2014 OLED Stakeholder Meeting Report

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DISCLAIMER

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COMMENTS

The Department of Energy is interested in feedback or comments on the materials presented in this document. Please write to James Brodrick, Lighting Program Manager:

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Table of Contents

1. Introduction

The 2014 Organic Light Emitting Diode (OLED) Stakeholder Meeting was convened by the U.S. Department of Energy (DOE) Solid-State Lighting (SSL) Program, hosted by OLEDWorks LLC, Corning, Incorporated, and the University of Rochester 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.

While the SSL program is the lead lighting program at DOE, there is an ongoing relationship is maintained with Basic Energy Sciences (BES) which funds projects that explain fundamental phenomenon that may contribute to SSL. As this was an open meeting the DOE SSL program obtained a list of Basic Science Researchers who would be interested in attending. In total, 39 “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

Dr. James Brodrick, DOE Lighting Program Manager, kicked off the meeting with an update on OLED progress that came about as a result of the previous OLED stakeholder meeting including forming the OLED Coalition, launching a DOE testing opportunity, and adding an emerging products category to the Next Generation Luminaires™ Competition. Additionally, Dr. Brodrick presented the results of a DOE analysis of the Energy Savings Potential for OLEDs, which found OLEDs could offer 73%, 52%, and 50% reduction in energy use over traditional lighting (including LED lighting) in corridor, retail, and reception area lighting scenarios respectively.

The meeting took place in two parts to achieve two distinct objectives:

> **Day 1** was led by board members of the OLED Coalition to share updates on OLED Coalition efforts to advance OLED lighting and market viability, as well as to seek feedback and encourage attendees to consider joining the coalition. The Coalition’s work at the Stakeholder meeting is discussed in Section 2 of this report.
>
> **Day 2** of the meeting was led by the DOE SSL program in order to identify critical core, product development, and manufacturing R&D needs for the continued advancement of OLEDs. Each participant was invited to give a 10 minute “Soapbox” presentation describing their thoughts on critical R&D areas for OLEDs. Sixteen participants gave presentations, and the presentations were followed by an open discussion of OLED research and industry needs. The presentations and resulting discussion are described in Sections 3-6 of this report.

Attendees were also given an opportunity to see working OLED night lights in a demo room for the new Golisano Children’s Hospital that is currently under construction. The night lights are shown in Figure 1.1 below. All the patient rooms will have these when the building opens next year.

Figure 1.1 Amber OLED Night Light in the Golisano Children's Hospital
Photographs courtesy of Mohammad Omary.

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:

- Market, Education, and Outreach (Section 2)
- OLED Materials (Section 3)
- OLED Light Extraction (Section 4)
- OLED Substrates, Integrated Substrates, and the Move Towards Flex Lighting (Section 5)
- OLED Products and Drivers (Section 6)
- OLED Manufacturing (Section 7)

An overall theme is that the OLED lighting industry has different requirements than the display industry so it must be careful about borrowing display materials and technology. In both the emitter materials and substrates, display quality materials may not be the best answer for OLED lighting, and therefore would benefit from OLED lighting specific R&D.

2. OLED Coalition Efforts

The idea for the OLED Coalition was conceived during the OLED stakeholder meeting held last fall. It was officially founded just over 5 months ago 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. A few of the coalition board members presented at the OLED Stakeholder meeting in order to provide an update on the status of the Coalition and its efforts.

2.1 Introduction & Updates

Michele Ricks of EMD Chemicals provided an introduction to the Coalition and updates on their efforts thus far. The purpose of the Coalition is to promote the OLED industry in the U.S., facilitate communication within and outside of the group, 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 (OMB), 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. In less than one year, the coalition has accomplished a lot. They have elected board members Keith Cook, Barry Young, Peter Ngai, Michele Ricks, Giana Phelan, Mike Hack, and Yukari Tanimoto. Membership fees have been established, and meeting attendees were encouraged to consider joining if they have not already done so. The coalition has created an educational brochure explaining OLED technology and the benefits to OLED lighting and plans to attend the DOE SSL Market Development Workshop to start educating the community and advocating for OLED as a crucial technology for general lighting. The coalition has also drafted a white paper advocating for a new manufacturing topic in a future call for DOE funding. As for lobbying plans, Assistant Secretary Danielson has accepted a meeting with the Coalition, but it has not yet been scheduled. There are also plans to go to Congress during that trip. The United Nations Educational, Scientific and Cultural Organization (UNESCO) proclaimed 2015 as the "International Year of Light" which will involve big promotional activities in the U.S. and around the world in order to promote light technology for improved quality of life. While not much is known at this time, the Coalition is hoping to leverage events and educational materials to promote OLED SSL, and plans to submit blog posts on event webpages.

2.2 How OLED Can Succeed

Peter Ngai with Acuity Brands Lighting gave his perspective as an OLED luminaire manufacturer on how OLEDs can succeed. Acuity has been an OLED luminaire manufacturer for about 4 years now, and in talking to architects and lighting designers has learned that OLEDs are an exciting tool, but that many believe it is still only a future possibility. However, in the last 12 to 18 months there have been tremendous advancements in the performance of OLEDs in terms of efficacy, color quality and lifetime, so they are more confident than ever that OLEDs will succeed. In order to succeed, Ngai proposed that we educate on OLED technology and capabilities, evolve OLED technology, advance OLED industry infrastructure, conceive new ways of lighting design with OLED, excel in marketing, and show what OLEDs are capable of right now.

He points out that we must educate people on why OLED is different from other lighting technologies, and stress that they do not compete head to head with LEDs. The value proposition for OLEDs is very different. They are calm, simple, and noble light sources that are thin and cool to the touch. OLEDs are sustainable. They have no hazardous materials and are thin and light which reduces the amount of luminaire housing material. People do not understand how the technology works, and we need to educate them on the physics and the structure. We should explain performance specifications as well so that they can understand the performance differences between LED luminaires and OLEDs.

OLED technology must continue to evolve, and costs must continuously be reduced. Reliability, color consistency, and lifetime are critical issues, but right now high cost is the biggest roadblock to commercialization of OLEDs in a popular way. There is a time-limited opportunity for OLEDs and if it takes too long to get costs down, OLEDs may miss their chance. Other things Acuity would like to see are color changing, tunable white light, intensity shaping, and longer shelf life.

OLED industry infrastructure must be advanced if we are going to be able to get the cost down and produce significant volumes of commercial products. For this to happen, cooperation among various OLED interest groups is desired. There must be standards and testing procedures. OLED specific drivers and controls should be developed since LED drivers are not optimized for OLEDs. Few OLED-specific drivers exist today.

OLEDs are unique, and Ngai stressed that we need to conceive new ways of lighting to take full advantage of what OLEDs have to offer, to set them apart from other light sources, and to give them a foothold in the market. OLEDs are diffuse light sources and can be used to light an entire room. We also need a better measurement of brightness, a volumetric brightness. The foot-candle is a poor measure of when the psychological appetite to brightness is satisfied. With OLEDs, the room may look brighter and feel better even with less foot-candles.

For OLEDs to be successful, he pointed to the importance of excelling in marketing them to customers with a message that they are effective and functional, but also good looking. Interest in OLEDs can be created through media and social media. Every OLED luminaire since 2011 has won some kind of award and advertising that can be advantageous. Most recently the Nomi wall sconce won the Next Generation Lighting award in the emerging technology category.[1] Also, since there are OLED products now, these can be shown to customers so they can touch them and experience their light. For this reason Acuity has showrooms in New York, San Francisco, and Atlanta, and there are plans to open showrooms in Chicago and Dallas.

2.3 The 10K Project: A Plan to Support Large Volume Manufacturing

John Hamer of OLEDWorks discussed a plan to get the cost of OLED panels down by supporting a large volume manufacturing initiative. Mike Hack of UDC started this discussion last year, calling it the "10K Project" because he believed that we need to make ten thousand panels to jumpstart the industry and flush out any manufacturing problems that we would only become aware of as we move to producing large volumes.

There are two types of problems that cause OLED panel sales and OLED luminaire sales to remain low, manufacturing related problems and market related problems. Manufacturing related problems include high panel costs and reliability concerns, while market related problems include low market awareness, lack of performance studies on panels in commercial applications, and limited demonstrations of system reliability. The 10K project proposal aims to solve only manufacturing related problems. Market related problems could be addressed with a Gateway demonstration type project.

Task M.05 in the 2014 DOE SSL Manufacturing Roadmap is a new proposal for government support for the development of manufacturing processes for practical OLEDs. More information regarding the task description and metrics can be found on page 98 of the 2014 DOE SSL Manufacturing Roadmap[2]. The proposed metrics emphasize the important challenges: good yield, good reliability, good uniformity, excellent color, and low price. Hamer stressed the importance of realizing that these are manufacturing

[1] For more information see: http://news.acuitybrands.com/US/acuity-brands-wins-best-in-class-award-at-ngl-ssl-design-indoor-competition/s/7572f39d-17e2-4093-86dc-2d4c79013a32

[2] The DOE SSL Manufacturing Roadmap can be found at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mfg_roadmap_aug2014.pdf

related problems and that they cannot be solved in a laboratory. Improving reliability and prices require manufacturing system improvement, and more work is needed at production scale. Possible projects to achieve cost reduction include increasing yield, reducing manufacturing waste, and increasing throughput.

The 2017 target for panel yield is 75% and we have a lot of work to do to get there. Major yield losses come from variability in color, visual defects (scratches, dark spots, bright spots), encapsulation defects (coating uniformity), and non-uniformity of brightness (mostly due to voltage variation). Currently there is also a lot of material waste due to material usage inefficiency (deposition issues) and also problems with incoming substrates. Incoming substrates may have scratches, smudges, pattern defects, misaligned ITO, and ITO thickness variations, but OLED lighting panel manufacturers aren't buying enough to get the substrate manufacturers' attention in fixing these issues. The 10K project could potentially help with this. Throughput of OLED deposition lines can be increased by running at faster deposition rates and using systems that allow for changes in the device structure and materials such that less time is spent on new product and process development.

The near-term target for panel reliability is less than one catastrophic failure in 5,000 panels, though reaching a panel reliability of less than one in 10,000 panels is important as this is what the luminaire manufacturers will require. The most common catastrophic failure is the development of a short between anode and cathode, which can develop over time at weaknesses in coated layers. These shorts are nascent defects, and the weaknesses can be related to scratches or roughness in ITO, "invisible" particles on the substrate, and thin spots in the organic layers. Over time the leakage current through the area of weakness grows until it is significant with respect to the panel current and causes a short. Another issue is that reliability testing takes time and a large number of panels.

Achieving low cost panels with high performance and high reliability, requires manufacturing-scale R&D for process design and evolution, product design and evolution, and equipment and tool set design and evolution. In order to achieve these objectives, the experiments must be done at production scale with cooperation between the participants. Hamer stated the importance of task M.O5 as a manufacturing R&D opportunity and discussed the importance of ramp up of the OLED supply chain to help identify and implement cost-reduction opportunities, identify and improve quality or variability related problems and performance related problems, and shake out any higher-production rate start-up problems for new lighting specific products.

2.4 Market Education Activities

Giana Phelan of OLEDWorks discussed the OLED Coalition's market education activities which leverage coalition relationships to foster basic understanding of OLED lighting, broaden representation (e.g. attend SSL Market Introduction Workshop), facilitate access to a team (the Coalition) that provides insight, promote that OLED lighting is real and not intimidating, and encourage creativity. Their first accomplishment was the creation of a high level educational primer in which the core message was that OLEDs offer a soft gentle light that can be used in a wide breadth of applications, and that there are exciting capabilities such as flexibility, transparency, color changing, and enabling novel form factors that we can look forward to seeing in the future. The primer is not a technology or specification sheet, but rather contains conversational language and images of current OLED lighting products to entice consumers to learn more. Next steps for the Coalition's Market Education Activities include finalizing the format of the primer for publication, making the material available to Coalition members (and others), promoting OLED education using the primer at the SSL Market Introduction Workshop, and mapping out additional workshop/conference participation opportunities and new strategy for educational activities.

2.5 OLED Cost Model

Barry Young of the OLED Association presented his OLED Lighting Cost of Ownership Model, which is a modification of a cost ownership model that was built in the early 2000's for OLED displays. The model is able to calculate total cost of ownership including panel cost (substrate, light extraction and grid, organic material, consumables, encapsulation and electronics costs) and capital cost (deposition equipment, evaporation equipment, test equipment, repair equipment, clean room cost, and building cost). The model is able to assess financial value of process and material changes; forecast the effect of time, volume increases, and panel size changes; evaluate process differences (e.g. vacuum thermal evaporation [VTE] vs. printing, single vs. tandem stack, thin film vs. glass encapsulation, glass vs. plastic substrates); account for the change in generation, total average cycle time (TACT), or yield; determine the effect of currency exchanges and geographic location; evaluate buy or build decisions; and perform mean time between failures (MTBF) or mean time to repair (MTTR) calculations.

In order to use the model you may select parameters you want to model, specify the device architecture, modify default settings, select labor conditions, and modify the process and/or material. Then you may calculate process flow and panel cost. Current process flow options include VTE (glass or plastic, batch or in-line); ink-jet printing (glass or plastic); three or two color; single or tandem stack; integrated or standard substrate; vary layer thickness; doped or undoped material; fluorescent, phosphorescent, or hybrid. The model can evaluate new products both today and in the future, provide insight into the benefits of larger substrates, help to define most efficient panel size, and provide input to proposals for R&D and Manufacturing Programs.

The model is available at no cost to the members of the OLED Coalition. Any interested members should contact Barry Young directly.

2.6 Discussion on Further Market, Education, and Outreach Needs:

Following the presentations by Ricks, Ngai, and Hamer, the group discussed additional market, education, and outreach needs. Some of the suggested priorities are listed below:

- The community should identify what standards and test methods are needed so that we can petition organizations to write them.
- There needs to be better metrics and targets to address the unique features of OLED lighting characteristics.
    - Identify a new metric to quantify brightness (as opposed to foot-candles) that more accurately measures when the psychological appetite for brightness is satisfied. This may be a volumetric brightness. With OLEDs they may look brighter or feel better, even with fewer foot-candles/area.
    - Identify a new metric for reliability of OLED panels, rather than setting a threshold for the number of allowable catastrophic failures per specific volume because it is difficult to normalize.

        - Suggested: A catastrophic failure rate given by the number of allowable catastrophic failures for a given number of panels over time. (For example, one catastrophic failure in 1000 panels over 1000 hours.)
    - Shelf life needs to last 7 years.
- OLED Days in the lighting showrooms could be organized so that we can bring in lighting designers and engineers to educate them on the technology and show what they can do.
- Germany drove solar power innovation and adoption in a big way because the government offered credits for solar installations. In the U.S. this kind of support mainly comes from utilities, so it may be worth reaching out to them.
    - Over one year ago California said that rebates can't be given unless color rendering index (CRI) is greater than 90, and many LED manufacturers did not try to meet that requirement. If OLEDs were able to meet that criterion, it could work to their advantage.
    - We may need to reach out to utilities and state legislature to encourage reasonable rebate requirements and availability for OLED Products.

2.7 Action Items

- OLED Coalition will schedule meeting with Assistant Secretary Danielson.
- OLED Coalition will publish and distribute educational primer on OLED technology and applications at the November 2014 SSL Market Introduction Workshop.
- OLED Coalition will explore outreach options associated with the 2015 International Year of Light.
- DOE announced FOA including OLED manufacturing R&D opportunity under Topic M.O5. Concept papers were requested by November 14.
- OLED Coalition will discuss having a (cheaper) membership option for independent researchers/academics.
- Interested attendees may contact the OLED Coalition at coalition@oled-a.org for membership and other inquiries.

3. OLED Materials

3.1 Discussion

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

- Investigating simpler structures. The best performance OLEDs right now are 20+ layers of material, and to be able to produce a basic, cheap product with only 2 or 3 layers would be significant in the attempt to getting OLED cost down and out to market.
- Developing emitter materials that are optimized for lighting applications, instead of relying on materials developed for the display industry. This includes developing broad emitters for amber, yellow, orange, and, most importantly, blue. Narrower red emission bands and broader emitting blue materials may help in improving the efficacy of white OLED lighting.
- More work may be done to improve the quantum efficiencies of OLED emitters.

- Work may be done to improve the lifetime and reliability of OLED emitter materials. It has been established that phosphorescent materials fail more quickly than fluorescent materials, but can that be improved?
- There is a potential to leverage material modeling and characterization in order to intelligently design and test new materials minimizing the cost of business in attempts to develop OLED materials with increased quantum efficiency.

3.2 Participant Presentations

Is it really time to raise the "Mission: Accomplished!" banner for OLED Materials and Device Stacks?

Mohammad Omary of University of North Texas argues that it is not and work remains, particularly on sustainability and device structure. Omary explained that today's state of the art devices are often multi-layer doped devices with polaron/exciton blocking layers, tandem cells, ultra-thin doped layers, conductivity dopants, optical "tricks", and as a result, 17-plus materials/layers are not uncommon. This adds cost and compromises reliability, scaling, reproducibility, and commercialization potential. Additionally, Ir-ppy devices use iridium, one of the least abundant materials on earth, and it has been predicted that a 1% market penetration of organic SSL will consume 15% of the world's iridium production highlighting the need for finding alternatives. There is current work to optimize efficiency by improving charge balance (by adjusting layer thickness) in tri-layer neat OLEDs, a substantial simplification on current stack devices. Theoretically, we could have even simpler bi-layer OLEDs if there is no need for ETL. If electron-only current from neat Pt(ptp)2 is comparable to hole-only current from HTL materials (TAPC or mCP) then simple bi-layer OLEDs might actually work.

Materials Development for OLED Lighting

Michele Ricks of EMD Chemicals presented opportunities for the DOE to fund targeted material developments for OLED lighting. Currently the OLED lighting industry tries to leverage material work from the OLED display industry. This has many advantages namely that the R&D money has already been invested, the materials have proven stability in manufacturing and long life, and that volume production has already been established for displays. The primary disadvantage is that from an emitter perspective they are optimized for display, the very deep blue and narrow spectra are subpar for lighting applications. Most lighting architectures would benefit from a broader blue, but there is no demand for this in displays so little work has been done. Similarly amber, yellow, and orange are useful in lighting but not in display, so they aren't worked on unless they come out of a red or green project. Also solution processable hole injection layer (HIL) compatible with a VTE stack may be useful for lighting, but is not used in displays. Ricks believes there is a lot of work that can be done with blue for lighting, e.g. it tends to be double-peaked, but is this optimal or even necessary? Deep blue emitters are typically less stable and efficient. Ricks suggests that we might just need a broader blue to improve the power efficiency in lighting. Additionally, green and red for lighting show significant overlap. Though emission at these wavelengths boosts power efficiency, high quality OLED lighting (high R9) could benefit from more emissions at longer wavelengths. Narrow emitting reds could provide a balance of high color quality and power efficacy (such that energy is not lost to emissions outside of the visible spectrum).

Density Functional Theory Study Bond Dissociation Energies for New Class of Phosphorescent Emitters

Tommie Royster of R-Display and Lighting presented findings of a collaborative study with materials on functional theory of bond dissociation energies for a new class of phosphorescent emitters which was initiated to address questions about blue emitters. Under high energy conditions or high current density, OLEDs still fail, and phosphorescent materials fail more quickly than fluorescent materials, especially in blue emitter systems. The goal is to design a new class of phosphorescent materials that have metal-ligand bonds with more covalent characteristics and link that to higher phosphorescent efficiency. Based on the premise of preferential hole transport, they look at the energy states associated with phosphorescence, determine the bond dissociation energy for radical, ground, and triplet excited states. They compared red phosphorescent material designed for this new class to a stable red emitter and found that metal-ligand bond energies of new emitters are significantly higher in the radical cation state. While this is all theoretical, photoluminescence measurements indicate higher efficiency for the new red emitter, a quantum efficiency (QE) of 0.52 compared to 0.45 for $Ir(1\text{-}piq)_3$. A yellow emitter showed a QE of 0.77. OLED manufacturers are interested in a stable blue phosphorescent emitter, so this project, which also looks at display, will move from yellow, to green and then to blue-green emitters.

Integrated Molecular Organic (Optoelectronic) Materials Development

Andrew Ferguson of the National Renewable Energy Laboratory (NREL) discussed the Organic Photovoltaic Group's (OPV) efforts in organic optoelectronic devices which they believe have similar material property desires to OLEDs. In both OLEDs and OPVs, performance is governed by carrier injection/extraction, carrier transport, exciton utilization, and light incoupling/outcoupling which requires similar contacts, transport layers, active layers, emitter materials, and substrates. Other important considerations include color purity (for OLEDs) and conversely wide absorption spectrum for OPVs. Both require material and device stability. Integrated molecular materials development at NREL uses a synergistic approach combining advanced active material modeling, targeted active material synthesis, and full material and device characterization in order to take unique organic building blocks, predict combinatorial structure, band gap positions, and optical spectra of new materials and characterize photoconductivity, structure determination, steady-state and time-resolved optical properties. These capabilities are applicable to the design and evaluation of transport, host, and emitter materials for OLEDs. This approach has predicted low band gap polymers that have had the breakthrough efficiencies. The approach allows them to be smart about what materials they would like to synthesize and therefore minimize the cost of business. They believe that there are opportunities to apply this to OLEDs. There are three opportunities to work collaboratively with the group at NREL to advance OLED materials: designing, synthesizing, and characterizing stable blue emitters with high internal quantum efficiency; effectively coordinating host materials with changes in emitter material in order to facilitate efficient energy transfer; and taking advantage of NREL expertise in novel transparent conductive materials and carbon nanotubes for contact modification.

OLED Challenges and Prospects

Ching Tang of the University of Rochester presented his perspective on current OLED challenges and future prospects. He sees continuing cost reduction (so that they are cheaper than LCD) and lifetime improvements (requiring a solution to the blue problem) as the two major remaining challenges facing the OLED industry. However, he believes the future for OLEDs is good because they will enable new applications (e.g. flexible/wearable displays) and they will be the next generation display technology, ultimately winning over LCD because of a lower cost structure. OLEDs' low-voltage, thin film RGB (red, green, blue) emitters; high efficiency and low power consumption; fast switching time; high contrast; wide view angle; flexibility; scalability; thin and light form factor; and sufficient lifetime for practical applications make it nearly perfect for display applications.

4. OLED Light Extraction

4.1 Discussion

- Novel structures such as the PlaCSH-OLED may be worth pursuing in an attempt to see breakthrough light extraction enhancement as opposed to incremental improvements of existing structures.
- Strong forward plasmonic scatterers are best to avoid losing extraction efficiency from multiple scattering events. .Silver has the highest scattering cross section of any material, and may be worth considering.
- The use of nanoparticles as scatterers can introduce problems with surface roughness, but work can be done to mitigate this issue with improved particle application and integration of particles into a smoothing layer that can improve extraction efficiency.
- It was suggested to establish a control, a standard for comparison across new light extraction techniques, because there are so many variables (substrate extraction, roughness, how you drive the device, thickness) that can be changed it is difficult to say where any improvements may be attributed to specifically.
- There is work to be done on light extraction layers: turning laboratory samples into actual OLED devices and understanding when improvements have been made versus when results are still in the noise.

4.2 Participant Presentations

PlaCSH-OLED (Plasmonic Cavity with Subwavelength Hole-array)

Ji Qi of the Princeton University Nanostructure Laboratory presented a new OLED structure called PlaCSH-OLED that they've found to have unprecedented performance and will receive DOE SSL program support beginning in November, 2014. 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 1.57x light extraction enhancement in electroluminescence over ITO OLEDs. External quantum efficiency, 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. PlaCSH is a good light absorber, achieving 3 fold lower ambient light reflection over a broad spectrum. This allows for high contrast, 5 fold higher contrast at nearly all viewing angles. High contrast, lower resistance, and uniform color over all viewing angles are advantages particularly for displays. Their tasks under this DOE SSL project are to implement PlaCSH to red and blue and create a white OLED with 130 lm/W, 65% external quantum efficiency (EQE), and CRI greater than 80 (already achieved 140 lm/W and 60% EQE in green by PlaCSH). There is also interest in work on flexible and low cost ITO-free white OLEDs over large area and MESH for transparent conducting electrode with figure of merit (FOM) better than our current 523.

Internal Light Extraction Strategy

Gene Chen of Pixelligent outlined Pixelligent's internal light extraction strategy. Pixelligent is a material company that produces high volume nanocrystals and focuses on solid state lighting. They have state of the art laboratories and a pilot manufacturing facility. They make 5nm mono-dispersed ZrO_2 nanocrystals with precisely engineered surfaces, high loadings (> 80 weight%) into polymers with minimal change in viscosity, and it is a highly scalable process. Generation 1 was a condensed scattering layer of the particles with high index smoothing which may eliminate the need for external light extraction because it can more than double light output. Pixellegent currently offers beta sampling of the high smoothing layer formulation. Pixelligent is currently developing Generation 2, a distributed scattering layer with high index layer (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. Generation 3 involves preferentially distributed scattering layer with a gradient high index layer, and it 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 Small Business Innovation Research (SBIR) phase 1 SSL R&D grant. The subject of future work (Generation 4), a distributed scattering layer with structured gradient high index layer, is the long term goal of Pixelligent in order to offer highest efficiency and the ability to direct light.

Light Extraction with Plasmonic Scatterers

Lewis Rothberg of the University of Rochester discussed using silver nanoparticles as scatterers to improve light extraction. The principle behind plasmonic scatterers is that you must scatter the light so it gets out where you want it, but you lose light with multiple scattering events so it is best to have strong forward scatterers. Silver has the highest scattering cross section of any material. Theoretical analysis predicts that 100nm diameter silver nanoparticles can support 90% scattering. To build a device on the scattering layer (i.e. on particles), you will have roughness and consistency issues. Rothberg's group uses vacuum deposited silver nanoparticle layers, which is a robust process compatible with OLED fabrication. Analogous wet process was also developed. Overall they saw good optical properties (e.g. waveguiding is gone), but they have more to do on ruling out effects of substrate extraction and roughness. These issues must be handled in order to determine a control for comparison.

5. OLED Substrates, Integrated Substrates, and the Move Towards Flex Lighting

5.1 Discussion

- The anode structures, extraction enhancement layers and substrate may be integrated to reduce costs and improve performance of OLEDs.
- Thin glass substrates have the potential to offer roll to roll (R2R) compatibility without sacrificing the superior performance of glass (e.g. barrier properties, low surface roughness, and high temperature capabilities), but improvement is needed to ensure that the glass does not break while being handled during processing and device manufacture.
- High quality architectural or "window" glass substrates may be a better, more cost effective alternative for most OLED Lighting applications in place of display glass.

- Plastic substrates offer the flexibility required for R2R manufacturing and are cheaper than glass, although quality is often reduced. However, using plastic and R2R may be valuable for getting a cheap basic product out to market.
- An integrated plastic substrate such as a silver nanowire composite electrode has the potential to match the surface conductivity, roughness and transparency of ITO/glass and it exhibits the positive traits of a polymer (flexibility, self-healing, etc.).

5.2 Participant Presentations

Towards Scalable, Flexible PLEDs

Jay Guo of the University of Michigan discussed his work on device structures. Inverted polymer-OLED (PLED) structures give an increase in stability without reactive metals, can be entirely solution processed, and are transparent (using metal mesh or ultra-thin silver film). Processes have been developed to continuously layer material, resulting in high throughput and reduced material waste. This allows scalable PLED fabrication, with R2R slit blade coating systems working on 6 inch wide flexible substrates. Guo also discussed metallic wire grid transparent conductors. They are used as a transparent structure for OLEDs and the geometry and thickness can be changed. It is possible to use R2R nanopatterning or photo roll lithography. Graphene is an emerging electrode material and combining metal mesh and graphene is a new approach. When metal is thin enough it becomes semi-transparent. Silver is good, but does not deposit continuously in silicon oxide, so they use thin film aluminum doped with silver. The thickness can be reduced to 6nm and still be smooth and stable even at high temperatures. The atomic size of aluminum and silver are nearly a perfect match which is why it works so well.

Corning Willow® Glass: Integrated Substrate for OLED Lighting

Mark Taylor of Corning believes their thin "Willow" glass substrate offers a great possibility for OLED lighting because it is R2R compatible and glass enables improved product performance. Thin glass has better barrier properties, lower surface roughness, and higher temperature capabilities when compared to plastic substrates. However industry lacks experience and improvements are needed to handle thin, flexible glass without it breaking. They are focusing on integrated substrates with external light extraction layers (ELEL), willow glass, internal light extraction layers (ILEL), and transparent conductive oxide (TCO) to improve product performance, and have a development plan to provide them on rolls or sheets. The plan calls for R2R process concept design with critical experiments enabling 40% light extraction with ILEL in 2015, a 300-500mm width R2R sampling line in 2016, and start building a 1000-1200 mm wide mass production line in 2017 for January 2018 supply. They believe this substrate will provide increased lifetime because of superior barrier properties, low cost because of R2R processing capability, high luminous efficacy from 3x light extraction, and conformable light panels that will allow unique design with natural light.

PPG Integrated Manufacturing Process

Dennis O'Shaughnessy of PPG described their approach to integrated substrate manufacturing as starting with a low cost process and then building value for the OLED lighting application into it, intentionally ignoring OLED display applications. It is a float glass process that currently measures throughputs in hundreds of tons per day. They are currently developing a tool that will embed particles below the glass in the forming process of float glass manufacturing. They were able to embed particles below the glass surface while maintaining a smooth surface, and the high density of embedded particles were fairly uniformly distributed. This approach is a way to get a low cost substrate that is valuable for OLEDs. There are tradeoffs between using window glass versus display glass. Display glass is more expensive and you can't embed particles in thin display glass. However, volume will drive pricing.

Cost Effective Integrated Substrates

Neil McSporran of Pilkington North America Inc. made a case for using tailored architectural glass in place of costly display glass as integrated substrates in OLED devices. By 2017, DOE targets low cost (less than \$60/m^2), low effective sheet resistance (less than 1ohm/sq), high performance extraction layers to enable high (greater than 50%) EQE, smooth deposition surfaces, and compatibility with OLED stack deposition techniques for integrated substrates. Currently substrate costs are significantly higher and need to be reduced significantly in a short time. Display glass is high cost, so McSporran instead suggests considering architectural glass with additional modifications if needed. There are a number of different deposition processes used in high volume today, and while they are believed to be low quality, that is not always the case. They are already producing high quality architectural glass substrates for touch screen and photovoltaic applications. The glass can range from 1mm to 1 inch thick. While OLEDs may be thin to demonstrate performance, for some applications McSporran suggests that it may be better to reduce luminaire structure and instead use thicker (and cheaper) glass. There are 3 principal coating technologies for major glass manufacturers: sputtering, sol-gel, and AP-CVD. Sputtering ZnO:Al and silver based transparent conductors offers good tunability of material optical properties for sizes up to 6m x 3m. Sol-gel large area capabilities are already employed in automotive applications and offers planarizing and light extraction structures. AP-CVD SnO_2:F (FTO) is one of the widest used transparent conducting oxides and can be planarized using HIL layer producing equal performance to ITO control. McSporran suggests that combinations of the various technologies could be used to produce integrated substrates, and since they are at high volume already it could help get costs down. However, he believes a collaborative approach is needed to use these technologies in tandem with other novel approaches. Taking advantage of existing large area commercial processes can speed development of integrated substrates at low cost.

Integrated Plastic Substrate for Low-Cost High-Efficiency OLED Lighting

Qibing Pei of UCLA's Department of Materials Science and Engineering discussed the potential for integrated plastic substrates for OLED lighting. The cost of OLEDs includes labor, depreciation, other materials, encapsulation, organic materials, anode structures, extraction enhancement, and substrate. The anode structures, extraction enhancement and substrate may be integrated to reduce costs and improve performance. For transparent electrodes, ITO/glass is expensive and there are extraction problems; ITO/PET performance is lower, but cheaper. Conducting polymers (PEDOT), single-wall carbon nanotubes (SWCNT), graphene, metal grid, and silver nanowires may also act as transparent electrodes, but surface roughness can be a big problem. They have developed a silver nanowire polymer composite electrode, which matches the surface conductivity, roughness, and transparency of ITO/glass and exhibits the mechanical properties of polymers (flexible, shape memorable, self-healing, and rubbery). It is formed by depositing the material onto glass and then separating it for use, therefore it is very smooth. Using GO-AgNW/PUA cathode and anode, you can make a stretchable polymer OLED. With this integrated substrate, performance targets are 5 ohm/sq conductance, ~2nm surface roughness, and 60% EQE. For comparison, ITO/glass has ~10 ohm/sq conductance, ~2nm surface roughness, and 20-25% EQE. Preliminary results show that solution processed substrate produces a wide viewing angle, color stability for 0 to 90 degrees, and an EQE of 30.5%. They have concluded that integrated plastic substrates could potentially replace and surpass ITO/glass in performance for SSL, and it is compatible with solution based processing, so it could be produced at substantially lower cost.

6. OLED Products & Drivers

6.1 Discussion

- It was suggested that for OLED products to realize best possible performance levels, more attention needs to be paid to OLED drivers. The status quo has been to use LED drivers, but they are not optimized for OLEDs and if the driver quality is poor, the quality of the overall lighting product will be poor.
- There was general agreement that OLEDs would benefit from determining a breakout application or product that can be low-volume and high-value with the current performance levels, however this has been suggested before and there is no clear path to making this happen. LEDs broke out into the market in niche applications (Christmas lights, flashlights, toys etc.) before moving to general lighting applications, because when LEDs first came around there were very distinct performance levels and lower quality applications that came about because they were "just making it". If we are aiming at competing with LED at $/klm basis it will be a long time before OLEDs can be competitive. In order to survive until that day we need other breakout products.

6.2 Participant Presentations

OLED Products and Drivers

Larry Sadwick of InnoSys, Inc. emphasized the need for OLED specific drivers in order for OLED lighting products to truly succeed. Sadwick cautioned that LED drivers are not optimized for characteristics of OLEDs, and if the driver is poor quality the overall quality of the lighting product will be poor. Nevertheless, 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. OLED drivers can be low cost, efficient, reliable, and robust. InnoSys has made a color changing smart OLED driver. InnoSys believes that "made in the USA" drivers can be cost competitive and valued propositioned. An original design manufacturer like InnoSys can offer much to the OLED 10K manufacturing project, and that could be the beginning of much more to come. InnoSys is fairly passionate about OLEDs and would like to go after opportunities in OLED lighting (i.e., driver/control) with OLED suppliers. InnoSys is serious about being an OLED driver supplier with products that are highly efficient, have added benefits of smart controls, cost effective, and make OLEDs even better.

Sunshine Window Shades: A Spearhead for OLED General Lighting

Wayne Hellman founder and chairman of Advanced Lighting Technology and Board Member and Business Advisory for Mustang Vacuum Systems (MVS) gave a "lighting guy's perspective" on the potential for OLEDs in general lighting applications. While their focus has been on metal halide, they are interested in all lighting systems and notes that the one thing in common with all lighting sources is that as they go from the lab to commercialization there needs to be one great breakout application. Hellman suggests determining where people need OLED-specific quality of light and where people would be willing to pay for it, because without sales, you cannot have a learning curve and the 10K project may not be enough. A possible spearhead of OLED general lighting is a Sunshine Window Shade, possible with either rigid or flexible panels. The shade can be opened to let in day light, or it can emit light with full range of dimming when closed, which takes full advantage of the fact that most rooms are situated to use light from the windows. There is a large niche market where people are willing to pay a premium price for health benefits. Hospitals and nursing homes add up to over 4.5 million square meters of window space. Mustang International group of companies is a world leader for vacuum deposition systems for automotive lighting products with over 200,000 square feet of manufacturing space, and they have glass and flexible solar deposition systems that would translate nicely for OLEDs. MVS OLED will roll out with flat glass and evolve into high volume R2R processing. MVS has a strategic business model that will enable others to expand OLED to general lighting market by selling complete specialty OLED lighting products, private label OLED products, OLED material to customer specification, or equipment as needed.

7. OLED Manufacturing

7.1 Discussion:

- The 10k project discussed in Section 0 presents a plan to support large volume manufacturing of OLED panels as described in priority task M.05 in the 2014 Manufacturing Roadmap. The proposed ramp up of the OLED supply chain will help identify and implement cost-reduction opportunities, identify and improve quality or variability related problems and performance related problems, and shake out any higher-production rate start-up problems for new lighting specific products. Therefore, it is an important manufacturing R&D opportunity.
- The OLED Cost model discussed in Section 2.5 is able to calculate total cost of ownership (including panel cost and capital cost), and therefore can be used to evaluate new products both today and in the future, provide insight into the benefits of larger substrates, help to define most efficient panel size, and provide input to proposals for R&D and Manufacturing Programs.
- R2R manufacturing is likely the best way to create products that have all of the advantages of OLED SSL (i.e. thin, flexible, large area, lightweight) at low cost.
- It was suggested that the OLED industry would benefit from a R2R pilot facility in order to provide a platform to optimize structures and processes and ultimately beta/small volume production. Such a pilot line would be a cost-effective prototype for future scale-up to wider widths and larger volumes. The creation of such a pilot line would likely need DOE support.
- Currently OLED production is nearly all vacuum thermal evaporation, but it was suggested that we should be working on solution projects in order to be ready to have hybrid or all solution possibilities. Both are R2R compatible, and each has clear advantages and disadvantages, therefore we should consider both until one is proven a clear winner.

7.2 Participant Presentations

OLED SSL Needs Roll-to-Roll Manufacturing!

Dennis Slafer of MicroContinuum made a case for why OLED needs R2R manufacturing and suggestions for how we can get there. This is time sensitive. Dropping prices and market acceptance are fueling LED lighting’s rapid growth, and they very likely will expand into the prime market territory for OLED SSL:

areal sources (panels). To compete, the OLED manufacturing community needs to create products based on the unique--and value added—strengths of OLED SSL (thin, flexible, large area, lightweight, quality light, inexpensive). Slafer suggests the most likely way to realize all of these advantages is through R2R manufacturing. Therefore, OLED SSL could be advanced by creating a R2R pilot facility capable of handling widths from 150 mm to 450 mm (i.e., half a foot to half a meter) for OLED panels, in order to provide a platform to optimize structures and processes and ultimately beta/small volume production. Such a pilot line would be a cost-effective prototype for future scale-up to wider widths and larger volumes. The pilot line design philosophy should be to avoid a large, integrated machine in favor of a series of individual lines, optimized for individual process steps, so that each process can run at optimum line speed. It would also reduce complexity and cost, minimizes time-to-product through parallel development, minimizes downtime due to failure of one machine, and enables cost advantages of one higher-speed machine feeding multiple slow, rate-determining machines. After the learning curve on the pilot line, some process steps might be integrated for next generation machines. R2R atmospheric and vacuum coatings are both well-established and each has distinct advantages and disadvantages. Flexible glass, area coated plastic, metal foil, or any combination are possible substrate options. The pilot line should be technology agnostic, and have the capability of investigating multiple technology pathways in parallel until a winner is declared or they all prove commercially viable. Unfortunately, no large U.S. company is interested in building a R2R pilot line, and equity investment for smaller companies is very difficult; OLED SSL development is too early and the market is unproven because LEDs already exist. Creating an OLED R2R Pilot Line will require DOE support. Slafer suggests that we may be able to use available existing R2R equipment from previous DOE projects, or that DOE could support collaboration with JV or NEWCO, to secure available equipment and a site for the pilot facility. With the support of DOE and the participation of technology companies, the establishment of an OLED R2R pilot line could offer a pathway to successful commercialization of OLED lighting.

8. Closing

There was widespread agreement that cost reduction and market demand remain the key issues facing the OLED industry. From the Coalition's updates, we see that they are working hard to solve these issues, and are making progress towards market education, cost modeling, lobbying for government funding, and seeking manufacturing scale up opportunities.

Key priority R&D areas voiced include:

1) OLED materials – stable emitter systems (including hosts and transport materials) – as well as better engineered emission profiles to get the best color/power efficiency trade-off
2) OLED specific drivers
3) Manufacturing scale-up to understand and address issues with yield and reliability
4) Breakthrough applications
5) Light extraction
6) Integrated substrates
7) Solution-based devices
8) Flexible substrates/R2R processing

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.