2015 OLED Stakeholder Meeting Report

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DISCLAIMER

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COMMENTS

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1. Introduction

The 2015 Organic Light Emitting Diode (OLED) Stakeholder Meeting was convened by the U.S. Department of Energy (DOE) Solid-State Lighting (SSL) Program, hosted by Kurt J. Lesker Company and open to members of the U.S. OLED lighting community with the purpose of creating an opportunity for open discussion concerning the development of OLED lighting.

In total, 49 "stakeholders" from academia, national laboratories, and industry participated in the two-day meeting, representing varying interests in OLED basic science, applied research and development (R&D), product development, and manufacturing R&D. This report is a summary of the input provided at this meeting and the subsequent discussions.

Process and Objectives

The meeting addressed two distinct objectives:

Identifying Critical R&D Needs: Participants were invited to give 10 minute "Soapbox" presentations describing their thoughts on critical R&D areas for OLEDs. John Hamer of OLEDWorks and Stéphane Altazin of Fluxim kicked off the meeting and led us into these soapbox presentations with presentations on "How OLEDs Can Succeed" (Hamer, Day One) and electrical and optical modeling of OLEDs (Altazin, Day Two). Fifteen participants presented over the course of the two-day meeting, providing a wealth of information to the community on the state of the art and outstanding R&D needs. Soapbox presentations were organized by topic and presentations on each topic were followed by discussion amongst the participants. The final session of the meeting was an open discussion of OLED research and industry needs that had not been addressed during the meeting or that warranted further discussion. The presentations and resulting discussion, described in Sections 2 through 7 of this report, will help the DOE SSL program identify critical core, product development, and manufacturing R&D needs for the continued advancement of OLEDs.

Identifying Market Development Challenges: Members of the OLED Coalition shared updates on OLED Coalition efforts to advance OLED lighting and market viability, and then moderated lively discussions to gather ideas from meeting attendees. The Coalition's work at the Stakeholder meeting is discussed in Section 8 of this report.

Attendees were also given an opportunity to tour Kurt J. Lesker Company.

Key Conclusions:

Based on the presentations from the attendees and the subsequent discussion, the critical challenges to the OLED industry could be grouped into a few broad categories:

- OLED Materials (Section 3)
- OLED Substrates and Encapsulation (Section 4)
- OLED Light Extraction (Section 6)

- OLED Panel and Luminaire Manufacturing (Section 7)
- Market, Education, and Outreach (Section 9)

2. How OLED Lighting Can Succeed: A U.S. Panel Manufacturer's Story

John Hamer of OLEDWorks opened the meeting by comparing the small number of people at DOE SSL workshops a few years ago who were interested in OLEDs, to the nearly 50 participants at this OLED specific meeting. He described the early progress the OLED industry has seen so far, and also the three things he believes the OLED industry must do going forward in order to succeed.

Today, OLEDs remain high-cost with few installations, but recent progress on lifetime, efficacy, and color quality has enabled the first OLED luminaires. Commercial panels with long lifetimes, such as the FL300 panel which has a lifetime of 50,000 hours at 3200 candelas per square meter (cd/m^2), are currently available. Both efficacy and lifetime are expected to further improve as internal light extraction (ILE) substrates and new materials become available. Most commercial panels have color rendering index (CRI) greater than or equal to 80, but increases to 90 or more (as seen in Lumiotec and LG Chem panels) are expected with improved materials and formulations. Reliability remains an issue, and more R&D, along with better accelerated test methods, is needed to understand and reduce long-term failures. Current LG Chem products use a very expensive substrate with four photolithography (PL) mask layers to sidestep reliability issues. Improving panel reliability would eliminate the need for such redundancies and enable lower-cost panels.

Acuity is the most active U.S. OLED luminaire maker, with several commercial OLED luminaire offerings and also residential fixtures sold direct to consumers through Home Depot. Other OLED direct-to-consumer fixtures, such as the Aerelight desk light by OTI Lumionics, are available for purchase online. IHS Technology estimates 5,500 OLED luminaires were sold in 2014[1], about two-thirds of which were for decorative and architectural lighting (including sculptural pieces in high-end commercial properties). To succeed, OLEDs need to expand into new market segments, for both commercial and consumer lighting applications. Gateway program demonstrations would help, but they require fixtures that are already designed and commercialized, so more companies will need to introduce products with OLED lights. However, the inorganic light-emitting diode (LED) fixture market is hot, and most fixture designers and fabricators are focused on LED right now. Additionally, current OLED designs use high-price panels in high-price luminaires. Lower-cost, accessible OLED fixtures are

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[1] IHS, "What will your OLED luminaire look like?" https://technology.ihs.com/527208/what-will-your-oled-luminaire-look-like

necessary to break into the market, and to do that the industry must realize a path to lower panel costs.

Hamer outlined three key things that are needed for the OLED industry to succeed: (1) cost reductions, (2) availability of more fixtures, and (3) flexible panels. His suggestions on how to bring down costs were focused on improvements in fabrication processes and equipment. Work should be done to reduce the equipment and maintenance costs of thin film encapsulation, reduce the number of PL mask levels or replace PL with a lower-cost process, find lower-cost processes for ILE, and reduce initial capital costs of equipment. The second need is for more available fixtures and can be addressed by empowering fixture makers with more low-cost driver options that are easier to integrate with building systems, controls, communications, and sensors. Hamer pointed out that fixture makers would appreciate that OLEDs require less engineering than LED fixtures because the panels are lighter weight, do not require optics, and do not have heat transfer problems; however, the OLED industry will need to educate them, encourage creativity, and seek out new players. The third need is to move to flexible panels as they offer a unique value proposition over other lighting technologies including LED. OLEDWorks has a joint development project with Corning to develop technology for flexible OLED lighting on Willow® glass.

3. OLED Materials and Device Design

1. Discussion

Participants proposed the following as important areas for materials R&D:

- Improving the lifetime of blue fluorophors and phosphors so that they no longer limit device lifetime.
- Increasing the purity of OLED polymer materials to enable more cost effective solution based processing.
- Investigating nanoscale inhomogeneity and possible lifetime implications.
- Considering ionic materials for OLED devices.

2. Participant Presentations

The biggest challenges for OLEDs for lighting… Starting with blue lifetime.

Stephen Forrest of the University of Michigan presented his views on the biggest remaining challenges for OLED lighting, the first of which is blue lifetime. Forrest believes that active-matrix OLED displays are driving the technology, but white light for lighting applications is the next big thing and flexible white light will follow. Major remaining challenges include (1) light extraction, (2) improving cost and yield, and (3) materials to enable high efficiency and long lifetime for blue light.

Light extraction ideally should be viewing angle independent, independent of OLED structure, and inexpensive; therefore it cannot be too sophisticated. Some common approaches to light extraction include optical gratings or photonic crystals, corrugations or grids embedded in the OLED, nanoscale scattering centers, and dipole orientation management. These approaches have been investigated with varying levels of success. As a novel light extraction approach, Forrest proposed a sub-anode grid incorporating a multi-wavelength scale dielectric grid sandwiched between the substrate glass and the transparent anode, that is planar, outside of the active region, scatters light into substrate and air modes, and can be easily integrated by the substrate manufacturer.

Cost and yield improvements can be influenced by patterning and deposition techniques and the associated throughput. Forrest points out the advantage of purity when using small molecules versus polymers, and the advantage of dry processes as compared to wet deposition techniques when dealing with complex, multi-layer structures for white OLEDs. Current options for dry processing small molecules with high throughput include vacuum thermal evaporation and organic vapor phase deposition.

Improvements in blue emitter systems have been a consistent need for OLED advancement, and simultaneously achieving high efficiency and long lifetimes (especially at appropriate brightness levels) has been an elusive task. Though phosphorescent emitters can be more efficient, panel manufacturers are currently using blue fluorophors instead because phosphors have too short of a lifetime (L_{60} on the order of 10's of hours). However, blue fluorophors (L_{60} on the order of 10 thousand hours) still limit the lifetime of the device as the lifetime (L_{60}) of reds and greens are on the order of 100 thousand hours. Forrest points out that in addition to considering materials chemistry, device physics should be considered as well. The lifetime of red is longer than green, which is longer than blue, implying that degradation is energetically driven. To better understand this, degradation routes are examined. Both exciton-exciton annihilation and exciton-polaron annihilation lead to luminance loss, and typically, the concentration of excitons in the host material increases over time. Therefore, reducing exciton density has the potential to increase lifetime. Forrest shared results that support this approach, maintaining a more uniform (lower) exciton density by stacking conventional devices and also by using a graded device. The current lifetime of stacked white OLEDs is L_{70} of 13,000 hours, and it is mostly limited by blue lifetime. Using graded devices has the potential to increase the lifetime fourfold.

To conclude, Forrest asserted that the large area, ultra-efficient, color tunable, and architecturally adaptable form factor make OLEDs too good of an opportunity to miss, but that the challenges discussed must first be addressed.

OLED Lifetime: Is loss embedded in transport at the nanoscale?

Chris Giebink of Pennsylvania State University discussed how the move from modeling transport in OLED devices as one-dimensional (1-D) drift diffusion to three-dimensional (3-D) simulations at the nanoscale can help our understanding of lifetime. We know that OLED lifetime depends strongly on current density which puts stress on small subgroups of molecules and accelerates bimolecular degradation reactions. The question remains, how much lifetime loss is built in due to nanoscale inhomogeneity, and what can we do about it? Observations from 3-D nanoscale modeling can help start this dialogue. Giebink described current filaments caused by on-site energetic disorder where carriers inject into lowest energy sites, which tend to initiate at electrode/organic interfaces and, less frequently, organic-organic interfaces. Sharp heterojunction interfaces increase the probability of high current filaments forming. Device implications of these current filaments include efficiency roll-off and lifetime reductions. Giebink also noted that when modeling a prototypical tris(2-phenylpyridine)iridium(III) phosphorescent OLED (commonly known as Ir(ppy)3), he has seen an order of magnitude difference in critical current density ($J_{50\%}$) due to increased exciton-polaron quenching, and a decrease in lifetime of two-to-threefold at SSL appropriate current densities. However, there has been no direct experimental evidence demonstrating inhomogeneity to date because sub-diffraction makes filamentary conduction hard to observe. Indirect evidence includes noise spectra of OLEDs that are consistent with filamentary conduction. Unfortunately, energetic disorder is inherent in amorphous thin film devices, but there may be ways we can make improvements through engineering at the interface. At the electrode/organic interfaces, we should look for opportunities to frustrate filament initiation. At organic/organic interfaces, grading between layers can reduce filament formation and is empirically known to extend lifetime.

OLED Research in the Bernhard Lab

Stefan Bernhard of Carnegie Mellon University discussed his lab's work to design luminophores. While most OLEDs use neutral materials, the Bernhard lab is exploring simple single layer devices using ionic materials, looking at light-emitting electrochemical cells that use an ionic transition metal complex. Benefits of these devices include purity (as they do not use polymers), easy fabrication (can be done in air), lower work functions, low direct current turn on voltages (3V), and the ability to be run on alternating current. They work by sandwiching a chromophore between gold and indium tin oxide (ITO) electrodes so charges are injected at both electrodes and then migrate to recombine, liberating a photon. Indium chromophores are positively charged, and need ions for mobility. Different metals with unique ligand geometries yield different colors and allow for color tuning. Bernhard explained that they are exploring other architectures in order to bind ligands more strongly to metals because bond dissociation would cause failure, and energies of blue light are high enough to break bonds. Ligand rigidification makes luminophores more robust by hindering thermal deactivation. Hemicage architectures in particular improve stability and can double the device efficiency. The origin of the pinene (European versus American) and chirality of ligands on the metal ion controls the helicity of luminophore, and Bernhard's laboratory hopes to observe circular polarized electro-luminescence right/left depending on origin of the pinene molecules.

4. Substrates & Encapsulation

1. Discussion

Participants proposed the following as important areas for substrate and encapsulation R&D:

- Encapsulation and substrate solutions should be flexible in order to be compatible with flexible lighting panels and roll-to-roll (R2R) processing.
- Ultra-barrier films for OLED devices could potentially offer better protection from oxygen and moisture ingress, thereby improving panel lifetime and reliability.
- Alternative substrates including engineered aluminum, flexible glass, and plastic should be considered as possible solutions to cost, form factor, manufacturing, and lifetime challenges.

2. Participant Presentations

Transparent Ultra-barrier Films

Ravi Prasad of Vitriflex discussed ultra-barrier films for OLED devices. OLEDs are sensitive to the environment, particularly to moisture, and therefore must be encapsulated from all sides. Barrier films for top emitting devices must be transparent (enabling light pass through encapsulation), compatible with pressure sensitive adhesive application, and hard coat. For bottom emitting devices, light exits through the substrate so the top encapsulation barrier does not need to be transparent. Vitriflex is offering a novel platform for encapsulation of flexible electronics that is flexible and transparent, thereby enabling the next wave of large-area electronic products. Ultra-barriers are widely considered to be barriers with measured water vapor transmission rate (WVTR) below the detection limit of the Mocon Permatran Test, less than 5 x 10^{-3}grams per square meter per day (g/m^2/day), though much lower WVTRs are required for OLED lighting applications. In principle, an ultra-barrier is a perfect layer of inorganic oxide film, a few nanometers thick, providing an adequate water and oxygen barrier. In reality, manufacturing is a challenge, and when scaling up, materials like the oxide tend to crystallize. Surface imperfections on the substrate lead to pinholes and film defects, and vacuum deposited films often show columnar growth and crystalline defects. Moisture can diffuse through these defects. One well known solution is to use polymeric multi-layers, multi-layer organic/inorganic coatings with polymer interlayers, to interrupt the growth of defect pinholes creating a tortuous path for water molecules, which is effective but costly. Other ultra-barrier technologies include atomic layer deposition, which needs to be faster to be cost effective, and flexible glass. Vitriflex offers a novel solution incorporating multi-factor barrier enhancement to add redundancies: substrate planarization, three-layer and five-layer inorganic stacks, and a hybrid polymer top seal. The substrate planarization works well to cover defects for surface roughness less than one nanometer (nm). The three to five layered stacks alternate diffusive and reactive layers. The reactive layers are inorganic layers that react with water, oxygen, or both, and are protected on both sides with a diffusive layer. The thicker the reactive layer, the longer the lifetime of the device. The hybrid polymer top seal increases barrier performance, protects the thin-film barrier, and is integrated for optical tuning. The approach for scale up to production levels has been to use reactive sputtering because it is well understood, available, and scalable to wide webs. Remaining challenges include the integration of the whole device and edge diffusion.

3M Barrier Film and Encapsulation Development

Chris Lyons of 3M gave an update on their barrier film development, which includes ultra-barrier solar films exhibiting environmental durability, flexible transparent films for general purpose display applications, and quantum dot (QD) enhancement films to protect QDs. 3M has large scale manufacturing capabilities for each and is now turning their attention to OLEDs. 3M barrier films are multi-layer constructions of polymer layers and oxide layers on flexible substrates. The polymer layers planarize the substrate and protect the oxide layers. The very thin oxide layers provide the barrier properties including good flexibility and high optical transmission and clarity. Additional oxide and polymer layers can be added to increase the barrier performance, but a focus on driving out defects may enable the use of single layers. 3M is also developing adhesive barrier materials. They use a calcium test to characterize the barrier and adhesive films by tracking the optical disappearance of calcium samples in 60°C, 90% relative humidity conditions. The adhesive barrier performance is characterized by the rate of edge decay in the calcium, and the barrier film performance by the rate of calcium decay in the center. The rate of calcium decay relates to the permeability of water vapor through the barrier film/adhesive. WVTRs of 10^{-6} $g/m^2/day$ are needed for OLED lighting devices. 3M's first-generation (Gen-1) barrier adhesive is not good enough in barrier performance for OLEDs, so they have developed a second-generation (Gen-2) adhesive that is more than two times better in barrier performance and can be supplied as a standalone material in either 25 or 12 micron thicknesses. Currently samples of the Gen-2 barrier adhesive is being supplied to interested users under a confidential agreement, but 3M hopes to commercialize it in 2016. Lyons concluded by saying that encapsulation must consider all of the layers together, and to do that, 3M will look at flexible barrier film substrates, barrier adhesives, and barrier films.

Engineered Aluminum Substrate for OLED Lighting

Kirit Shah of Alcoa suggested considering an alternative substrate in order to address cost, flexible form factor, and lifetime; glass and plastic substrates currently used in OLED panels do not address all three, but aluminum potentially can. Alcoa has the expertise to engineer aluminum to meet the requirements of OLED lighting substrates. Engineered aluminum substrates are lower cost than glass, steel, and plastics with barrier films, as well as being non-breakable, flexible/conformable, and recyclable. They have excellent barrier properties, good thermal management, and they offer both manufacturing and design flexibility (can be either rigid or flexible based on the alloy). However, challenges, namely substrate smoothness, dielectric coating, and device structure (requires top emission), remain. Alcoa has demonstrated a flexible 1 inch square pixel device, and preliminary evaluations of large area devices on the Alcoa substrate shows good promise on par with glass substrates. Compared to other competitive substrates, aluminum could enable low cost, R2R processing with improved device performance compared to glass, but lags in technology readiness. Continued work on top emission technology suitable for large area devices, yield enhancement, and product validation are needed.

5. Multiscale Modeling of OLEDs for Lighting Application

Stéphane Altazin of Fluxim opened day two of the meeting with a presentation on how multiscale modeling of OLEDs can help to optimize efficiency, monitor and understand lifetime, and scale to commercial production levels. Fluxim's approach involves using easy-to-use simulation software "SETFOS" to simulate OLEDs and organic photovoltaics on different scales plus easy-to-use all-in-one characterization platform "PAIOS" to extract device and material parameters by dynamic characterization. Microscale modeling of OLEDs starts with drift diffusion equations and uses charge transport modeling to solve exciton continuity equations, treating every radiatively decaying exciton as an emitting dipole in an optical cavity. However, in order to get accurate simulations, you need accurate parameters. PAIOS was created as an all-in-one measurement platform that takes transient measurements of a device that can then be used to determine parameters including charge carrier mobility, charge dynamics, exciton lifetime, and electroluminescence decay. In order to optimize the full device stack, Fluxim's optical modeling capabilities allow for the optimization of the thin film in the OLED layer stack and the evaluation of scattering features' impact on device performances. Their electrical modeling capabilities allow for the evaluation of the influence of material properties (e.g., charge trapping, charge transport), the study of device degradation, the evaluation of losses introduced by non-ideal electrodes, and the optimization of electrode geometry.

One motivation for using multiscale modeling is to better understand polar OLED materials and their electrical properties. Decreasing the operating voltage in OLEDs is of primary importance and requires high mobility/conductivity electron transport layers (ETL) and well matched energy levels. Many ETL materials are known to be polar and exhibit spontaneous molecular dipole orientation, which leads to charged layer boundaries in the device. Modeling can help determine the interfacial charge density and how device electrical properties will be impacted. To simulate the light emission from an OLED, microscale optics are modeled as emission from a dipole embedded in an optical cavity. This model has been validated for top and bottom emission OLED devices, and emitted radiance was well reproduced with SETFOS. Combining SETFOS and angular PL measurement allows us to extract the dipole orientation, which is a critical point for good light outcoupling. SETFOS is capable of simulating the complete OLED stack to determine emission and light scattering by using a Mie particle and rough surface bidirectional scattering distribution function (BSDF) calculator. The Mie particle scattering feature of SETFOS allows us to calculate the BSDF of layers with scattering particles given key parameters of size, concentration, refractive index contrast, and size distribution. Simulations varying the parameters can help optimize the device. Fluxim has seen very good agreement between simulations and experiments. However, there are challenges associated with moving from simulations of small area "laboratory" OLEDs and large area OLED panels. For small area OLEDs a 1-D model is sufficient, and optimizing ageing, transport, charge carrier balance, and light outcoupling is possible. For large devices, a 3-D model is necessary and brightness inhomogeneity, and sheet resistance must also be optimized. Fluxim currently combines two-dimensional (2-D) and 1-D coupling, solving semiconductor equations in the vertical direction and Ohm's law in the large 2-D anode. This approach has been successfully applied to study the effect of conductivity enhancement in OLED panel.

6. OLED Light Extraction

1. Discussion

Participants proposed the following as important areas for OLED light extraction R&D:

- Light extraction materials should have refractive index greater than 1.8 at 550 nm, percent transmittance greater than 90% in the visible region, thermal stability up to 150 to 250°C, and compatibility with current manufacturing processes.
- The use of nanoparticles as scatterers could potentially lead to manufacturing and light extraction improvements, particularly given the opportunity to embed complexity in the materials to simplify manufacturing with a single formulation.
- Novel structures such as the Plasmonic Cavity with Subwavelength Hole-array OLED (PlaCSH-OLED) may be worth pursuing in an attempt to see breakthrough light extraction enhancement as opposed to incremental improvements of existing structures.
- Integrated substrates (consisting of a substrate, internal extraction layers, and conductive anode) have the potential to simplify the manufacturing process of the OLED stack for manufacturers thereby reducing manufacturing costs.
- An encapsulant or substrate that has a refractive index of 1.7 would help prevent losses due to total internal reflection.

2. Participant Presentations

Overview of Pixelligent's ILE Program

Greg Cooper of Pixelligent outlined Pixelligent's ILE strategy. Pixelligent is a developer of nanocrystal dispersions. They have state of the art laboratories and a pilot manufacturing facility. They make mono-dispersed zirconium dioxide (ZrO_2) nanocrystals with precisely engineered surfaces, narrow size distribution (5nm-10nm), high loadings (greater than 80% by weight) while maintaining 95% transmittance, high refractive index (greater than 1.8), and tunable viscosity. Their manufacturing process is highly scalable with the potential for low cost (solution processing). Pixelligent described four generations of their light extraction approach. Gen-1 is a condensed scattering layer of the particles with high index smoothing. They have demonstrated that these scattering layers can more than double light output. Pixelligent recently launched an OLED family of Gen-1 commercial products that are available on their website. They meet performance targets for OLED light extraction materials including: refractive index greater than 1.75 to 1.85 at 550 nm, percent transmittance greater than 90% in the visible region, planarization scattering structures on substrate to less than 1 nm, compatibility with current manufacturing processes, stability at 150 to 250°C for up to 30 minutes (while maintaining high refractive index and percent transmittance), and compatibility with polymers, scatterers, and chemical processing used in ITO patterning. Gen-2 is a distributed scattering layer with high index matrix (i.e., the particles are dispersed in the high index layer). Gen-2 is more efficient than Gen-1, and while it is a more complex material, it can be formed by a simpler manufacturing process. Pixelligent is currently developing materials formulation and manufacturing process for Gen-2 under a DOE Small Business Innovation Research Phase II SSL R&D grant with the focus on commercializing the formulation. Pixelligent will sell a single bottle formulation for Gen-2, and they are currently working to optimize the size, kind, and concentration of the scatterers, composition of the polymer, the "flavor" of the nanocrystals, nanocrystal polymer ratio, and the curing mechanism. This formulation will be compatible with slot-die, spin coat, inkjet, and spray coat deposition methods independent of substrate. Gen-3 involves a preferentially distributed scattering layer with a gradient index layer, and is more efficient than the simple distributed scattering layer of Gen-2. The manufacturing process is more complex than Gen-2, and Pixelligent is currently developing materials and manufacturing processes under a DOE SSL R&D grant. The subject of future work (Gen-4), a structured gradient high index layer, is the long term goal of Pixelligent in order to offer highest efficiency and the ability to direct light. This approach would use 3-D optical features in the graded index layer, which would require more complex manufacturing processes than Gen-1 through Gen-3, but the ability to tailor the light distribution profile could justify the expense. Overall, Pixelligent's strategy is to put complexity into the materials, e.g., creating a liquid formulation that can be deposited in one step to create a scattering layer, so that high performance devices can be achieved with simple manufacturing. With fairly modest changes to composition, the formulation could be used in many types of manufacturing, independent of the substrate.

Plasmonic Cavity with Subwavelength Hole-array OLEDs: Significant Increase of OLED's Utility Efficiency and Contrast

Ji Qi of the Princeton University Nanostructure Laboratory presented a new OLED structure, PlaCSH-OLED, which they have found to have unprecedented performance in terms of high light extraction, high light absorption, and high contrast. For OLED display applications, the high absorption of ambient light leads to low ambient light reflection and high contrast. PlaCSH-OLEDs will not require antireflection coatings, polarizers, or light absorbers, which all reduce light extraction efficiency, in order to reduce ambient light reflection. This, along with improved light extraction, has the potential to significantly increase efficiency. The new structure replaces ITO with a sub-wavelength hole-array, and the nanoplasmonic cavity makes the OLED an excellent light radiator and absorber. Demonstration over a large area has yielded compelling data showing an average 1.57 times light extraction enhancement in electroluminescence over ITO OLEDs. External quantum efficiency (EQE), power efficiency, and brightness were 1.57, 1.6, and 1.86 fold higher respectively, and sheet resistance was 2.5 fold lower when compared to ITO OLEDs. As stated before, PlaCSH is a good light absorber, achieving 3 fold lower ambient light reflection over a broad spectrum. This allows for up to 5 fold higher contrast at nearly all viewing angles. Princeton's Metallic Electrode with Subwavelength Hole-array (MESH) is a potential ITO anode alternative. It is very flat and uniform so that an active layer can be smoothly deposited on top of it. Additionally, MESH has demonstrated resistance of only 5 ohm/square and 89% transmission. The MESH can be fabricated using a plate or roller nano-imprint on either hard or flexible substrates. This work is the subject of a current DOE SSL project to implement PlaCSH to red and blue and to create a white OLED with 130 lumens per watt (lm/W), 65% EQE, and CRI greater than 80. There is also interest in future work on flexible and low cost ITO-free white OLEDs over large area and MESH for transparent conducting electrode with high figure of merit.

Corning integrated substrates: Roadmap to roll-to-roll and outlook for commercial availability

Mark Taylor of Corning discussed Corning's integrated substrate and their roadmap to R2R production. The OLED cost reduction curve is similar to the LED curve, but with a seven year lag. Today panel prices are around $200 per kilolumen (klm). As prices drop to $125/klm and lower, we will see them in more luxury/niche applications, which is where we expect to be in 2016. By 2020, if panel prices drop to $35/klm we will begin to see them in hospital and retail applications. As panel prices drop to $23/klm, likely around 2022, we will see them in transportation, commercial, and residential applications. Thus, the real question becomes how to reduce cost to achieve these milestones and achieve faster adoption? Corning's integrated substrates, consisting of a glass substrate, internal extraction layers, and conductive anode, may be a solution because they could simplify the manufacturing process for manufacturers of the OLED stack. Challenges including materials and manufacturing costs, efficiency, lifetime, LED competition, and technology change fatigue require cooperation between substrate producers and OLED producers. Flexible substrates are important to expand functionality, create new desired form factors, and provide distinguishing features when compared with LEDs. An integrated substrate roadmap will help drive market growth. Taylor presented one such roadmap that estimates rigid panels will drive the market until flexible panels on a rigid carrier are introduced (somewhere around 2018) as an intermediary between rigid manufacturing and flexible R2R which we would expect to see the following year or two. Corning Willow® Glass-on-carrier technology allows panel makers to deposit flexible OLEDs without R2R technology. R2R would drive faster market adoption by lowering cost more than 30%, and Corning Willow® Glass provides a flexible substrate with the best barrier properties in a R2R format. Corning's integrated substrate value proposition is to: reduce cost and complexity for panel makers by providing a deposition-ready substrate; unlock the conformability value element for OLED lighting with thin, light, and flexible glass; and provide a path for greater than 30% cost reduction versus current sheet-to-sheet process through R2R process capability. Within the integrated substrate, the ILE layer currently provides twofold extraction enhancement, but 2.5

fold is needed by 2016 in order to keep driving costs down. Corning is ready to sample their integrated substrate as rigid or flexible substrates.

Manufacturability of OLED Encapsulation and Light Extraction

Russell Kurtz of Luminit discussed his company's capabilities in producing sheets of textured surfaces for optical purposes and their desire to get involved with OLEDs. OLEDs require encapsulation for protection, but the encapsulant or substrate can also help extract light. OLEDs and ITO typically have refractive indices near 1.7, while encapsulants and substrates are typically around 1.5. Total internal reflection leads to waveguided modes causing losses. Ray tracing models indicate that patterning the surface could increase light output. With a patterned diffuser, models show a wider, flatter, and 50% higher light distribution peak. Ray tracing with Luminit's current material set gives a factor of two increase in light output, if materials with 1.7 refractive index are developed, modeling indicates that a threefold increase is possible. Optics of OLEDs can be improved with single layer encapsulant (multiple layers lead to loss, and multiple materials are more expensive and harder to manufacture), an encapsulant or substrate with a refractive index of 1.7 (matching the refractive index of ITO will prevent some waveguide modes and corresponding losses), and manufacturable methods for OLED assembly (R2R processing and automated encapsulation). An ideal solution would be an encapsulant or substrate that has a refractive index of 1.7, is flexible, seals against all hazards, and does not affect material or operation.

7. Panel & Luminaire Manufacturing

1. Discussion

Participants proposed the following as important areas of R&D for panel and luminaires:

- The new technical memorandum,TM-30-15, an IES method for evaluating source color rendition, introduced two new color metrics in attempt to better define color quality; however, more human factors studies are needed to determine color preferences.
- Using a combination of OLEDs and LEDs in luminaires allows improved performance and cost reductions.
- R&D should focus on materials and manufacturing processes compatible with R2R processing because it offers the potential to reduce manufacturing costs and make OLED luminaires more affordable.
- It was suggested that there needs to be more commercial OLED luminaires and a good way to do that is to attract and educate new talent and luminaire manufacturers.
- Flexible panels would allow for conformable luminaire designs, and create a unique value proposition.
- It was suggested that for OLED products to realize best possible performance and color tunability, more attention needs to be paid to smart OLED drivers.

- Precision shadow masks could potentially improve thin film deposition processes compatible with OLED manufacturing which could in turn improve yield and material utilization.

2. Participant Presentations

Hybrid OLED/LED Luminaires

Michael Lu of Acuity Brands gave an overview of the recently published TM-30-15 as well as Acuity's recent efforts in LED-OLED hybrid luminaire designs. TM-30-15, an IES method for evaluating source color rendition, was published in August 2015. Whereas CRI measures just color fidelity, TM-30-15 provides color metrics for fidelity and gamut, Rf and Rg, respectively. Rf is a fidelity index valued between 100 (no color error, i.e., perfect fidelity) and 0 (very large average color error). Rf is computed in a fashion similar to the CRI, but using 99 color samples versus a reference, rather than the 8 samples used for CRI. Rg represents "color gamut" and is used to describe the ability of a light source to increase or decrease the chroma of objects' colors. An Rg above 100 indicates that objects' colors appear more vivid (saturated) on average, while a value below 100 indicates that objects' colors appear duller (desaturated) on average. Lu compared a 3000K OLED panel with an Rf and Rg of 86 and 98, respectively, to a 3000K LED with an Rf and Rg 86 and 99 respectively, noting that the OLED achieved similar excellent color quality without a peak in the blue as seen for the LED.

Lu also reported on Acuity's Duet product line. Acuity has created hybrid luminaires with OLED downlights and LED uplights, and demonstrated four different hybrid suspended fixtures at Light Fair this year. By supplementing the pleasing direct light of the OLEDs with the majority of light coming from the LEDs that is reflected off of the ceiling, Acuity created a fixture that has appropriate lumen levels and distribution for an existing consumer application while introducing the aesthetic appeal of OLEDs as direct light sources. Acuity wants to spur market interest in the next generation of lighting designers. They hosted a contest in which students at California Lighting Technology Center (CLTC) of University of California, Davis were given four OLED panels, a driver, and a dimmer in order to design a fixture. Acuity sponsored the top winner to go to Light Fair, and the CLTC sent two runner ups. The three designs were featured in Acuity's booth and given awards. Lu concluded his talk by acknowledging that efficacy remains a real barrier for the OLED business case, and that commercial panel efficacy has been stuck at 60 lm/W for about a year.

How DOE Can Help OLED Lighting

Michael Boroson of OLEDWorks explained how he thinks DOE can help advance OLED lighting. The problems that need to be addressed are too few luminaire manufacturers, too few options for consumers looking to buy OLED products, and too few opportunities for architects, lighting designers, and consumers to see and experience OLED lighting. Acuity is the most active U.S. luminaire maker and the only major player currently using OLEDs. The only options for purchasing OLED luminaires are online (where Home Depot sells Acuity fixtures, and OTI

Lumionics offers a desk light) or through commercial sales representatives. OLEDs need to expand to new market segments, and more companies to need to introduce non-commercial, residential consumer products with OLED lights, maybe even built-in products (e.g., furniture). To do this, we need to enable creativity and find new players who would be interested in OLEDs in addition to, or instead of, LEDs. To accelerate the market, demonstrations with a range of luminaires and panels and possibly a Gateway demonstration of OLED lighting would be helpful. To avoid direct competition with LEDs, we should take advantage of the unique selling proposition of flexible OLED panels. DOE can help by funding projects that support flexible OLED panels and products, such as low cost plastic or thin glass integrated substrates, low cost flexible encapsulation, and low cost flexible electrical connections. Other areas of concern are blue efficacy and lifetime and panel reliability, where DOE can help by supporting blue phosphorescent and thermally activated delayed fluorescence developments along with short reduction, lifetime prediction, and identification of weak panels.

How can Advantech U.S. support the OLED lighting industry?

Volker Heydemann of Advantech U.S., Inc. described his company's capabilities and how they can help OLED lighting. Advantech's core expertise is in thin film deposition using precision shadow masks, and they are capable of designing, selling, and licensing custom process equipment. Thin film deposition options include physical vapor transport, electron beam evaporation, low pressure sputter, and deposition of metals, dielectrics, semiconductors, and organics. They have the ability to work with pre-patterned substrates, create precision shadow masks directly from CAD (computer-aided design) drawings, and mount masks with precision using a multi-mask alignment system. The masks are electro-formed thin nickel foil, with thickness between 5 and 25 microns and apertures defined by PL that can be any continuous outlined shape with openings from 5 to 1000 microns. Masks are cleaned with a wet-chemical process and have a life cycle exceeding 2 years. Also, resistors and capacitors can be embedded. Using Advantech's precision shadow masks and alignments allows for selective deposition of the correct materials, in the correct sequence, in the correct location, with the correct geometry on a wide variety of substrates, and makes for a competitive advantage in the OLED industry.

OLED Manufacturing

Salahud Din of Kurt J. Lesker Company gave an equipment supplier's perspective on OLED manufacturing. OLED manufacturers must consider substrates, materials, device structures, deposition equipment, manufacturing costs, and potential applications for the final product. Global challenges to the OLED lighting industry include efficacy and light output, lifespan, cost of manufacturing, tests, and standards. Currently, no commercial OLED products provide a strong competitive advantage over conventional technologies. To improve OLED performance, work is needed for light extraction and to develop a long lasting blue emitter. To address lifetime and reliability issues, work on high current density and environmental degradation is needed. Lower-cost device and luminaire materials, as well as investment in manufacturing infrastructure, is needed in order to develop affordable commercial OLED products. Reliable standards and test methods are needed to establish consistency and reduce uncertainty. Increasing device structure complexity increases materials and manufacturing costs, but at this time a simple structure is not yet a reality. Din compared the benefits of four common types of OLED structures: a single emissive layer, multiple emissive layers, color conversion, and tandem. A single emissive layer has acceptable efficiency, a relatively simple manufacturing process, but poor lifetime. Multiple emissive layers have better efficiency and lifetime as compared to a single emissive layer, but a more complex manufacturing process. Color conversion using down-converters results in efficiency losses. Tandem structures offer the best efficiency and lifetime of the group, but are the most complex to manufacture. Low demand for systems in the United States, a large variation in proprietary device structures, and inability to access the right materials make it difficult for equipment suppliers to address the needs of the OLED industry. In response, Lesker Company is focusing on the research and development of OLED related processes and products. They are working on: deposition sources to enhance host/dopant ratio control, deposition uniformity, and materials utilization; deposition techniques to address layer uniformity, interfaces between organic and inorganic layers, high precision masking, and TAKT time; and a systems integration approach to deposition, substrate cleaning, and substrate patterning in order to optimize system efficiency. Specific examples of their R&D include fast cooling low temperature evaporation sources, O-HERO, glovebox integrated systems, off-axis sputtering source, dual wedge tool, and cluster tools. HERO, Highly Efficient Rate Optimization, is an innovative deposition approach that uses a point source, has a compact design with load locks for source refill, is scalable for substrate sizes, has deposition rates from less than 0.01 to 20 angstroms per second, and materials utilization of 25% to 30% with further room for improvement. Off-axis low energy sputtering onto organic layers could potentially enable alternative device structures, encapsulation, and scalability for large size substrates. A cluster tool involves combining multiple tools in one set up. Sheet-to-sheet deposition has been performed using HERO, with a dedicated chamber for each layer making it possible to reclaim material. However, it is a work in progress and some elements would benefit from collaboration. Kurt Lesker Company has ideas to help the OLED lighting community, but only by thinking creatively and collaborating together can the industry come up with lower-cost solutions.

Intelligent electronic modules for OLEDs

Larry Sadwick of InnoSys, Inc. emphasized the need for intelligent OLED specific drivers in order for OLED lighting products to truly succeed. OLEDs have tough competition from established products such as LEDs, and new possibilities, such as QD LEDs, are being explored. In terms of brightness, LEDs are favored and the glare issue with LEDs has largely been addressed. LEDs currently lead in color tunable applications, but OLEDs could, and should, be color tunable as well. However, it will be much harder for OLEDs to compete with LEDs in terms of efficacy or price. Sadwick suggested that it might be more important for OLEDs to do something that LEDs cannot easily do, such as flexible, evenly lit surfaces. He also pointed out that there are opportunities to use LEDs and OLEDs together to improve lighting quality and experience. Sadwick proposed that OLEDs must be intelligent, networked, and connected to succeed, and it starts with the power supplies. InnoSys has demonstrated a color changing smart OLED driver with Pioneer/Mitsubishi panels. However, Sadwick emphasized that driver efficiency and reliability remains a real issue. Drivers are usually the last part of a lighting product to be considered, and cost is the primary emphasis. In his experience, no matter how much the panel and luminaire costs, manufacturers expect to shave off cost on the driver and driver efficiency is often sacrificed.

8. DOE Program Update

Joel Chaddock of DOE National Energy Laboratory gave an update on the current state of the DOE SSL R&D portfolio and explained the solicitation processes as well as the collaborative DOE OLED Testing Opportunity. SSL R&D solicitations seek to maximize the energy-efficiency of SSL products in the marketplace, remove market barriers through improvements to lifetime, color quality, and lighting system performance, reduce costs of SSL sources and luminaires, improve product consistency while maintaining high quality products, and encourage the growth, leadership, and sustainability of domestic U.S. manufacturing within the SSL industry. R&D projects fall into one of three categories: core, product development, and manufacturing. Historically, the funding has been shared about equally, with 28% of funding going towards manufacturing, 38% towards core, and 34% towards product development. Additionally, the 51 OLED projects to date have addressed 15 different priority tasks set by the SSL Program. The SSL Project Portfolio is available in its entirety at: http://energy.gov/eere/ssl/downloads/2015-project-portfolio. DOE initiated a collaborative R&D OLED Testing Opportunity with the purpose of developing a collaborative R&D framework to accelerate developments in OLED lighting technology and manufacturing. Component and luminaire manufacturers who apply to have their components tested through this opportunity benefit from quicker turnaround for funding compared to solicitations, less daunting application process, rapid results, collaboration with panel manufacturers, and a technology validation status report summarizing test results and recommended actions and improvements. Currently, DOE has qualified one testing laboratory to date and seeks additional qualified testing laboratories. Three products have been evaluated to date, and feedback has been largely positive. Applications for support under this program can be submitted at any time and awards are made in a rolling evaluation process. More information on the OLED Testing Opportunity can be found at: http://energy.gov/eere/ssl/oled-testing-opportunity.

9. OLED Coalition: The OLED Market and Global Development

The idea for the OLED Coalition was conceived during the OLED stakeholder meeting held in the fall of 2013. It was officially founded in fourth quarter of 2013 as a group of U.S. companies and advocates of OLED technology joined together to be the recognized voice for the OLED General Lighting Industry in the U.S. in order to promote the industry and provide consolidated industry inputs on standards, as appropriate. The OLED Coalition moderated a portion of the meeting discussing the OLED market and accelerating the growth of OLED lighting.

1. Introduction & Updates

Michele Ricks of EMD Chemicals provided an introduction to the OLED Coalition and updates on their efforts thus far. The purpose of the OLED Coalition is to promote the OLED industry in the U.S., facilitate communication within and outside of the group, promote the OLED lighting industry in the U.S., assist in communicating requirements for OLED lighting standards, ensure the needs of the industry are well understood by Congress, DOE, and the Office of Management and Budget, assist with prioritization of intercompany activities related to DOE efforts, and produce an annual report on the progress made by the U.S. OLED industry. OLED Coalition members include 15 companies, and the elected board members are Michele Ricks, Barry Young, Peter Ngai, Giana Phelan, Mike Hack, Yukari Tanimoto, and Keith Cook (retired). Membership fees have been established, and meeting attendees were encouraged to consider joining if they have not already done so. The OLED Coalition created a thorough educational brochure explaining OLED technology and the benefits to OLED lighting which they have distributed at various workshops to help educate attendees. The OLED Coalition also drafted a white paper advocating for a new manufacturing R&D topic which was included in the latest funding opportunity announcement. The OLED Coalition has also visited members of the Appropriations Committee to educate and advocate for the continued inclusion of a budget line item for SSL by explaining the future for OLED technology. Plans of future work include exhibiting OLEDs at both the Harvard Graduate School of Design's Adaptive Architectures and Smart Materials Conference, Chicago, IL (October 1-2, 2015) and DOE Technology Development Workshop, Portland, OR (November 17-18, 2015), working with Navigant to expand their lighting forecast model to include OLEDs, and working with PNNL to identify opportunities for Gateway demonstrations using OLED luminaires.

2. Enabling an OLED Lighting Future

Barry Young of the OLED Association discussed enabling a future for OLED lighting in the face of competition from LEDs. LEDs gained 5% of the lighting market in 2014, and are expected to hold roughly 10% in 2015 and 30% by 2020. Currently, OLEDs in the lighting market are practically nonexistent; however, LEDs are already losing the display market to OLEDs. OLED smartphones are expected to move from 25% market share to 75% in the next 5 years. OLED TVs have been judged to have the best performance and are on target to reach cost parity with liquid-crystal display TVs by 2017. However, as OLEDs replace LEDs in backlighting, the metalorganic chemical vapor phase deposition overcapacity situation in in China will continue to drive LED costs lower, which is bad for the competitiveness of high-cost OLEDs. Young also described the difficulties in forecasting the future of OLED lighting, citing a wide range of results from a plethora of forecasters as evidence. Problems include uncertainties in the 2015 revenues, an unrealistic tenfold difference between estimates of where we are today and where forecasts have OLEDs in 5 years, and lack of communication with OLED panel makers and those who make the forecasts. To get the necessary scientific view of what the market is and will be, there needs to be an unbiased model that is well informed from industry partners. The OLED Coalition hopes to forecast OLED panels in general illumination applications and validate that with the OLED fabrication forecast, and inputs were solicited. Young expressed that comparing LEDs to OLEDs is like comparing apples and oranges, but that the fairest comparison would consider warm color LED (higher cost and less efficient than cool) lamps for area lighting, including the cost of light guides and diffusers. The cost and efficacy of such LED lamps can be compared with an OLED panel plus the electronics. DOE forecasts LED package costs to drop to $0.50/klm in 2020, and assuming the package cost makes up 10% of the lamp cost, the lamp cost would be about $5/klm. The LG Chem roadmap for Generation 5.5 plans to price four inch square panels at $5, or $8.5/klm panel cost, by 2018 which would be competitive with $5/klm LEDs.

3. OLED-LEAP Program at the LRC: Encouraging OLED Lighting Applications

Nadarajah Narendran of Rensselaer Polytechnic Institute's Lighting Research Center (LRC) discussed their OLED Lighting Education and Application Program (LEAP) and other OLED efforts at the LRC. New York State Energy Research and Development Authority provided support for the LEAP initiative with the goal of helping New York-based companies to develop energy efficient OLED lighting products and to create market demand for lighting products that deliver value. Narendran noted that manufacturers and other stakeholders from outside of New York can partner with New York manufacturers to access the program benefits. Benefits include access to the LRC laboratory and equipment for testing, targeted research, application development; educational services; and help from the LRC team which has synergistic partners around the globe for product and market development. Other OLED efforts at the LRC include laboratory studies, education and outreach, and industry collaboration. Researchers at the LRC study optical, electrical, and mechanical properties of the OLED panels to address issues such as panel uniformity and lifetime, human factors to understand preference and response, and architectural lighting designs to look for new ways to provide value. The LRC offers short courses, open to anyone interested to help train and retrain talent in the industry, in addition to summer internships and graduate student theses to educate and engage students. The Alliance for Solid-State Illumination Systems and Technologies sponsored an eight-week summer internship for undergraduate students to investigate technology and application issues surrounding SSL. One such project explored innovative OLED luminaire design, identifying the distinguishing characteristics that make OLEDs desirable in lighting applications, identifying the best applications for current OLED technology, developing and testing concepts for an OLED luminaire, creating a working prototype of luminaire using OLED panels, and finally, surveying and evaluating the project success. Some graduate student work involves characterizing similarities and differences between edge-lit LED and OLED panels in terms of technology performance, human factors and subject preference, and luminaire design options. The LRC also performs case studies and is experienced in evaluating value propositions to specific lighting applications. Narendran commented that when it comes to adoption of lighting technologies, there is a combination of a technology push and a market pull. Lighting systems will succeed only if people can realize the benefits. Educating the public on OLED benefits and applications in which they can perform better than LEDs will help to generate a market pull, and therefore help to drive adoption.

4. Accessing the Luminaire Supplier Market

Michael Boroson of OLEDWorks described the difficulties of accessing the luminaire market. With efficacies of 40 to 60 lm/W, lifetimes of 10 to 50 thousand hours, and lumen outputs up to 300 lumens from a four inch square (Philips high brightness panel), OLED panels are ready for use and good enough for many applications (e.g., retail, healthcare, transportation, residential, industrial, and appliances/furniture). OLED panels are easy to design and build with, so they are a great opportunity for smaller luminaire manufacturers, like OTI Lumionics who just released the Aerelight OLED desk lamp. OLED performance trajectory mirrors LED in efficacy, lifetime, CRI, and cost, but it is a different experience adding thinness, light quality, direct viewing, and cool to the touch panels. This enables new designs using OLED panels, including hybrid luminaires that use both LED and OLED sources. But getting new fixture designs is not so simple. The OLED lighting industry infrastructure is lacking efficient drivers, cost effective supply, and standards. Also, the very attributes that enable new designs also challenge existing paradigms (e.g., no shades, no reflectors). There needs to be an emphasis that OLEDs are an area source and are not competing for the Edison socket. Boroson described an "80/20" rule that applies to OLEDs: "80% of people will not know what to do with it, but 20% will see it and have to have it." The current focus should be going after the 20% who want to work with OLEDs. To access the market, cost reductions, ease of use and connectivity, and reliability must all be improved. Furthermore, because OLED lighting value is very experiential, to encourage market adoption, we need demonstration installations to educate on more than just the box specifications. Boroson then engaged the community in a discussion of how OLEDs can access the market, which is described in the following section.

Discussion Summary

- Participants agreed that OLED education must be more experiential.
- Suggestions for demonstrations included:
    - State fairs which have free booth space.
    - Recreational vehicles and campers might be a good niche market.
    - A demonstration like the LG Chem panels in the library, where users can then participate in polls or studies to get feedback.
    - Ask who will pay a premium? Maybe students will, or parents of students, for their dorm room if they are durable and improve concentration.
    - Installations at science museums.
    - Undercabinet lights, because people are willing to spend on kitchen renovations.
    - Engage a marketing company to present the new technology.

- Homes of the future.
- Submit an abstract to International Association of Lighting Designers for 60 minutes to educate on and demonstrate OLEDs.
- Light Fair, a communal booth.
- A solar decathlon type competition, light project building entirely by OLEDs.
- Work with the National Institute of Health for a Gateway healthcare demonstration.

- Suggested mechanisms for funding an installation study:
    - Caliper: Laboratory
        - Must have several partners that contribute to funding.
        - DOE purchases a selection of market available lamps or luminaires through normal purchasing channels.
        - DOE tests the lamps/luminaires in the laboratory and publishes a report on the results.
        - Quantitative measurements only, no survey.
    - Gateway: Site
        - Requires a host interested in re-doing their lighting, someone either DOE or the lighting companies need to find.
        - Take data pre- and post-installation
        - Previous Gateway demonstrations have included, street lights, federal buildings, and part of the lobby of a hotel in Columbus, Ohio.
        - Requires a list of available OLED products that can be installed, and suggestions for sites who would be interested.

5. Discussion on Further Market, Education, and Outreach Needs:

Following the presentations by Ricks, Young, Narendran, and Boroson, the group discussed the following barriers to OLED adoption:

- Technical:
    - LEDs have improved quite a bit in efficacy, but OLEDs have been stuck around 55 lm/W for 18 months. Need to get to 90 to 100 lm/W to be competitive.
    - Lifetime is a barrier, and it is difficult to validate.
- Standardization:
    - Driver complexity is an issue. Having a certified driver that has the correct current-voltage characteristics would help luminaire manufacturers.
    - Standardizing the voltage per panel so that drivers are compatible with more than one company's panel.
    - Standard size panels would be required to match the form factor in order to allow for multiple panel manufacturers fulfilling panel supply for one luminaire design.
- Certification differences for LED vs OLED:

  - UL certification 1598. Class 2 current/voltage limitations are all the same. LM79 is also same. There are no internationally recognized standards on panels. But luminaires are the same for LEDs.
  - Restrictions on selling replacement panel because of sharpness of edge and thickness issues.
- Cost:
  - Which would you rather buy, a 50 lm/W panel at $5 or a 90 lm/W panel for $30?
- Market:
  - Need one uniform message when it comes to OLED benefits.
    - Perhaps targeted brochures for benefits of OLEDs in each application.
  - Car companies are using OLEDs in tail lights of cars, and that might be the first mass market for OLED. OLEDs offer benefits over LED automotive products today.
  - Go for the decorative integrated luminaire market and small manufacturers who would appreciate innovative luminaires.
    - OTI, Black Body, LiteControl
  - Architects are early adopters, and we can target events to reach them.
  - Gateway demonstration requires a commercially available example of how they perform and where you can buy them. May need to use a prototype to become available before end of demonstration.

10. Closing

There was widespread agreement that cost reduction and market demand remain the key issues facing the OLED industry.

Key priority R&D areas voiced include:

1. OLED Materials
2. OLED Substrates and Encapsulation
3. OLED Light Extraction
4. OLED Panel and Luminaire Manufacturing
5. Market, Education, and Outreach

DOE would like to thank all attendees for their participation and for their valuable insights into what needs to be done to help the OLED industry overcome the challenges it faces, as well as how DOE can facilitate that process. It is active participation from members of the OLED community, and collaborative efforts initiated between research groups as a result of this meeting, that will continue to drive the technology forward.