2016 OLED Stakeholder Meeting Report

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COMMENTS

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1. Introduction

The 2016 organic light emitting diode (OLED) Stakeholder Meeting was convened by the U.S. Department of Energy (DOE) Solid-State Lighting (SSL) Program, hosted by Corning Inc. and open to members of the U.S. OLED lighting community with the purpose of fostering open discussion concerning the development of OLED lighting.

In total, 46 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.

A total of 23 participants volunteered to give presentations on critical R&D areas and market challenges for OLEDs. The presentations and resulting discussion, described in Sections 2 through 10 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.

Day 1 of the meeting began with Thomas Wehlus presenting on past, present, and future OLED topics being pursued at OSRAM. This was followed by discussions of OLED light production, supporting structures, market evaluations, impressions from the field, and the OLED value proposition for lighting fixtures. The day concluded with a brainstorming session on how to exploit the value proposition to jumpstart the OLED market.

The second day of the meeting shifted focus to opportunities for manufacturing R&D. John Hamer of OLEDWorks provided a panel manufacturer's perspective and was followed by presentations on innovative manufacturing techniques and opportunities for roll-to-roll (R2R) manufacturing of OLEDs in the U.S. A brainstorming session on manufacturing technology gaps followed the presentations, and then attendees broke out into small groups to further discuss the issues facing the OLED community. The day concluded with an update from the DOE SSL Program and then attendees were given an opportunity to tour OLED installations at the office of DKB Accounting in Rochester, NY.

2. OLED Development at OSRAM: Past, Present and Future Topics

Thomas Wehlus of OSRAM opened the meeting by discussing past, present, and future OLED topics being pursued at OSRAM. Wehlus explained that the first area of interest in the pursuit of OLEDs at OSRAM was general illumination, but they decided to refocus on automotive OLEDs in 2012. The performance of panels was good enough for general illumination, but concerns about high costs encouraged the shift to automotive lighting where cost is less of an issue, and lighting is strongly design driven. It is also the hope that addressing automotive applications first may later enable general illumination OLEDs. However, as a result of the more extreme operating environment, automotive applications have different requirements than general illumination. For instance, high temperature, high humidity, corrosive gases, and direct ultraviolet (UV) exposure are challenging issues during both operation and storage.

Why does OSRAM pursue OLEDs? Wehlus explained that unique OLED features (e.g., ultra-flat, light weight, thin, segmented, mirror finish, transparency and flexibility) enable completely new design options for many applications, including automotive lighting. OLEDs can be a mirror in the off-state, which allows seamless integration in mirrors and high quality aesthetics. Segmenting OLEDs with a minimized gap between sharply defined addressable segments, and differing brightness levels for these segments, allows for the creation of 3-dimensional effects (e.g., shadowing, animation). This is another key differentiating opportunity because it is very difficult to accomplish with inorganic light emitting diodes (LED) and is desirable for taillight design. Wehlus noted that transparent OLEDs currently have efficacy penalties because they cannot use traditional light outcoupling methods effectively, but that it remains an area of interest for OSRAM. Flexible OLEDs are the next technology evolution that the automotive industry is looking for. OSRAM has a flexible automotive technology demonstrator for tail lights, but more development is needed to establish that they can survive in harsh environmental conditions. Currently their focus is on rear (tail) lights, but they expect to pursue interior lighting, stop (brake) light indicators, and accent lighting in their future automotive application roadmap. To make this happen, Wehlus emphasized the need for better organic materials and stack development, flexible OLEDs to be automotive ready, price decreases (perhaps through R2R), surface refinement, and personalization/individualization of OLEDs.

3. OLED R&D Talks: OLED Light Generation

Efficient and Stable OLEDs Employing Square Planar Metal Complexes

Jian Li of Arizona State University presented work on square planar metal complexes for efficient and stable white OLEDs. These complexes produce blue-green light (monomer emission), or orange emission (excimer emission) when the molecules are stacked. The combination of blue-green and orange light can produce white light from a single emitter if the ratio of monomer and excimer emission is appropriately balanced. The appeal of these materials is the voltage independent spectrum, simple structure, and manufacturing ease (and therefore lower cost). Further, improved energy transfer from blue to red emitters, and improvements in differential aging and color changing over time, is expected. Li explained that they first examined platinum (Pt) based phosphorescent excimers, but are now exploring palladium (Pd) based excimer complexes with promising results. In practice, they have achieved good stability, with L_{70} lifetime (the time it takes until emitted light reaches 70% of the initial output) in the range of 5,000 to 8,000 hours at 1,000 cd/m^2, but they need to improve efficiency. They have explored the formation of aligned layers and the effect of narrower line shapes on light extraction. Effort continues to improve external quantum efficiency (EQE) and produce balanced monomer/excimer emission, with the ultimate goal of commercializing a single doped white OLED.

NONcrystallizable™ OLED Technology

Mike Molaire of Molecular Glasses presented his company's NONcrystallizable™ OLED technology, which he believes will help bridge the gap between the two previous classes of OLED materials (i.e., small molecule and polymer). OLED organic layers are expected to be amorphous upon deposition and to remain in their amorphous state for proper device performance and longevity; however, crystallization can occur, negatively impacting devices. Molaire indicated that the materials produced by Molecular Glasses are structured to prevent aggregation and crystallization without compromising performance. This allows for an amorphous structure at all device conditions throughout the entire lifetime of the device. Further, the materials have a high entropy of mixing and are excellent solvents for dopant emitters which is expected to improve device performance and lifetime. The materials are compatible with current vacuum processes as well as future solution printing opportunities. The synthesis of these materials employs conventional building blocks, but modifies the structure of material mixtures so that they cannot align to crystallize. They will not melt or crystallize, even after thermal cycling. Molaire showed one example of their host material, Molaicular™ HT-1700, which was completely transparent, and no crystallization developed even after 144 hours at 125°C. By comparison, a conventional material host, NBP, crystallized and appeared foggy after only 20 hours.

Molaire explained that five state-of-the-art NONcrystallizable™ materials from Molecular Glasses had recently been tested through the DOE testing opportunity. Compared to the mCBP control material, they saw up to 28% improvement in EQE and impressive lifetime improvements. Specifically, the NONcrystallizable™ OLED materials demonstrated value with 6 to 15 times lifetime improvements, high quantum efficiency (20% EQE), excellent exciton/electron-blocking characteristics, superior thermal/vacuum deposition characteristics, and good solubility of the dopant emitter.

Hyperfluorescence™, a 4th Generation solution to Current OLED Technical Challenges

Christopher Savoie of Kyulux presented on Hyperfluorescence™, a possible solution to current limitations of conventional fluorescence and phosphorescence processes. Fluorescence has low efficiency because it takes advantage of only the singlet state; however, it is completely organic, low cost and can yield deep blue color. Phosphorescence has higher efficiency because it employs singlet and triplet states but has limited design, high cost, and difficulty with deep blue stability. Thermally activated delayed fluorescence (TADF) takes advantage of compounds that, under high heat conditions, will spontaneously fluoresce as high heat triplets flow following the singlet path. Savoie indicated that this can be accomplished at room temperatures using high electricity, and it is possible to achieve 100% internal quantum efficiency (IQE). Actual device EQE has reached 22.5% at this time. Unfortunately, there is a wide emission spectrum when combining singlet and triplet energies in TADF, which is a big problem for display applications, and lighting would benefit from narrow red and narrow blue emitters as well.

Savoie proposed a next generation solution called “hyperfluorescence”, which enables fluorescent material emission using TADF to harness triplet energy plus fluorescence material with a slightly lower singlet energy state. This would result in a narrower emission and higher intensity than from either TADF or fluorescence alone. However, it requires a precise combination of multiple materials - TADF (exciton generation), fluorescence (emission), and stable host materials. Savoie described their use of computational R&D and quantum simulation to identify candidates for testing which creates feedback to focus and improve computational screening.

4. OLED R&D Talks: Supporting Structures

Low Cost Corrugated Substrates for OLEDs

Norman Bardsley, on behalf of Franky So of North Carolina State University (NCSU), presented on low cost corrugated substrates for OLEDs. The strategy employs moving the emitting layer away from the cathode to suppress the surface plasmon polariton (SPP) mode and using a buckle structure to suppress both thin film guided mode and SPP mode. The challenge in buckling is to achieve a high ratio of corrugation depth to nominal horizontal periodicity, while avoiding complete periodicity. Sub-micron structures have been created by imprinting and by etching through an irregular mask. NCSU has achieved corrugation depths of 90 nm with quasi-periodicity of 260 nm and has demonstrated that the color does not vary significantly with angle. Further, experiments have shown that their buckling technique does not introduce leakage current, yields a 56% enhancement in cd/mA and 87% enhancement in efficacy. Their new project targets 70% EQE.

Overview of Pixelligent’s OLED Lighting Program

Gregory Cooper of Pixelligent presented an overview of Pixelligent’s OLED program, which focuses on nanocrystal dispersions for improved light extraction. The dispersions are fully uniform and create fully uniform films. Clumping of the nanocrystal additives is prevented because they are coated with capping agents that make them soluble, individual nanoparticles. Even at high loadings, films are still highly transparent (with up to 95% transmittance). Furthermore, a wide choice of solvents, nanocrystals, capping agents, polymer types, curing conditions, molecular weights, additives, loading, and polymer to nanocrystal ratios, makes the technique broadly compatible. Pixelligent nanocomposites have high refractive index, high transparency, low haze, and low absorption. Scatterers can be incorporated into the high refractive index layer to assist in OLED light extraction. Pixelligent has four generations of light extraction structures. Generations 1 and 2 involve a high index smoothing layer with scatters at the interface (Gen 1) or dispersed within the high index layer (Gen 2), whereas generations 3 and 4 involve graded index layers that can be used to control light distribution. The graded index layers can be formed by varying the nanocrystal loading in the film. Scatterers or internal structuring of the film can be used to extract and possibly direct the light.

There are remaining questions to resolve in the manufacturing of light extraction structures, namely how to make it compatible with inkjet printing, how to get the formulation to stick to rigid glass, and how to reformulate in real time. Additionally, Cooper proposed new terminology to more accurately describe light extraction. Currently "internal" and "external" are used to refer to the physical location of the extraction layer, and internal is assumed to be more efficient. However, Cooper proposed that the index of light extraction matters more than where it is physically located, and he suggested using "high index" and "low index" to refer to the optical location, knowing that high index has the potential to be more efficient.

Integrated OLED Substrates for Low Cost and Enhanced Light Extraction

Quibing Pei of the University of California, Los Angeles presented work on integrated OLED substrates for low cost and enhanced light extraction. The underlying motivation is that with conventional indium tin oxide (ITO) on glass substrates, extraction structures must be added to overcome inefficiencies, and while the device may be stable, efficient, and bright enough, the cost is very high. Pei described how integrated structures with silver nanowires and carbon nanotubes can be used in place of ITO. The silver nanowires and carbon nanotubes are embedded in the polymer substrate surface so that the surface roughness remains suitable for OLEDs. The starting materials are deposited via a solution-based, low temperature process, and then they are put in a vacuum to dry and UV cure. The process can be quickly scaled up using sheet-to-sheet equipment developed for flexible active matrix-OLED displays. Pei says the resulting structure is very simple compared to today's high performance OLEDs, and it is two times more efficient than ITO/glass OLED experimental controls. Internal light extraction can be added to the formulation/architecture. Data showed close to 50% EQE and 2.5 times light enhancement results from a yellow/blue, vapor-deposited triplet system, yielding warm white OLEDs at 1000 cd/m^2 with 110 lm/W. Silver nanowire-based electrodes usually have low stability at temperatures above 200°C or at high current density; however, Pei's group uses a conformal coating of a protective material and a thermally stable polymer in order to improve stability. With zinc or aluminum oxide to protect silver nanowires, the nanowire network remains intact after 300°C for 30 minutes or 155 mA/cm^2 for one hour. Pei believes the integrated substrate is a viable replacement for ITO/glass and external light extraction structures, with added benefits of improved efficiency and possibilities for R2R production.

Driver Solutions for OLED Luminaires

Mike Lu of Acuity Brands presented his perspective as a luminaire manufacturer on the topic of OLED driver solutions. Using existing LED driver solutions for OLEDs presents challenges, particularly when OLED panels short and fail. Panel voltages are approximately 3V per stack, so multi-stack solutions bring panel voltage to 6V or 9V for two and three stack devices, respectively. Additionally, panel voltage increases due to aging. The UL Class 2 limit is 60V direct current (DC), which means the number of panels that can be put in series is limited to about eight panels. But, for a reasonable amount of light, dozens of panels per luminaire are needed. One option is to use multiple drivers to run strings of panels in single series. Alternatively, panels can be run in parallel, but if one panel shorts the other panels in that series are brighter, while the parallel series panels are all dimmer. In early luminaires, Acuity used multiple drivers in order to keep panels in single strings. Additional driver requirements include power factor (>0.9 for commercial, >0.7 for residential), dimming (down to 1% and even 0.1% are becoming industry standards), and flicker. Lu also discussed the current Acuity driver solutions for OLED luminaires. For large luminaires with many panels (6W to 100W), Acuity uses programmable drivers that are tuned to the number of panels in a fixture. These are also used for LED luminaires and are up to 87% efficient. For smaller luminaires and lower wattage devices (less than 5W) Acuity uses a custom solution which is much less efficient. Neither constant current reduction (CCR) nor pulse width modulation (PWM) is a perfect solution. CCR is not great for dimming at low levels, and PWM has issues with flicker. Hybrid HydraDrive™ is a possible solution that has intrinsically much less flicker, and it acts like CCR at high lumen output and PWM at lower lumen output.

Lu also provided an update on Acuity's work on a DOE funded project to create an OLED luminaire with panel integrated drivers and advanced controls. The proposed architecture has a base station that performs alternating current/direct current (AC/DC) voltage conversion and an integrated driver at each panel that performs DC/DC current regulation. This allows each panel to interpret the power line communication to determine how bright it should be, providing single strand data integrity over multiple panels. Lu demonstrated that panels within two strands of 11 panels could be individually turned on/off and dimmed using this architecture.

5. Market Evaluations

An Introduction to the OLED Coalition

Michele Ricks of EMD Performance Materials provided a quick introduction of the OLED Coalition before moderating a segment on the market for OLEDs. Formed in 2013, the OLED Coalition is a group of U.S. companies and advocates of OLED technology joined together to be the recognized voice for the U.S. OLED general lighting industry. Their mission includes promoting the industry to the government, public, and the lighting community as well as providing consolidated industry inputs on standards, as appropriate. Ricks provided an update on recent Coalition activities, which included creating a brochure for OLED lighting, demonstrating products to educate attendees at relevant conferences, holding their first workshop for designers and manufacturers in May 2016, drafting white papers advocating for new topics to be included in DOE funding calls, and visiting members of the Appropriations Committee to educate and advocate for the continued inclusion of a budget line item for SSL.

On May 16, 2016 the OLED Coalition hosted a workshop at the California Lighting Technology Center in order to foster the development and growth of the domestic OLED lighting community and provide cross-educational opportunities between lighting designers, luminaire manufacturers, and OLED panel manufacturers. At the workshop, panel manufacturers learned the importance of user defined form factor (size and shape) and that round is highly desired. Luminaire manufacturers learned that cost and performance have improved dramatically in state of the art OLEDs. Lighting designers began brainstorming how they could use OLEDs to solve real problems in the field by taking advantage of unique OLED properties such as thinness, flexibility, and mirror off-state. Due to the success of this first workshop, a second annual workshop is tentatively planned for June 2017, in Chicago adjacent to NeoCon.[1]

OLED Lighting Products: CALiPER and Capabilities

Naomi Miller of Pacific Northwest National Laboratory presented her observations of the capabilities, challenges, and potential of OLED lighting products, based on recent efforts to help the OLED industry through Gateway studies and evaluations of commercial luminaires. The first OLED Gateway case study, published in March 2016, documents the successes and challenges of an OLED installation project at the Aurora Lighting Design offices in Grayslake, IL.[2] Additionally, an overview report on OLED technology and applications was published in May of 2016.[3] Lastly, a CALiPER report based on independent testing of off-the-shelf OLED lighting products (including accelerated testing and laboratory tear downs) was published in October of 2016.[4] Additional Gateway studies are expected to continue to track future OLED performance.

Miller emphasized that one of the biggest challenges for OLED lighting is the driver. There are very few dedicated OLED drivers, and LED drivers need to be strung together which results in low overall efficiency. Further attention must be paid to dimming methods because PWM modulation is often used for LEDs but CCR is preferred for OLEDs. Additionally, power draw requirements may increase 33% over the lifetime of the panel because OLED panel impedance increases as it ages. This results in voltage and wattage rise over time in order to maintain a constant current, so the driver needs room to maintain target current. Manufacturers must communicate the end of life power draw so that lighting and dimming circuits can be designed for their full loads and energy code compliance documentation reports the maximum loads. Driver efficiency is another issue, and CALiPER testing of products showed between 47% and 80% driver efficiency.

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[1] For more information on NeoCon please see: http://www.neocon.com/

[2] For more information on the OLED Gateway project please see: http://energy.gov/eere/ssl/articles/doe-publishes-gateway-report-oled-lighting-office-setting

[3] OLED Lighting Products: Capabilities, Challenges, Potential available at: http://energy.gov/eere/ssl/downloads/oled-lighting-products-capabilities-challenges-potential

[4] For more information on the OLED CALiPER project please see: http://energy.gov/eere/ssl/articles/doe-publishes-caliper-report-testing-oled-luminaires

CALiPER testing found that OLED system efficacy of available architectural products in 2016 ranged from 23 to 45 lm/W. The panels were reported as 40 to 50 lm/W (per manufacturer data), and driver efficiency caused a big hit. The average efficacy of LED commercial luminaires listed in the DOE's LED Lighting Facts®[5] database was 86 lm/W in 2014 and 98 lm/W in 2016, showing that OLEDs are still lagging in performance. However, unlike early LEDs, claimed performance of the OLED luminaires matches actual tested performance really well, and manufacturers are not wildly exaggerating products.

Other OLED challenges include maintenance issues, durability, and cost. Lifetime claims range from 10,000 to 100,000 hours (L_{70}), and panels must be replaceable in the field. Glass panels can be fragile, and that makes shipping and installation difficult. It is yet to be determined if OLEDs can be safely shipped in the luminaire or if they will be shipped separately and installed on site. OLED system cost also remains a real issue. Task lights can be affordable, but other products are limited to specialty items because of high system cost; however, panel costs are dropping and mass production methods may further decrease costs dramatically. Until then, economic viability is strained compared to LED technology, and edge-lit LEDs and micro-LEDs (in development) will be tough competition. However, OLEDs can also set themselves apart from LEDs through their excellent uniformity, lack of shadows/highlights, and thin flexible form factors.

Reliability Testing of OLED Luminaires

Lynn Davis of RTI International presented the method and results of reliability testing that was recently conducted on commercially available OLED luminaires. Davis explained that with LEDs, they have used harsh conditions for testing (assuming LEDs were robust) and found they performed very well, but with OLEDs they used more mild stresses in the testing. The first test was to bake a 5 panel luminaire running at 150 mA in an oven at 45°C. A temperature of 45°C was chosen as a mildly accelerating stress level because it is used in CALiPER studies for PAR38 and A-type lamps, and it is the temperature for the ENERGY STAR® elevated temperature test. One of the five panels failed early, at around 500 hours, and power consumption dropped. Complete failure occurred at 1,750 hours and the electrical failure in the driver was traced to the metal-oxide-semiconductor field-effect transistor (MOSFET) which likely was caused by changes in driver load due to a second panel failure. Additionally, impedance of OLED panels increased by a statistically significant amount after 4,000 hours of 45°C operation and was consistent with an electrical short. The decay of luminous flux could be fit with either an exponential or linear model with high accuracy, but assuming a linear model, the time to reach L_{70} in 45°C ambient is about 10,000 hours. The OLED equivalent of LM-80

[5] For more information on the DOE LED Lighting Facts® program and a database of listed LED products, please see: http://www.lightingfacts.com/

and TM-21 measures do not yet exist. The chromaticity shift of the OLED panel was towards the blue, and spectral changes point to reduction in emissions from green and red phosphorescent emitters, relative to the blue fluorescent emitter, as the cause for chromaticity shift.

OLED luminaires were also tested in a more aggressive accelerated lifetime testing environment. Davis reported that luminous flux decay rate speeds up at higher temperature and higher currents, and chromaticity shift continues in the blue direction due to faster reduction in green and red emissions relative to blue. When the OLED luminaire was tested at 75°C and 75% relative humidity for 1,000 hours, one of the five panels failed within 750 hours and the metal backplane disappeared. However, Davis noted that while this environment is common for LEDs, it is extreme for OLEDs.

Energy Savings Potential of OLEDs in Select Applications

Kelsey Stober of Navigant presented the DOE SSL Program's U.S. lighting market model and the results of a scenario forecasting OLED potential in select general illumination lighting applications. In September 2016, DOE published the seventh iteration of the *Energy Savings Forecast of Solid-State Lighting in General Illumination Applications* forecast analysis, hereafter referred to as the "Forecast Report", a now biennial report from the DOE SSL Program.[6] As in past iterations, this study provides updated predictions of LED market penetration and energy savings compared to conventional lighting sources – incandescent, halogen, fluorescent, and high-intensity discharge – in all general illumination applications from present-day through 2035.

In the report, the expected annual lighting energy consumption is described using two scenarios: The Current SSL Path which describes the expected future path for LED lamps and luminaires given continuation of current levels of SSL investment and effort from DOE and industry stakeholders. And the DOE SSL Program Goals, which predicts the future path for SSL given DOE goals outlined in the annual SSL R&D Plan are met. However, in the report, neither of these scenarios include the impact of OLED technology.

In response, the OLED Coalition approached the DOE SSL Program about leveraging the existing U.S. lighting market model to develop future projections for OLED adoption. Using input from the Coalition for OLED price and performance improvements the energy savings opportunity for OLEDs was evaluated using the conditions described in the Current SSL Path scenario. The model exclusively evaluated OLED luminaires in the decorative and linear fixture submarkets for both the commercial and residential sectors, and projected that by 2035, 366 million OLED luminaires would be installed in the U.S. This represents a 15% installed

[6]The 2016 Energy Savings Forecast of Solid-State Lighting in General Illumination Applications is available here: http://energy.gov/sites/prod/files/2016/09/f33/energysavingsforecast16_2.pdf

penetration into the decorative and linear fixture submarkets by 2035. Looking at the total U.S. lighting market, these 366 OLED installations represent 4% of all U.S. lighting installations, while LED lamp and luminaires combined make-up about 83% of installations. In terms of energy savings potential, by 2035, OLEDs are projected to contribute an additional 164 tBTU annually of source energy savings over a scenario that considers LEDs only. The majority of this additional energy savings is projected to come from OLEDs in the commercial linear fixtures submarket.

6. Impressions from the Field

Observations on OLEDs: Feedback from Conference Attendees

In the past eight years, Jack Curran of LED Transformations has spoken to over 12,000 attendees at various conferences and conventions around the U.S. on the subject of SSL technology. He discussed his observations and feedback from presenting to those in the lighting community who are unfamiliar with SSL (e.g., architects, specifiers, facility managers, building owners, electrical contractors, and lighting distribution companies). Today, on average, 15% of his audience claims they have familiarity with OLEDs, while only 5% have actually worked with them. On the contrary, when he started presenting on LEDs years ago, 60% of his audience had some familiarity with LEDs and 20% had experience working with them. These differences suggest that the progression of OLED technology is more than six years behind LED. Curran went on to describe the kinds of questions his audience asks during his OLED talks. These include:

- Where can I see and/or buy them?
- Are they better than LEDs?
- Why are they not brighter?
- What is the largest size they come in?
- Can they be dimmed, and how low will they go?
- How long do they last, and how reliable are they?
- Are OLEDs real?

Curran also explained that his LED and OLED presentations are not equivalent in terms of the demonstration equipment he is able to leverage. When he presents on LED technology, he has polished demonstrations, while for OLED he only has access to a rugged panel and driver configuration. Additionally, Curran indicated that the lighting community frequently asks about the Acuity OLED fixtures available at Home Depot for under $300, but show a lack of interest in large, high cost luminaires. High cost and the absences of OLED at accessible retailers are the largest turn-offs for audiences when it comes to OLED technology. However, the lighting community is very interested in the potential for flexible panels, transparent features, and mirror finish in the off-state, as well as the light color and glare-free look. Curran concluded his talk with the following suggestions for the OLED industry in order to accelerate adoption:

- Increase the availability of OLED samples and professional demonstrations
- Publish standards
- Pursue product designs that combine LED and OLED technology
- Examine customer interface to assess whether it is user-friendly
- Address the gap between technology development and market awareness
- Push driver manufacturers to provide LED/OLED compatible units

7. How to Exploit the Value Proposition to Jumpstart Market

7.1. Participant Presentations

OLEDs – A Fixture Manufacturer's Perspective

Jay Eissner of Visa Lighting presented their perspective as an architectural lighting style manufacturer focusing on build-to-order fixtures specified by architects, lighting designers, and electrical engineers. Visa Lighting has been building OLED prototypes and technology demonstrators since 2013. In terms of lighting design, OLEDs are appealing because of the slimness, unique design opportunities, no glare, great appearance on or off, as well as the "cool-factor" derived from newness. However, there are numerous challenges including high cost, low lumen output, small panel size, low efficacy, short lifetime, low durability, and limited replaceability in the field. Furthermore, people just are not sure where or why to use them. Eissner also cautioned that all luminous ceilings should not be part of the OLED value proposition, since this may be easily done with less expensive technology, and it does not highlight the unique design benefits that OLED technology can provide. In terms of engineering and manufacturing, OLEDs are appealing because they do not require circuit boards, and heat management is simple. However, many challenges remain, including: lack of robustness for current assembly techniques, early "flexible" OLEDs not being flexible enough, high minimum purchase quantities, and power conversion devices that are too bulky compared to the panels.

Enabling Technologies to Bring OLEDs to Lighting Fixture Market

Mike Fusco of LED Specialists discussed their efforts to develop electrical and mechanical OLED panel accessories to facilitate OLED adoption as part of a development project that is co-funded by the New York State Energy Research and Development Authority (NYSERDA). The project is currently in the first phase, market research. The project development areas include power distribution (power conversion methods, power over Ethernet, maximizing efficiency, low voltage fixture wiring interconnects, OLED array interconnect scheme), OLED specific drivers (efficiency, small size, thin profile), controls (wired, wireless, by panel, by fixture, by group), and mechanical interconnection (panel attach tool-kit, scalable OLED arrays, flexible fixtures and shapes, ease of mounting).

7.2. Brainstorming Session

A brainstorming session seeking ideas for how to exploit the value proposition of OLEDs to jumpstart the OLED lighting market was moderated by Mike Hack of UDC. The content of this session is summarized below.

- **Question**: What are the main reasons the market is not growing faster?
  - Cost:
    - Participants suggested that given the current high cost of OLEDs, it is important to be able to quantify the benefits of OLED lighting in order to justify paying more for an OLED fixture. For more expensive LEDs, the value proposition is that they save quantifiable amounts of energy costs. For OLEDs it is difficult to convey qualities such as appealing light or cool to the touch that cannot be described quantitatively.
    - Other participants indicated that cost is not so much of an issue as the pricing on Home Depot OLED products is competitive, and that there is a clear pathway to lower cost panels that can be achieved with time.
  - Efficiency:
    - Some participants indicated that efficiency may be an even bigger problem than cost right now, noting that there has not been any significant efficacy improvements in commercial OLED panels in recent years, and that they are stuck around 60 lm/W.
    - While some participants raised concerns that the low efficacy of panels meant that they would have difficulty competing with LEDs, others felt current OLED efficiency was adequate for commercial products.
  - Quality:
    - Some participants indicated a need to address quality issues such as early failures, lifetime, visual experience, and uniformity.
  - Competition with LEDs:
    - Participants indicated that for small/medium luminaire makers, all of the LED hype and potential distracts from OLED potential.
    - To successfully compete, participants asserted that OLEDs must produce a functional amount of light from a single device with the unique technology that looks great.
    - In addition to lower cost panels for general lighting, a parallel track for OLED lighting that emphasizes aesthetics and design would allow for unique OLED products are visually identifiable.
  - Lack of awareness:
    - In general, participants agreed that lack of consumer awareness and understanding of OLEDs is a major obstacle to OLED adoption.

        - Some suggested that more effort in marketing the real recognizable products out there right now is needed, as opposed to discussing hypothetical future OLED products.
        - Participants also indicated that OLEDs would benefit from a killer initial application that would be immediately recognizable and give consumers hands on experience with OLEDs, like flashlights were for LEDs. It was suggested that automotive tail lights may be it, but cautioned that unless car companies advertise them as OLEDs, people would not recognize them.
- **Question**: What can DOE do to help?
    - Education efforts
    - Helping to get rebates in place
    - Install OLEDs in government buildings
    - Create specifications and standards
    - OLED luminaire funding opportunities

8. OLED Panel Manufacturing

John Hamer of OLEDWorks presented his perspective as an OLED Panel Manufacturer. In the next 10 years, Hamer envisions only solid-state lighting being installed, shared between LED and OLED. He believes that OLEDs will be favored in applications that are close to the user (because of low glare, low temperature, and broad spectrum) and applications that use the unique form factor of OLEDs (e.g., having special design elements that take advantage of thin, light weight, and/or curved panels).

Current panel prices put the industry slightly ahead of the IDTechEx predicted cost curves, but current adoption puts OLEDs behind their market predictions. Yole Developpement projects that OLED panel revenue could grow by more than 10 times in the next five years. Typical performance of today's OLEDs includes roughly 60 lm/W efficacy, 50,000 hour lifetimes, and excellent color rendering, with CRI greater than 90 and R9 greater than 50. While efficacy is expected to improve, today's performance is already suitable for most applications. Hamer also noted that an OLEDWorks Brite 3 panel with 80 lm/W is due for release in 2018. In addition, Acuity has seen an 86 lm/W demonstrator panel from LG, but it has not been made widely available yet.

Hamer provided a look at the price of OLEDs, and explained why he believes they may not need to reach cost parity with the price of LED packages. In the DOE SSL Program R&D Plan[7], DOE estimates the cost of OLEDs decreased to about $200/klm in 2016, and prices have fallen further

[7] The 2016 Solid-State Lighting R&D Plan is available at: http://energy.gov/eere/ssl/downloads/solid-state-lighting-2016-rd-plan

to approximately $100 to $150/klm in large volumes. Further cost-reductions for OLEDs can come from lower-cost organic materials (while increasing lifetime and efficacy), higher yields, lower-cost electrical interconnects, lower-cost encapsulation, and lower-cost integrated substrates. The R&D Plan estimates that $2/klm and 130 lm/W was typical for a warm-white LED package in 2015. But for most LED luminaire products, the dominant subsystem cost has become thermal/mechanical/electrical components, which represent the housing, heat sinking elements, electrical connectors, and mechanical fasteners. OLED luminaires, on the other hand, have no optical parts, no thermal parts, simpler electrical parts (fewer panels than LED packages for complimentary luminaires), and simpler mechanical parts (due to lighter weight). Having a simpler design and fewer parts also means lower assembly costs. Hamer demonstrated through a hypothetical example using an LED downlight, that if the overhead and driver costs were the same for an OLED, while the assembly cost was 33% lower due to fewer parts, the thermal/mechanical/electrical components were 66% lower due to simpler design, and there were no optics costs, fixture cost parity was possible at an OLED price of $20/klm. On the current path, it is possible for OLEDs reach this parity by 2020, or a bit later due to on-going cost reduction in LED fixtures. Furthermore, LEDs are not perfect, and they are designed with various tradeoffs in mind (e.g., to reduce costs, they can use fewer LEDs and drive them harder, but that reduces efficiency, reduces lifetime, and reduces reliability). Tradeoffs will be necessary for OLEDs too, and will be acceptable as long as they stay at the high quality end of the spectrum.

Hamer also discussed new activity in OLED lighting, and their implications on the OLED market as a whole. LG Display announced their Gen 5 production line that has been predicted to bring costs down by 10 times, and R2R projects exist in Europe (Pi-Scale), Taiwan (ITRI), and Korea (GJM). Currently, reaching lower cost is the main challenge, and this will come with larger scale machines and higher industry volumes. Therefore, Hamer indicated that the OLED industry needs to generate larger volumes to get costs down, but that is difficult to do given low demand at current prices. Moving to flexible panels and R2R manufacturing are commonly discussed options for addressing these issues and progress is being made on both. Flexible barrier-coated plastic substrates are under development, and LG Display has plastic-based OLED light panel samples, although issues with shorting exist when they experience bending at small radii. Glass has also been considered, but there are challenges regarding electrical contacts and robustness. Furthermore, Hamer believes the Gen 5 sheet-cut machine being developed by LG (set to be operational in 2017), will be the next step to enable lower cost. To further cost reduction, the industry will need to develop R2R processing. Hamer also indicated he is uncertain as to whether moving from Gen 5 rigid to Gen 5 flexible or Gen 8 rigid would be more beneficial. However, if the industry is prioritizing flexible manufacturing, now is the time to start developing and commercializing these technologies. Hamer also identified masking for vacuum thermal evaporation deposition and substrate handling and transport as two areas of OLED R&D which particularly need improvement.

9. OLED R&D Talks: Innovative Manufacturing Techniques

Roll-to-Roll Holography for OLEDs

Seth Coe-Sullivan of Luminit described holography, its compatibility with R2R processing, and the opportunities for holography for OLED lighting. Light shaping diffusers (LSD), which mimic diffuser function with surface relief, are enabling the application of holography to both lighting and displays. Holographic recording uses interference of laser beams to make pseudo-random patterns (either symmetrical or asymmetrical) that refract light at the surface. Coe-Sullivan explained that surface relief is possible without loss from scattering sites or particles, so there is no wavelength dependence. Luminit has numerous commercial products, and their largest market is currently LED lighting. However, Coe-Sullivan believes their technology can be applied to OLED lighting as well. LSD is manufactured on R2R for both flexible and rigid substrates, and Luminit has a manufacturing plant in California that is shipping more than 1,000 rigid panels per month and more than 100,000 R2R linear feet per month. Coe -Sullivan explained their existing facility is ideal for producing OLED light extraction films. LSD is currently used for external light extraction, but could also be applied to internal light extraction. The microstructure can be replicated in high or low index materials and designed for positive or negative images. Furthermore, Coe-Sullivan indicated that Luminit can fabricate computer generated arbitrary (or proprietary) designs inexpensively. In conclusion, Coe-Sullivan highlighted that emerging holographic products (such as holographic optical elements for augmented reality) have many properties that would be beneficial to OLED lighting applications.

R2R Manufacturing of Enhanced OLED Substrates

Dennis Slafer of MicroContinuum discussed their project to develop an enhanced, flexible substrate for OLED deposition that is compatible with R2R manufacturing and has improved light extraction and transparent conductor performance, as well as an incorporated barrier layer. For improved outcoupling, they use two integrated outcoupling structures, an internal periodic nanoarray and an external diffraction optical element (motheye). Slafer described how a continuous metal micromesh transparent conductor is then used to reduce resistive losses by acting as a high current-carrying backbone over a field conductor (e.g., ITO, PEDOT:PSS, or silver nanowires), which bridges non-conductive areas between the metal grid, creating continuous conductivity over the entire surface. Because it is secondary to the metal mesh, the field conductor can be thin, which alleviates issues with expense, transmissivity, surface smoothness, and tendency to crack. The R2R formation of internal and external extraction structures begins with the substrate selection, and possible substrates include polycarbonate, polyethylene terephthalate (PET), or polyethylene naphthalate (PEN). The selected substrate then moves through the imprint station. Slafer indicated that while it is possible to print the internal pattern on one side and the external pattern on the other, this creates challenges when including the barrier coat. Instead, MicroContinuum processes the integrated substrate as two separate pieces, using one roll for each side. They then bond the pieces together with the barrier film resulting in the laminated structure. In addition, the metal mesh and field conductor must be conformal with the nanopattern to ensure that the OLED stack contacts the anode. Slafer indicated that this is accomplished with subtractive processing, which allows for increased line thickness, thereby increasing conductivity, without an increase in surface roughness since the metal lines are below the nanoarray surface. Micro Continuum's vision is to develop an integrated substrate technology (with extraction features and a metal conductive grid) such that it is ready for OLED deposition and compatible with R2R processing.

Innovative Manufacturing Techniques: Integrated Substrates for OLED Lighting

George Burkhard of Sinovia presented their work on a DOE funded project with the goal of developing flexible integrated substrates for OLED lighting. Sinovia believes moving to flexible OLEDs is key to increasing adoption, and that plastic substrates have a number of advantages that will help enable this transition. In particular, Burkhard indicated that plastic substrates are lightweight, durable, create freedom in luminaire design, and involve lower cost materials and less expensive process methods. Specifically, R2R processing could lower processing cost by 35%, increase throughput, and enable large area panels. Sinovia's focus has been the development of an "off-the-shelf" integrated substrate solution which would enable panel manufacturers to maintain their existing processes. Specific objectives are to create a plastic substrate optimized for OLED lighting that serves as a transparent electrode, flexible protective barrier, and light out-coupling enhancement layer. Sinovia also aims to demonstrate that flexible integrated substrates are compatible with R2R manufacturing and will enable cost-competitive OLED lighting. Partners for the project include Sinovia (contributing transparent electrodes), Vitriflex (contributing flexible barrier films) and Solvay (contributing custom nanowire synthesis). Sinovia explained that their transparent electrodes are developed using a random assortment of nanowires embedded in the surface of a polymer based composite. The nanowires are relatively large (200 nm diameter) resulting in good light scattering, and are buried so that the surface is smooth enough for OLED deposition. Burkhard indicated that the polymer is applied independently of the nanowires, which allows the polymer choice and nanowire diameter and density to be tunable which can yield unique advantages (functional properties of the polymer are imparted to the final composite). In addition, sheet resistances typically range from 1 to 10 ohms/m^2, and are compatible with solution processed R2R. The film is integrated with a polymer substrate as the base, followed by the Vitriflex barrier film, then the Sinovia transparent electrode (made up of a polymer and Solvay nanowires). The resulting structure also benefits from out-coupling enhancement and allows for new opportunities in patterning, as either the wires or the polymer can be patterned during manufacture. Burkhard indicated that this could enable further cost reductions, as compared to lithography or laser patterning, without damage to the film or surface. Lastly, Burkhard indicated that currently the project has achieved goals for haze and water vapor transmission rates for the integrated structure, and they are working towards larger scale substrate development.

Advances in Slot Die Coating Technology for OLED Applications

Miguel Friedrich of nTACT presented slot die coating (SDC) technology and its potential application for OLED manufacturing. SDC is used in various applications for the deposition of liquids onto glass, stainless steel, and plastic substrates. It is achieved through precisely metering the process fluid and dispensing it at a controlled rate while the coating die is precisely moved relative to the substrate. Friedrich indicated that the advantages of slot die coating include: robustness to a wide range of process materials (both high and low viscosity fluids), ability to deposit a wide range of thicknesses (from 20 nm to more than150 microns), excellent coating uniformity (typically better than ± 3%), high material utilization (typically 95%, because fluid is only wasted during a pre-dispense step), ability to scale from small R&D to large panels, high-volume mass production, highly reliable process (with yields up to 95%), applicability to both sheet-to-sheet and R2R processing, and the ability to coat an array of rectangular shapes in a single pass. The slot die coating process is controlled by several key process parameters including coating gap control, die motion control, die design, and dispense control. Control software that gives programmable control of all process parameters, data monitoring, and feedback loops. Friedrich believes that SDC has OLED market applications including: conductive layers, active layers, light extraction, barrier/encapsulation, and flexible substrates. nTACT has begun work with Momentive for thin film encapsulation; however, one of the limitations has been the ability to do patterning. While nTACT has made progress over the past 5 or 6 years, challenges remain to ensure an array of patterns or shapes can be created as film is deposited. With selective coating or "patch coating", an array of rectangular patterns or shapes can be created by blocking certain parts of the die and using controls to start and stop the pumping of the fluid. This process has yielded individual segments ("patches") with good uniformity and very good leading/trailing edge control.

Friedrich also indicated that selective removal could be another option. nTACT has developed an edge removal system in which enables sharp leading/trailing edges, eliminating one of the previous significant limitations to SDC. A solvent jet spray combined with a vacuum system is used to dissolve the edge and immediately remove the particles. Friedrich also highlighted that selective removal could be used for patterning. However, the success of this process varies by material, and also affects speed.

10. Opportunities for Roll-to-Roll Manufacturing of OLEDs in the U.S.

10.1. Participant Presentations

Roll-to-Roll Manufacturing of Flexible Hybrid Electronics

To kick-off the U.S. R2R manufacturing discussion, Mark Poliks of the Center for Advanced Microelectronics Manufacturing (CAMM) at Binghamton University presented on their R&D center's flexible electronics and R2R capabilities. In working with flexible electronics, CAMM has used a variety of substrates (including glass, PET film, PI (polyimide) film, PEN film, Corning's flexible Willow® glass, metals, ceramics and more) and processing techniques (including vacuum deposition, photolithography, wet/dry processing, slot-die coating, ink-jet printing, and aerosol ink-jet printing). They have designed and fabricated technology in fine circuitry, sensor, medical, passive display, lighting, optical waveguide, solar energy conversion, and active display backplane devices. CAMM has R2R equipment for thin film deposition and laser processing, photolithography, and wet chemical etching/cleaning. Poliks indicated that R2R manufacturing is anticipated to reduce cost. While CAMM currently is not focusing on OLED applications, they have had success with thin film resistors and believe there is an opportunity to apply their R2R learning to OLEDs. Poliks mentioned that CAMM is currently investigating whether Corning Willow® glass is compatible with their R2R systems. Additionally, they have discovered their R2R systems are suitable for demanding applications (e.g., flexible displays) and have additional benefits of high dimensional stability, thermal capability, and chemical compatibility. Poliks highlighted that their R2R systems could enable devices with improved resolution, performance, and lifetime, and they offer benefits over devices produced on other flexible substrates. Specifically, CAMM has demonstrated thin film transistor gate patterning, photolithography, 5 to 10 micron patterning, and ITO antennas on 100 micron thick Corning Willow® glass. They also employ R2R inspection capabilities.

CAMM has also successfully demonstrated R2R vacuum deposition and cyclic conveyance, utilizing tool sets for 500 mm glass web widths and sputtering of aluminum, chromium/copper, ITO, silicon oxide (SiO_2), indium gallium zinc oxide (IGZO), indium zinc oxide (IZO), and aluminum zinc oxide (AZO). They also completed R2R patterning of aluminum on PET using photolithography. Poliks stated that application and process development for etching is underway, with the initial process development completed and etch rates and uniformities established for SiO_2, silicon nitride (SiN), amorphous silicon, photoresist, and silicon.

10.2. Brainstorming Session

A brainstorming session, focused on how to improve R2R manufacturing for OLEDs, was moderated by John Hamer of OLEDWorks. The content of this session is summarized below.

- **Question**: Where are the technology gaps, and what can DOE do to help?
    - Web handling and guidance
    - Electrode deposition
    - Barrier Properties:
        - OLEDs are sensitive to moisture, and for plastic substrates a barrier layer is required.
        - Participants indicated that all patterning must be inside the encapsulation or else moisture will leak in from the edges, and therefore, new technologies, must be capable of being patterned. Of the companies represented at the meeting:

        - Luminit indicated that their technology is capable of being patterned, but that the pattern must be periodic.
        - Sinovia indicated that they use hydrophobic surfaces wherever fluid is not wanted in order to create a pattern.
        - Pixelligent indicated that their approach is compatible, but work needs to be done. They can use inkjet printing to pattern their materials, but that tuning will be needed in order to print onto the various substrates.
    - Printing:
        - Participants indicated that printing has a lot of challenges to overcome because very little work has been done on printing lighting. Formulations will be different for inkjet vs. slot die for instance.
        - As a result of current challenges, some participants suggested that in the short timeframe, the focus should be on vacuum deposition instead.
    - Film based subtractive processes.
        - Currently, all work employs metal masks.

11. DOE OLED Testing and Funding Opportunities

Clark Robinson of DOE's National Energy Technology Laboratory gave an update on the current state of the DOE SSL Program's R&D portfolio, explained the solicitation processes, and discussed the collaborative DOE OLED Testing Opportunity. The SSL Program strategy is a cycle that begins with the Stakeholder meeting (in September/October) to collect input to help shape the annual DOE SSL Program R&D Workshop (in January/February). The content and input collected at the Stakeholder meetings and Workshop both influence the update of the R&D Plan report (published May/June) which documents the R&D tasks that ultimately frame the solicitations for new projects. Robinson indicated that we are nearing the end of the 2016 award cycle, with new projects awarded in September and review of existing active projects underway. For the 2017 cycle, the solicitation was announced this October, and Robinson explained that the award is expected in the fall of 2017. Robinson reiterated that this Stakeholder Meeting will provide valuable input which will feed into the upcoming Workshop (January 31st through February 2nd in Long Beach, CA), R&D Plan, and next funding opportunity announcement in the 2018 cycle.

Robinson indicated that the DOE SSL Program's 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

- 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. Robinson highlighted that historically, the funding has been shared about equally, with product development receiving 33%, core receiving 41%, and manufacturing receiving 26%. Additionally, the 55 OLED projects to date have addressed 14 different priority tasks set by the DOE SSL Program. The SSL Project Portfolio is available in its entirety at: http://energy.gov/eere/ssl/downloads/2016-project-portfolio.

Lastly, Robinson discussed the collaborative R&D OLED Testing Opportunity initiated by DOE 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. To date, the test facility has conducted seven rounds of testing, involving five different organizations. The testing has covered electron blocking layers, two integrated substrates, transparent conductive material as a replacement for ITO, host materials, hole and electron materials, phosphorescent hosts, fluorescent (blue, yellow, and red) emitters, and high mobility electron transport material for plasmon decoupling layer applications. Following completion of component testing, the laboratory will complete a Technology Validation Status Report that summarizes the product tested and the test results, provides any recommended actions and/or improvements in design, operation or future testing of the OLED component, but does not identify the manufacturer/product developer. The appendix to this report is a comprehensive technical report that contains detailed coverage of the testing process, testing results and observations, recommendations for improvements/best practices, and conclusions. Additionally, all test data is provided. DOE is currently reviewing multiple other component applications and inquiries. Participant organizations have indicated that the detailed test results and observations are valuable in determining next steps. 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.

12. OLED R&D Topic Table Discussions

Participants were divided into five groups and given a series of questions to spark discussion. The questions and a summary of collected input are provided below.

1) **What are the key technological challenges that are obstacles to OLED adoption?**
    - Cost:

    - Encapsulation cost (barrier films and thin film encapsulation, rather than cavity glass)
    - Yield - prevent particle generation
        - Integrated substrate consistent with high yield
    - Equipment with lower cost of ownership
    - Simpler stacks
- Reliability and lifetime:
    - Encapsulation is the leading cause of failure, but improved material performance would ease encapsulation requirements.
    - More stable blue emitter/host system
    - Color consistency
    - Early failures (shorting)
- Efficiency:
    - Phosphorescent, TADF of hyper-fluorescent blue
    - Improved light extraction, especially for flexible panels
- Form factor:
    - Flexible
    - Transparent
- Drivers:
    - More compact, preferably thin film
    - More efficient, especially at low power levels
    - More adaptable
- Easier luminaire formation:
    - Need common interconnects
    - Replaceable panels
    - Lack of accessories
- Greater robustness in harsh conditions:
    - Military applications
    - Auto, aviation and other transport applications
- Market awareness:
    - Quantification of OLED advantages
    - Applications in transportation industry and medical (where certain factors such as efficiency and cost may not matter so much)
- Standards:
    - Early for panels
    - Should be focused on interconnects, power supplies, drivers, supporting hardware

2) Which R&D efforts could offer the biggest impact in the near term?

- Improved outcoupling techniques:
    - Compatible with flexible panels
    - Options that preserve the mirror finish
    - Cost-effective
    - Integrated inside of OLED stack
    - Demonstrations of effectively making the OLED on top of an internal light extraction layer

    - Light distribution films to direct the light
- Better materials:
    - More efficient materials may remove need for outcoupling
    - Stable materials for longer lifetimes
- Color:
    - Greater color control
    - Color tunable (color temperature)
- Improved flexible barrier coatings
- Integrated product development:
    - More products need to be available
    - Drivers customized for OLED
        - Compact
        - Efficient
    - Small, flat power supplies
    - Luminaire integration and light engines
- Customized manufacturing tools for process steps
- Products with multiple benefits (e.g. light and health)

3) What areas of R&D have potential for transformational impact in the long term?

- Energy efficiency improvement
    - New approaches to emitter systems
    - High efficiency OLED materials
- Cost down manufacturing techniques
    - Atmospheric processing including printing
    - Roll-to-roll technologies
    - Barrier coating
- Thin film power supplies
- Seamless tiling of panels
- Center of excellence for manufacturing
- Flexible panels

4) What R&D efforts will best promote reliability? Manufacturing cost? Power efficacy improvements? Which of these is most urgent?

- See answers to question 1
- There was no consensus on which was the most urgent
- Reliability
    - Moisture barrier
    - Particle reduction
    - In-line inspection for particle defects
    - Short mitigation methods

5) What were the most significant R&D achievements in the past few years?

- Thin film encapsulation
- Phosphorescent material

- Internal light extraction layers
- Panel reliability
- Process control
- Stacked OLEDs

6) What activities should the community as a whole be pursuing to accelerate OLED adoption?

- Connect with lighting designers and artistic community
  - Focus on luxury
  - Patrons of the arts organizations
  - OLED-based art competition
- Greater availability of affordable products
- Wider range of shapes and sizes
- Developing appropriate standards
  - Product design
  - Testing methods
  - Connection schemes
- More effective marketing and education
  - Rebates
  - American Chemical Society
  - Effective demo kits
  - Take advantage of cool-to-touch (night lights)
- Support from States
  - NYSERDA
  - Government installations
- Put more high quality OLED products into market
- Go for the right applications
  - Flexible
  - Where thin and lightweight is critical

7) Do you have recommendations for specific topics or speakers for the January SSL R&D Workshop?

- Architects and luminaire designers
  - Manufacturer/designer forum
- Technology updates:
  - Component availability
  - DOE R&D projects
- Intellectual Property issues
- Manufacturer/designer forum
- Equipment manufacturers
- Power supply and driver companies
- Specific speakers and companies (noted by organizers)
- Human factors
- Experts from related areas (flexible electronics, organic materials)

13. 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 Reliability and Testing
5. OLED Drivers
6. OLED Luminaire Design
7. Innovative Manufacturing Techniques
8. Roll-to-Roll Manufacturing

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, in part as a result of this meeting, that will continue to drive the technology forward.