Roundtable Discussions of the Solid-State Lighting R&D Task Priorities

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DISCLAIMER

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COMMENTS

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1. Introduction

The Multi-Year Program Plan (MYPP) for the Solid State Lighting (SSL) Program forms a basis on which the Department of Energy (DOE) develops research and development (R&D) funding solicitations. This plan is updated annually. As part of the annual update process the DOE invited a number of SSL experts to Washington, DC on the 2nd and 3rd of November 2011 for a set of "roundtable" planning meetings to advise DOE on which R&D tasks are currently most needed to advance solid state lighting products.

The meetings were conducted over two days. The first day was dedicated to discussion of Light Emitting Diode (LED) based lighting and the second day dedicated to Organic Light Emitting Diode (OLED) based lighting. The roundtables began with a brief introduction and summary of the goals of the meetings. This was followed by presentations from each of the roundtable attendees which allowed them to highlight what they believed to be the most important areas for research (see Appendix A).

During the discussion that followed, participants referred to the complete list of 62 Core Research and Product Development tasks in the 2011 MYPP to consider which should be prioritized in the near term to support the goals of the DOE SSL Program.[1] Due to likely funding constraints, the participants were charged with limiting the priority list as much as possible. Ultimately, the roundtable participants identified a total of 12 preliminary priority tasks. The final selection of priority tasks will be made after analyzing further stakeholder inputs from the R&D workshop.

After the prioritization discussion, participants discussed the current status and targets for various metrics assigned to the prioritized tasks. The final stage of the roundtable was to review the DOE SSL Program's overall efficacy targets and milestones for LEDs and OLEDs.

2. Annual Planning Process

The November roundtable was the first step in the annual MYPP update process. Following the roundtable, the DOE will host the 2012 Solid-State Lighting R&D Workshop in February. During this workshop, the task discussion will continue and feedback on the preliminary priority R&D tasks identified at the roundtables will be solicited. All these recommendations will be considered by DOE when making the final decision on task priorities for the 2012 MYPP. This priority task list will heavily influence the solicited R&D topics in the competitive Funding Opportunity Announcements (FOAs) for fiscal year 2013.

[1] The definitions of Core Research and Product Development and a complete list of R&D tasks are provided in Appendix C and D, respectively of the SSL MYPP. This document is available at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mypp2011_web.pdf. In short, Core is applied research advancing the communal understanding of a specific subject; and Product Development is research directed at a commercially viable SSL material, device or luminaire.

3. Prioritization Discussion

The original R&D task list was developed for a DOE program planning workshop in November of 2003 and has typically been slightly modified each year. The current task structure, as presented in the 2011 MYPP, which includes 12 LED core tasks, 23 LED product development tasks, 9 OLED core tasks, and 19 OLED product development tasks, resulted from a complete review and revision of the task structure for the 2009 MYPP. Also in 2009 a new direction was initiated to provide additional emphasis on manufacturing R&D, resulting in an SSL Manufacturing Roadmap.[2] As was the case in 2010 and 2011, SSL manufacturing issues, objectives, tasks and priorities will be explored in a separate workshop with an updated Manufacturing Roadmap in 2012.

Roundtable participants reviewed the set of R&D tasks and offered their suggestions for priorities for the coming year. This discussion is summarized below in Section 3 of this report. Ultimately the LED participants proposed three core technology priority tasks and four product development priority tasks. Five of these tasks were previously prioritized in the 2011 MYPP. The OLED participants also proposed two core technology priority tasks and three product development priority tasks. While both core technology tasks were previously prioritized in the 2011 MYPP, all three OLED product development tasks represent new potential priorities for 2012. All twelve priority recommendations are discussed in the following sections.

After the preliminary prioritization had been completed, participants reviewed the content of each prioritized R&D task. The first step was to verify that the description properly communicates the work to be performed. Participants then selected appropriate metrics that would best measure progress for the task. Participants also provided the current status and the 2020 target. Targets are intended to be challenging but achievable.

[2] http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mypp2010_web.pdf

3.1. Proposed LED Priority Tasks

The following sections summarize the conclusions and discussion points for each of the preliminary LED priority tasks proposed for prioritization in 2012. To be consistent among the tasks, the definitions in the table below for various colors and color temperatures are used throughout.

Emission wavelengths and color definitions for sections 3.1.1 and 3.1.2

<table>
<tr><th colspan="2">Color</th><th>Wavelength/CCT range</th><th>CRI</th></tr>
<tr><td colspan="2">Blue</td><td>440-460 nm</td><td>-</td></tr>
<tr><td colspan="2">Green</td><td>520-540 nm</td><td>-</td></tr>
<tr><td colspan="2">Amber</td><td>580-595 nm</td><td>-</td></tr>
<tr><td colspan="2">Red</td><td>610-620 nm</td><td>-</td></tr>
<tr><td rowspan="3">White</td><td>Warm</td><td>2580-3710 K
(ANSI 2700, 3000, 3500 K)</td><td>80 - 90</td></tr>
<tr><td>Neutral</td><td>3711-4745 K
(ANSI 4000, 4500 K)</td><td>70 - 80</td></tr>
<tr><td>Cool</td><td>4746-7040 K
(ANSI 5000, 5700, 6500 K)</td><td>70 - 80</td></tr>
</table>

3.1.1. Proposed LED Core Research Priority Tasks

A.1.2 Emitter Materials Research		
Description: : (1) Identify fundamental physical mechanisms of efficiency droop for blue LEDs through experimentation using state of the art epitaxial material and device structures in combination with theoretical analysis. **(2)** Identify and demonstrate means to reduce current droop and thermal sensitivity for all colors through both experimental and theoretical work. **(3)** Develop efficient red (610-620 nm) or amber (580-595 nm) LEDs which allow for optimization of spectral efficiency with high color quality over a range of CCT and which also exhibit color and efficiency stability with respect to operating temperature.		
Metric(s)	**2011 Status(s)**	**2020 Target(s)**
IQE @ 35 A/cm^2	80% (Blue) 38% (Green) 75% (Red) 13% (Amber)	90% (Blue, Green, Red, Amber)
EQE @ 35 A/cm^2	64% (Blue) 30% (Green) 52% (Red) 10% (Amber)	81% (Blue, Green, Red, Amber)
Power Conversion Efficiency @ 35 A/cm^2	44% (Blue) 21% (Green) 33% (Red) 7% (Amber)	73% (Blue, Green, Red, Amber)
Droop – Relative EQE at 100 A/cm^2 vs. 35 A/cm^2	77%	100%
Thermal Stability – Relative Optical Flux at 100°C vs. 25°C	95% (Blue, Green) 50% (Red) 25% (Amber)	98% (Blue, Green) 75% (Red, Amber)

Discussion Points:

- Identifying mechanisms for droop and reducing its impact will improve efficiency at higher drive currents and reduce cost.
- Developing tunable narrowband emitters (especially in the red and amber wavelengths) will allow LEDs to be optimized over the entire range of CCTs. For these reasons, A.1.2 was recommended as a priority task.
- There was an inquiry into the difference between core research task A.1.2 (Emitter materials research) and A.2.2 (Novel emitter materials and architecture). The distinction between the two was explained as follows: A.1.2 refers to conventional monochromatic

visible LEDs concerning issues such as droop and IQE. A.2.2 on the other hand refers to novel architectures such as nanorod LEDs and photonic crystal LEDs.

- It was recognized that, in general, emitter research requires state-of-the-art LED material in order to provide results that are relevant to efficient LEDs used in lighting. While this task does fall under core research, the question arose as to how effective the project would be if industry chose not to apply to core
- The question was posed as to whether emitter research has already received enough core research funding. It comes down to the question: are we actually going to find a solution to droop or the green gap? And at what cost?
- In reference to the first statement of the task description, it was noted that a suitable metric to track progress in identification of fundamental mechanisms had not been identified.
- A discussion on efficiencies for blue, green, red and amber led to several changes of status and target values.
    - The value of 38% for the current status of green IQE was questioned. There were no changes at the time but it remains marked for follow-up.
    - The current status of red EQE was updated to 52% from 60%.

A.1.3 Down Converters		
Description: Explore new regulatory compliant, high-efficiency wavelength conversion materials for improved quantum yield and phosphor conversion efficiency for the purposes of creating warm white LEDs, with a particular emphasis on improving spectral efficiency with high color quality and improved thermal stability. Non-REM (rare earth metal) down converters are encouraged.		
Metric(s)	**2011 Status(s)**	**2020 Target(s)**
Quantum Yield (25°C) across the visible spectrum	90%	95%
Thermal Stability across the visible spectrum – Relative Quantum Yield @ 150°C vs. 25°C	90%	95%
Avg. Conversion Efficiency (pc–LED)	66%	69%
Spectral Full Width Half Max. (FWHM)	150 nm (Red)	<30 nm All colors
Color Stability (pc–LED)	Color Shift 0.012 u'v' over life	Color Shift < 0.002 u'v' over life
Spectral Efficiency relative to a max. LER ~345 lm/W	90%	100%
Flux Density @ 85°C		

Discussion Points:

- In the description it was proposed that 'non-toxic' be changed to 'regulatory compliant' and the phrase 'non-REM (rare earth metal) down-converters are encouraged' added. Issues relating to the mining and use of REMs were a recurring theme in several of the soapbox presentations. REMs lead to supply chain dependence on non-US sources.
- It was proposed to add the metric "flux density at temperature'."
- Thermal quenching and long term stability were identified as key issues,
- The topic of color yield was raised but eventually determined to remain a manufacturing issue.
- Color stability was an issue raised in several soapbox presentations and during the task discussion. Color shift and maintenance were regarded as areas for improvement due to its effect on customer satisfaction.
- The 'Spectral Full Width Half Max (FWHM)' target for 2020 for red emitters was felt to be too large. After some discussion this was reduced to <30 nm.

- While the main focus would remain on red emitters, it was recommended that the revised 2020 FWHM target be specified for all colors to enable the realization of efficient emitter architectures based on multiple narrow-band sources Additionally, it was recommended that the same narrow FWHM target be specified for all colors since FWHM affects efficacy,
- The question arose of whether an LER (luminous efficacy of radiation) specification was redundant. It was noted that an LER of 345 may be feasible for phosphor-converted LEDs. Higher LER values, specifically high luminous efficacy at high radiant flux, are desirable.
- There was support for the development of phosphors having a relatively flat excitation spectrum near the peak emission of the LED to compensate for changes in the emission spectrum.

A.2.2 Novel LED Emitter Architectures		
Description: (1) Devise novel emitter geometries and mechanisms that show a clear pathway to efficiency improvement; **(2)** Demonstrate a pathway to increased chip-level functionality offering luminaire or system efficiency improvements over existing approaches; **(3)** Explore novel architectures for improved efficiency, color stability, and emission directionality including combined LED/converter structures. (Possible examples: nano-rod LEDs, lasers, micro-cavity LEDs, photonic crystals, system on a chip)		
Metric(s)	**2011 Status(s)**	**2020 Target(s)**
EQE @ 35 A/cm^2	64% (Blue) 30% (Green) 38% (Red)	81% (Blue, Green, Red)
Droop – Relative EQE at 100 A/cm^2 vs. 35 A/cm^2	77%	100%
Thermal Stability – Relative Optical Flux at 100°C vs. 25°C	95% (Blue, Green) 50% (Red) 25% (Amber)	98% (Blue, Green) 75% (Red, Amber)

Discussion Points:

- It was suggested that this task should share several of the metrics identified in task A.1.2 (emitter materials research), namely droop and thermal stability.
- The development of novel emitter architectures was highlighted due to its potential to increase light output and reduce efficiency losses.
- Including an IQE metric was also discussed but it was concluded that IQE is a fundamental materials issue and less dependent on emitter architecture. However it was also noted that the intrinsic IQE of a given emitter material may change depending on emitter architecture.
- There was discussion on whether to add a metric relating to directionality or light shaping. The importance of this feature was enforced by several soapbox presentations surrounding customer satisfaction.

3.1.2. Proposed LED Product Development Priority Tasks

B.1.1 Substrate Development		
Description: Develop alternative substrate solutions that are compatible with the demonstration of low cost high efficacy LED packages. Suitable substrate solutions might include native GaN, GaN-on-Si, GaN templates, etc. Demonstrate state of the art LEDs on these substrates and establish a pathway to target performance and cost.		
Metric(s)	**2011 Status(s)**	**2020 Target(s)**
Price of LED Package @ target efficacy	\$10/klm (cool) \$15/klm (warm)	\$1/klm
Though the following metrics are examples for a GaN substrate, this task is not meant to be exclusive to GaN substrates.		
GaN Substrate Price	>\$2,000 (25–50 mm)	<\$500 (>200 mm)
Droop – Relative EQE at $100 A/cm^2$ vs. $35 A/cm^2$	77%	100%
Thermal Stability– Relative Optical Flux at 100ºC vs. 25ºC	85% (Blue, Green)	95% (Blue, Green)
GaN Transparency (absorption coefficient)	2-10 cm^{-1}	<0.5 cm^{-1}

Discussion Points:

- Alternative substrate development was considered to be an area of performance improvement (especially with regard to droop). However, in order for non-sapphire substrates to be a viable option, reducing substrate cost is critical.
- The ability to develop substrate solutions using existing cheap large area substrates such as GaN-on-Si was considered a promising approach that offered excellent prospects for cost reduction through efficient scaling. However further work was required to optimize material quality and wavelength uniformity on larger diameter substrates.
- Questions arose as to the potential benefits of alternate substrates. For example, will GaN substrate developments solve the droop issue? Will continued investigation of alternative substrates provide any performance or cost benefits? Should money continue to be invested in this?
- There was also some discussion regarding the classification of this task as product development rather than core research. However, it was decided that this task remains a product development effort.

- It was recommended that wavelength uniformity metrics and targets be added to this task. Specifically these values were proposed at 5nm standard deviation (sd) for 200 mm GaN-on-Si for 2011 status and similarly 2 nm sd for the 2020 target.
- The addition of an additional cost metric was also advocated, such as ‘wafer cost’, ‘epi cost’ or ‘total chip cost’. Of the three, ‘epi cost’ was considered to be the best option.
- However it was also pointed out that metrics for wavelength uniformity and epi cost had already been identified in the manufacturing roadmap and targets would need to be made consistent.

B.3.6 Package Architecture		
Description: Develop novel LED package and module architectures that can be readily integrated into luminaires. Architectures should address some of the following issues: Thermal management, cost, color, optical distribution, electrical integration, sensing, reliability, and ease of integration into the luminaire or replacement lamp while maintaining state of the art package efficiency. The novel packages could employ novel phosphor conversion approaches, RGB+ architectures, system in package, hybrid color, chip on heat sink, or other approaches to address these issues.		
Metric(s)	**2011 Status(s)**	**2020 Target(s)**
Change in Chromaticity over time	Delta u’v’ @ 6khrs < 0.003	Delta u’v’ < 0.002 over lifetime
Price of LED Package	$10/klm (cool) $15/klm (warm)	$1/klm
Price of Luminaire or replacement lamp	$50/klm	$5/klm
System Efficiency		
System Price		

Discussion Points:

- It was noted that many of the components, issues and metrics contained in this task are important to advance technology, but redefining the LED package is not the sole target/goal. Future architectures may dispense with the need for such a package
- In reference to setting system efficacy and system price targets for 2020, it was decided that being too descriptive or definitive with these metrics was not prudent. The goal is to increase performance and decrease price, defining the means by which this is accomplished is not as important.
- It was proposed that chip-on-heat-sink packaging technology be incorporated into the task description.

- There was some debate over whether task B.5.2 (color maintenance) could be incorporated under task B.3.6 (package architecture) or B.6.3 (system integration). It was concluded that it was most closely related to package architecture
- It was proposed that the metric for ‘Change in Chromaticity over time’ should be extended to insure that the color point also remain within Delta u’v’ of the blackbody locus.
    - The current status for Delta u’v’ over 6,000 hrs was set to <0.003.
    - The target for 2020 was set to <0.002
- It was suggested that TM-21, which provides a method for lumen maintenance projections, be extended to include lifetime testing based on color maintenance.
- For the Price of LED Package metric, the 2011 status for cool white was changed to $10/klm and for warm white to $15/klm
- The luminaire/lamp price target for 2020 was set to $5/klm (based primarily on prices for A-19 lamps), although there was some concern over this being too high.
- Another suggestion for reducing costs was standardization of the LED package.

B.6.3 System Reliability and Lifetime		
Description: Collection and analysis of system reliability data for SSL luminaires and components to determine failure mechanisms and improve luminaire reliability and lifetime (including color stability). Develop and validate accelerated test methods taking into consideration component interactions. Develop an openly available and widely usable software tool to model SSL reliability and lifetime verified by experimental data. This task includes projects that focus on specific subsystems such as LED package, driver, and optical and mechanical components.		
Metric(s)	**2011 Status(s)**	**2020 Target(s)**
Mean Time to Failure (either catastrophic, lumen maintenance >70%, color shift, loss of controls)	Device Lumen Depreciation data	Tool to predict Luminaire lifetime within 10% accuracy

Discussion Points:

- Reliability remains an important issue. There is still a need for some form of accelerated life testing, which will most likely be on components and subsystems accompanied by a means to then predict luminaire life. Driver quality and reliability is a particular concern as accurate assessment is still a challenge. Reliability models that provide accurate results are needed.
- Test protocols for hazardous environments and for color point stability are required.

B.6.4 Novel LED Luminaire Systems		
Description: Develop truly novel luminaire system architectures and form factors that take advantage of the unique properties of LEDs to save energy and represent a pathway toward greater market adoption. An important element of this task will be the integration of smart controls/sensors for digital controllability, optimized dimming, color tunability, self-commissioning, occupancy sensing, etc. Luminaire designs should be consistent with the use of materials and production methods that minimize any negative environmental impact. Key attributes will include low weight, compact size, directionality, and/or durability.		
Metric(s)	**2011 Status(s)**	**2020 Target(s)**
System Energy Consumption		
Controls		
Environmental Impact		

Discussion Points:

- Several soapbox presentations discussed the importance of novel luminaire systems. Support for continued novel product development was emphasized for its utility in the luminaire market as it promotes going beyond replacement strategies.
- Defining metrics for this task proved difficult because by definition it is novel and thus fairly undefined. Also it may require application specific metrics.
- One suggestion for a metric was ‘Net change in energy per application’.
- It was recognized that color tunability is still a real demand and should be included in the description.
- Incorporating some reference to architectural space integration in the description for future targets was a possible idea posed for additional emphasis. Utility value was also suggested as an alternative/complement.
- With respect to the ‘low weight, compact size’ reference in the task description, one suggestion for a metric to address this property was lm/kg (mass); however, there was no consensus to add it as a metric.

3.2. Proposed OLED Priority Tasks

The following sections summarize the conclusions and discussion points for each of the preliminary OLED priority tasks proposed for prioritization in 2012.

3.2.1. Proposed OLED Core Research Priority Tasks

C.1.2 Stable White Devices

Description: Develop novel materials and structures that can help create a highly efficient, stable white device. The devices should have good color, long lifetime and high efficiency even at high brightness. Color shift over time should be minimal. The approach may include the development of highly efficient, blue emitter materials and hosts or may comprise a device architecture leading to longer lifetime. Any proposed solutions should keep cost, complexity and feasibility of scale-up in mind. Materials/structures should be demonstrated in OLED devices which are characterized to ascertain the performance as compared to the metrics below. Novel materials/structures should demonstrate a significant improvement in stability, while maintaining or improving other metrics.

Metric(s)	2011 Status(s)	2020 Target(s)
Lumen Maintenance (L70)	30,000 hrs @ 3,000 lm/m^2	>50,000 hrs @ 10,000 lm/m^2
Voltage Rise		<15%
Color Shift (delta u'v')	<0.004	<0.002
EQE without external extraction enhancement	~22%	25-30%
Voltage @ 2mA/cm^2	~3.4V	<3V
CRI	84	>90

Discussion Points:

- The importance of developing novel materials and structures was a prominent theme in many of the soapbox presentations. The group noted however, that the previous task C.1.2 (Novel OLED Materials and Structures) was very broad. They recommended that it should be narrowed and renamed "Stable White Devices."
- The development of stable white devices was deemed a priority issue. While stability should be the focus, efficiency and other valuable qualities and metrics like CRI and brightness should still be preserved or advanced.
- In redefining the task to focus on stability (at high efficiency), the group noted that several key research areas would now not be prioritized under task C.1.2, but still remain important areas. These included:
  - The development of narrow red emitters to achieve high spectral efficiency and high quality of light or CRI.

- Creating novel structures that promote good light extraction and reduced costs.

- In particular, the development of more stable blue emitters should remain a prerogative under this task. Currently, the lifetime of blue phosphorescent emitters is too short to be incorporated into state-of-the art white OLED architectures. However, the efficacy of fluorescent-phosphorescent white OLEDs is intrinsically limited by low quantum efficiency of the fluorescent blue emitter.
- Device structure simplification was also a major topic of discussion. There is a need to simplify device structures while maintaining high efficiency. Complex devices increase costs and may not be robust.
- Participants also commented on the need to reduce efficiency roll-off at high brightness.
- It was also recommended that the task description include mention of encapsulation.

C.6.3 Light Extraction Approaches		
Description: Devise new optical and device designs for improving OLED light extraction while retaining the thin profile and state of the art performance of OLED panels (for example, extraction layers should not lead to voltage increases, reduction in device efficacy, angular dependence of color). The proposed solution could involve modifications within the OLED stack, within or adjacent to the transparent electrode, and external to the device. Applicants should consider how their approach affects the energy loss due to waveguided and plasmon modes and should include any modeling or quantitative analysis that supports the proposed method. The approach should provide potential for low cost and should be demonstrated in a device of at least 1 cm^2 in size to demonstrate applicability and scalability to large area (panel size) devices.		
Metric(s)	**2011 Status(s)**	**2020 Target(s)**
Extraction Efficiency	40% (in laboratories)	70%
Angular Dependence of Color		2 step MacAdam ellipse

Discussion Points:

- Light extraction was a major topic in the soapbox presentations, specifically the need to reduce losses due to the internal waveguide and plasmon modes. The need to develop a simple, scalable, low cost, wavelength-independent solution was highlighted throughout the roundtable discussions/presentations and was strongly supported as a priority task.
- Internal waveguide mode extraction is very challenging to do at a low cost. Potential or partial solutions were presented, but development of a low cost, color-independent technique is still recognized as a core research need.
- It was proposed to include a qualification in the description that modeling justification or a basis in quantitative analysis for the approach is necessary.
- It was also recommended that the task description emphasize the importance of evaluating all optical modes, including the plasmon mode, for improvement.
- One participant commented that top emitting OLEDs may have some light extraction advantage in that the substrate modes are eliminated.

3.2.2. Proposed OLED Product Development Tasks

D.4.1 Light Utilization		
Description: Maximize the ratio of useful light exiting the luminaire to total light from the OLED sources. This includes reducing all optical losses in the luminaire; including optical losses from beam distribution and color mixing optics. This task also includes beam shaping to reduce glare or optimize light distribution for the application. Light shaping methods may involve structures within the OLED cavity or may be achieved through the panel placement in luminaire design, for example.		
Metric(s)	**2011 Status(s)**	**2020 Target(s)**
Color vs. angle		2 step MacAdam ellipse
Optical Losses in Beam Shaping		<10%
High Angle Glare		

Discussion Points:

- Light distribution, intensity shaping, and directionality were all topics present in soapbox presentations and discussions.
- It was suggested that the description emphasize that beam shaping is included in this task and that the light utilization solutions proposed should comply with the light distribution industry standard, RP-104.
- Several new metrics were suggested included high angle glare, and optical losses in beam shaping. There was not agreement on a specific high angle glare metric, but a specification for percent of light within a 65 degree half angle cone was mentioned. However, it was also mentioned that metrics will also need to be customized per the intended application of the luminaire.

D.4.2 Novel OLED Luminaire		
Description: Develop novel luminaire system architectures and form factors that take advantage of the unique OLED energy saving properties and represent a pathway toward greater market adoption. It is important that the novel luminaire capture the unique aspects offered by OLEDs, such as lightweight, thin profile, or flexibility of form factor. Proposals should provide quantitative targets for distinctive performance and assess the potential customer appeal.		
Metric(s)	**2011 Status(s)**	**2020 Target(s)**
Lumen Output		
Color stability		
Temperature		

Discussion Points:

- Defining the differentiating features of OLEDs and comparing this technology with LED and traditional lighting was recognized as a crucial need for OLEDs so that they may gain a foothold in the lighting market.
- The description for this task should capture the value proposition aspects of OLEDs. Those that were discussed at the roundtable are listed below. However, there was significant discussion surrounding each one of these potential advantages and whether when pitted against LED luminaires these remained as unique benefits to OLEDs.
    - Lightweight
    - Thin
    - Flexibility of form factor
    - Low operating temperature
    - Light shaping
    - Color tunability
    - Low cost production mechanism
    - Diffuse, large area light source
- It was generally agreed that the output of this task should not be a niche product. Rather should be a general illumination or commodity white lighting product of a novel form factor.
- Adding lumen output as a metric was recommended. Although a 2020 target of 200 lumens was suggested, there was concern that this target was too low to be a viable general illumination luminaire.
- In general, it was agreed that the remaining metrics will need to be customized by the applicant since it will be highly dependent on the application of the luminaire.

D.6.2 Panel Packaging		
Description: Scale up practical, low-cost packaging designs that result in improved resistance to the environment (particularly water and oxygen impermeability) and thermal management. Encapsulation considerations should involve compatible materials, appropriate processes, etc. Edge effects should be considered. Demonstrate a high-efficiency OLED panel that employs such a packaging design and exhibits improved lifetime.		
Metric(s)	**2011 Status(s)**	**2020 Target(s)**
Panel Shelf Life	3-5 years (display)	20 years
Packaging Cost	$300/m^2$ (glass with desiccant and seal)	<$5/m^2$
Operating Lifetime Relative to Existing Packaging Methods		

Discussion Points:

- This task was supported as a priority task as it was agreed that encapsulation is a key issue.
- One participant suggested that encapsulation is currently the largest cost component of OLED panels, accounting for 50-70% of cost. Other participants wanted further examination of this cost breakdown before prioritizing the task.
- Flexible and plastic substrates and their encapsulation becomes a much more significant issue. Referencing the need for panel packaging solutions to be low cost was also part of the discussion.
- While the discussion focused primarily of developing low cost, simple solutions, it was also emphasized that the panel operating lifetime should not degrade relative to conventional packaging methods.
- The addition of a metric as well a lifetime metric tests the product 85 degrees C and 85 percent humidity was considered but not adopted at this time as qualifying it would involve too many assumptions.

4. Milestones Discussion

The final group activity at the roundtable meeting was to review the LED and OLED program milestones as reported in the 2011 MYPP (Chapter 5). Milestones for LEDs were extended out to 2020. The tables and charts below summarize the updates suggested at the roundtables. The performance targets assume adequate funding for the SSL Program.

4.1. LED Milestones

Milestone	Year	Target
Milestone 1	FY10	LED Package: >140 lm/W cool white; >90 lm/W warm white; <$13/klm (cool white)
Milestone 2	FY12	Luminaire: 100 lm/W; ~1000 lm; 3500 K; 80 CRI; 50,000 hrs
Milestone 3	FY15	LED Package: ~$2/klm (cool white) ~$2.2/klm (warm white)
Milestone 4	FY17	Luminaire: >3500 lm (neutral white); <$100; >150 lm/W
Milestone 5	FY20	200 lm/W luminaire

Assumption: packaged devices measured at 35 A/cm2.

Discussion Points:

- It was agreed that a new metric was needed that tied together performance and cost such as lm/W $
- There was also some discussion about the possibility of adding a product quality milestone but this would be application specific and consequently difficult to define.
- When setting target milestones it was important to keep in mind that they should demonstrate a realistic progression from year to year
    - Milestone 4 efficacy target was increased from 140 lm/W to 150 lm/W
    - A warm white LED package price metric was added to milestone 3.
    - A new 2020 milestone, consistent with the luminaire efficacy roadmap, was added.

4.2. OLED Milestones

Milestone	Year	Target
Milestone 1	FY08	> 25 lm/W, < $100/klm; 5,000 hrs pixel
Milestone 2	FY10	> 60 lm/W panel
Milestone 3	FY12	200 lm/panel; > 70-80 lm/W; > 10,000-20,000 hrs LT70 (laboratory panel)
Milestone 4	FY15	< $25/klm (cost), > 100 lm/W panel @ 10,000 lm/m^2 (commercial panel)
Milestone 5	FY18	50,000 hour lifetime; >10,000 lm/m^2 panel

Assumptions: CRI > 85, CCT < 2580-3710 K for an OLED panel >200 cm2. All milestones assume continuing progress in the other overarching parameters - lifetime and cost.

Discussion Points:

- For milestone 2, participants agreed that 60 lm/w was accurate to what laboratory panels can achieve.
- In milestone 3, participants suggested removing the "< $45/klm panel" targets because it was not realistic.
- It was noted that a longstanding issue with LEDs in terms of their credibility was amount of light so using a metric such as panel lumen output or other brightness or lumen output metrics was discussed. High brightness coupled with an appropriate lifetime was offered up as well for the revised 2012 milestone.
- For milestone 4, discussion centered on whether the efficacy metric should continue to be emphasized as it is already a focal point of the previous milestones. Lifetime efficacy, brightness and lumen output were all suggested metrics for this milestone.
- The addition of a cost metric to milestone 4 was adopted. Participants strongly believed that by 2015, low cost is crucial. However, there was concern of how DOE could measure cost (as opposed to price) to determine if the milestone had actually been achieved.
- In general, throughout the milestone discussions, there were many comparisons to the state of LEDs as they will likely be competitors to OLEDs in the future. It was noted that the 2020 milestone for LEDs was set at 200 lm/W and questions arose of whether a similar milestone should be set for OLEDs

Appendix A Participant Presentations

Participants were given the opportunity to prepare short "soapbox" presentations outlining what R&D tasks they believed are particularly important and should be included in the SSL program, or on new areas of study that offer a potential for innovation and energy savings. The presentations were limited to 10 minutes and were followed by an open floor for questions. Summaries of these presentations are given below in the order that they were presented.

LED Presentations, November 2, 2011

I. Eric Haugaard, Ruud Lighting, Inc./BetaLED

- Life cycle costs are the basis upon which purchasing decisions are made and thus should be the basis on which system reliability is analyzed
- Research on how to assess driver quality and reliability levels is necessary. In addition, there is a need to develop standardized test methods for drivers
- Test protocols for harsh environments should be conceived that incorporate particle ingress and fouling factors. These research efforts should also focus on areas including:
  - Investigation into effects on lumen maintenance factors
  - Development of prescribed maintenance schedules
- A focus on improved accelerated life test methods should be emphasized , specifically those which will increase TM-21 multiplication factors and reduce test times
  - A method for measuring LED-luminaire characteristics and more specifically methods for equating useful life and lumen maintenance test results for LEDs, modules and luminaires should receive more research attention
  - Color point stability protocols and prediction methods for ten or fifteen years in the future should also be included in these efforts

II. Robert Harrison, Osram Sylvania

- Lumens per watt should be deemphasized. There is currently much focus on efficacy which can delay early adoption of LED technology by incentivizing consumers to wait. The market will drive further improvements in efficacy.
- The challenges to commercial viability are cost and product quality. LED performance already dominates other available lighting products
- Light quality, color quality, and color consistency need improvement. A lack of good color definition and tight color control slow consumer adoption rates
- Lifetime reliability also deserves research attention. Consumers will not view LED products as a mature technology if performance is not consistent with product performance claims
- Product quality should also be better addressed and regulated

III. Jeremy Yon, Litecontrol

- Increased LED adoption will be a result of focusing on customer's needs. Thus customer needs should drive research and development
- Novel luminaire product development can accelerate the LED market beyond replacement strategies
- Application design research will benefit from being founded on the basis of providing solutions to customer needs, instead of just the product itself. This will offer multiple benefits, which include:
    - Encouraging creativity in product development by defining success metrics
    - Promoting breakthrough innovation and fostering creativity
    - Lowering project cost
    - Stimulating consumer adoption of LED products

IV. Jerry Zheng, iWatt

- More effort should be invested in educating customers on the quality of light and user experience
- Drivers are a weak link in the LED system and therefore should be an area of concentration
    - Driver current stability is one such area remains a significant technical challenge
    - Currently, there are no standards for lifetime measurements. LED driver reliability is an essential part of SSL success.
- In addition to driver reliability improvements, reliability of the dimming control system also needs further development
    - LEDs need an easy, simple and low cost dimmer system
    - A guideline for dimming and dimmer recommendations to meet energy efficiency would also be advantageous
- Improvements in color stability (i.e., change in color temperature) should also be highlighted. Specifically, the development of simple and low cost ways to control color should be emphasized
- Standardization of manufacturing methods is an important and valuable area to direct focus as this will lead to more simplified manufacturing processes which will be instrumental in decreasing costs.

V. Monica Hansen, Cree

- SSL product adoption rates remain low which is primarily due to high associated costs. Therefore, a primary focus of product development should be on lowering these costs.
- One facet of this effort should be defining and setting cost-performance metrics that will stimulate technology choices and innovations. The optimal cost-performance metric should include:
    - A cost component such as lumens per watt per system cost
    - An element that addresses lifetime reliability
    - Finally, the ideal metric should be equivalent across different application areas and different technologies such as phosphors vs. BSY + red (Note: BSY = blue shifted yellow)

- The state of current BSY+R LED technology is one already characterized by high efficacies (>150 lm/W at 1300 lm) and high CRI (>90 at 2800K) relative to other lighting technologies. Other key areas still need improvement. Specifically, these areas of emphasis include:
    - Fixture level color mixing improvements
    - Advancements in the required complex control systems
- Two long-term industry target areas for increasing SSL market penetration rates should be:
    - Incorporating all spectral benefits of BSY+R plus the low cost aspect of blue LED + phosphor blend, defined by an industry-wide cost-performance metric
    - Developing novel spectral materials for blue pumped warm white LEDs to match BSY+R performance (LER/CRI)

VI. Dave Bartine, Lighting Science Group

- There needs to be focus on technology advances that will allow die bonding directly to the heatsinks
- Benefits of LED to heatsink die bonding include:
    - Reduction in thermal loading on the LED
    - Reduction in parts, processes and assembly
    - Increased manufacturing throughput
- Necessary technology advancements to reach this goal are:
    - Development of dielectric material printing process with reflective properties to avoid darkening during bonding
    - Process innovation that allows electrical circuitry to be printed directly onto dielectric material
    - Development of a method that allows uniform heating of heatsink for LED die attachment
- These advancements are important as packaging represents 1/3 of LED cost, so automating at least part of this process will reduce the overall LED cost thereby making the industry more competitive

VII. Steve Lester, Bridgelux

- DOE's stated 2012 target for wall-plug efficiency (WPE) is 50% on 6 inch wafers
- A WPE of > 50% on 8 inch 200mm GaN-on-Si wafers has been demonstrated
- Wafers must be flat and crack free On the 8 inch wafers wavelength uniformity was at ~1% (5 nm standard deviation). However, wavelength uniformity needs to be half this value.
- Performance progress thus far has been in line with DOE product development objectives
    - Already well below DOE 2020 substrate price targets in 2011 with GaN-on-Si at $50 (200mm)
    - DOE 2020 thermal stability flux target of 95% for blue LEDs is achievable; they are currently at 88%
    - 90% EQE at 350 mA can already be achieved (Note: DOE's 2020 target is 100%)

- The industry is moving towards 8 inch wafers and GaN-on-Si. This could change the cost structure of LEDs
- R&D challenges still exist. These include:
    - Manufacturability and thermal mismatch between GaN and Si (epitaxial challenges)
    - Wavelength uniformity
    - Scaling-up of wafer fabrication

VIII. Decai Sun, Philips Lumileds

- Improving lumens per watt is still a challenge for warm white (WW) LEDs. Currently, they lag cool white (CW) LEDs efficacy by about 30%
    - Opportunities to achieve improvements in WW LEDS exist in the development of a better narrow red phosphor
    - The benefit of finding a better narrow red LED is that it can be used to achieve relatively good CRI and efficacy (despite the associated poor hot/cold factor disadvantage)
- Another important area of focus is cost reduction of high power LEDs packages
    - In order to achieve cost reduction in high power LEDs it is necessary to look beyond die on ceramic packaging to package efficiency improvements and advancements in thermal handling capability
    - Lens free LED packages are an option but chip-level extraction efficiency must be improved to first
    - Phosphors and QD materials are also a possibility if the package can be redesigned to reduce converter layer temperatures thus enabling QD material integration
    - Another potential solution to reducing cost is standardizing package design for whole industry, especially for certain applications,
- Other proposals for improving lumens per dollar or similarly reducing costs of high power LEDs include:
    - The use of high voltage LEDs which enable simpler driver circuits with higher efficiency and decreased overall system cost
    - Increasing the power density which in turn increases the lumens per dollar thereby reducing cost
- Other areas that require advancements are reliability and quality of light. This includes improving lifetime, color stability, and consistency.
- Hot testing and freedom from binning present yet another area with opportunities for improvements.

IX. Seth Coe-Sullivan, QD Vision

- Narrowband down-conversion materials are an important area to direct research means. The efficacy performance gap between warm white and cool white LEDs is predicted to continue to decrease from around 40% in 2008 to only 1% by 2020
- There is an ideal combination of down-conversion color peaks to achieve the maximum LER for a given CCT/CRI
- There is a need for tunable narrowband emitters in order to optimize the entire range of CCT/CRIs

- Efficiency gains of about 10% are still attainable in CW and/or low CRI color specs
- Non-REM down-conversion materials are a necessary innovation in order to reduce dependency on rare-earth metal elements. Reducing this dependency is important for the following reasons:
    - Regulatory compliance prohibits the use of certain (toxic) elements
    - It will decrease dependency on individual nations, potentially capping US LED innovations and giving other nations and advantage over US markets
    - And increase US availability and supply chain security

X. Xie Yuming, Intematix

- Phosphor materials which need further development include:
    - Aluminates which illuminate full spectrum
    - Nitrides/Oxynitrides that provide high reliability
    - Quantum dots which are characterized by high thermal stability
    - Long decay phosphors developments for use with AC drivers
- Phosphor processes to improve yield and phosphor conversion efficiency are also essential as customers are always pushing for high brightness
- Research in remote phosphor materials is critical, specifically:
    - Developing new substrates/molding processes for flexible designs
    - Improving capability and reliability with respect to high temperature applications
    - Improving spectral response and reduced costs
- In terms of lighting quality, further phosphor development is necessary to improve spectral coverage of phosphors especially in the blue-green range to achieve high CRI
- It is important to create new materials and improve existing phosphors which are less reliant on rare earth elements (such as nitrides and QDs)
- In addition, the development of more robust phosphors can prevent color shift, improving reliability, an area in which LEDs have received less praise.
- Lastly, cost reduction is critical. Specifically, developing/tailoring different phosphors for different applications will reduce cost

XI. Jon Wierer, Sandia National Laboratories

- The use of lasers for SSL can have several benefits, including:
    - High luminous efficacies as a result of narrow line widths and increased spectral efficiency
    - Directionality of light offers (potentially) more efficient remote phosphor configurations
    - Potential to provide cheaper photons
- Measurements on lasers could provide insight into and identify mechanisms behind droop in LEDs. InGaN lasers and InGaN LEDs share the same kind of active regions. There are measurements possible with lasers that aren't yet possible with LEDs such as optical gain and injection efficiency at high current densities
- Lasers could also help to overcome efficiency droop by eliminating the contribution of leakage currents and non-radiative recombination processes to the overall recombination process (when operated above threshold).
- However there are challenges that exist with lasers. These challenges include:

  - The need to conclusively demonstrate that high quality white light can be achieved using narrow line sources
  - Like LEDs, the green gap needs to be overcome
- In addition to lasers, nanowire architectures also offer opportunities to advancing SSL lighting. Proposed research on nanowire architectures includes:
  - Growing InGaN on small dimensional nanowires leads to relaxation of lattice mismatch strain of InGaN on GaN
  - Forming arrays of these nanowires may provide better light extraction by scattering or photonic crystal effects

XII. Uwe Happek, University of Georgia

- Further efficacy improvements above 100 lm/W may result in diminishing returns. Thus, concentrating research in other areas may be more beneficial.
- The effects of lumen maintenance on color stability warrants further study. For example an 8% loss in red phosphor efficiency over lifetime equates to a 0.007 color shift. Customers are sensitive to these high color shifts.
- Fundamental research is required on phosphor degradation, impact of 405 vs. 450 nm excitation, defect formation, and behavior at high photon fluxes.
- Device level research is required on active feedback/control methods, discrete architectures, hybrid designs (e.g. BSY+R), and RGB LEDs
- Scarcity of rare earth materials is more speculation than fact
- Reliability needs improvement and prices need to be decreased

XIII. Christian Wetzel, Rensselaer Polytechnic Institute

- LEDs still face material & structure challenges. For example, in non-polar m-plane MOVPE growth, lumen output drops off at green wavelengths due to defects created during growth of the quantum wells
- The use of nanopatterning of the substrate prior to growth, even on cheap sapphire, produces material with very low densities of threading dislocations
- Some success has also been demonstrated using nanopatterning on bulk GaN substrates but experiments limited to small pieces, work needs to be done using substrate sizes
- Nanopatterning on sapphire has shown a 3 fold increase in light output power at 520 nm (green) due to fewer defects, improved IQE, and better light extraction.
- Future needs for SSL lighting include:
  - Good bulk GaN with various crystal orientations
  - Nano-patterned substrate and template growth
  - InGaN growth at higher pressure; which raises temperature thereby reducing defects
  - Improved in-situ characterization during MOCVD growth to better understand fundamental growth mechanisms

OLED Presentations, November 3, 2011

I. Asanga Padmaperuma, Pacific Northwest National Laboratory

- DOE should continue to fund core research priorities:
  - Improving light extraction from OLEDs
  - Developing new white OLED materials and architectures
  - Increasing efficiency and color control
- We need to be aware of international competition. International (e.g., Asia & EU) investments are larger than domestic investments
- Light Extraction core research should consider size/scalability requirements. Also, all research should be done in the context of a good optical theoretical model:
- White architectures core research needs include:
  - Development of a long lived stable white. Ultra high efficacy OLEDs may not be necessary.
  - Stable blue development remains a priority

II. Sebastian Reineke, Massachusetts Institute of Technology

- Current OLED panel prices are estimated at $3.60/lm. To meet Lumiotec's 2017 projection of $0.05/lm, the following requirements must be met::
  - Efficiency > 100 lm/W (factor of 10 increase)
  - Panel cost ~ $55 (85% reduction from current costs)
- Efficiency plays an important role in developing next generation materials and device concepts.
  - Device structures should be simplified while maintaining high efficiency
  - Further improvements in outcoupling efficiency are still needed
  - Core research should focus on efficiency roll off so high efficiency can be achieved
- Reducing size and increasing brightness of device is a way to decrease panel cost
  - First must gain a better understanding and improve efficiency roll-off at high brightness, especially with phosphors
  - To improve high brightness performance, need novel material, architecture and manufacturing process concepts/designs

III. Alexander Shveyd, University of Rochester

- OLED degradation using mass spectrometry studies is their current area of focus.
- Photochemical oxidation of a blue dopant
  - The process included modification of thin layers in the blue OLED structure using the blue phosphorescence dopant Flrpic
  - Experimental conclusion reached was that OLED instability could be due to the oxygen bonds
- Electrical aging in a single layer device
  - The process included testing electrochemical stability of a host by electrically aging for 24 hours
  - The goal was to determine where degradation originates through a process of elimination

- Multi mass spectrometry is a promising technique for investigating OLED degradation, identifying chemical mechanisms for failure, developing material and structure designs to increase OLED lifetimes and advancing the method of characterizing isotopically enriched compounds

IV. Steve Forrest, University of Michigan

- Prominent OLED challenges include:
  - Longer lifetime for blue OLEDs
  - High efficiency at high intensity
  - Thermal management
- Electroluminescence efficiency roll-off at high intensities remains a challenge. This is caused by singlet-triplet annihilation. However, this roll-off may be able to be mitigated via triplet managers.
- Light outcoupling is still a significant issue. Approximately 80% of the emitting light in the glass substrate is lost
  - Losses are due to: internal reflection, glass modes and waveguide modes
  - There is a need to enhance light extraction so we are not fundamentally limited at 20% internal efficiency
  - Doubling light output is a partial solution to this but the best solution will be simple, low cost, wavelength independent, and compatible with large substrates.
- OLED temperature and degradation is still a complex problem Exciton-Exciton annihilation and Exciton-Polaron annihilation are the main routes that lead to blue degradation.
- OLED lifetime is also an important consideration.
  - OLEDs run cool, even when driven at high current surface temperature only increases by ~8 degrees. This is an important factor in lifetime,
  - Increasing recombination zone width can theoretically help extend lifetime
  - Stacked OLED (STOLED) architecture provides significant improvements (approximately double) in lifetime compared to single unit OLEDs with similar color and power efficacies

V. Franky So, University of Florida

- OLED EQE has remained poor because of low outcoupling efficiency due to refractive index mismatch. This results in large amounts of emitted light being trapped in the organic layer and glass substrate
- In an optimized device you can achieve 25% extraction efficiency. 20% is due to substrate and the rest is thin film guide mode and a big part of it is that lost to the surface
- Microlens arrays have been used as a low cost and straightforward technique in substrate mode extraction
- Thin film guided mode extraction is very challenging to do at a low cost, other options include:
  - Waveguiding vector reduction will allow light extraction. This can be accomplished by using a periodic grating structure which produces a grating vector in the opposite direction.

- Corrugated structures and photonic crystals are other options
- The problem with these methods is that they strongly impact the emission spectrum. We want uniform enhancement across wavelengths.
    - Using high index materials is an effective way to extract light but it is not low cost
    - Using defective grating (OLED fabricated on defective microlens array), one can achieve non-uniform periodicity and amplitude. The enhancement factor across the spectrum is fairly uniform and thus there is weak wavelength dependence

VI. Seth Coe-Sullivan, QD Vision

- Spectral control using narrow band down conversion emitters is a necessary goal for the OLED industry to make high efficiency white lighting This is particularly true for red but it is important across the spectrum
- The lighting market requires more than one color; you need a continuously tunable range to meet consumer specifications
- The large-area light source market holds the greatest potential for OLEDs. The industry needs to determine fundamental advantages OLEDs have over other lighting technologies. Need to focus programs on these differentiable benefits

VII. Mathew Mathai, Plextronics

- Core research should focus on:
    - Light extraction
    - Increasing thickness of layers without impacting voltage
    - Addressing fundamental limitations at interfaces between injection, transport and emissive layers. Injection efficiency plays a key role in improving electrical efficiency of materials
    - Emitter and host material technology to improve efficiency and lifetime. There is a need to develop a narrow spectral bandwidth reds and higher EQE.
- Focus should be directed towards product development on decreasing panel cost (focus is on OLED as a luminaire). Examples of opportunities to this aim are:
    - Large-area layer thickness uniformity
    - Reduce time for process steps in device fabrication
    - Develop metrics around light shaping
    - Color uniformity as a function of angle of viewing
    - Color stability over lifetime
- In product development there needs to be an emphasis on manufacturing, specifically defect tolerant manufacturing
- The industry also needs to develop new metrics (quality metrics) for large area OLED panels

VIII. John Hamer, OLEDWorks

- Current OLED performance is currently adequate, but reducing the costs of OLED lighting is important to increase the rate of penetration. We will not be successful as an industry if we wait and rely on volume increases to drive down the cost
- Focus on cost reduction of panels is key, possible opportunities include:

- Development of low cost substrates with good light extraction
- Development of on novel equipment and processes that have better capital cost to output ratio and reduced material usage
- Need small, low cost manufacturing equipment coupled with process improvement and innovation

- We need good commons/collaboration to support the US OLED lighting industry. Better infrastructure helps everyone
- The current process of thermal vacuum evaporation involves slow and expensive equipment with low material usage efficiency. Once the industry has grown and volumes are large, solution deposition may be a lower cost solution, but small scale solution deposition processes are expensive.
- Process Innovation is an essential area for focusing research efforts
- Need Core research on the effects of evaporation and condensation rates on OLED properties
    - Better knowledge/understanding of rate limiting steps
    - Focus on developing evaporator sources with innovative design
- Cheap and small size OLED manufacturing equipment will allow more people to start making panels. Future manufacturing equipment features should include:
    - Ability to keep material cool when not evaporating or ability to add more material during operation (to prevent degradation)
    - Deposition of vapor only where desired (to improve material usage efficiency)
    - Reduce the size and complexity of the machines (to reduce the cost)
- Future pathways to industry success:
    - Industry will need more machines; US could supply these This could be a US advantage from an equipment supply chain perspective
    - Equipment must be low cost (to buy *and* operate)
- Why does an industry grow and succeed in one nation but not another? Because they have achieved a concentration that attracts the industry. We must have a commons – need communication and everyone helping one another to succeed (Japan is a good example of this)

IX. Mike Hack, Universal Display Corporation

- Critical Elements for OLED Lighting include:
    - Energy saving products and cost effective products for OLEDs
    - Focus on infrastructure, supply chain and consumer education
    - Government incentives and OLED standards need development. Currently there is a lack of OLED standards is likely to hamper growth
- Technical areas of focus include:
    - Cost effective thin outcoupling solutions
    - Intensity shaping
    - Designing for high yield and thinking for encapsulation
- Industry areas of focus should cover:
    - Incentives for panel manufacturing and luminaire prototypes
    - Driver and electronics developments, specifically integration with building controls to save energy
    - High utilization and yield as well as lower cost OLED deposition equipment

  - Niche products or applications for consumer awareness that address color tunability
  - OLED demonstration projects to expose more consumers to the products
- The key challenge that OLEDs currently face is cost reduction

X. Joe Laski, Osram Sylvania

- Current typical OLED performance values are summarized as follows:
    - 2000 – 3000 cd/m²
    - 30 – 45 lm/W
    - 5000 – 10000 hrs (L70)
- Further study into degradation mechanisms is necessary. Namely, we need to decrease reaction rate of transport and identify emissive material degradation processes. Benefits include reduced voltage rise and better lumen maintenance.
- Need to develop stable blue phosphorescent emitter. Blue phosphorescent emitters life still too short to be incorporated into white state-of-the art OLED architecture
- Improving light outcoupling will allow OLEDs to surpass the 100 lm/W barrier.
  - Largest fraction of generated light is wave-guided through the high index materials in the OLED cavity.
  - The introduction of a scattering medium within these layers is a key technique to significantly increase the out-coupling efficiency and, as consequence, the overall device performance
- There is a need to develop reliable integrated intelligent OLED drivers (with long life-time)
  - Need to develop plug-and-forget lighting systems. This allows OLEDs to be truly embedded into architectural designs
  - OLEDs can benefit from customized drive conditions The low quality of the current provided by most common LED electronic control gear (ripple, duty cycle) is harmful to the OLED and reduces its lifetime. Applying specific OLED driving schemes may increase the device lifetime.

XI. Joseph Shiang, GE Global Research

- Three key OLED general lighting targets are:
  - Reduced costs (<$10/klm)
  - Increased efficacy (>60 lm/W)
  - Increased lifetime with high brightness
- Cost reductions are the largest obstacle for OLEDs currently. Need to focus on reducing cost per area.
- We need to understand what the limiting factors are in efficiency and life
- We also need to consider the variable versus fixed costs. This fundamental consideration is a matter of how a particular technology is going to scale
- Material usage should also be a focus as
  - Material costs are a serious issue
  - OLEDs need a material that has greater stability and high brightness
  - As well as a low cost product design!
- Core research should work on improving lumens per watt while product development should concentrate on costs and scaling up to large areas

XII. Yuan-Sheng Tyan, First O-Lite

- Cost is a big issue for OLED panels. A cost analysis was done in China, with the following key observations and conclusions:
  - Currently, encapsulation is the biggest cost, representing 50% – 70% (including depreciation)
  - This is primarily due to the fact that most common technology for OLED panels is still simple glass substrate with perimeter glass seal system
  - The industry needs a new concept for encapsulation. This will involve new engineering and new ways to implement
- In the near term OLED panels are not likely to be very large in size due to yield concerns and anode conductivity limitations
- Materials and equipment cost represent a large part the overall costs.

XIII. Mike Lu, Acuity Brands Lighting

- Constant luminance drive and their potential benefits are the current primary area of focus
  - Light loss factors (LLF) are used in determining realistic long-term average maintained illuminance. Lamp lumen depreciation is a component of LLF, which for SSL is typically 70% (L70)
  - Lighting designers base specifications off of maintained illuminance. Thus lumen depreciation results is larger luminaire quantities needed to meet illuminance targets
  - Utilizing constant luminance drive where drive current is increased to compensate for OLED aging leads to fewer luminaires needed to meet target illuminance
- Shelf-life/Storage life (device not being operated) is also a key area of focus
  - Shelf Life - for fluorescents and LEDs are not an issue
  - For OLEDS it is purely a function of encapsulation and/or desiccant
  - The minimum is defined to be 7 years (>10 yr preferred) for lighting products
  - There is no conclusive study of relevance on accelerated life testing
- OLED Degradation also remains a challenge
  - Possible degradation mechanisms are complex: Polaron related, exciton related, polaron-exciton interactions, etc.
  - Degradation can be studied by academia even without access to the latest materials. Companies may not have the resources or expertise to perform these kind of studies