home and workplace lighting technology is about to undergo a paradigm shift not seen since the transition from candles to gas lighting and incandescent bulbs. As the economic elements work themselves out, I believe interior designers and ergonomic engineers will hold the key to widespread adoption of radically different lighting designs enabled by OLED technology. These designs will actually reduce the stress levels in

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industry news

iPod Touch and Amazon Kindle Dazzle with New Displays

Among this fall's numerous portable-device updates are two that feature greatly improved displays – Apple's iPod Touch and the latest generation of the Amazon Kindle.

The new iPod Touch incorporates Apple's "Retina Display," introduced last summer in the iPhone 4. The 3.5-in. 960 × 640 capacitive-touch display has a high-enough pixel density that, according to Apple's literature, "… your eye is unable to distinguish individual pixels." RGB pixels are arranged on a horizontal grid spacing of 78 μm, resulting in 326 pixels/in. The display uses LED backlighting and has an ambient-light sensor that automatically adjusts the luminance of the screen for optimal viewing and battery life. While at least two major display manufacturers have been cited by journalists as makers of the display, Apple did not respond to inquiries on this subject. The iPod Touch has two cameras, front and back, which enable the FaceTime calling feature that debuted with the iPhone 4. It also comes with HD 720*p* video recording and a faster processor, Apple's A4 chip.

The new iPod Touch features the high-density "Retina Display" used in the latest iPhone. Image courtesy of Apple.

Writing about the Retina Display as used in the iPhone 4, Charles Annis, Vice-President of Manufacturing Research for DisplaySearch, said that the new display is so compelling that it has upped the ante for many similar products. As he wrote in a recent article, "The release of the June 2010 iPhone 4 with its 327-ppi Retina IPS-LCD has sparked great interest in super-high-density displays for smartphones."

Less colorful but just as compelling is the display used in the latest Kindle from Amazon. Admittedly, the product's most arresting feature may be its $139 price tag, but the Kindle also features the stunning, latest-generation, super-high-contrast, electronic-ink technology from E Ink. The device is 21% smaller than its predecessor, but a thinner bezel allows the 6-in.-sized reading area to remain the same. The new 8.5-oz. Kindle is also 15% lighter, offers 20% faster page turns, and features built-in WiFi, as well as up to 1 month of battery life with the wireless off. The new Kindle has double the storage of the last version, to a total of 3500 books. Amazon is also offering the Kindle 3G, which adds free 3G wireless for $189.

– Jenny Donelan

guest editorial

OLED Lighting: Coming of Age

by Mike Hack

OLEDs are now catching the attention of the consumer. OLED smart phones can be found in every store and are offered by all the major carriers. Fabulous early-entry OLED TVs are now available on a limited basis and offer truly spectacular visual experiences. While the early focus of OLED development was for flat-panel-display applications, through the use of phosphorescent OLEDs, energy-efficient solid-state lighting is now also being realized.

Lighting is at a cross roads. Incandescent lamps are being banned worldwide because of their environmental impact, while compact fluorescent lamps have limited visual appeal, as well as safety concerns with regard to residential lighting due to their mercury content. Both LEDs and OLEDs provide safe and efficient replacements for these older lighting technologies and can complement each other in how they are used. LEDs offer bright point-source illumination, while OLEDs are large-area, thin, diffuse sources of light. Of course, pricing will have a major impact on how widely each approach is adopted by the marketplace.

Many companies have now expressed their interest in developing OLED lighting products, from panels to luminaires. Over the next few years, we will see a range of these products enter the marketplace, and it will be very exciting to see how consumer reaction shapes and drives this industry.

In this special issue, we have three diverse perspectives on the promise and reality of OLED lighting. Starting with a key technology developer, Universal Display Corp. (UDC), we see how its phosphorescent-OLED technology is a critical element for OLED lighting to become an energy-efficient, visually pleasing, thin, and high-quality source of area illumination. Samsung SMD develops this theme, expanding on how the inherent characteristics of OLED lighting inspire a revolutionary change in solid-state-lighting applications. From Samsung's perspective as a leader in OLED-display manufacturing, the authors describe the key issues for the production of OLED lighting panels. In our third article, Acuity Brands Lighting explores the value proposition for OLED lighting for the consumer from its position as a global luminaire company with an extensive portfolio and market share in all lighting technologies.

UDC discusses how phosphorescence is a key enabling technology that may enable OLEDs to become a new appealing and energy-saving form of solid-state lighting. UDC describes its recent results, including a 15 cm × 15 cm panel that exceeds 50 lm/W. OLEDs are shown to have very desirable color quality, and the UDC authors outline their recent progress in improving their all-phosphorescent white device lifetimes. OLEDs offer a radically new view of lighting – until now, all lighting has been based on point or linear sources of light, and OLEDs break this mold by providing inherent area lighting. Examples of prototypes showing transparent PHOLED light art and flexible light sources add to the excitement of the possibilities offered by this new technology.

Samsung SMD also suggests that the inherent characteristics of OLEDs, such as ultra-slim thickness, transparency, flexibility, and color changeability can provide an opportunity for OLEDs to be a new revolutionary lighting source. The authors describe some of the technologies under development for OLED lighting to meet efficiency and lifetime requirements, including phosphorescence for its efficiency,

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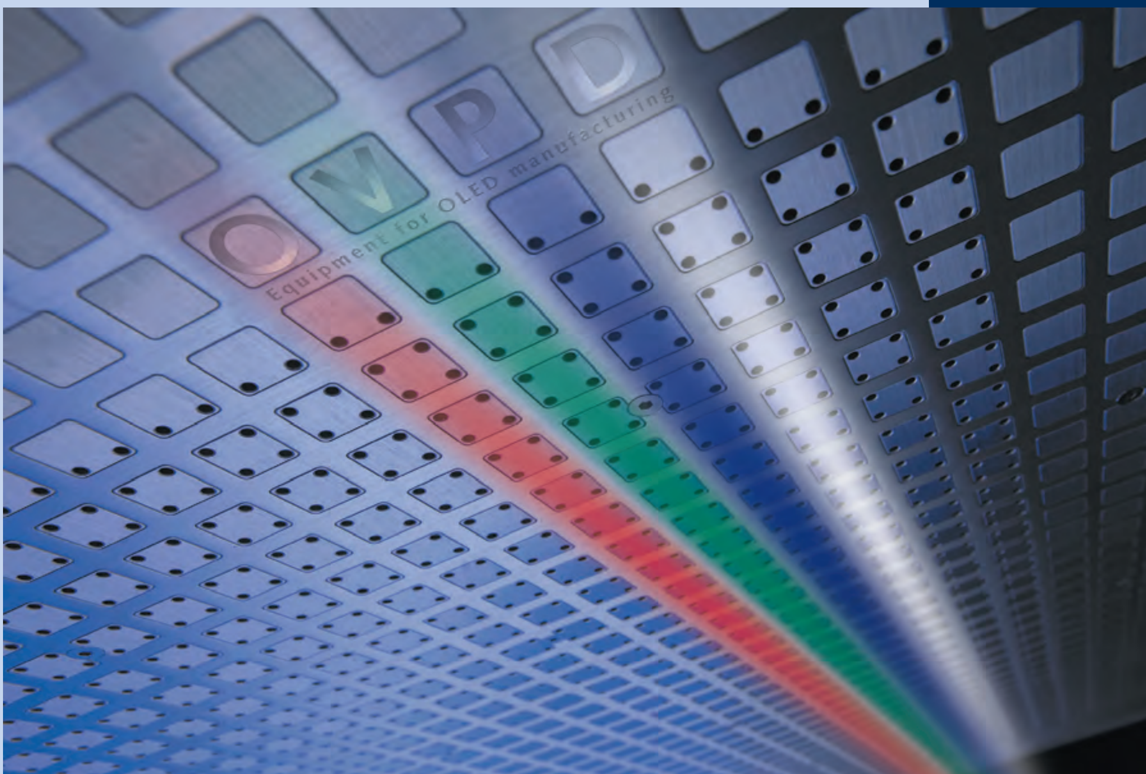

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OLED Requirements for Solid-State Lighting

Rapidly improving efficacy and lifetime make OLEDs practical for general illumination. Panel requirements for a number of product categories from a luminaire manufacturer's perspective will be discussed. In particular, the necessary efficacy is derived from both required illumination and thermal constraints. Based on the progress reported with regard to hybrid tandem OLEDs at this year's SID Symposium,[1] OLEDs should be able to meet the product roadmap outlined in this article.

by Min-Hao Michael Lu and Peter Ngai

SOLID-STATE LIGHTING promises to drastically reduce electricity consumption by utilizing sources with much higher efficacy (lm/W) than conventional sources such as the incandescent bulbs, compact fluorescent tubes (CFLs), and, eventually, linear fluorescent tubes. Inorganic light-emitting diodes (LEDs) are gradually gaining market acceptance, especially in outdoor lighting applications due to their high output intensity and long product life. As LEDs improve in color quality [color-rendering index (CRI)] and efficacy, they are making in-roads into the replacement market because they can be easily engineered into standard source geometries such as type A and PAR38 lamps.[3]

In contrast to their inorganic cousin, there have yet to be any high-volume OLED luminaire products on the market, despite the availability of AMOLED displays for mobile applications and small TVs. It is logical that early interests in OLEDs were focused on display applications because the unit area value is much higher for displays than for lighting. As OLED metrics and manufacturing technology improve, however, there has been an earnest effort in developing organic solid-state lighting. In this article, we will briefly discuss the market potential for OLED lighting before turning our attention to OLED efficacy and lifetime requirements from a lighting manufacturer's perspective.

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OLED Market Potential

The annual global lighting-fixture market is approximately $US50 billion, of which the U.S. represents $9 billion, or just under 20%.[3] The market can be broken down into four segments (Fig. 1): commercial and institutional (C&I, 40%), residential (20%), outdoor (25%), and industrial (15%).

The C&I segment includes indoor lighting applications for offices, libraries, public and commercial buildings, *etc.* Currently, the most popular light sources for this segment are linear fluorescent lamps, followed by compact fluorescent and lower-wattage high-intensity discharge (HID) lamps. The residential segment includes lighting for residential homes, apartments, and some hospitality facilities such as hotel guest rooms. It accounts for about 20% of the lighting market. The most common light sources used are incandescent and compact fluorescent lamps. There is a small percentage of luminaires designed with linear fluorescent lamps. High-intensity discharge lamps such as metal-halide types are seldom used. The industrial segment includes lighting for factories of various types, warehouses, and distribution centers. A large percentage of these applications employ high-intensity discharge lamps such as metal-halide lamps. Fluorescent luminaires represent a very small portion of the segment. Finally, the outdoor segment includes lighting for parking lots, motorway lighting, tunnels and bridges, *etc.*

The industrial and outdoor segments employ light sources with very-high-luminous exitances. The diffuse nature of OLEDs is

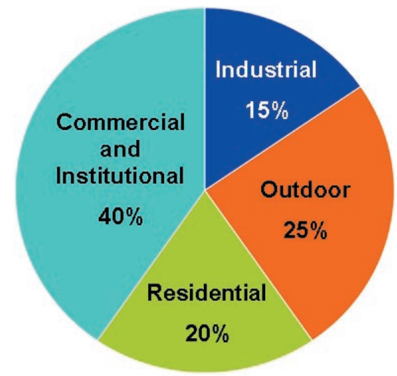

Fig. 1: The global lighting-fixture market is broken down by segment.

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instead ideal for both the C&I and the residential markets – it is in that 60% of the pie that opportunities for OLEDs lie.

OLED Efficacy Requirements

For the purposes of this article, the efficacy required of OLEDs for lighting is derived in two ways. In this section, we consider workplace Illuminance requirements. The illuminance required on a work surface is typically 500 lux in a bright office setting. At the same time, the energy allotted to lighting [lighting power density (LPD)] is approximately 10 W/m^2 as per current building codes.[4,5] These two factors allow us to calculate the minimum luminaire efficacy.

A number of factors determine the intensity of illumination: luminaire-intensity distribution, luminaire optical efficiency, thermal factor (change in source efficiency at operating temperature, thermal factor, and optical efficiency together represent luminaire photometric efficiency), room surface reflectance, and room geometry (expressed as room cavity ratio RCR = 2.5× perimeter of room × workplane-to-luminaire height/area).

Further consideration is given to a set of factors affecting the realistic long-term averaged maintained illuminance of the space. These are referred to as the light-loss factors (LLFs), which include the room surface dirt depreciation factor (RSDD); lamp lumen depreciation factor (LLD); driver factor (DF), where the driver is designed to drive the luminaire to a fraction of its maximum output); and lamp-burnout factor (LBF). The total LLF is the product of all these contributions:

$$LLF = RSDD \times LDD \times LLD \times DF \times LBF.$$

Under the most optimistic assumptions:

- OLED luminaire optical efficiency is 99% (with conventional down-lighting intensity distribution).
- No thermal loss.
- Room size (60 × 64 × 9 ft.): RCR = 1.
- Room surface reflectance: 80%, ceiling; 50%, wall; and 20%, floor.
- Coefficient of utilization: CU = 1.03. It is the combined result of OLED luminaire photometric properties, room geometry, and reflectances.
- OLED lumen retention, 85% (L85).
- RSDD and LDD combined, 90% (very clean).
- LBF = 1.0.
- DF =1.0.
- Average illuminance required: 500 lx (50 fc).

By multiplying all of the above: $1.03 \times 0.85 \times 0.9 \times 1.0 \times 1.0 = 0.79$, or 79%

It follows that for a 500-lux average illuminance, the OLED source needs to generate 500/0.79 or 630 lm for 1 m^2 of the workplane. If the energy allowance is 10 W/m^2, then the OLED efficacy has to be 63 lm/W.

While 63 lm/W may be representative for an initial product requirement, it must be realized that as the energy-efficiency standards continue to tighten and as OLEDs compete with other technologies on the merits of energy savings, the efficacy requirements will become correspondingly more demanding.

Thermal Constraints

The second derivation of an OLED efficacy requirement comes from thermal constraints inherent in large OLED panels. OLED lifetime is a sensitive function of temperature. While the exact figures for current state-of-the-art devices are hard to come by, a 2002 paper based on a fluorescent OLED implied a 31–47% lifetime (to 50% of initial luminance) reduction due to a 10°C rise above room temperature.[6] While heat generation is generally not a factor in lab-scale devices (< 5 mm^2) unless driven at very high current densities, it is of grave concern in large panels even at operating conditions considered routine for lighting (2000–4000 cd/m^2). Since simplicity and form factor are among the greatest appeals of OLEDs, OLED luminaires generally forgo additional heating-sinking elements; thus, the heat generated should be such that natural air convection can maintain an acceptable operating temperature.

In a large-area panel, the temperature at the center is usually the highest in steady state. For free-standing panels dissipating heat by radiation and natural convection, simple expressions for the temperature rise (ΔT) at the center have been derived.[7] Measured and calculated temperature rises at the center of a vertically oriented 15 × 15-cm^2 ITO-coated glass substrate are plotted in Fig. 2 and show good agreement. The ITO/glass panel was resistively heated from two metalized stripes located at opposite edges of the panel, similar to how the panels are to be driven in real life.[8]

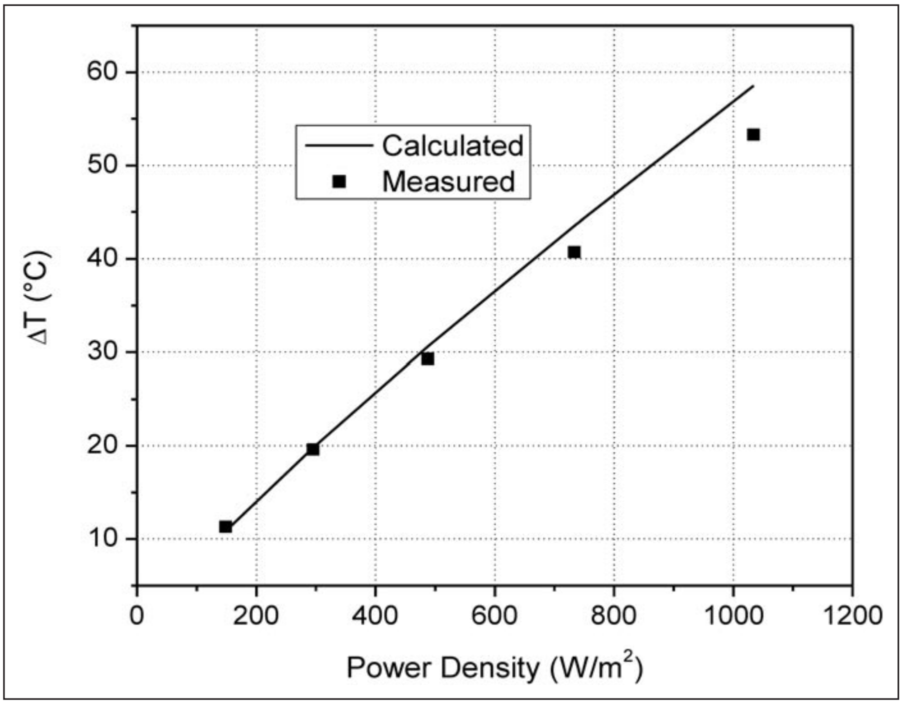

***Fig. 2:** The above graph shows calculated (line) vs. measured (squares) temperature rise at the center of a vertically oriented, 15 × 15-cm^2 ITO/glass panel.*

In general, horizontally oriented panels experience a similar degree of temperature rise.[6]

The amount of heat generation (W/m^2) can be calculated from the wall-plug efficiency (WPE), and the luminous exitance of the panel. WPE, defined as the amount of optical watt out/the amount electrical watt in, is obtained by dividing the luminous efficacy (lm/W) by the luminous efficacy of radiation (LER, lm/W), a quantity solely determined by the emission spectrum. A typical LER of 330 lm/W is assumed in this calculation. Assuming that the OLEDs are operating at 2000 cd/m^2 and a slight deviation from Lambertian distribution, the panel exitance is approximately 6000 lm/m^2, corresponding to 18.2 optical W/m^2. It is then straightforward to calculate the amount of heat generation and look up ΔT from Fig. 2 for OLED efficacy ranging from 20 to 80 lm/W (Table 1).

Table 1: OLED panel efficacy and temperature rise during operation.

Efficacy (lm/W)	WPE (%)	Optical (W/m^2)	Heat (W/m^2)	ΔT (°C)
20	6.1	18.2	282	20
40	12.1	18.2	132	12
60	18.2	18.2	72	<10
80	24.3	18.2	57	<5

Given the sensitive dependence of OLED lifetime on temperature, the temperature rise should not exceed 10°C, preferably staying under 5°C during operation, implying an efficacy requirement of 60–80 lm/W. It should be noted that the preceding calculation is for a free-standing panel. In a real-life scenario, the panel might be in contact with either the housing or some other elements of the luminaire; thus, more stringent thermal constraints may be imposed. At any rate, it is an interesting coincidence that considerations of required illumination and thermal constraints both point to the same minimum efficacy.

OLED Lifetime, Roadmap, and Daylight Harvesting

Lifetime is the other critical performance metric that determines the market acceptance and competitiveness of OLED lighting products. In this section, the lifetime requirements for each anticipated product category are described.

Solid-state lighting, *i.e.*, both OLEDs and LEDs, is expected to gain widespread market acceptance due to superior efficacy, color quality, and innovative designs. The lighting industry will transition from an old-fashioned industrial sector where product cycles are measured in decades to one akin to the nimble semiconductor sector where product cycles are measured in months. Thus, the service life of the luminaire is expected to shorten as the industry devises superior products that compel replacement of existing installations more frequently than ever before. In our estimation, a service life of 10–12 years, corresponding to 45,000–50,000 hours of operating life, is sufficient for this new breed of luminaires.

Table 2 outlines the authors' current roadmap for OLED panel efficacy and lifetime as OLED lighting products mature. Since the cost of OLED panels bears a direct relation to the panel area, we expect the operating luminance to increase from 2000 cd/m^2 in early products to 3000–4000 cd/m^2. Above that upper bound, the panel might appear too intense. In terms of panel lifetime, in early products LT70 (time to decay to 70% of initial luminance) from 2000 cd/m^2 of 15,000–25,000 hours may be acceptable. In commodity-grade products, the lifetime, now defined as LT85, should exceed 45,000 hours from 3000 cd/m^2. The final target lifetime specification is made more stringent in light of what linear fluorescent lamps can achieve: 90 lm/W and LT94 of 36,000–42,000 hours.

Table 2: The OLED efficacy and a lifetime roadmap through 2016 and beyond.

Time	OLED Luminaire Requirements	
2012–2013	Efficacy LT70 @ 2000 cd/m^2	60–80 lm/W 15–25 khours
2014–2015	Efficacy LT70 @ 3000 cd/m^2	80–110 lm/W 30–40 khours
2016+	Efficacy LT85 @ 3000 cd/m^2	110+ lm/W 45+ khours

The device performance targets outlined above are lofty goals that can only be achieved with the best-in-kind material, device architecture, outcoupling enhancement, and last, but not least, low-cost and high-throughput manufacturing technology. One way luminaire manufacturers can assist in this endeavor is by the use of intelligent control systems such as daylight harvesting. Daylight harvesting is simply dimming based on the feedback from a sensor for in-door illuminance levels. An OLED luminaire incorporating daylight harvesting need not be driven at full power when there is partial daylight, saving energy and, more crucially, lengthening the lifetime. OLED lifetime is a strong function of the luminance level, generally expressed as

$$LT \propto 1/L^{\alpha},$$

where LT is the lifetime, L is the luminance, and α is a phenomenological constant normally between 1 and 2. For $\alpha = 1.5$, a 50% reduction in luminance will increase the lifetime by a factor of approximately 3×. Table 3 shows the expected increase in lifetime if a certain portion of the operation is carried out at a reduced luminance level. For example, if

Table 3: OLED lifetime extension due to operation at 50% luminance level (daylight harvesting).

Rated Operating Lifetime (hrs)	% of time at reduced (50%) output	Hours at reduced (50%) output	Hours at 100% output	Effective operating lifetime (hrs)
Assumption: light output at 50% results in 3× the rated lifetime				
20,000	10.0	2,000	18,000	24,000
20,000	20.0	4,000	16,000	28,000
20,000	30.0	6,000	14,000	32,000
20,000	40.0	8,000	12,000	36,000
20,000	50.0	10,000	10,000	40,000

the luminaire operates at 50% luminance 30% of the time, the effective lifetime is increased by as much as 60%. This is not an unrealistic approximation of what daylight harvesting may achieve. Operating at 50% luminance 30% of the time represents an energy savings of 15%, while in real-life deployment of intelligent control systems, an energy savings of 25% has been observed.[3]

Lifetime Reporting Standards

In reporting OLED lifetime, it is important to fully describe the testing conditions, since they have an enormous impact on the results. The lifetime requirements described in Table 2 are all based on an initial luminance of 2000 cd/m^2, lumen maintenance of 70%, and measured from a large-area panel (*e.g.*, 15 × 15 cm^2) under real operational conditions. Too often, lifetimes are reported from an initial luminance of 1000 cd/m^2, lumen maintenance of 50%, and measured from a small-area pixel (*e.g.*, < 5 mm^2) at room temperature.

Some of the more prevalent testing conditions, *e.g.*, initial luminance of 1000 cd/m^2, are conventions originated from the display industry, while others such as 50% lumen maintenance, are legacy items that have no relevance to any products, be it for lighting or displays. The upshot of such unrealistic testing conditions is that many reported lifetimes must be scaled back to estimate the product lifetime. Table 4 lists the testing conditions and approximate impact on measured lifetime. Some of these factors may be overly aggressive but have to be applied in the absence of proper data.

Table 4: Impact of various conditions on measured lifetime.

Measurement Condition	Approximate Impact on Lifetime
LT70 *vs.* LT50	2.5×
L_0 = 1000 cd/m^2 *vs.* 2000 cd/m^2	3×
Room temperature *vs.* ΔT = 10°C	2×
Dot to panel 35% loss of efficiency	1.6×
Total	**24×**

Fig. 3: *Two OLED luminaires unveiled by Acuity Brands Lighting at LightFair International in Las Vegas in May 2010: left, OLED panels by Osram and right, OLED panels by LG Chemical.*

Examples of OLED Luminaires and Conclusion

Recently, Acuity Brands Lighting unveiled two OLED luminaires at LightFair International, the premiere North America trade show for the lighting industry. As can be seen from Fig. 3, the thin form factor and diffusive emission of OLEDs afford luminaire designers a whole new vocabulary of expression. In the end, it is these innovative designs that will drive end-user demand. The OLED panel requirements are tough but achievable using demonstrated device technology and mass-production techniques. We believe whole-heartedly that OLED lighting will have a bright future.

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OLEDs: A Lighting Revolution?

Significant improvement in OLED performance levels has been made over the past decade. OLED technology has the potential to bring about a new era in lighting.

by Ok-Keun Song and HoKyoon Chung

ORGANIC LIGHT-EMITTING DIODES (OLEDs) are among the most promising sources for the next generation of display and solid-state lighting because of their energy-saving and flexible design aspects. OLEDs' inherent characteristics make it possible for both passive- and active-matrix versions to be successfully commercialized for display applications. And the potential of OLEDs goes beyond displays. An OLED is basically a thin-film-based device on glass or plastic substrates. Its ultra-slimness, transparency, flexibility, and color tunability make it a new and potentially revolutionary source for lighting. It is a flat-area light source that provides advantages over LEDs (which are point sources), including heat management and design flexibility. OLEDs' properties are totally different from those of lighting sources such as LEDs, incandescent light bulbs, and fluorescent lamps, and offer a whole new range of lighting applications that would be impossible to imagine with previous lighting sources.

OLED lighting can be used for general-lighting purposes or for premium-grade applications such as architectural, hotel chandeliers, and pendent lighting. The OLED panels shown in Fig. 1 were introduced at the Light & Building 2010 exhibition in Frankfurt.[1] These concepts are excellent examples of the types of lighting designs that are possible only with OLEDs.

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Highly Efficient Materials and Outcoupling Technology

The operational voltage of OLEDs is usually in the range of a few volts, and the internal quantum efficiency is relatively high compared with LEDs,[2] although these features can introduce other concerns due to the relatively high current densities needed for the interconnection wiring. In general, however, these properties should make it possible for OLEDs to become an effective light source with high power efficiency. For state-of-the-art OLED devices using phosphorescent materials, it was recently reported that the internal quantum efficiency of a small-molecule OLED is almost close to the theoretical limit of 100%.[3] Various efforts have been made to improve the performance of OLED lighting, but key technologies in this area can be classified into three major categories: high-efficiency material, low driving voltage, and effective outcoupling technology.

Highly efficient phosphorescent materials have recently enabled several major OLED players to make considerable progress in power efficiency and reliability. Light-extraction technology is also one of the most effective methods to improve the power efficiency of highly emissive phosphorescent materials. A simple OLED structure has a significant amount of its emitted light trapped inside, due to the refractive-index mismatch between the substrate and organic layers. In a conventional bottom-emission OLED, only about 50% of the generated photons will propagate into the substrate and the remainder will be wave-guided and dissipated in the organic layers due to the refractive mismatch between the organic stack (n = 1.7–1.9) and the substrate (n = 1.5). Finally, only 40% of the photons reaching the substrate will be emitted into the air due to the total internal reflection at the substrate/air interface. As a result, only 20% of all photons formed in an emitting layer can escape from the glass substrate into the air.[4] From this point of view, the improvement of the light-extraction efficiency is critical to enhancing the power efficiency, lifetime, and brightness.

Performance Results to Date

As shown in Fig. 2, Universal Display Corp. (UDC) has demonstrated the year-on-year improvement of power efficiency and lifetime of its white OLEDs. These impressive results range from warm to cool white, with varied power efficacies of 54–102 lm/W. According to UDC's reports, depending on the specific device designs employed, the color-rendering index (CRI) varies from 70 to 88 and lifetimes vary from 4,000 to 17,000 hours (to 70% of initial luminance at 1000 nits) using UDC's high-efficiency phosphorescent materials and outcoupling technology. Although reliability still needs to be improved in order to satisfy requirements for practical applications, this achievement is significant because the power efficiency of white OLEDs surpasses the power efficiency of two current major indoor lighting technologies: incandescent bulbs with a power efficiency of 15 lm/W and fluorescent lamps with a power efficiency of 60–90 lm/W. According to UDC's projections, a power efficiency of > 110 lm/W at 1000 nits can be achieved within this year. If so, it means that OLED lighting may also be able to

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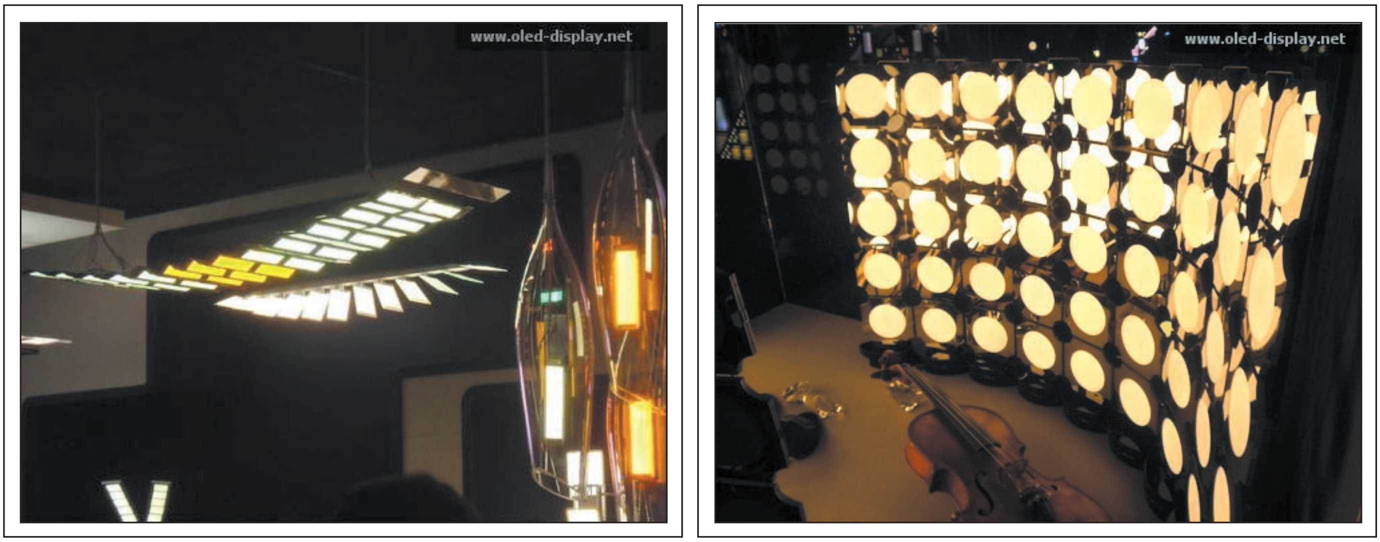

Fig. 1: OLEDs can be used for premium-quality functional lighting applications. Source: www.oled-display.net.

compete with LED lighting in terms of energy efficiency. Initially, it may be hard to achieve the total luminance levels required in the same-sized packages as LEDs based on a total luminance of approximately 1000 nits. However, in the future, as total luminace levels approach 4000 nits, the total package sizes might become comparable.

From an applications perspective, it is noteworthy that the performance of OLEDs exceeds Energy Star Category A, which includes a color specification of CRI ~ 80 and an efficiency specification of > 35 lm/W.[5] The Energy Star lifetime specification of ≤ 25,000 hours should be satisfied soon, considering the improvement speed of OLED performance. Lighting generally requires high brightness and a good Planckian locus, which is the color a blackbody takes in the chromaticity space as the blackbody temperature changes. One of the most popular technologies for achieving higher brightness is a tandem structure with a combination of emitting layers. Figure 3 shows a typical hybrid tandem structure for different color temperatures. This structure generally provides higher brightness and longer lifetime because of the two emitting units, which are connected by intermediate layers (or charge-generation layers). The high brightness of > 10,000 nits and long lifetime of L70 > 50,000 hours at 1000 nits can be achieved by using these hybrid tandem structures at 3000 and 5000 K.[6]

In addition to higher brightness and longer lifetime, another advantage of this structure is that the color temperature of devices can be easily adjusted by simply switching the order of emitting units. These results strongly indicate that a hybrid tandem structure is a key

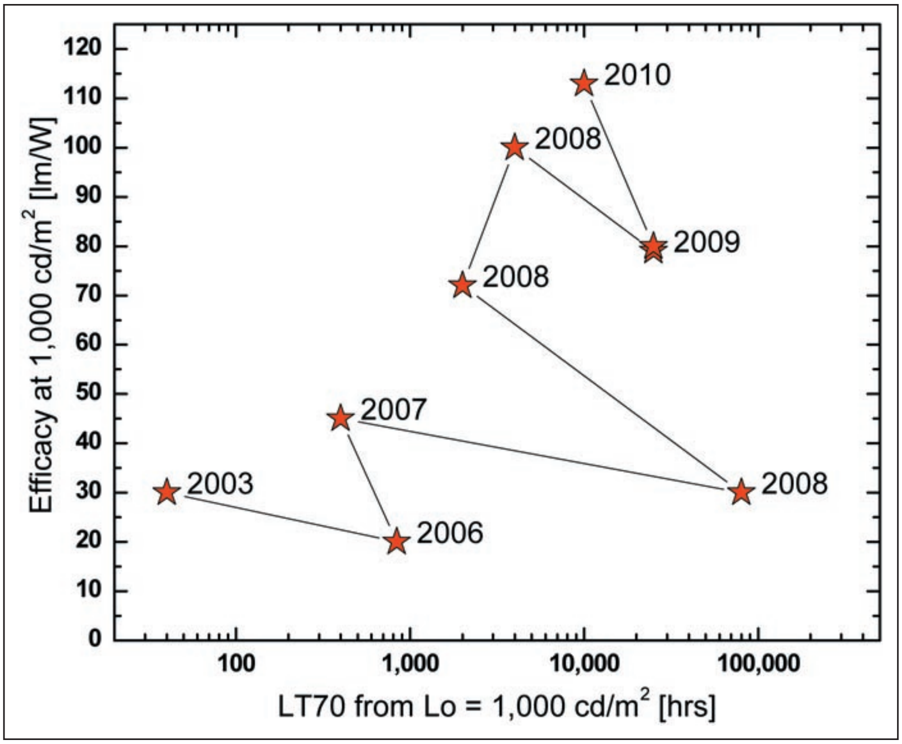

Fig. 2: Recent tests by UDC demonstrate a high efficacy for white OLEDs. Source: Universal Display Corp.

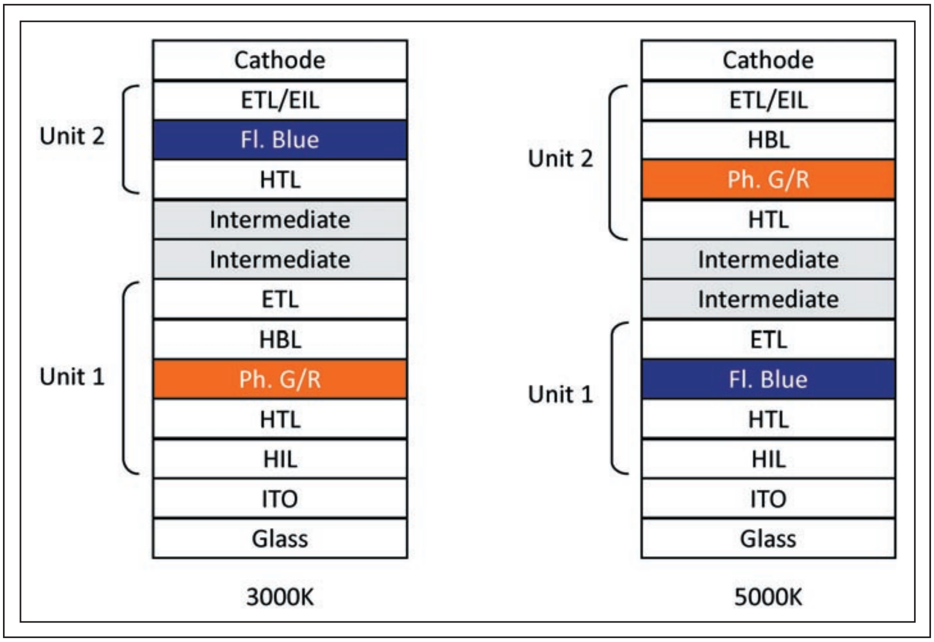

Fig. 3: *A hybrid tandem structure is shown for white OLEDs at 3000 K (left) and 5000 K (right). Source: Samsung Mobile Display.*

approach to the performance enhancement of OLED lighting.

Novaled has recently shown that with a combination of key technologies such as a long-life tandem white OLED, a low-voltage-operated PIN structure, and good outcoupling technology, it could achieve a power efficiency of ~51 lm/W at 1000 nits with a warm-white color coordinate of (0.45, 0.45). While this efficiency appears much lower than others discussed earlier, it can partially be explained by Novaled's choice of color temperature as well as its selection of different emitting materials that may have other advantages not disclosed currently. As shown in Fig. 4, by collecting the total light in a device with a macroscopic lens, the power efficiency could be improved from 28 to 85 lm/W. The high efficiency of 120 lm/W at 1000 nits was achieved in a green monochromatic emission PIN OLED.[7]

The introduction of a microlens-array film between glass and air is one of the most effective solutions in reducing waveguide mode loss due to refractive-index mismatch at the glass/air interface. In 2009, Kodak reported that a light-extraction efficiency of 92% was achieved through a newly developed external-extraction structure. It was also reported that a dramatically improved light-extraction efficiency of 128% can be easily achieved by introducing an internal extraction structure composed of a high-index coupling layer and scattering layer at the glass/ITO interface.[8]

The Asahi Glass R&D group discovered that it could also achieve a light-extraction efficiency of 80% by using a scattering layer whose matrix was made of high-refractive-index glass.[9] Without a doubt, the outstanding results of outcoupling technology will be very helpful in shortening time-to-market for OLED lighting.

Creating Market Opportunities

Among the most important factors for OLED applications are new market opportunities. It will take a while for OLED technology to reach the performance levels needed for many conventional lighting applications, but that should not stop more innovative applications and OLED-based solutions from being created now. Recently, several major OLED lighting companies and designers have created products for a new lighting market.

Osram has shown that it is possible to create a new premium-grade product with a completely new concept of OLED lighting, even though the power efficiency is relatively low (~25 lm/W at 1000 nits). Philips has also demonstrated very attractive, design-oriented OLED lighting with its OLED panel technology, Lumiblade, with a power efficiency of 23 lm/W at 1000 nits. Lumiotec in Japan recently announced small-volume production

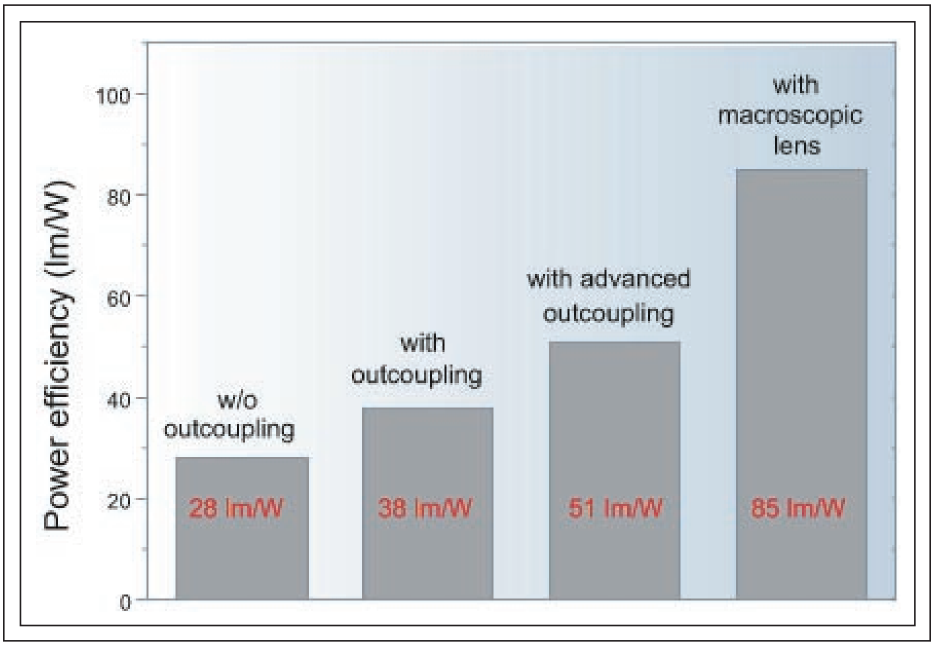

Fig. 4: *The power efficiency of a long-life tandem white OLED was dramatically improved by using outcoupling technology and a macroscopic lens. Source: Novaled.*

of its OLED lighting panels, whose efficiency is about ~23 lm/W.

According to DisplaySearch, the OLED lighting market will start to pick up in 2011, and the major OLED players such as Philips, Osram, GE, Konica Minolta, Ledon, and Comedd will gear up for mass production. The total market, consisting of decorative flexible and rigid general lighting, rigid healthcare lighting, and flexible signage lighting, is expected to be $391 million and $862 million for 2013 and 2014, respectively.[10] By 2018, it will reach $6.3 billion. Over 100 companies and universities are currently working to create new applications for OLED lighting.

The Challenges of Mass Manufacturing Technology

Outstanding progress has been made, as mentioned above, to create a new category of OLED lighting, but many challenges still exist before OLED lighting can be completely commercialized. Improvements need to be made in the fabrication process, in device performance, and in cost reduction.

With respect to performance, it is noteworthy that the performances of products in small volumes have thus far been relatively inferior to those in the laboratory. Laboratory results are usually obtained from very small test cells, which are relatively free from the effect of internal heat generation. OLED panels, which are larger than the test cells, more easily generate internal heat and are very sensitive to the thermal environment, and phosphorescent materials are even more sensitive. Mass production requires relatively high processing temperatures for reasonable yields. For that reason, materials that show excellent performances as test cells often cannot be used for mass production due to thermal decay. This phenomenon indicates that manufacturing technology for mass production is clearly one of the most important challenges. The remaining issues involve cost and are directly related to materials utilization rate, facility investment, and product yields. Finding a collective solution for cost reduction in these areas ultimately will be crucial for the commercial success of OLED lighting.

With regard to fabrication, the thermal evaporation process is well-established and currently the most popular method. A roll-to-roll process for OLED fabrication has been under development at companies such as GE and Konica Minolta for some time in order to lower the manufacturing cost, but there remain many more unsolved technological challenges to take OLEDs into roll-to-roll mass production. The materials development and encapsulation technology will most likely be the most challenging process element to resolve.

A Promising Future for OLED Lighting

In summary, remarkable progress in OLED performance has been made and outstanding new concepts of OLED lighting have been successfully introduced. Although many challenges confront its commercial success, OLED lighting looks promising. The lighting market/applications will need to change somewhat before the technology becomes widespread. The technology needs to improve, and the market needs to adapt in order to exploit OLED's unique features, as well as its limitations. When the technical challenges are overcome, OLEDs' enhanced performance combined with their unique inherent characteristics will be able to inspire a revolution in lighting.

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Phosphorescent OLEDs: Lighting the Way for Energy-Efficient Solid-State Light Sources

Phosphorescent-OLED lighting is an emerging technology that offers power-efficient and high-quality illumination with compelling form factors such as thinness and flexibility. This article focuses on the development of OLED lighting panels, where phosphorescent emitters are used to realize high energy efficiency and long operational lifetime.

by Peter A. Levermore, Michael S. Weaver, Mike Hack, and Julie J. Brown

THE LIGHTING INDUSTRY is currently in transition. The incandescent lamp is still a principal source of illumination, despite its very low efficiency (*e.g.*, 12 lm/W), and consumes a considerable portion of the world's electricity. New sources of energy-efficient lighting are therefore critical to the future reduction of worldwide energy consumption. Both light-emitting diodes (LEDs) and organic LEDs (OLEDs) have the potential to become new solid-state forms of general illumination, replacing current technologies with safe and energy-efficient alternatives. OLEDs offer a thin, lightweight, energy-efficient, and large-area diffuse source of lighting with excellent visual quality. Importantly, OLED lighting panels do not contain materials known to be hazardous. In addition to the environmental benefits, there is an aesthetic design dimension to OLED lighting that is not possible to replicate with fluorescent lamps or LEDs.

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In recent years, the OLED lighting industry has undergone a period of rapid expansion. There have been frequent reports of high-efficacy laboratory test pixels[1,2] and numerous demonstrations of large-area prototypes that explore the unique architectural potential of OLED lighting.[3-7] In this article, we focus on the development of 15 × 15-cm phosphorescent OLED (PHOLED) lighting panels that match efficiency (50 lm/W) with visual impact (total panel thickness of less than 2 mm).[1] By using phosphorescent emitters, we demonstrate that it is possible to deliver energy-efficient illumination while maintaining the unique and attractive form factor of OLED lighting.

The basic principle of OLED operation is that electrons and holes are injected into organic films, where they combine to form excitons, which then generate light. The exciton can have a total spin of S = 0 (singlet state) or S = 1 (triplet state). Approximately 25% of generated excitons are thought to be in the singlet state, while 75% are in the triplet state. In terms of spin conservation and how it applies to photon emission, in fluorescent OLEDs only singlet excitons produce optical emission. Professors Stephen Forrest and Mark Thompson from Princeton University and the University of Southern California, respectively, first reported a major breakthrough in device efficiency based on phosphorescent emitters in OLEDs in 1998.[8] Phosphorescent emitters contain a heavy metal atom that facilitates mixing of singlet and triplet states, allowing singlet-to-triplet energy transfer through intersystem crossing. Mixing of singlet and triplet states enables triplet states to radiate. Therefore, in phosphorescent devices, up to 100% of excitons can potentially produce optical emission, compared to approximately 25% in conventional fluorescent devices. This pioneering work by Forrest and Thompson, followed by the continuing development of phosphorescent OLEDs, is a critical technology that enables OLEDs to become an efficient and viable general illumination source.

Low-Cost Device Architecture

Several OLED device architectures can be used to achieve white emission: (a) multiple emitters in a single emissive region, (b) stacked OLEDs (SOLEDs) with multiple emissive regions, or (c) patterned monochrome OLEDs with an additional low-cost color-mixing layer. Here, we focus on multiple emitters forming a single emissive

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region, which is expected to be the architecture with the lowest manufacturing cost. For example, in an all-phosphorescent device, just six organic layers can be used: a hole-injection layer (HIL); a hole-transport layer (HTL); a red–green phosphorescent emissive layer (RG EML); an adjacent blue phosphorescent emissive layer (B EML); a blocking layer, one function of which can be to block charge migration; and an electron-transport layer (ETL). The inset of Fig. 3 shows a typical white-PHOLED architecture.

To reduce power consumption and extend device lifetime, a highly stable blue phosphorescent emitter is required. Here, we focus on the use of a light-blue emitter with a peak wavelength of 474 nm, 1931 CIE (*x, y*) coordinates of (0.17, 0.37), an external quantum efficiency (EQE) greater than 20%, and a luminous efficiency greater than 45 cd/A at 1000 cd/m^2. This emitter is ideally suited to high-efficacy warm-white emission. For example, alongside phosphorescent red–green, it is straightforward to demonstrate high-efficacy white emission with a color-rendering index (CRI) of greater than 80 and a correlated color temperature (CCT) from 2700 to 4000 K.[9,10]

In addition to higher efficacy and reduced power consumption, the use of a phosphorescent blue emitter also simplifies the manufacturing process. The explanation of this is simple – when fluorescent blue is deposited alongside phosphorescent red–green, there is typically energy loss between adjacent layers. Specifically, the low triplet energy of the fluorescent blue emitter quenches emission from the phosphorescent material. Spacing layers are therefore required in hybrid phosphorescent–fluorescent white OLEDs, which adds to the manufacturing cost. In contrast, in the all-phosphorescent architecture shown in the inset of Fig. 3, spacing layers are not required. Manufacturing costs are therefore expected to be lower for this architecture than for SOLEDs (fewer deposition steps are required).

Phosphorescent OLED Lighting

Figure 1 shows a pair of 15 × 15-cm PHOLED lighting panels designed and fabricated at Universal Display Corporation (UDC) using the simple all-phosphorescent device architecture shown in the inset of Fig. 3.

Panel 1 on the left of the photo is designed taking into considering mainstream commercial lighting applications,[1] while Panel 2 on the right is a design concept, with decorative bus lines defining a lighting flower. A low-cost light-extraction film with a thickness less than 0.5 mm is used in each case to deliver 1.5× efficacy enhancement and realize uniform emission color across all viewing angles. The total thickness of each panel, including substrate, encapsulation glass, and light extraction film is less than 2.0 mm. These phosphorescent panels showcase the attractive thin form factor of OLED lighting and deliver high-quality light with extremely low power consumption.

Fig. 1: This pair of 15 × 15 cm (6 × 6 in.) PHOLED lighting panels was designed and fabricated at UDC. Panel 1, on the left, is designed for mainstream commercial lighting applications. Panel 2, on the right, is a design concept, where decorative bus lines define a lighting flower.

In this article, we focus on Panel 1, the performance of which is summarized in Table 1. The emissive area is divided into equally sized squares, and bus lines are used to transport charge from electrode contacts located at the edge of the panel. The high-conductivity bus lines minimize resistive losses that would otherwise arise from the relatively low conductivity of the transparent conductive oxide (TCO) anode typically used for bottom-emission OLEDs. The panel drive voltage then approximately matches the equivalent pixel voltage, thereby maximizing panel efficacy from a voltage perspective. As a result, resistive heating across the panel is minimized, which means panel temperature remains low, enabling excellent operational lifetime. The bus lines also provide the benefit of improved luminance uniformity, which ensures that any aging occurs uniformly across the panel. Spectrometer measurements confirm a luminance uniformity of 92% across the 15 × 15-cm panel after life-testing to LT70 (70% of the initial luminance).

When characterizing small-area OLED pixels, it is appropriate to quote luminance in units of cd/m^2. However, when scaling up from pixels to large-area OLED lighting panels, it is also important to account for fill factor and total light output. Here, the critical parameter is luminous emittance in units of lm/m^2, which expresses the total light output delivered by per unit area by the panel as perceived by the human eye. For an approximately Lambertian emitter, the conversion is simply luminous emittance (lm/m^2) = π × luminance (cd/m^2) × fill factor. As a general guide, for mainstream commercial lighting applications, a luminous emittance of approximately 9000 lm/m^2 is required.[11] For example, a typical fluorescent ceiling luminaire housing with three linear T8 fluorescent tubes has a fixture area of approximately 1 m^2 and delivers a total output of approximately 9000 lm. An OLED lighting panel with a

Table 1: Shown is the performance of UDC 15 × 15-cm all-phosphorescent OLED lighting Panel 1. Efficacy, voltage, and lifetime are measured at a luminance of 1000 cd/m^2. All data includes 1.5× light-extraction efficacy enhancement.

Panel Metric	Panel 1 Performance
Area	15 × 15 cm
Efficacy	50 lm/W
Luminance	1000 cd/m^2
Luminous Emittance	2200 lm/m^2
Voltage	4.0 V
CRI	84
CCT	3000 K
CIE 1931 *(x, y)*	(0.447, 0.425)
d*uv* (or Δ*uv*)	0.006
Luminance Uniformity after Aging	92%
Color Shift with Angle (Δ*uv* = 0–60°)	0.002
Color Shift with Aging (Δ*uv* at LT70)	0.007
Lifetime (LT70)	10,000 hours

70% fill factor must operate at a luminance of 4000 cd/m^2 to deliver a luminous emittance of 9000 lm/m^2. For OLED lighting to become a competitive general-lighting illumination source, it is essential that high power efficacy and operational lifetime are maintained at this high-luminance level. For other applications, a lower luminance may be used.

Figure 2 shows the efficacy (lm/W) and luminous efficiency (cd/A) of Panel 1 as a function of luminance (including 1.5× light-extraction-efficacy enhancement).

At 1000 cd/m^2 (approximately 2200 lm/m^2), the efficacy of Panel 1 is 50 lm/W, while at 4000 cd/m^2 (approximately 9000 lm/m^2) the efficacy is reduced to 37 lm/W. Over the same range, the luminous efficiency falls from 64 to 59 cd/A. The observed slight drop in efficacy can be attributed to a small rise in drive voltage at higher luminance. The efficacy of Panel 1 is comparable to typical fluorescent luminaires (less than 50 lm/W when ballast and fixture losses are included).[12] This exceptional OLED performance is achieved using all-phosphorescent emitters in a low-voltage architecture. In a later section, we propose a roadmap that describes a path forward from 50 to 150-lm/W white-PHOLED lighting panels.

An important consideration for OLED lighting panels is not only efficacy, but also the color and quality of light delivered. Standard metrics used to describe the color of light are CIE 1931 (*x, y*) coordinates and correlated color temperature (CCT). Figure 3 shows a plot adapted from Energy Star Program Requirements for Solid-State Lighting – Version 1.0.[13]

The Planckian blackbody curve is shown as a line passing through CIE 1931 (*x, y*) chromaticity space. Quadrangles are used to identify CCTs along the curve from 2700 to 7000 K. Each quadrangle defines the chromaticity range that is acceptable by Energy Star standards for a light source at each color temperature. For example, chromaticity coordinates too far above the quadrangles are considered too green, while coordinates too far to the left are considered too blue, *etc.* Quadrangle dimensions are based on seven-step MacAdam ellipses at each color temperature. Panel 1 has a CCT of 3000 K, with a CIE 1931 (*x, y*) coordinates of (0.447, 0.425). In this case, the CIE *y* co-ordinate is fractionally too high, although this could easily be corrected in future device optimization.

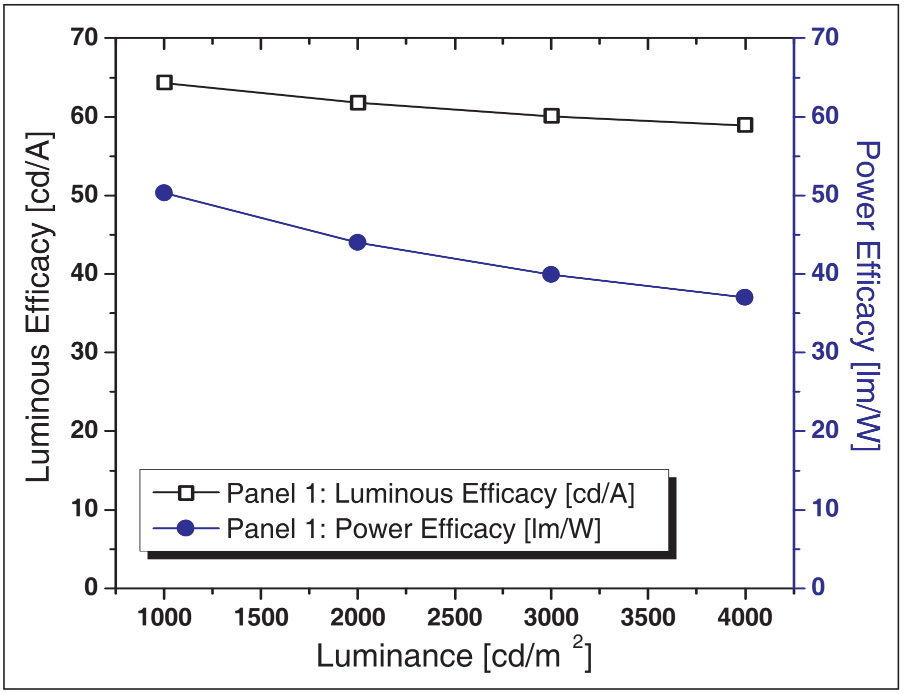

Fig. 2: Power efficacy (filled circles) and luminous efficiency (empty squares) versus luminance for Panel 1 are shown above. At 1000 cd/m^2 (approximately 2200 lm/m^2), Panel 1 has an efficacy of 50 lm/W. At 4000 cd/m^2 (approximately 9000 lm/m^2), Panel 1 has an efficacy of 37 lm/W.

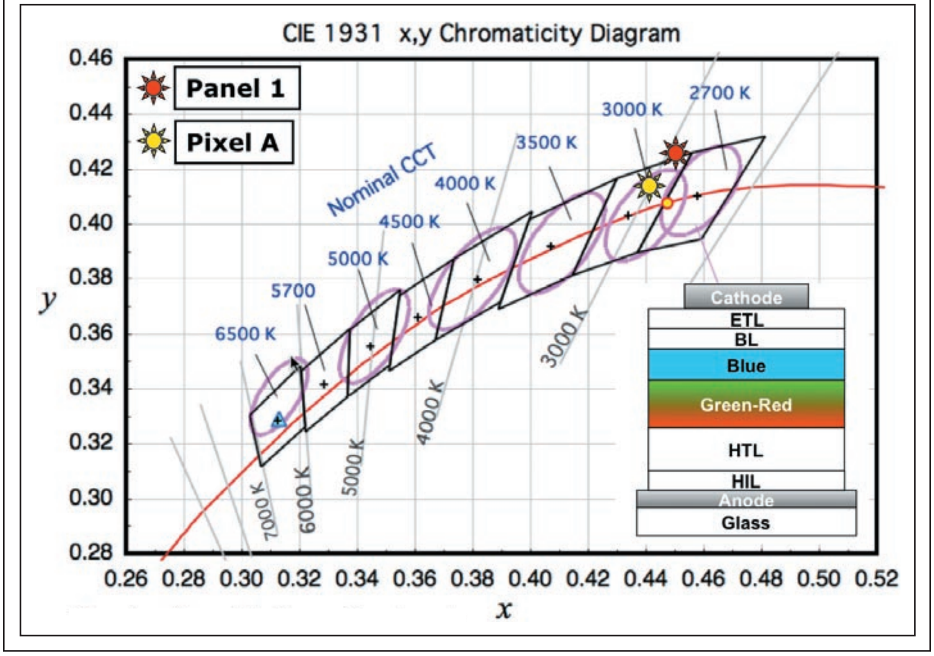

Fig. 3: Chromaticity and color temperature of Panel 1 (red star) and Pixel A (a UDC-made device referenced later on) are plotted against the Planckian curve. Inset shows the simple six-organic-layer device structure.

In CIE 1931 (x, y) color space, the MacAdam ellipse size varies with color temperature, dependent on the photopic response of the human eye. In order to compare differences in color, it is therefore instructive to convert into CIE 1976 (u', v') color space, where coordinate differences are proportional to perceived color differences. The conversion is very simple: $u' = 4x / (-2x + 12y + 3)$ and $v' = 9y / (-2x + 12y + 3)$. A measure known as d$uv$ (or Δuv) = $(\Delta u^2 + \Delta v^2)^{1/2}$ can then be used to quantify how far the chromaticity of a light source lies from the blackbody curve. As a general rule, when designing an OLED lighting panel, one should target a $\Delta uv < 0.005$ with a CCT from 2700 to 7000 K.[13] The chromaticity will then fall within one of the quadrangles shown in Fig. 3.

Of equal importance to the color of a light source is how well other colors are rendered by that light source. Although metrics such as the color-quality scale (CQS) have been developed in recent years,[14] at present the only universally accepted measure of lighting quality is the color-rendering index (CRI). Standard test samples are used, and the CRI is rated on a scale of 0–100 (although negative CRIs are possible), with 100 meaning that all samples illuminated by the light source appear to standard observers to have the same color as when illuminated by a standard reference source. For color temperatures of 2000–5000 K, a blackbody radiator is used as the reference light source, while above 5000 K the reference is an agreed upon form of daylight.[15] Typically, eight standard test samples (R1–R8) of low-to-medium saturation are used to calculate CRI, and this is the number that is quoted in most publications. Additional test samples (R9–R15) can also be included to calculate special CRIs. In particular, for certain light sources, a high R9 value is desirable, as this certifies effective rendering of deep red.

One of the innate advantages of OLED lighting is the broad emission spectra of organic molecules, which enable high-quality rendering of a wide range of colors. Unlike fluorescent lighting and inorganic LED lighting, a high CRI can therefore be achieved by OLED lighting without compromising efficacy. For example, using a phosphorescent light-blue emitter, Panel 1 has a CRI of 84 averaged across all viewing angles. Using a slightly more saturated blue emitter, a CRI > 90 is readily achievable for OLEDs.[16] This quality of light emission is comfortably in excess of Energy Star criteria (CRI > 75) and is thought to be appropriate for mainstream indoor lighting fixtures (CRI > 80). More importantly, for Panel 1, there is also remarkably little variation in chromaticity or color rendering as a function of viewing angle (Δuv from 0 to 60° is 0.002). This exceptional uniformity with viewing angle is achieved using a low-cost and thin-form-factor light-extraction film that also delivers 1.5× efficacy enhancement.

The final consideration in OLED lighting panel design is operational lifetime. Here, it is imperative to design for low temperature to extend the lifetime of the organic materials. One critical element in reducing panel temperature is the use of phosphorescent red, green, and blue emitters, all with very high internal quantum efficiency (IQE). Minimal heat is then generated from non-emissive exciton states, ensuring significantly lower temperature and longer lifetime than an equivalent fluorescent OLED lighting panel. Table 1 shows that the lifetime of Panel 1 is LT70 >> 10,000 hours at 1000 cd/m^2 (approximately 2200 lm/m^2), with LT70 >> 1600 hours expected at 3000 cd/m^2 (approximately 6750 lm/m^2), and LT70 >> 1000 hours expected at 4000 cd/m^2 (approximately 9000 lm/m^2). This lifetime is already sufficient for initial niche lighting products where

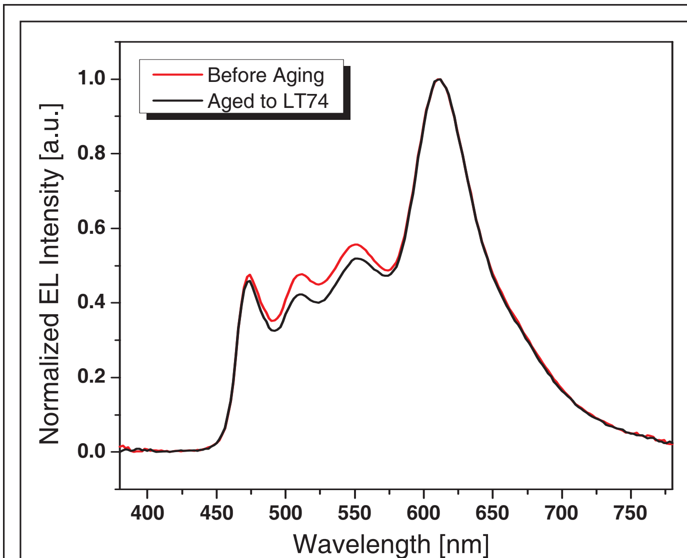

Fig. 4: *Normalized electroluminescence (EL) intensity of Panel 1 is measured initially (red line) and after aging to LT74 (74% of initial luminance). There is minimal color shift with aging.*

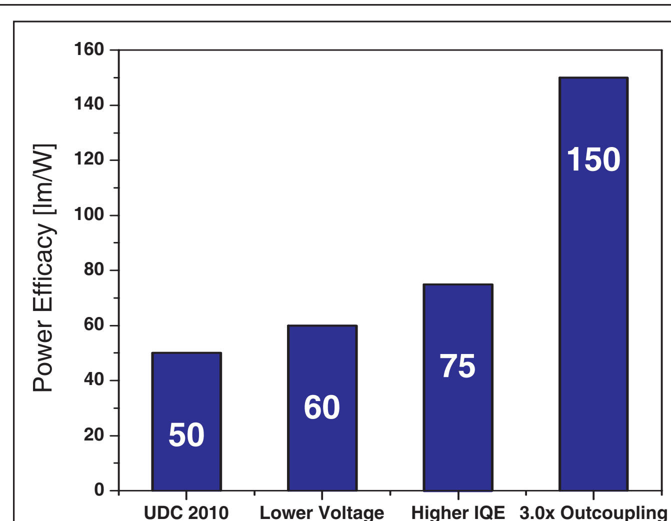

Fig. 5: *A road map from 50 lm/W demonstrated by UDC in 2010 shows an increase to 150-lm/W OLED lighting in the future. Efficacy can be increased by lowering voltage, increasing IQE through improved charge balance, and developing low-cost and thin-form-factor light-extraction techniques.*

lower luminance is required. Importantly, there is also minimal shift in color with aging for Panel 1 with $\Delta uv = 0.007$ after aging to LT74 (74% of initial luminance). Normalized electroluminescence spectra before and after aging are shown in Fig. 4.

This result is extremely encouraging and demonstrates the exceptional stability assured by the simple all-phosphorescent OLED stack.

The Road Ahead

Phosphorescent OLED lighting efficacies are already comparable to fluorescent lighting efficacies, when one takes into account system-level losses, *e.g.*, ballasts and optics. However, further improvements in efficacy and lifetime are essential. Figure 5 shows a roadmap of efficacy improvement from a current UDC 2010 status of 50 lm/W to about 150 lm/W for future OLED lighting panels by about 2020.[11] About 160 lm/W appears to be the potential physical limit for the efficiency of OLED lighting panels.[17]

Key areas where efficacy gains can be made are (a) reduced voltage through the development of lower-voltage EML and transport materials, (b) higher IQE through improved charge balance and the ongoing development of phosphorescent emitters that maintain efficiency at high luminance, and (c) techniques that extract light that would otherwise remain trapped inside the OLED device layers.[17] The most significant efficacy gains are to be made through improved light extraction. For example, if outcoupling enhancement could be doubled from 1.5× (Panel 1) to 3.0×, then the efficacy could also be doubled. At higher efficacy, less heat would be generated and panel lifetime would also be improved.

An example that shows that 3.0× outcoupling enhancement is possible is a 113-lm/W white-PHOLED pixel with a CRI = 80 and CIE 1931 (*x, y*) coordinates of (0.441, 0.414), reported by UDC at SID 2010.[1] This device is plotted as Pixel A in Fig. 3. In this instance, a high-index glass substrate was used to remove the optical barrier at the glass/anode interface, and an index-matching hemisphere macro-extractor was used to ensure all light rays propagate normal to the surface, ensuring maximum light extraction. The challenge for the future is to demonstrate the same order of light-extraction enhancement using outcoupling techniques that are both low cost and do not add thickness to the OLED lighting panel. This idea is shown schematically in Fig. 6, where light-extraction enhancement is plotted against added thickness for various outcoupling systems.

Unique Appeal of OLED Lighting

Phosphorescent-OLED lighting panels can now be engineered to produce power-efficient high-quality white light. However, the same could be said of other, more mature technologies, such as inorganic LED lighting. So what sets OLEDs apart from competing energy-efficient light sources? One straightforward answer lies in the revolutionary thin form factor of OLED lighting. OLEDs by nature produce diffuse light distributed over a large surface area that provides a refreshing and compelling alternative to point-source lighting. Operating at 4000 cd/m^2 (approximately equivalent to 9000 lm/m^2 assuming a fill

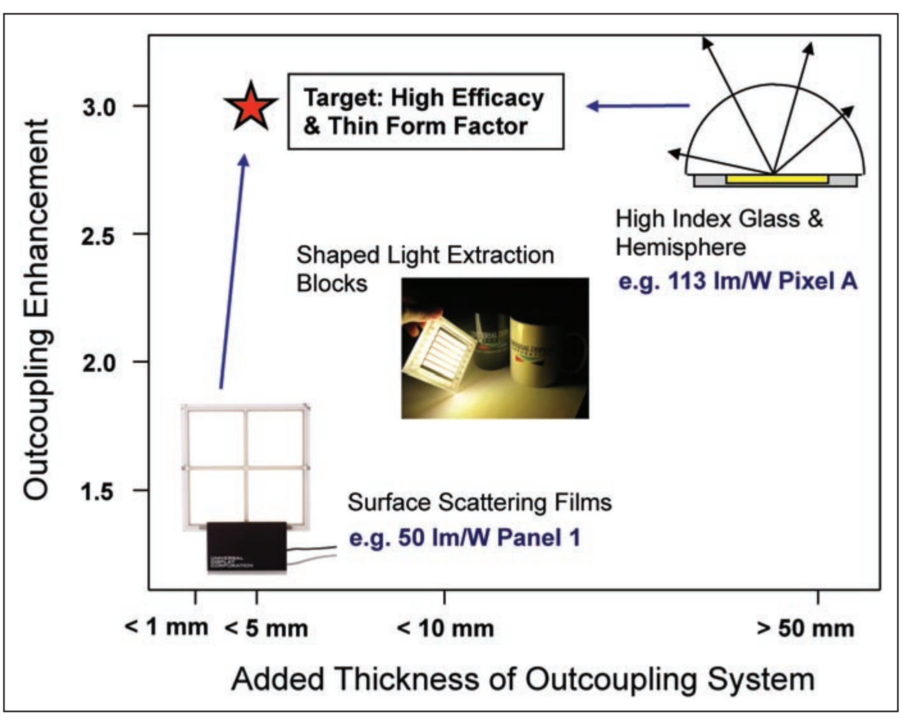

Fig. 6: The figure shows light-extraction enhancement as a function of thickness added. At present, the highest OLED efficacy is achieved using outcoupling techniques that add substantial thickness to the panel. The ultimate aim is to demonstrate a light-extraction enhancement of greater than 3.0× while maintaining an attractive thin form factor.

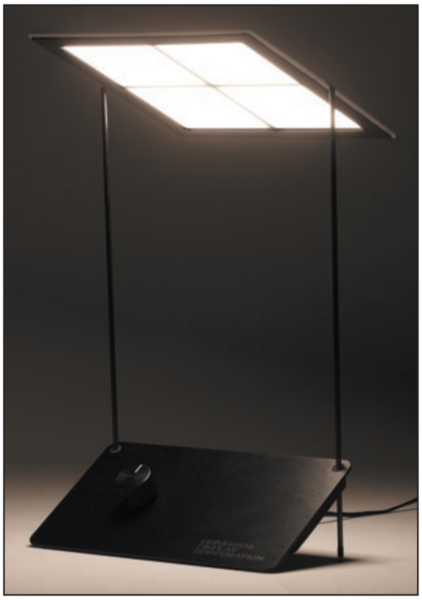

Fig. 7: This white PHOLED desk lamp was designed by Emory Krall, a designer at UDC. The delicate form is achieved using Panel 1, which provides an even and diffuse light source with a thickness less than 2 mm. The head can rotate a full 360° on carbon-fiber supports. The panel is fully dimmable.

factor of 70%), OLED panels can provide uniform, bright, and excellent visual quality illumination with very little glare. They can be viewed directly and admired for their simplicity without the added cost and complexity of baffles or louvers to mask the lighting element. In addition, OLED lighting panels can be transparent. All the organic layers in a PHOLED stack are transparent, so the use of transparent electrodes allows for a light source that is transparent in the off-state and can emit light through both surfaces when energized. By making OLED lighting panels consisting of individually addressable red, green, and blue stripes, it is also possible to make fully color-tunable OLED lighting panels with uniform appearance. Furthermore, these panels can be fully dimmable, offering rich luminance and color dynamics.

The UDC phosphorescent-OLED lighting prototypes in Figs. 7–9[18] showcase OLED panels that are thin, lightweight, transparent, and flexible, opening up exciting new applications and design concepts. Figure 7 shows a thin-form-factor desk lamp using Panel 1 as the illumination source. Figure 8 shows Transparent Light Origami (TLO), where red, green, and blue emission from transparent OLED panels is added to produce secondary colors and white light. Figure 9 shows a 15 × 15-cm lighting panel fabricated on a flexible metal foil substrate.

The exceptional OLED characteristics provide an innovative design platform allowing previously unrealized integration of lighting and architecture.[19] It is this unique marriage of exciting form factors, novel applications, and energy efficiency that ensures a bright future for phosphorescent-OLED lighting.

Fig. 8: Transparent Light Origami (TLO) designed by Emory Krall, UDC, features transparent primary-color PHOLED lighting triangles mounted on adjustable hinges. When panels overlap, secondary colors of light appear. For example, red + green = yellow. White light appears when red, green, and blue panels all overlap along the line of sight.

Fig. 9: A flexible white-PHOLED panel designed and fabricated at UDC uses a 15 × 15-cm metal foil substrate held in a flexed arrangement. A top-emission device architecture is used with a transparent cathode and thin-film encapsulation.

Acknowledgments

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When Can I Get My AMOLED TV?

Prototypes have whetted consumers' appetites for AMOLED TVs. Meanwhile, companies are working to overcome production challenges in order to produce the TVs in volume.

by Barry Young

FLAT-PANEL TVs have taken the TV monitor market by storm, beginning in the early 2000s, and have replaced CRTs as the dominant technology with a 74.4% market share in Q2 '10 (Table 1). Both PDPs, with an 8.0% share, and TFT-LCDs are imperfect solutions, but the consumer has embraced the thin form factor and the larger sizes of flat panels. CRTs were generally limited to < 40 in. on the diagonal, and now flat-panel TVs 55 in. and larger are quite common. However, the anticipated power savings derived from the more-efficient LCDs have been offset by the larger sizes, such that there is a renewed emphasis on reducing power consumption.

The ascendancy of TFT-LCDs over PDPs is due, in large part, to their flexibility in size and resolution. To achieve full HDTV, plasma TVs need to be at least 40 in. on the diagonal, while TFT-LCD TVs achieve full HD at smaller sizes. Thus, TFT-LCD manufacturers can amortize their investment over a wider product range, including monitors and notebooks, while PDP sales struggle below 40 in. even though it is generally agreed that the plasma colors are more vibrant, the blacks blacker, the contrast higher, the response time faster, and the prices lower than those of LCD TVs. However, it is important to note that in order to narrow these performance differences, TFT-LCD TVs have made significant progress:

- Replacement of CCFLs with LED backlights in approximately 30% of LCD TVs, resulting in thinner form factors, higher color gamut, and lower power consumption.
- Edge-lit LED technology that can reduce the thickness of LCD TVs to < 15 mm.
- Rear-lit LED LCDs with local dimming; a 50% improvement in power consumption also comes with a dynamic contrast ratio benefit.
- Color filters and polarizers that are more efficient and less expensive to produce.

Advent of OLEDs

Recently, OLED-display manufacturers have recognized both 2-D and 3-D TVs as a new opportunity. The first OLED TV, 11 in. on

Table 1: Q2' 10 TV shipments and shares are shown by technology (RPTV stands for rear-projection TV). *Source: DisplaySearch*

Technology	Units (m)	Share
LCD TV	41.8	74.4%
PDP TV	4.5	8.0%
OLED TV	0.0	0.0%
CRT TV	9.9	17.6%
RPTV	0.0	0.0%
Total	**56.2**	**100.0%**

Fig. 1: *LG recently introduced a 31-in. 27-mm-thick full-HD AMOLED TV at a trade show in Berlin. Image courtesy LG Display.*

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the diagonal with a 3-mm-thick panel, was introduced in late 2007 by Sony; the second, a 15-in. HD TV that was 2.7 mm thick, was introduced in late 2009 by LG Display. Neither of these TVs demonstrated the scalability or the financial viability of the process. However, they did show that the consumer recognized the performance differential and could visually observe the front-of-screen benefits of OLEDs. The new TVs set off a wave of speculation as to when OLED TVs would be introduced at larger sizes with competitive prices. What these speculators did not take into account was that both TVs had been produced on Gen 3 fabs and at low volumes, so the costs were extraordinary, as reflected in prices of approximately $2500. But OLED manufacturers have continued to perfect their technology, and at the 2010 IFA show in Berlin, LG recently showed a 31-in. 2.7-m-thick full-HD AMOLED TV with the capability to handle both 2-D and 3-D (Fig. 1.)

Concurrent with the release of the three TV demonstration products from Sony and LG, Samsung Mobile Display (SMD) began mass producing millions of AMOLED smartphone displays on a Gen 4 (730 mm × 920 mm) fab. And while doing so, the company solved many of the production-level challenges of AMOLEDs, including:

- Full color patterning using vacuum thermal evaporation (VTE) and fine-metal masks (FMM).
- TFT production using low-temperature polysilicon (LTPS) for smartphone displays with yields greater than 80% with sufficient reliability and uniformity
- Integration of phosphorescent red with fluorescent green and blue.
- Microcavities and top emission
- Pixel densities exceeding 250 ppi
- Power consumption with 40% of the pixels on at comparable levels to that of TFT-LCDs
- Production costs, even absorbing depreciation close to Gen 4 LTPS-LCD fabs.

Recently, Samsung (SMD) announced that it was building a Gen 5.5 fab (1300 × 1500 mm) that would be ready for mass production in 2011, and it is likely that LG Display will follow closely behind. Because Gen 5.5 has the capacity to produce six-up 31-in. panels and LG demonstrated a 31-in. OLED TV, the announcement was taken by many people as a sign that the new fabs would be used for OLED TVs. However, instead, Samsung has reported that it expects to use its capacity for small-to-medium–sized displays to fulfill the extraordinary demand for AMOLED panels used in smartphones.

Therefore, a small volume of 28-, 31-, and 40-in. TV panels can be expected in the near future, but both SMD and LG Display agree that the output of a Gen 5.5 will not be price-competitive with TFT-LCDs built on Gen 6, 7, and 8 fabs. Table 2 compares the number of panels per substrate for each of the fabs. Although Gen 5.5 can fit six-up 31-in. panels, Gen 8 will produce 18 panels and the per panel costs of labor, depreciation, and overhead will be lower for Gen 8 than for Gen 5.5. As shown in Fig. 2, the market for 31-in. and smaller-sized LCD TVs is 70% of the total, but this area is very cost-sensitive and not the best opportunity for higher-end consumers.

Given the plans for Gen 5.5 by SMD and LG, it can be assumed that the manufacturing process will scale beyond 730 mm × 920 mm. In fact, SMD will likely use the same technology for Gen 5.5 as it is using for Gen 4.5 by cleverly partitioning the manufacturing process. For example, by increasing the excimer-laser line beam to longer than 420 mm, two excimer lasers can be used to concurrently convert a-Si into poly-Si on a Gen 5.5. Moreover, a Gen 4 vacuum thermal evaporation (VTE) tool can be used to deposit and pattern the organic material using shadow masks, even if the substrate is held horizontally. One short-term innovation is the use of a linear array where the substrate is held vertically to double material utilization, minimize the fine-metal mask (FFM) sagging, and eventually allow a larger size substrate.

Table 2: Panelization for Gens 3, 4, 5.5, 6, and 8 are compared above. (W stands for wide form factor.) *Source: DisplaySearch*

Generation	Size	W28	W31	W37	W40	W42	W46	W47	W52	W55
Gen 4	730 × 920	2	2	1	1	0	0	0	0	0
Gen 5.5	1300 × 1500	6	6	3	2	2	2	2	2	2
Gen 6	1500 × 1850	10	8	6	4	3	3	3	2	2
Gen 7	1870 × 2200	15	12	8	8	6	6	6	3	3
Gen 8	2200 × 2500	18	18	10	8	8	8	8	6	6

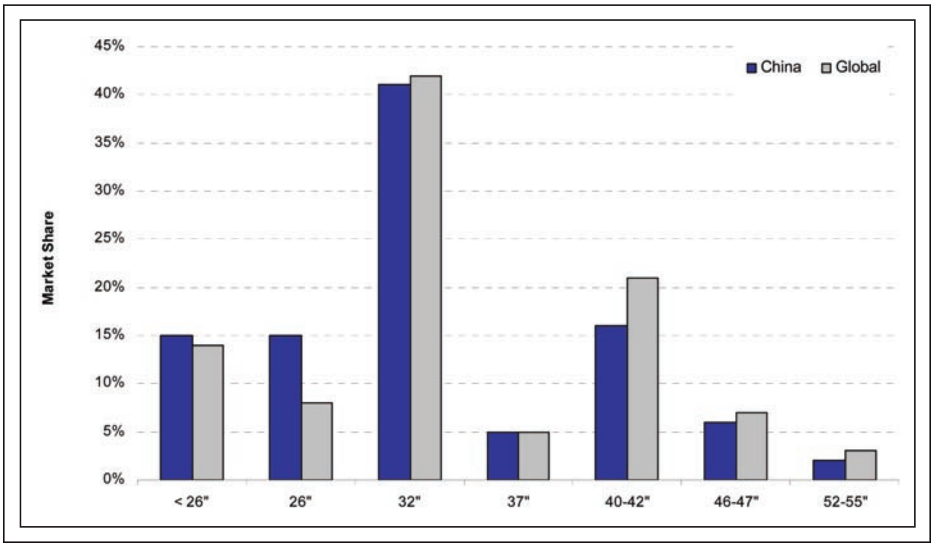


Fig. 2: A distribution of LCD TVs by size for Q2 '10 shows the largest market share by far belongs to the 32-in.-diagonal products. Note: "Global" legend at top excludes China.Source: Wits View.

Technology Challenges

However, these innovations will not solve the cost challenges for AMOLED TVs. Dr. S. S. Kim, CTO of Samsung Mobile Display, claimed at SID's Display Week in May 2010 that AMOLED TVs were "the next big thing," but that it would take a Gen 8 or larger fab to achieve cost parity with LCDs. There are several technology challenges that need to be overcome in order for AMOLEDs TV panels to be built on Gen 8 substrates:

Backplane: Although LTPS has proven to be a mature solution for backplanes up to Gen 5.5, LTPS creates substantial problems to scale to Gen 8:

- LTPS has very slow total average cycle time (TACT), more than double the typical 60 sec for a-Si, and the capital cost for the array process is twice that of a-Si.
- Scaling up the excimer line beam typically increases the non-uniformity, which at a minimum complicates the compensation circuitry.
- The longer the line beam, the greater the potential for dangling bonds and grain-size irregularities, reducing the yield.
- Alternatives to LTPS using excimer lasers include solid-phase crystallization, which converts a-Si to poly-Si using an annealing process. The operating temperature exceeds 600°C, requiring more expensive glass and causes warping and shrinkage in addition to increasing the component costs and lowering the yields. A second alternative is using multiple metal oxides as the active material. These solutions offer mobilities in the 20 cm^2/V-sec range and use the existing a-Si tool sets. However, the technology is immature and does not have the required reliability as yet. Figure 3 compares the three types of backplane solutions.

Frontplane: Vacuum thermal evaporation with a fine-metal mask has been used effectively up to one-half Gen 4 configurations. However, it is believed that this approach has run its course because as the substrate size increases, the weight of the FMM increases and the sag becomes unworkable.

- Alternatives using either polymer or small-molecule material in solution and printing include:
  - *Ink-jet printing:* Epson, Panasonic
  - *Slot printing:* DuPont, Dai Nippon Printing

TFT Backplane technology : LTPS → *High performance & Low Cost Backplane*

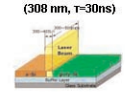
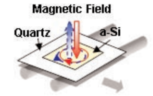
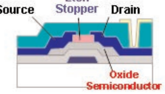
ITEM		LTPS: ELA	LTPS: ASPC	Oxide
Schematic		Excimer Laser (308 nm, τ=30ns) 	Magnetic Field, Quartz, a-Si 	Source, Etch Stopper, Drain, Oxide Semiconductor 
Key	Performance	●	●	△ ~ ○
	Scalability	~G8	~ G8	> G8
	Tech. Maturity	○	○	△
Advantages		▪ Superior Device Performance: Mobility, Stability ▪ Proved Technology in Mfg. line	▪ Superior Uniformity ▪ Good Stability	▪ Scalability over Gen.8 ▪ Good Uniformity
Issues		▪ Laser Scanning Mura	▪ Glass Warpage / Shrinkage ▪ Scalability	▪ Need to improve Device Performance: Mobility, Stability
Current Status		Under Mass Production	Under Mass Production	Under Development

Fig. 3: *TFT-backplane alternatives include excimer-laser annealing (ELA), solid-phase crystalization (SPC), and oxide TFTs.*

	FMM	LITI	WOLED	Printing
Position Accuracy (um)	5	2.5	1.5	5
Glass Size (G)	<6G	>6G	>6G	>6G
Resolution (ppi)	250 ppi ~ 310 ppi	>300 ppi	>300 ppi	<200 ppi
Life Time (hrs)	>60,000 hrs	~20,000 hrs	~5,000 hrs	~5,000 hrs
Efficiency (cd/A)	20 ~ 25	18 ~ 22	12 ~ 15	12 ~ 15
Material	Small Molecule	Small Molecule	Small Molecule Color Filter	Soluble (Small or Polymer)
Investment Expenses	Middle	Mid./High	Mid./High	Low

Fig. 4: *Patterning alternatives for OLED manufacture are compared. Source: Samsung SMD.*

- Patterning can be eliminated using R,G,B,W with a color filter as proposed by Kodak (but is still needed to form the addressable white subpixels under the color filters).
- Patterning using VTE and laser-induced thermal imaging (LITI) as demonstrated by SMD and 3M.

The strengths and weaknesses of the alternatives are shown in Fig. 4.

The existing process of VTE and FMM uses fluorescent and phosphorescent in the native configurations and therefore has the highest lifetimes and efficacies. Each of the other approaches sub-optimizes the material in solution, except in the case of polymers, which are created naturally for solution-based processing. However, the polymers are fluorescent materials and perform less efficiently than phosphorescent materials. In the future, it is likely that if printing or LITI is used, the material will be optimized for that configuration and achieve competitive performance. Figure 4 summarizes the performance and challenges of the alternatives.

Blue Material: The wide band gap in the blue material formulation causes difficulty in

***Fig. 5:** Power consumption with different backgrounds is compared for TFT-LCDs and AMOLEDs. Source: Samsung SMD.*

getting blue organic material with proper CIE x,y coordinates, efficacy (cd/A), and lifetime. To date, the best material has efficacies of 7–9 cd/A and lifetimes of ~20,000 hours at 1000 cd/m^2. What is needed is a blue that has a lifetime > 50,000 hours, an efficacy of ~20 cd/A, and CIE x,y coordinates approaching (0.14, 0.08). Universal Display Corp. (UDC), which has the majority of IP for phosphorescent material (the highest performing organic emitters), offers a unique solution to the problem by proposing a two-blue color approach:

One of the blues is a fully saturated blue, but has low efficacy and low lifetime and would be excited only when a fully saturated blue is required

A second color, sky blue, which has higher efficacy and lifetime, would be excited for all other uses of blue material. The approach would require an added set of subpixel TFTs but would solve the saturated blue problem.

OLED Performance

Much has been written and demonstrated about the front-of-screen benefits of AMOLEDs in terms of

- Black levels
- Viewing angles
- Contrast ratios
- Response time
- Form factor

A discussion of these attributes does not require repetition in this article. However, there are some characteristics that merit some explanation:

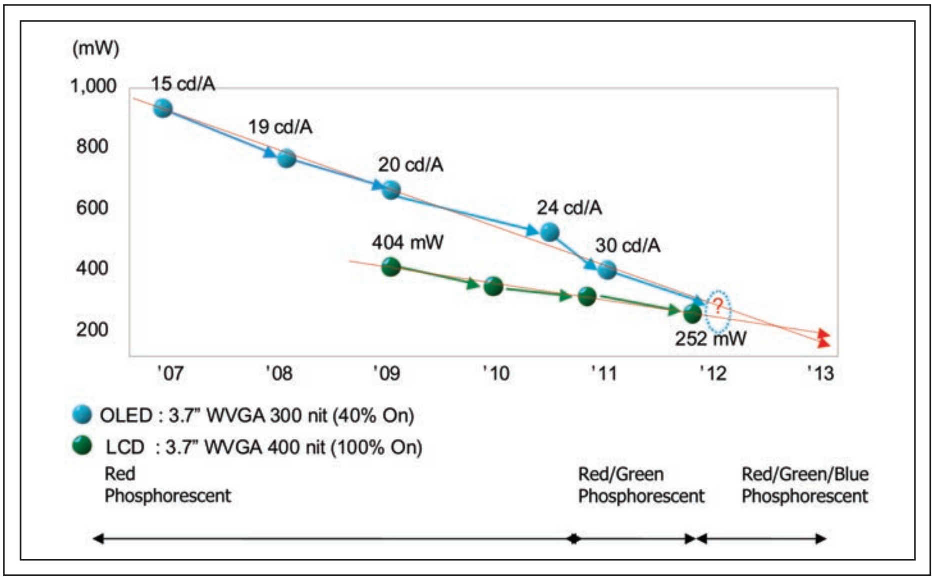


***Fig. 6:** AMOLED vs. TFT-LCD power consumption is compared for a 3.7-in. OLED and LCD. Source: Samsung SMD.*

Power Consumption: OLEDs operate at somewhat of a disadvantage vs. most LCDs of the same size when it comes to displaying large-sized all-white areas, but are much more efficient in video and imaging applications, as shown in Fig. 5.

Due to the high percentage of lower gray scales in video and TV applications, AMOLEDs have a natural advantage in power consumption vs. LED TFT-LCDs. This advantage is reduced by 35–50% when rear-lit backlights with local dimming replace edge-lit LEDs, but the share of the rear-lit LED LCDs is less than 1% due to the high price differential. Figure 6 uses actual power consumption on commercial products comparing a 3.7-in. LCD with a 3.7-in. AMOLED. The expanded use of phosphorescent material is expected to result in lower power consumption even as LCDs take advantage of the 10% per annum growth of lm/W forecasted by LED manufacturers. If one translates the trends in power consumption for 3.7 and 40-in. TVs, AMOLEDs could be expected to use

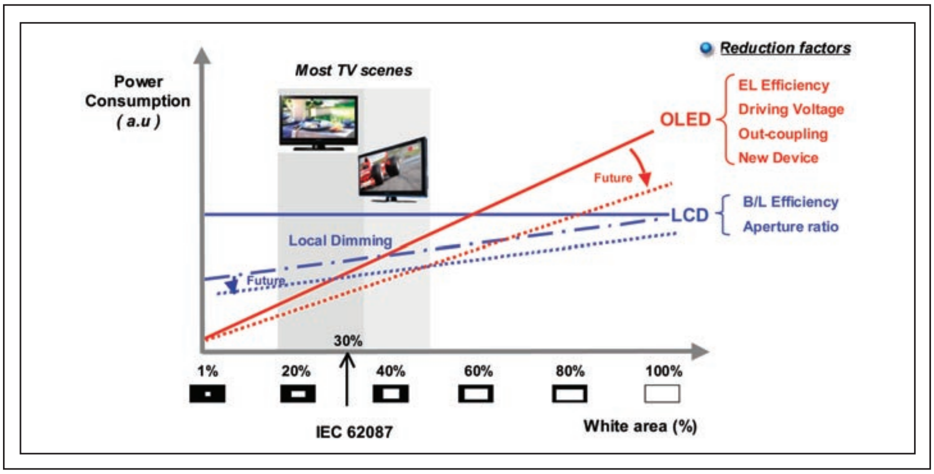


Fig. 7: *Comparison of LCD- and OLED-TV power consumption. Source: LG Display*

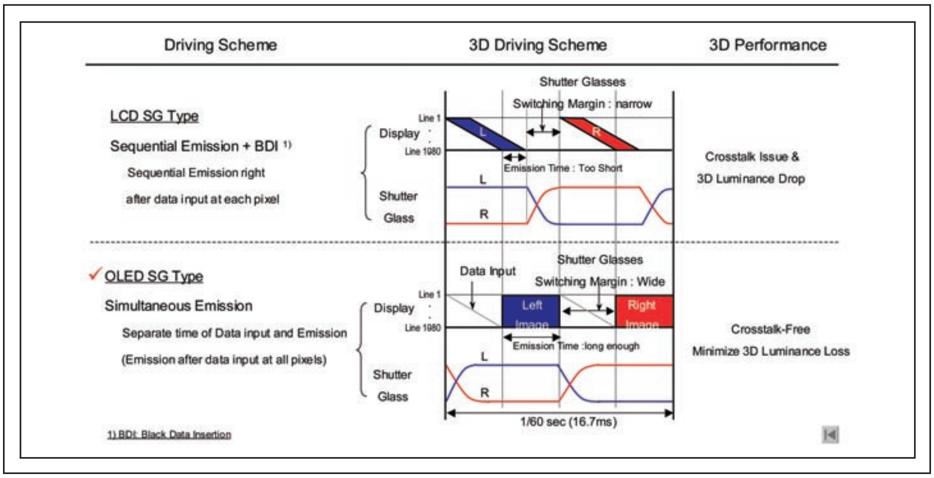


Fig. 8: *A comparison of AMOLED vs. TFT-LCD 3-D performance shows a lack of crosstalk and minimal luminance loss for the OLED type. Source: LG Display.*

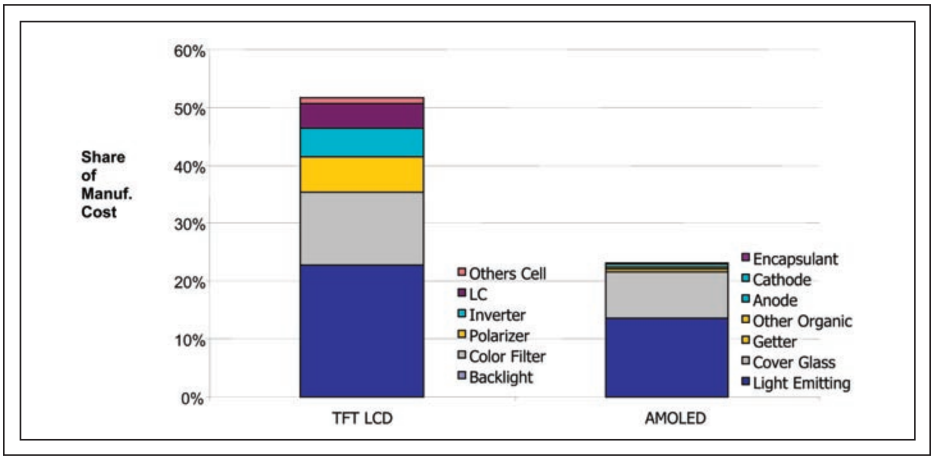


Fig. 9: *This side-by-side cost comparison for a 42-in. LCD and an AMOLED panel is a simulation based on Gen 8 production in 2013. Source: OLED Association.*

20% less power than rear-lit LED LCDs by 2013, assuming a 40% overall luminance level when displaying real video content, and 40% assuming the normal TV luminance level as shown in Fig. 7.

3-D Performance: Yet another benefit of AMOLEDs over TFT-LCDs is the combination of fast response time and 3-D imaging. To realize 3-D, the image is split into two halves: one to address the left eye and the other to address the right eye. The net effect is to halve the time available to resolve the image. Because the LCD operates at a response time of 1–5 msec, it is susceptible to crosstalk, as shown in Fig. 8. However, AMOLEDs, which switch in microseconds, do not suffer from crosstalk and therefore display much sharper 3-D imagery. Plasma TVs also provide a similar benefit, but that response time is not as fast as that for OLEDs.

Short- and Long-Term Degradations: OLED designers must overcome the undesirable phenomena associated with all self-emitting displays – image sticking and differential aging. To prevent image sticking, which could occur on TVs where there are ticker-tape-type images on news and sports programs, the ITO must be pre-treated using plasma to improve the charge stability and reduce the charge redistribution. Differential aging occurs over time when some subpixels are used more frequently than others, and consequently age faster. This issue is overcome by maintaining charge stability and extending the lifetime. Currently, red and green have lifetimes (T50) of greater than 200,000 hours at 1000 cd/m^2. Blue has a lifetime of ~18,000 hours at 1000 cd/m^2, which translates to 70,000 hours at 500 cd/m^2, a typical TV luminance specification. The OLED TVs can meet the lifetime requirements, but a more conservative performance level would be 500,000 to T50.

Costs: AMOLED TVs must reach parity with TFT-LCDs in price if they are to attract consumers beyond the early adopter class. LG projects AMOLED TVs to be 3× the cost of TFT-LCDs in 2013, 1.5× the cost in 2015, and 1× the cost in 2017. The cost-down tasks will be to improve the yields from 70% of that of LCDs in 2010 to 100% in 2017, reduce the component costs from 150% of that of TFT-LCDs to 60% by 2017, scale the process from Gen 4 to Gen 8, and reduce the capital costs from 5× that of LCDs to 150% of that of a same-sized LCD fab. Figure 9 is derived

Fig. 10: This conceptual image of a rollable AMOLED display could be the TV of the future. Source: Samsung SMD

from a simulation of AMOLED and LCD 42-in. panel costs on a Gen 8 fab in 2013 and demonstrates that OLED unique-component costs represent only 22% of the total manufacturing costs, while LCD unique-component costs represent over 50% of the total. If AMOLED's other production costs, such as depreciation, labor, overhead, and utilities, are comparable, OLED-TV panels do have an opportunity to be less costly than TFT-LCDs.

In summary, large-area AMOLED TVs may begin to appear as early as mid-2011, but they will be priced at levels that only early adopters can afford. It will not be until the major OLED manufacturers solve the scaling and material issues that AMOLED TVs will be produced for the mass market, which is not likely to occur until 2015. However, if these manufacturers make the right choices in active-matrix backplane technology and in the deposition and patterning of organic material, OLEDs can reach parity in costs with LCDs and the consumer's choice can be driven by performance rather than price.

Flexible OLEDs

Meanwhile, OLED R&D teams are moving forward. Dr. H. K. Chung, advisor to SMD and recipient of the First Annual OLED Leadership award, stated at the OLED Summit in San Francisco in September 2010, that "the next, next big thing is the flexible and transparent OLED, which will result in rollable OLED TVs, the thickness of wall paper." Such a display, as shown in Fig. 10, could be worth the wait. ■

How to Patent Inventions on a Tight Corporate Budget

Companies should think twice before deciding not to file a patent due to cost concerns. There are many ways to control and reduce the costs of patent procurement.

by Clark A. Jablon

MOST corporate legal departments are now being asked to do "more with less." This is a reverse of previous trends, in which corporate legal budgets grew far faster than inflation and far faster than the percentage increase in company revenue. For companies that are active in building a patent portfolio, patent prosecution costs must be kept under control, especially considering that the lifetime external costs of preparing, obtaining, and maintaining a typical U.S. patent in the electrical/computer arts is about $24,000–36,000 today. Controlling costs is much easier said than done, however, due to certain developments that are thwarting these efforts, including lower patent application allowance rates (the percentage of applications that result in an issued patent) and the increased number of Office Actions that are issued per patent application, thereby requiring more responses (and greater expense) to be made per application. Nonetheless, much can be done to control the costs of the patent process, while not compromising the quality of the resultant patent portfolio. Some of these processes are discussed below.

1. Consider a provisional application. For inventions that are still in the R&D phase or in very early commercialization, consider filing a provisional patent application as the initial application to delay the cost of preparing a full (non-provisional) application by about 1 year. A provisional application requires a written description of the invention, with drawings as applicable, but does not require preparation of claims or an Information Disclosure Statement. Preparing claims and conducting even a limited review of the prior art may constitute as much as half of the cost of a non-provisional patent application. The government filing fee for a provisional application is very small, currently $220 for a large entity and $110 for a small entity, compared to respective fees of $1180 and $590 for a non-provisional application. If there are marketing advantages to doing so, an invention can be referred to as "patent pending" once a provisional application has been submitted, in the same way as after a non-provisional application has been filed. (The "patent pending" designation must be removed if the pendency is terminated.) The USPTO provides a discussion of provisional applications at: http://www.uspto.gov/web/offices/pac/provapp.htm.

One advantage of filing the first application as provisional is that if, or when, the application is converted to a non-provisional version, the disclosure can be revised and additional embodiments added. Such an addition of "new matter" is not permitted during prosecution of a non-provisional application. A new, separate non-provisional application would need to be filed to revise or add embodiments if the first application is non-provisional, which is a far costlier approach to protecting closely related inventions.

Another advantage of filing the first application as a provisional application is that it buys additional time to determine if any non-provisional application filing should occur at all for the invention, especially for inventions that will not be foreign filed. An invention that originally looks promising can sometimes be determined to be less worthwhile a year or so later, and thus the expense of filing a non-provisional application can be completely avoided. The filing of a provisional application satisfies the statutory bar deadline requirements in the U.S. that a patent application be filed within 1 year of the invention being described in a printed publication available anywhere in the world or placed in public use or put on sale in the U.S. Thus, the provisional application allows a company to buy almost 2 years of time before having to commit to the full expense of the non-provisional application because the provisional application can be filed shortly before the 1-year deadline, and then an additional year can pass until the conversion deadline.

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2. Use timing to your advantage. Take advantage of the USPTO's current backlog of 2–5 years for receiving a first action in the examination process. No significant costs are typically incurred after the filing of a non-provisional application and before the USPTO issues a first Office Action. Prosecution costs, issuance costs, and maintenance fee costs are thus all deferred until the examination process commences. The USPTO has various procedures for accelerating examinations, but the default and least-expensive option is to go through the normal process and wait until the application comes up in turn. The USPTO has even recently proposed a three-track examination process that would allow applicants to request prioritized examination for payment of an additional fee (Track I); traditional examination under the current procedures; (Track II), and an applicant-controlled delay for up to 30 months (Track III). If this process is implemented, companies can selectively choose delayed examination for inventions that have no compelling reason to be examined quickly. No additional fees are being proposed for Tracks II and III.

3. Find an expert patent practitioner with experience in your technology area. Try to work with a very experienced patent practitioner who still practices patent prosecution for the bulk of his or her practice and who practices in the same general area of technology as the invention (*e.g.*, electrical, mechanical, chemical, software, biotech). Such a practitioner is much more likely to either efficiently write the application himself or herself or supervise a junior practitioner who will write the application.

However, finding such a practitioner can be more easily said than done. The explosion of patent litigation has significantly thinned the ranks of such practitioners in the past 10 years because the litigation work tends to be more lucrative and more highly rewarded by law firms. On the flip side, working on patent litigation is invaluable for patent prosecutors to learn how to write better patents, so litigation experience should not be discounted. In seeking out a patent practitioner, companies should not confine themselves to the local marketplace, which may severely limit the pool of quality practitioners, especially if the company is not located in a large metropolitan area.

4. Write the claims in person, with all parties present. Try to get the patent practitioner and the inventors to write the claims together in an in-person claim-drafting brainstorming session. This process should improve the efficiency of the preparation process and should result in a higher-quality application that more accurately captures the novel and unobvious features. Such an application is less likely to require expensive amending during prosecution. While additional travel costs might be incurred by this step if the patent practitioner is not local, the benefits should easily outweigh the costs. Also, these types of sessions sometimes lead to a conclusion that preparing a patent application with claims that are likely to be patentable may be too difficult or premature, thereby resulting in a cost-saving cancellation or deferral of the project.

5. Consider having a patentability search conducted prior to preparing the patent application. If very close prior art is discovered, the company might decide not to file at all, thereby saving a large sum of money on that particular invention. If there still appears to be potentially patentable subject matter, the claims can be more precisely tailored upfront, thereby making it less likely that they will require expensive amending during prosecution. In this manner, most or all of the costs of the patentability search are often recouped.

Avoid Cutting Corners

One approach that has been taken in the past few years by some companies is to simply demand that the patent practitioners who are writing the patent applications (whether in-house or outsourced to a law firm) do the work more cheaply, either by accepting lower fixed-fee payments, or by increasing in-house productivity. Many companies are now discovering that this approach has resulted in lower-quality work since some patent practitioners have merely reduced the efforts that they spend in preparing the application to match the reduced fees received and/or time allotted. Since a well-crafted patent application can be vastly more valuable in protecting an invention than a bare-bones application, other approaches should be investigated before turning to this one.

While patents cost more than ever to obtain on an inflation-adjusted basis, the cost of not procuring or obtaining patents may be even greater, and thus procurement costs must be weighed against other business concerns. For example, a technology startup that has no patent portfolio may face a difficult time if it wishes to seek a second round of financing or sell itself for a premium price. A company with a successful new product or service may find that competitors can easily knock it off without violating any other forms of intellectual property. A company that is sued by a competitor for patent infringement may find that one or more patents in the portfolio can be used for a countersuit or for settlement negotiations. The average cost of defending a patent litigation is well over $1 million today, which is magnitudes greater than the cost of building a substantial patent portfolio that may function much like an insurance policy.

In sum, there are many ways to control and reduce costs of patent procurement that should be investigated before a decision is made not to file at all due to cost concerns. Furthermore, even if costs cannot be reduced without sacrificing quality, there still may be strategic reasons to continue to build a patent portfolio. ■

editorial

continued from page 2

our work lives and be able to improve our recreation and home lives as well. Governments will help by imposing regulations already under way in some parts of the world that address minimum standards on energy efficiency and ergonomics. These regulations will benefit LEDs as well as OLEDs, but I think the ability to shift from point sources to illuminating surfaces will be the key to OLEDs' success. As real opportunities for living-space improvements become viable, the advantage – even at a cost premium – will be compelling enough to drive the technology into homes and businesses. And, given *Star Trek*'s record for predicting the technological future, I'm fairly sure we will not need to wait 200 years to enjoy our new home and work environments.

As you will discover in this issue of *Information Display*, which focuses on OLED technology, OLED lighting has many practical challenges to be resolved. These include scalable manufacturing, energy-efficient materials, and suitable economic models, but the future is overwhelmingly bright and that pun is intended with light-hearted enthusiasm.

If you want to gain a better understanding of the general illumination marketplace and the practical technical requirements for the development of OLED-based lamps and light sources, read our first Frontline Technology feature, "OLED Requirements for Solid-State Lighting," by Min-Hao Michael Lu and Peter Ngai from Acuity Brands Lighting, Inc., Within this very comprehensive and detailed discussion of the specifics of luminaire design, I learned a whole new vocabulary, along with a better appreciation of the complexity of factors that must converge for a near-perfect ambient light source design. Naturally, the authors are fairly bullish on the future for OLED lighting, but their enthusiasm is well supported by their objective and carefully considered analysis of the design space made available by OLED technology.

Even more insight into the potential of OLED lighting is provided by our second Frontline Technology feature from the Samsung Mobile Display R&D Center, "OLEDs: A Lighting Revolution?," by Ok-Keun Song and HoKyoon Chung. Here, the authors discuss some of the challenges of getting sufficient total light output as well as some of the newest structures to obtain better white points and luminous efficiency. Supporting this discussion with an even more comprehensive survey of the state of the art for phosphorescent OLED technology is our third feature, "Phosphorescent OLEDs: Lighting the Way for Energy-Efficient Solid-State Light Sources." In this article, authors Peter A. Levermore, Michael S. Weaver, Mike Hack, and Julie J. Brown from Universal Display Corp. (UDC) provide the most comprehensive look at the company's trademark PHOLED technology. As the inventors of PHOLED, the team at UDC is uniquely positioned to be able to see far into the future, and after reading its assessment of the many opportunities the technology provides, I have a strong feeling that UDC is on the right path for commercial adoption.

Of course, by this point you are probably wondering what has happened to OLED TVs. Do we even care anymore and why all the emphasis on OLEDs for lighting applications? To be honest, I was surprised, as I have noted earlier this year, that OLED TVs were not more prominent at Display Week and are not in retail box stores by now. Clearly, the people with significant investment in OLED technology are looking for all the possible avenues to commercial adoption. The fact that the same technology can also enable a new generation of solid-state lighting products is a great opportunity for them but I do not think it has diminished anyone's zeal for commercial television applications. However, as I think is often the case, the promise, the hype, and the marketing can get a little ahead of the real effort needed to make new display products completely successful in high-volume-manufacturing terms. To help us understand this better, author Barry Young, Managing Director of the OLED Association, has provided his very detailed assessment in this month's Display Marketplace feature, "When Can I Get My OLED TV?" I will not steal Barry's thunder by giving away the ending, but I will note that the real timeline for OLED TVs is probably a bit longer than we have been hearing and any investment in the underlying technology for lighting applications can only help with manufacturing technology, yields, and related concerns.

Finally, this month I am very pleased to welcome back long-time contributor and greatly respected IP attorney Clark Jablon, who offers his timely thoughts on "How to Patent Inventions on a Tight Corporate Budget." I don't think it has ever been a more daunting process to protect one's IP, and with the economic conditions we are all facing, the decision to move forward with the patent process is no small matter. I really think for those of us concerned about our IP strategies and the strategic planning of our R&D roadmaps, this article is a must-read to help sort out the best policy to implement within our own businesses. Once again I really appreciate Clark's valuable contributions to our collective education with regard to this issue.

There is one other item I want to note this month. Each year SID recognizes the best display products released to the marketplace during the previous 12 months and confers the Display of the Year Awards on them in recognition. As a member of this DYA selection committee, I can tell you firsthand that a great deal of debate, analysis, and personal energy goes into making the final recommendations. We review countless nominations and always many more worthy candidates than we can recognize. But until now, we have focused only on commercially available products, excluding really clever technology and product demonstrations that promise a bright future. Often, by the time these innovations become commercial products, most of us have moved our attention on to the next unsolved challenges. All this is about to change because beginning in 2011, SID will also recognize the best and brightest exhibits at the annual Display Week Exhibition. The brand new Best in Show awards will be presented at the Wednesday Luncheon after our team of roving reviewers has had enough time to survey the show floor on Tuesday. So, if you were still on the fence about exhibiting next year or looking for a new venue for your technology demonstrations, this is a perfect opportunity for you to come to Display Week and hopefully get the recognition you deserve. You can read more about this new program in our SID news section in this issue. ■

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guest editorial

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tandem device architectures for extended lifetime, PIN doping for further reductions in device voltage, and the importance of cost-effective light extraction. They point out that today, given that phosphorescent OLEDs enable nearly 100% internal quantum efficiency, effective outcoupling is perhaps the largest efficiency loss and therefore the largest area for efficacy improvement. They believe that OLED lighting has a considerably wide market window, from premium-grade decorative lighting to general lighting, and several key factors such as frequency of use, operational cost over time, visual comfort, and specific design parameters need to be considered. Finding a collective solution among these parameters to reduce the cost will be ultimately crucial for the commercial success of OLED lighting. Finally, the authors consider the challenges for the mass production of OLED lighting panels.

Acuity Brands Lighting introduces its article from the company's perspective as a major supplier to the approximately US$50 billion annual global lighting-fixture market. The authors see great potential for OLED lighting because the diffuse nature of OLED lamps is ideal for both commercial and residential markets – which together represent a 60% share of the lighting market. They outline their current roadmap for OLED panel efficacy and lifetime as OLED lighting products mature. Acuity Brands Lighting is currently leading the charge in demonstrating OLED fixtures, and the authors show photographs of two revolutionary OLED luminaires that Acuity exhibited at LightFair earlier this year.

Given the momentum that is now developing, OLED lighting seems to be at the tipping point. If the technical performance and cost targets can be realized in the next few years, OLED lighting will have a significant impact on reducing our energy consumption and provide an elegant and appealing solution to many of our lighting needs. The revolutionary form factors enabled by thin, flexible, and transparent OLEDs will really transform the way we use and see light. ■

Mike Hack *is Vice-President of Universal Display Corporation and their General Manager of OLED Lighting & Custom Displays. He can be reached at mikehack@universaldisplay.com.*

SOCIETY FOR INFORMATION DISPLAY NEWS

SID to Introduce New "Best in Show" Awards at Display Week 2011

In 2011, the Society for Information Display will be initiating an exciting new industry honor, the Best in Show awards, highlighting the most significant new products and technologies shown on the exhibit floor during Display Week. "The exhibition at SID's Display Week has often been the initial showcase for some of the most important new product developments and technological innovations of the display industry," says Bob Melcher, Chairman of the SID Display of the Year Awards Committee. "An unbiased panel will select one exhibitor in each of three separate categories, recognizing the most significant products and developments being shown."

An independent panel of display experts will review those products nominated for the awards on the show floor, and the winners will be selected for their ability to excite not only display experts, but the general public and press as well. SID will promote local, national, and international press coverage for the prize-winners. Best in Show Blue Ribbons will be presented to the winners at the SID Awards Luncheon on Wednesday during Display Week.

This competition will be open to all exhibitors on the show floor during Display Week 2011. Prizes will be awarded in the three categories of small, medium, and large organizations. This will allow exhibitors of all sizes to compete for the prizes. Self-nominations are encouraged! Nomination forms and details of the awards criteria can be found at www.sid.org/awards/awards.html.

– Jenny Donelan ■

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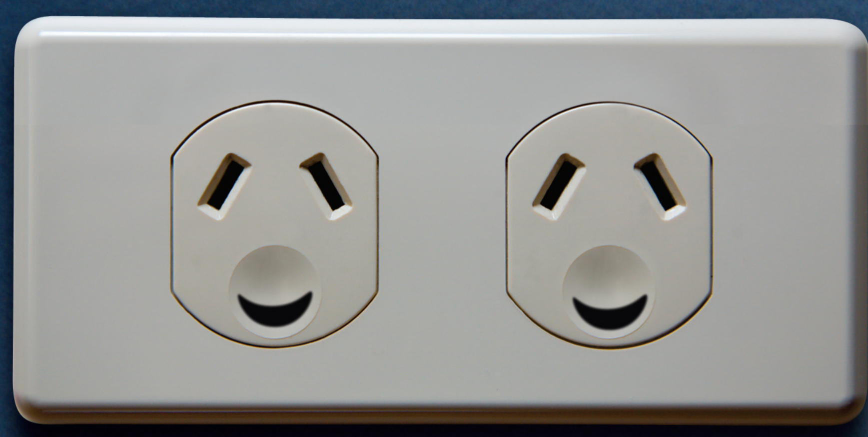

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3. What is the organization's primary end product or service? (check one)

310 ☐ Cathode-ray Tubes
311 ☐ Electroluminescent Displays
312 ☐ Field-emission Displays
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314 ☐ Plasma Display Panels
315 ☐ Displays (Other)
316 ☐ Display Components, Hardware, Subassemblies
317 ☐ Display Manufacturing Equipment, Materials, Services
318 ☐ Printing/Reproduction/ Facsimile Equipment
319 ☐ Color Services/Systems
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