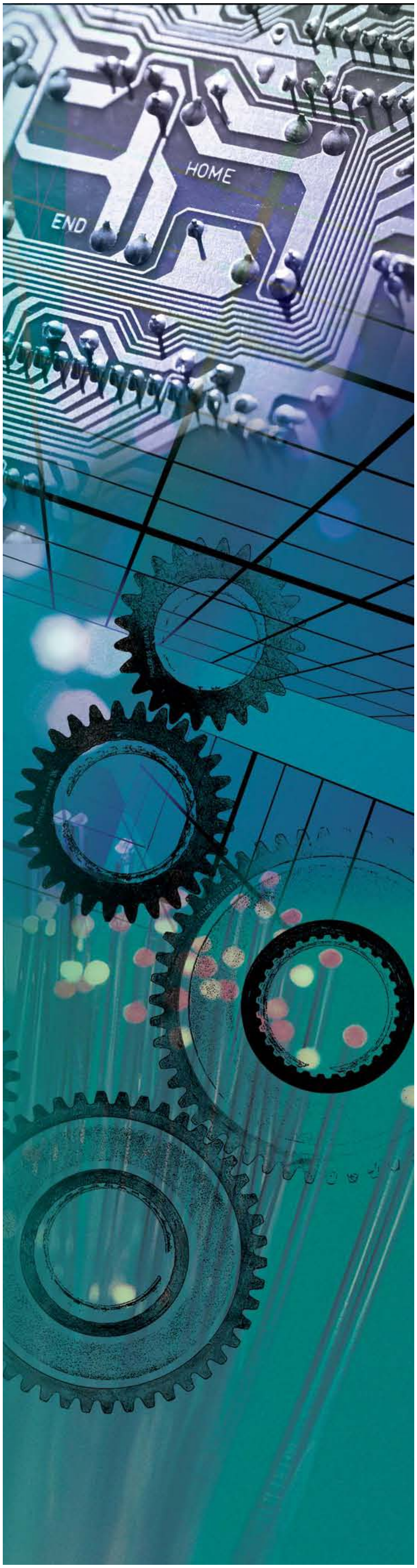

Solid-State Lighting Research and Development: Manufacturing Roadmap

July 2010

Prepared for:

Lighting Research and Development
Building Technologies Program
Office of Energy Efficiency and Renewable Energy
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DISCLAIMER

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COMMENTS

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Preface

The Energy Policy Act of 2005 (EPACT 2005) directed the Department of Energy (DOE) to carry out a "Next Generation Lighting Initiative" to include support of research and development of solid state lighting (SSL) with the objective of lighting that would be more efficient, longer lasting, and have less environmental impact than incumbent lighting technologies. Much progress has been made towards these goals, and, indeed, many efficacious light emitting diode (LED) lighting products are now appearing in the marketplace.

In 2009 the Department of Energy launched a new SSL manufacturing initiative to complement the SSL Research and Development (R&D) Multi-Year Program Plan (MYPP) which guides the Core and Product Development R&D programs. That initiative, which included expert roundtables and two workshops, culminated in the 2009 SSL Manufacturing Roadmap, intended as an extension of the 2009 MYPP. The 2009 SSL Manufacturing Roadmap focused on the R&D needs for achieving cost effective, high quality manufacturing capabilities for solid state lighting products, including packaged devices, replacement lamps, or complete luminaires. The report included a number of graphs and summary tables outlining needed and anticipated progress in SSL manufacturing. As is the case with the MYPP, it is DOE's intention to annually review and update this report in collaboration with industry partners.

This year, building on the general timelines and targets identified in 2009, there has been an emphasis on identifying specific areas of prioritized work during the next year or two in order to achieve the ultimate goals of the program.

Much of the background for the SSL program, including a summary of significant accomplishments, research highlights, the legislative framework, and financial support of the program may be found in the March, 2010 Multi-Year Program Plan. We will not repeat that material here, but readers are urged to review it as background for reading this SSL Manufacturing Roadmap.

The 2010 Multi-Year Program Plan can be downloaded at:
http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mypp2010_web.pdf

1.0 Introduction

The goals of the SSL Manufacturing Initiative are to:

- Reduce costs of SSL sources and luminaires;
- Improve product consistency while maintaining high quality products; and
- Encourage a significant role for domestic U.S. based manufacturing in this industry.

DOE believes that pre-competitive cooperation in understanding best practices, common equipment needs, process control, and other manufacturing methods and issues is the best path to achieve these goals.

This SSL Manufacturing Roadmap will guide future planning for DOE R&D actions including funding of solicited cooperative R&D projects. It is the result of a highly collaborative and participative effort that has taken place during the course of this year. The work for the 2010 update began March 16-17, 2010 when DOE convened two expert panels for LEDs and organic light emitting diodes (OLEDs), to recommend specific tasks to be accomplished in the near term, as well as updates to the roadmap itself. Then, on April 21-22, 2010, exactly one year after DOE's initial manufacturing workshop in Fairfax, VA, about 280 representatives of a broad cross-section of the SSL value chain assembled in San Jose, California for the 2010 Manufacturing Workshop[1] and roadmap update. This number is a significant increase over the attendance at the 2009 workshops, with a large fraction of the attendees were attending a DOE SSL workshop for the first time.

As mentioned, the primary goal of the Roadmap is to guide the R&D program and to help direct funding solicitations. In addition, it provides guidance for equipment and material suppliers, based on industry consensus on the expected evolution of SSL manufacturing, which reduces risk, and ultimately the cost of undertaking SSL manufacturing. Supporting the development of multiple sources of key equipment and standardized components can also improve quality and lower costs. At the same time, identifying best practices, to the extent firms are willing to share their experiences, can reduce product variability and increase yields.

It should be noted that many of the activities discussed in the various specific 'roadmaps' of this document are beyond the scope of the DOE SSL Manufacturing Initiative and, in some cases, beyond the scope of the DOE SSL Program in general. The DOE SSL Program will endeavor to address all of the issues which fall within the Program charter, but it is anticipated that some activities on the DOE SSL Manufacturing Roadmap will be more appropriately addressed by industry, industry consortia, or other stakeholders. It is also anticipated that with each revision the DOE SSL Manufacturing Roadmap will become more comprehensive, refined, and more detailed. This is a living document subject to continuous improvement.

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[1] Workshop presentations and handouts can be found at http://www1.eere.energy.gov/buildings/ssl/sanjose2010_materials.html.

The organization of this document follows the same pattern as the 2009 version and is divided into separate LED and OLED sections. A new chapter, describing R&D tasks prioritized by the work of the roundtable and the subsequent workshop breakouts has been added for this update as more details of the needs have emerged. A fifth section continues an effort begun last year to update progress on SSL-related standards. Where participants identified additional or continuing needs for standards not yet available, these recommendations have been noted. Appendix A provides information about existing and pending standards efforts in many areas, including testing and performance metrics not directly related to manufacturing but relevant.

1.1 Key findings and general recommendations for 2010

While the 2009 Roadmap provided in broad outline much information on the anticipated evolution of SSL manufacturing, an important component of this year's update was to gather some consensus around key specific tasks needed to accomplish immediate goals in order to make progress along the roadmap paths. Discussions during the March roundtables provided several suggested R&D topics which were distilled into a limited number of proposed priority tasks introduced at the workshop. Workshop participants discussed and refined these tasks during separate breakout sections for LEDs and OLEDs.

In addition, these groups recommended changes in the overall Roadmap, some of which were along the lines of bringing the numbers up to date to reflect the current status, and others to clarify and detail certain discussions in the 2009 edition. The next sections summarize the priority tasks as well as some of the additional changes to be found detailed in subsequent chapters of this report.

1.1.1 LED Manufacturing R&D Priorities

During the March Roundtables, seven priority tasks for LEDs were identified. At the Workshop in April, two of these were combined, and another identified. The Workshop choices are listed by title and brief description below; more detail may be found in Section 4.2.1.

Table 1. LED Manufacturing R&D Priority Tasks

M.L1.	**Luminaire/Module Manufacturing** Automation, manufacturing, or design tools to demonstrate high quality flexible manufacturing at low cost
M.L2.	**Driver Manufacturing** Improved design for manufacture for flexibility, reduced parts count and cost, while maintaining performance
M.L3.	**Test and Inspection Equipment** High-speed, non-destructive, and standardized equipment, for all manufacturing steps
M.L4.	**Tools for Epitaxial Growth** Tools, processes and precursors to lower cost of ownership and improve uniformity
M.L5.	**Wafer Processing Equipment** Tailored tools for improvements in LED wafer processing
M.L6.	**LED Packaging** Improve back-end processes and tools to optimize quality and consistency and to lower cost
M.L7.	**Phosphor Manufacturing and Application** High volume phosphor manufacture and efficient materials application

Of these tasks, the first two are associated with luminaire manufacturing, and the last four with the LED chip and package. Task L3 applies to both.

There were a number of specific recommendations that arose out of the workshop discussions relating either to individual tasks or other aspects of the roadmap, discussed throughout the document. There were also a number of more general recommendations not specifically related to the Roadmap which are listed here:

- Provide education and certification on LED luminaire design
- Consider the end-of-life of an LED luminaire and possibly a recycling program
- Define standard footprints for LED packages to facilitate interchangeability/replacement
- Encourage development of an industry-wide accessible data base of components and materials

1.1.2 OLED Manufacturing R&D Priorities

Five candidate tasks for prioritization for OLED manufacturing were identified at the roundtables. Of these, only four received significant support at the workshop, as listed below. The fifth, regarding in-line monitoring, was incorporated into task M.O2. There were some changes to the titles and descriptions of these tasks following discussions at the workshop. More details may be found in Section 4.2.2.

Table 2. OLED Manufacturing R&D Priority Tasks

M.O1.	**OLED Deposition and Patterning Equipment:** Manufacturing equipment for high speed, low cost, uniform deposition, and/or patterning of state of the art OLED structures and layers.
M.O2.	**Integrated Manufacturing and Quality Control:** Methods to integrate the many process steps, to check the quality and compatibility of materials or to study the reliability and reproducibility of the finished devices.
M.O3.	**OLED Materials Manufacturing:** Advanced manufacturing of organic and inorganic OLED materials
M.O4.	**Back-end Panel Fabrication:** Tools and processes for the manufacturing of OLED panels from OLED sheet material.

In addition to the manufacturing task recommendations, there were a number of recommendations for tasks from the roundtable that were judged to be more suitable for the Core and Product R&D programs. These will be considered in the 2011 update to the Multi-Year Program Plan.

There were also a number of general recommendations for the program as pertaining to OLEDs:

- Develop specifications for products, processes, tools and packaging
- Partition the pilot line processes and define them clearly
- Use the partitioned processes to define tools needed
- Define clear interfaces between layers and system components
- Consider a repair and materials recycling strategy to minimize waste and reduce cost
- Investigate international standards to assure compatibility with those developed here

1.2 Overall projections/contributions to cost reduction

1.2.1 LED Lighting

A number of speakers at both workshops proposed roadmaps for improvement in various areas, and the breakout discussions refined those thoughts. From a high-level perspective, it should be possible to identify principal sources of cost reduction over time, which can then be refined into more specialized goals for materials, processes, or capabilities.

Figure 1 shows a high-level cost breakdown and projection for cost reductions in LED based luminaires. The initial cost split for 2009 is based on information provided by Cree LLS at the April 2010 Workshop. This figure reflects projected cost reductions based on LED Package price targets from the SSL Multi-Year Program Plan, inputs from the presentations at both workshops, and discussions in the luminaire breakout sessions.

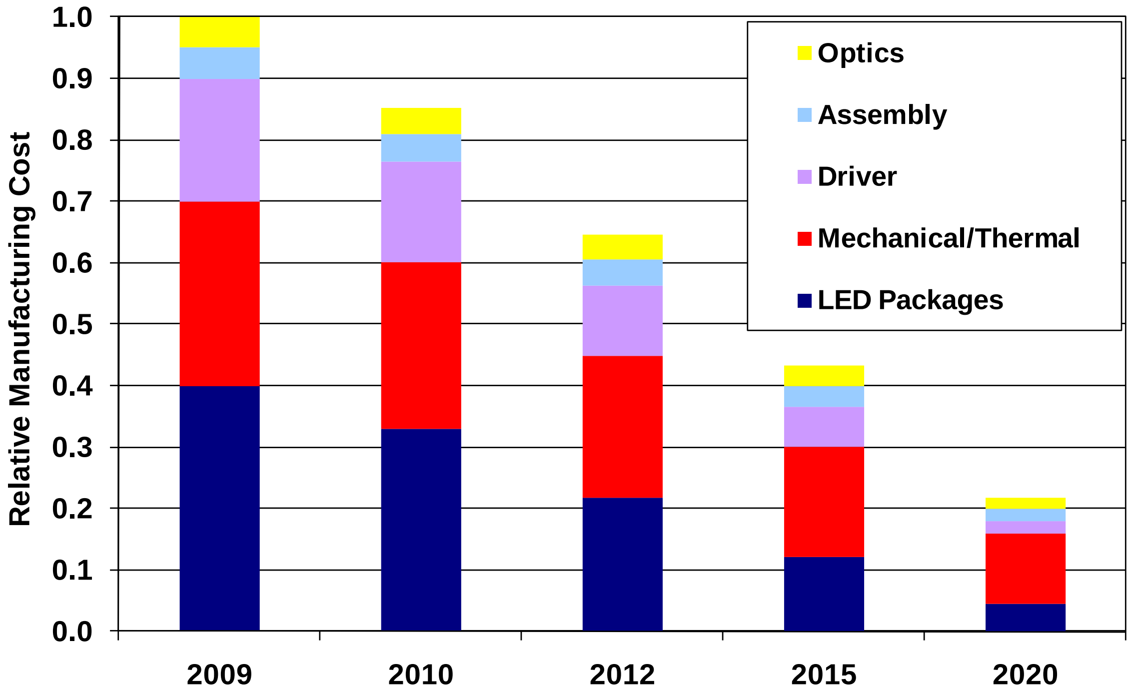

Figure 1. Projected LED Luminaire Cost Track
Source: DOE Manufacturing Workshop consensus

The projections in Figure 1 account for potential cost savings from improved manufacturing processes and from luminaires "designed for manufacture", which would most directly affect the 'Mechanical/Thermal' and 'Driver' costs.[2] In this context, 'Mechanical/Thermal' includes both the mechanical components, comprising the complete luminaire fixture and means for mounting the LED(s), driver, optical components; and the thermal components which are required for proper management of the heat produced within the fixture. 'Driver' refers to the power source with integral control circuitry designed to operate an LED package or module or lamp. Note that this includes the power source for conversion to DC from the electrical branch circuit as well as the controlling electronics. In addition, there could be cost savings as automated manufacturing and assembly operations replace manual processes for the manufacture of luminaires and the sub-components. Since this new lighting technology is based on semiconductor technology and manufacturing processes, the final luminaire products may be able to take advantage of automation technologies developed for the manufacturing and assembly of consumer electronic products. Automation could reduce the labor cost for the full luminaire and for the sub-components of the luminaire, removing one of the drivers for moving luminaire manufacturing out of the U.S. Overall goals for LED based luminaires, as reflected in DOE's 2010 Multi-Year Program Plan, project price reductions (in terms of dollars per kilolumen ($/klm)) of approximately 22% per year, representing a factor of about four by 2015 and a factor of about 16 by 2020.

[2] See Section 5.1.1 for definitions of LED and OLED components.

As shown in Figure 2, a similar high-level cost breakdown and cost reduction projection was developed for LED packages. The cost breakdown and projection is based on preliminary data provided by the Cost Modeling Working Group. Care should be exercised in comparing these cost projections with the price projections shown in Table 3. These cost projections are based on raw dollar manufacturing costs per package whereas the price projections in Table 3 are normalized to lumen output and include additional factors such as gross margin.

Figure 2 indicates that packaging costs represent the largest contribution to the overall cost of an LED package. Though not reflected in the cost projection, improvements in an earlier part of the manufacturing process, such as improved uniformity in the epitaxial process, will have a “lever” effect and can greatly impact the final device cost and selling price through improved binning yields.

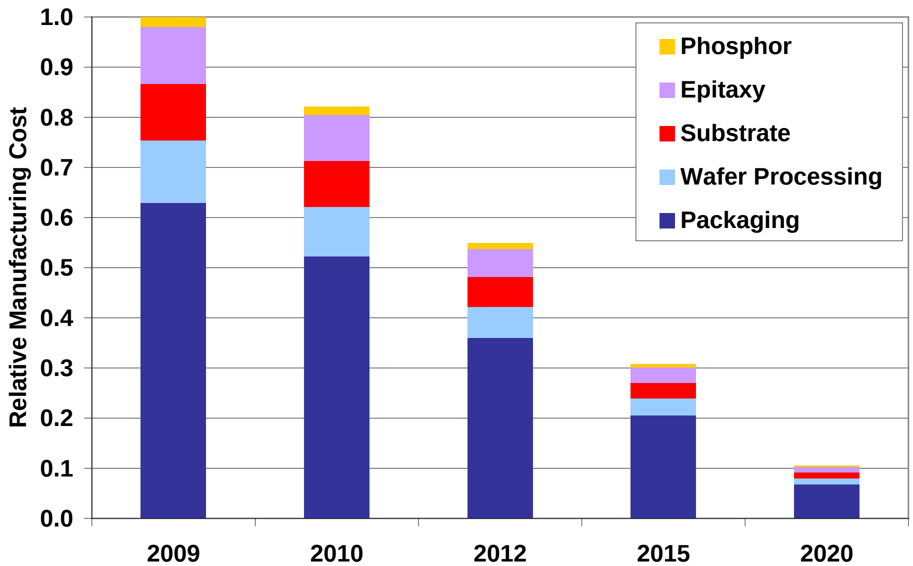

Figure 2. Projected LED Package Cost Track.
Source: Preliminary data provided by the Cost Modeling Working Group

A Pareto analysis of the SSL manufacturing cost in 2010 (combining luminaire and LED manufacturing cost breakdowns) is shown in Figure 3. The mechanical/thermal manufacturing costs currently dominate the overall luminaire cost. Driver costs and LED packaging costs are the next largest contributions however these are both projected to come down rapidly. Consequently, the mechanical/thermal costs will become increasingly dominant and steps will need to be taken in the future to actively address cost reduction strategies for this segment. This form of analysis can guide the DOE SSL Manufacturing Initiative and it is expected that the projections will continue to be refined in upcoming manufacturing workshops and through the efforts of the Cost Modeling Working Group.

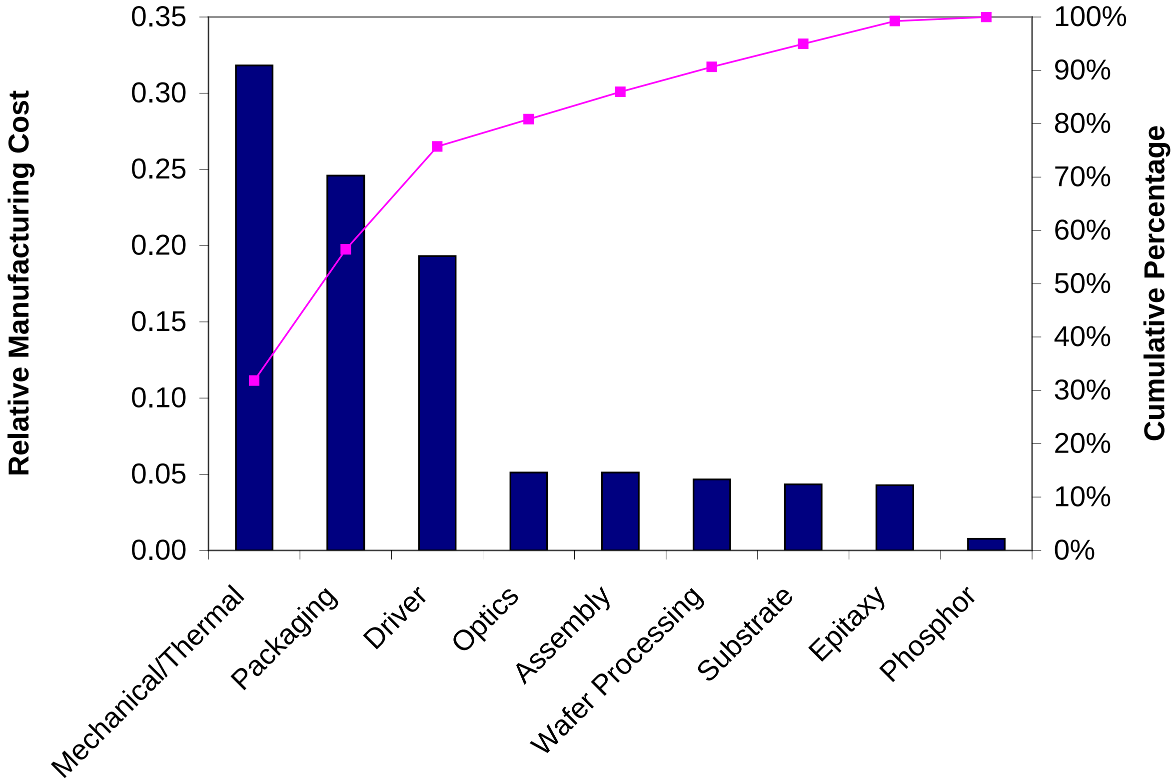

Figure 3. Pareto Analysis of SSL Manufacturing Costs. 2010 Projection[3]

1.2.2 OLED Lighting

Thus far, OLED manufacturing practices have been largely determined by display applications. The requirements of lighting applications are simpler in some respects but more challenging in others. One of the challenges associated with lighting applications is that in order to compete with other lighting technologies the costs must be drastically reduced from the $2000/m^2 typical of OLED displays. Some of these savings can come from the elimination of expensive components not required for lighting applications, such as the thin film transistor (TFT) backplane and borosilicate glass, and most process steps that require sub-micron patterning. Further economies can be made by implementing faster fabrication on larger substrates and by simplifying manufacturing methods possibly through the use of solution processing. Figure 4 presents one projection of how such savings could be achieved. This forecast was constructed to show the potential advantages of increases in substrate size in conventional evaporation manufacturing approaches along with shorter processing times and less material wastage, as discussed below in Section 3.1.1.

[3] The Pareto analysis does not account for margins in the costs presented. Between the actual cost to fabricate the LED and the price of the LED that luminaire manufacturer must pay there will be a margin built in. At reasonable margins the exclusion of the margin does not impact the general findings of the analysis (*i.e.*, with or without the margin included the costs stay in the same ranking and close to the same relative value).

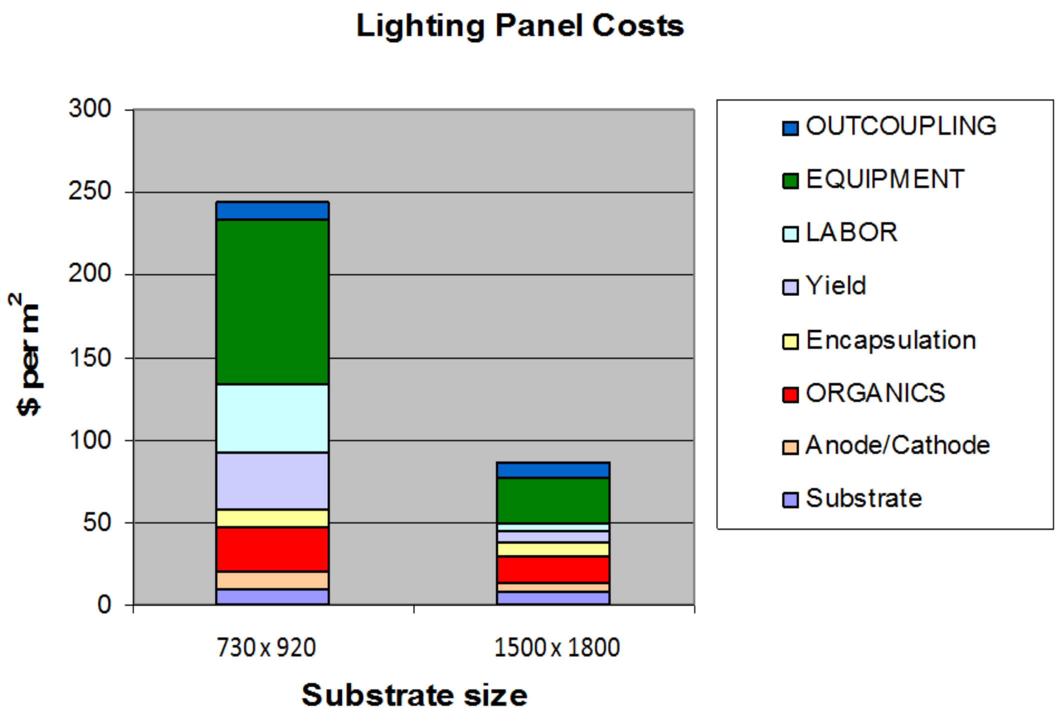

Figure 4. Dependence of OLED Manufacturing Costs on Substrate Size
Source: Mike Hack, Universal Display Corporation, "OLED Lighting", SSL Manufacturing Workshop, Fairfax, VA, April 2009

These estimates indicate that substantial cost reductions are possible, in comparison to past costs for OLED displays. However, realizing the benefits of manufacturing on large substrates will require substantial capital investment. Most developers are hesitant to commit such funds while so many uncertainties remain about the architectures to be fabricated and the equipment to be used. Thus the immediate priority is to focus on cost reductions that can be achieved on relatively small substrates.

The analyses described below will show that manufacturing costs scale more directly with panel area, rather than light output. Thus, increasing OLED brightness may turn out to be a critical component of meeting market-driven $/klm cost objectives. The final cost target achieved in this projection is consistent with the 2009 MYPP price target of $10/klm, provided that the light output of the device is greater than 10,000 lm/m^2. However, unless the stability of OLED devices can be improved substantially, devices with such high luminous emittance would likely have lifetimes that are unacceptable for most applications. This suggests that additional R&D to extend product life at high current densities is important to meeting long term goals.

2.0 LED Roadmap

2.1 Cost and quality drivers for LED lighting

As shown in Figure 5 below, the greatest potential for LED-based luminaire cost reductions is in reducing the costs of LED packages (viewed as incoming materials from the luminaire maker's perspective). However, in addition to LED packages, the cost of the remaining components will need to come down in order to meet cost targets. Driver cost reductions will come from standardization of the LED power requirements. In turn, this will lead to savings from higher volume manufacture of fewer subsystems. Improved optical engineering and the availability of higher efficacy LEDs (especially at higher drive currents), multiple LEDs per package, or LEDs with larger total die areas may allow for the use of fewer LED packages to achieve the required illuminance levels, which can result in significant cost savings. Higher efficacy LEDs will also reduce costs for thermal management components, and optimization of the fixture architecture will reduce other fabrication costs. In addition to the factors shown in Figure 5, advanced manufacturing techniques, including integrated system design and automation, can further bring down the cost of the luminaire.

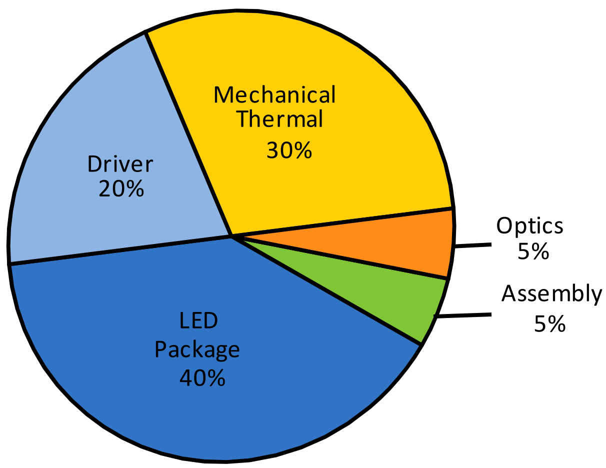

Figure 5. Approximate Cost Breakdown for LED Luminaire in 2009
Source: Paul Pickard, Cree LED Lighting, "An Integrated Approach to SSL Manufacturing," SSL Workshop, San Jose CA, April 21, 2010

The manufacture of high power LED packages involves a number of steps, each of which contributes to the final device cost. The typical cost breakdown for an LED package is shown in Figure 6. Compared with prior analyses, DOE refers to 'Wafer Processing' to include any processes performed on the complete wafer (previously referred to as 'Other Front-End') and 'Packaging' to include processes performed at the die level (previously referred to as 'Other Back-End'). The data represents high volume manufacturing of 1 mm^2 die on 100 mm diameter sapphire substrates and packaging of the die to produce high power cool white pc-LED lighting sources. Note that the preliminary analysis fails to fully account for wafer yields at the epitaxy and wafer processing steps and therefore likely underestimates these contributions.

Figure 6 illustrates that a large proportion of the cost is concentrated in the die-level packaging stage. This result is not too surprising since the final product is a packaged die and there are many thousands of such die on each wafer (around 5,000 1 mm^2 die on a 100 mm diameter substrate). Therefore, costs associated with die-level activities will tend to dominate. Thus, manufacturers will need to address die-level packaging processes in order to realize the required cost reductions. However, the optimum approach is difficult to define at this stage and will depend on a broad range of considerations due to complex interdependencies and trade-offs throughout the manufacturing process.

There is plenty of room for innovation in this area and DOE anticipates many different approaches to cost/price reduction including:

- Increased automation
- Improved testing and inspection
- Improved upstream process control[4]
- Improved binning yield
- Optimized packages (simplified designs, multichip, etc.)
- Higher levels of component integration (hybrid or monolithic)

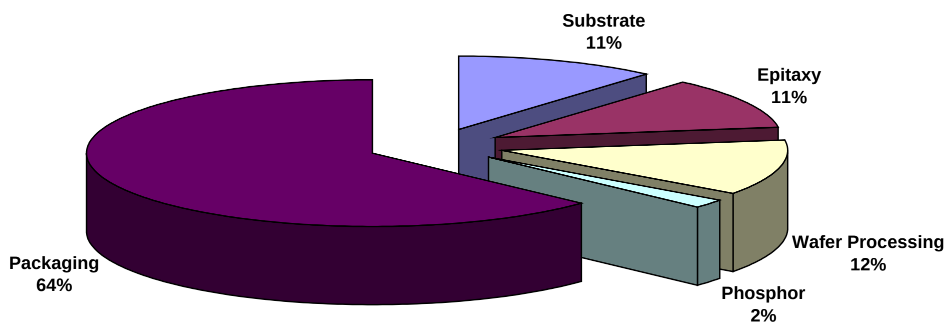

Figure 6. Typical Cost Breakdown for an LED Package
(100 mm sapphire substrate; 120,000 wafers/year; 1 mm^2 die; phosphor converted; high power package)
Source: Preliminary data provided by the Cost Modeling Working Group

The top level metrics for LED device efficacy, LED device price, and original equipment manufacturer (OEM) lamp price are shown in Table 3. The current and projected values for device efficacy and OEM lamp price are taken from DOE's 2010 MYPP.[5]

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[4] Wafer-level costs such as substrates, epitaxial growth, and wafer processing, comprise a smaller percentage of the final device cost but improvements here can have a significant impact on packaging costs and device performance (see Section 2.3.2).

[5] Assumes an integrated LED lamp at reasonable volumes (several 1000s) with CRI=70 - 80 and CCT = 3711-4745K

A review of commercially available devices[6] confirmed that the best efficacies available during 2009 for cool white[7] and warm white[8] LED at a current density of 35 A/cm^2 were 113 lumens per watt (lm/W) and 78 lm/W respectively, in good agreement with the roadmap. During the first half of 2010 warm white LED efficacy has increased to 93 lm/W, which already exceeds the 2010 target, whereas improved efficacy cool white LEDs have yet to appear on the market.

Device prices in $/klm terms continue to decline rapidly. One route to lower cost has been to reduce the size and complexity of the package while another route has been to use larger die areas in more conventional packages (either a single larger die or multiple smaller die). For example, the Luxeon c product achieves a price point of $20/klm by packaging a conventional cool white 1 mm^2 die in a small form factor package (2.04 x 1.64 x 0.7 mm^3). In contrast, the Cree XP-G product incorporates a 100% larger die area (1.4 x 1.4 mm^2) in a conventional XP style package (3.45 x 3.45 x 2.0 mm^3) while maintaining substantially the same selling price. Consequently the $/klm price drops to $20/klm (warm white) and $16/klm (cool white). Alternatively the Cree MX-6 product uses 6 smaller (~0.25 mm^2 die) to provide 50% more die area in a simple package design which can be sold at a significantly lower price. In this case the price at 35 A/cm^2 drops to between $11/klm and $16/klm for cool and warm white devices respectively, meeting the 2010 targets. The similarity of final packaged LED prices for different die areas, and numbers of die, tends to indicate that die cost is not a significant component of the final LED package cost.

Table 3. LED Metrics Roadmap
Source: DOE MYPP

Metric	Unit	2009	2010	2012	2015
LED Efficacy (2580-3710K, 80-90 CRI)	lm/W	70	88	128	184
LED Price (2580-3710K; 35 A/cm2)	$/klm	36	25	11	3
LED Efficacy (4746-7040K, 70-80 CRI)	lm/W	113	134	173	215
LED Price (4746-7040K; 35 A/cm2)	$/klm	25	13	6	2
OEM Lamp Price	$/klm	130	101	61	28

2.2 LED luminaires

At the DOE SSL Manufacturing Workshop in San Jose, CA and at the LED Manufacturing Roundtable discussion in Washington, D.C., manufacturing related barriers to adoption of LED based luminaires were discussed in the LED sessions. The manufacturing roadblocks identified last year were expanded upon and clarified and additional roadblocks were brought up for

[6] Values obtained during 2009 for quantities of 1000 units from various suppliers including Future Electronics and Digi-Key for power LEDs manufactured by Cree, Lumileds and OSRAM.

[7] CCT = 4746-7040 K; CRI = 70-80; 35 A/cm^2 current density at 25 C

[8] CCT = 2580-3710 K; CRI = 80-90; 35 A/cm^2 current density at 25 C

discussion. A list of the luminaire manufacturing roadblocks identified at the DOE SSL Manufacturing Workshops is shown in Figure 7 below. Figure 7 presents the issue or suggestion that was discussed, the entity or activity who is addressing the activity, and a suggested timeline for the activity to be started and completed. As noted in the introduction, some of the identified issues/suggestions may be more appropriately addressed by the LED industry, industry consortia, or other stakeholders. The 'roadmap' below is meant to identify all of the manufacturing related barriers to the adoption and production of LED based luminaires, regardless of the appropriate entity to address the barriers. These SSL luminaire manufacturing roadblocks can be classified as related to manufacturing, standards development, Core and Product Development R&D, and education. The roadblocks related to manufacturing which could be addressed directly through the DOE SSL Manufacturing R&D Program were consolidated into three R&D tasks:

- Luminaire/Module Manufacturing
- Driver Manufacturing
- Test and Inspection Equipment

The 'Luminaire/Module manufacturing' and 'Driver Manufacturing' tasks directly address the two major cost components in LED based luminaires – thermal and mechanical integration and the cost of drivers. The third task, 'Test and Inspection Equipment', addresses the manufacturing goal of improved quality of LED based luminaires and, possibly, reduced manufacturing costs through the development of test and inspection tools and techniques. These manufacturing R&D tasks will be discussed further below and a full task description with R&D metrics is provided in Chapter 4.0.

Over the course of the manufacturing roundtable and workshop discussions several issues related to manufacturing and commercialization standards were brought up for discussion. These issues are listed below and will be discussed further in Chapter 5.0 of this document:

- Standardization of reported performance data for luminaires
- Standardization of reported performance data of the LEDs, power supplies, and other components of the luminaires.
- Standardization of the luminaire components in terms of mechanical footprint, electrical interface, thermal interface, and/or optical interface.
- Expedited and internationally reciprocated standards (ENERGY STAR, UL, etc.) compliance testing and certification.

Other manufacturing roadblocks were also brought up for discussion:

- The need for education in LED based luminaire design.
- Development of the manufacturing infrastructure to enable efficient manufacturing of LED based luminaires and components with efficient supply chains, short product lead times and low inventories.
- Transitioning of existing conventional luminaire production capability into LED based luminaire capability.
- The role of current droop and thermal degradation of IQE on the cost of the LED and the luminaire.
- Understanding and manufacturing for luminaire reliability.

The issues related to standards and education are outside the direct scope of the DOE SSL Manufacturing R&D initiative. However, there are numerous other DOE SSL initiatives which are considering these topics. Chapter 5.0 and Appendix A: Standards have discussions on the various DOE supported standardization efforts. In addition, DOE is developing programs to educate stakeholders on all aspects of LED and LED based luminaire performance and design. It should also be noted that several LED manufacturers offer training and certification on the design of LED based luminaires. The development of the manufacturing infrastructure for efficient manufacturing of LED based luminaires can be accelerated through supported manufacturing R&D in the task area of luminaire/module manufacturing. Likewise, the transition of existing conventional luminaire production to LED based production capacity can be aided through the development of new tools and integrated components which could be supported through the luminaire/module task area. R&D in the areas of current droop, thermal droop, electronics reliability, and luminaire system reliability is currently being solicited by the DOE SSL Program in the SSL Product Development solicitation.

Issue/Suggestion	*Activity*	2010	2011	2012	2013	2014	2015
LED Packages							
Standardization of LED package 'footprint'	Standards Development						
LED Performance reporting standard	Standards Development						
LED consistency and availability	DOE Manf. R&D Task - LED tasks						
LED Cost	DOE Manf. R&D Task - LED tasks						
Reduced LED Cost related to current and thermal droop	DOE Product Development R&D Task						
Luminaire Manufacturing							
Luminaire Manufacturing Cost	DOE Manf. R&D Task - Luminaire/Module Manufacturing						
Luminaire Integration/Design for Manufacturing	DOE Manf. R&D Task - Luminaire/Module Manufacturing						
Availability of luminaire manufacturing tools	DOE Manf. R&D Task - Luminaire/Module Manufacturing						
Color Perception/Consistency/Tolerances by lighting application	External R&D and Standards Development						
Support Development of luminaire software modeling tools	DOE Manf. R&D Task - Luminaire/Module Manufacturing						
Education in Luminaire Design and LED technology	DOE Commercialization Effort						
LED Drivers							
Driver Cost	DOE Manf. R&D Task - Driver Manufacturing						
Driver ease of integration	DOE Manf. R&D Task - Driver Manufacturing						
Driver performance reporting standard	Standards Development						
Test and Inspection							
Test/validation/inspection of incoming components	DOE Manf. R&D Task - Test and Inspection						
Testing/Qualification of luminaires within Manf Process	DOE Manf. R&D Task - Test and Inspection						
Luminaire Performance Standards							
Expedited compliance testing and certification (Energy Star, UL, etc.)	Standards Development Bodies						
Internationally reciprocated standards (Energy Star, UL, etc.)	Standards Development Bodies						
Harmonization of international standards	Standards Development Bodies						
Luminaire Reliability							
Uncertainty in luminaire reliability	DOE Product Development R&D Tasks						
Uncertainty in driver/power supply reliability	DOE Product Development R&D Task						

Existing Activities
Future Activites

Figure 7. Roadmap for Addressing Luminaire Manufacturing Issues
Source: DOE Manufacturing Workshop Consensus

2.2.1 LED Packages in Luminaires

LED packages are a critical component of all LED based luminaires, and luminaire manufacturing is affected by LED package cost, performance, color consistency, form factor, and availability. These LED manufacturing-related issues are addressed in detail in Section 2.3 along with specific suggestions for manufacturing R&D tasks. Workshop participants suggested that the DOE support R&D in the areas of current droop and thermal droop as a means of reducing the cost of the LEDs in the luminaire. These R&D topic areas are appropriate for the Core or Product Development activities and have been identified as priority tasks in the 2010 MYPP. While the Manufacturing, Product Development, and Core R&D topics are being addressed, luminaire manufacturers still must contend with LED issues.

Understanding issues such as how much performance variability can be tolerated and which performance parameters are critical for the development of luminaires of consistent performance is crucial. Variability in lumen output, correlated color temperature (CCT), and forward voltage, is currently handled by testing each package and placing it into a specific performance bin. Color consistency of the LED package is seen as the most important binning issue, while forward voltage and lumen output variations are considered much less significant. Regarding color consistency, several people cited a need for research into the sensitivity of the market for color variation – what is humanly visible and what is the tolerance for variations in color and output with respect to the lighting application?

One clear proposal from the luminaire group of the 2009 SSL Manufacturing Workshop for dealing with chromaticity variations in LEDs was to have all LED manufacturers bin and label LEDs using a consistent set of chromaticity bins. This would enable luminaire manufacturers to more readily compare and use LEDs from different suppliers. This issue, discussed in further detail in Section 5.3, has been partially addressed with the recent publication of NEMA SSL 3-2010[9] which provides consistent formulation for sub-binning. This creates a consistent set of sub-bins which LED manufacturers and luminaire manufacturers can use when describing the color of LEDs.

Ultimately, the need for binning should be eliminated through LED fabrication improvements such as improved LED growth uniformity and optimized application of phosphors. However while variations in LED performance persist, binning issues can be addressed to some degree by the luminaire manufacturers through engineering and integration techniques. These strategies include: secondary binning by the luminaire manufacturer for more consistent LED color within the manufacturers' bins and homogenization of the color from several LEDs using an LED array/module. Manufacturing R&D that simplifies luminaire integration with respect to binning and LED performance variability will be considered under the task area – Luminaire/Module Manufacturing.

It was also suggested during the luminaire manufacturing discussions that the availability of components with standard form factors, and optical and electrical interfaces, particularly LED

[9] NEMA SSL 3-2010 "High-Power White LED Binning for General Illumination"

packages, would greatly expedite the luminaire design and manufacturing processes. Such standardization would positively impact LED package cost, availability, and consistency. However, while the luminaire manufacturing discussion group agreed that component standardization would simplify luminaire manufacturing, it was pointed out that standardization could stifle performance and integration innovations in LEDs and other luminaire components, and that standardization may be premature at this time.

2.2.2 Luminaire/Module Manufacturing

At the DOE SSL Manufacturing Workshop in San Jose, CA there were several presentations by luminaire manufacturers about the challenges of manufacturing LED-based luminaires and how luminaire manufacturing will fundamentally change with LED technology. The nature of the LED light source lends itself to an integrated luminaire design due to the long lifetime and thermal handling demands. The long liftime of the LED light source means that the light source no longer needs to be easily replaceable. Since LEDs do not radiate heat out, but rather, need to have the heat conducted away, luminaires need to be specifically designed for thermal conduction away from the LEDs. An integrated LED luminaire does not fit into the existing lamp and fixture model that exists today in the lighting industry which could lead to a fundamental change in the lighting industry. As a result of the LED technology, the lamp portion and luminaire portion of the lighting fixture are likely to merge, and companies which can engineer the luminaire together with the source will benefit. However, in the short term, LED sources will be made to fit into, and work with, existing luminaires as 'LED replacement lamps', even though this may be viewed as 'shoe horning' the new technology into an existing infrastructure and not fully taking advantage of the design flexibility that this new light source offers.

There are a number of challenges that luminaire manufacturers are currently facing as a result of this paradigm shift. The challenges revolve around engineering and manufacturing a quality luminaire within the constraints imposed by performance and supply chain uncertainties that exist in the components today. Luminaire components, particularly LEDs, are rapidly improving but high demand and limited production capacity can result in long delivery lead times. Thus, the LED product life cycle may be shorter than the luminaire design cycle. This situation is particularly acute with LEDs but can apply to most of the luminaire sub-components which have rapidly changing performance, cost, and availability. This creates a difficult supply chain for manufacturers but also an opportunity to develop components that can be more rapidly integrated into luminaire designs and portions of the supply chain within the U.S.

A fundamental change to luminaire manufacturing is how luminaire reliability is considered which impacts the design and sub-component selection of LED based luminaires. The long life of the LED has led to the expectation of longer lived luminaires and replacement lamps. This requires not just a well integrated long life LED, but also long lives from all of the luminaire sub-components and reliable design and integration of the product. This new expectation of reliability also requires a new understanding and application of luminaire system testing for long term reliability.

The need for a high level of integration of LED based luminaire products may have a significant impact on how luminaires will be manufactured. This level of integration may require automated manufacturing to bring down the assembly costs and reduce the possibility of human error in the manufacturing process. This integration also represents a roadblock to existing luminaire manufacturers who may not have the necessary tools or expertise to develop the LED products.

Throughout the DOE SSL Manufacturing Roundtable and Workshop process there was consistent support for work to reduce LED based luminaire product design cycle time, improve product quality and consistency, increase manufacturing throughput, reduce product cost, and reduce component inventory. These goals have been expressed in a variety of contexts by a variety of stakeholders from the largest lamp manufacturers to the smallest independent luminaire designers. The commonly expressed theme was the need for an efficient manufacturing environment. Some of the specific topics in these discussions were the need for readily available 'building block' components which could be integrated into standard or custom luminaire products, the need for shorter component lead times which would lead to reduced inventory on hand, and low cost of ownership manufacturing tools for LED based luminaires.

These topics have been consolidated into the priority research task – Luminaire/Module Manufacturing. The scope of this task is very broad and could include a wide variety of work from manufacturing automation and tool development to the development of multi-functional components which reduce design time and facilitate product integration. Although expressed differently, this task also addresses roadblocks identified in the previous version of the Manufacturing Roadmap – LED binning and software modeling tools. Approaches to facilitate the integration of LEDs from varying color and performance bins would be included in this task area, as would software approaches to reduce the luminaire design cycle and accelerate the integration of varying components. An overriding suggestion in all of the luminaire discussions was that enhanced and standardized performance reporting of the luminaire and all of the sub-components could enable the development of software tools to reduce the design cycle time, predict luminaire performance and reliability, and support enhanced lighting design using LED luminaires.

The need for education in the new technologies required for the manufacturing of LED based luminaires was also raised. Compared to conventional luminaire manufacturing, an almost entirely new skill set is required to design, engineer, and manufacture LED based lighting. The DOE SSL Program offers LED educational programs for various audiences and many LED manufacturers offer courses to their customers on LED based luminaire design. Educating existing luminaire manufacturers on these LED systems is critical to the success of solid state lighting, since the luminaire manufacturers intimately understand the needs and requirements of the lighting market.

2.2.3 Driver Manufacturing

Consistent with the discussion on drivers from last year's manufacturing meetings, the need for drivers with improved design for manufacturing, integration, and flexibility within the luminaire was once again identified. Approaches for the development of flexible, high efficiency, low cost drivers could include the disaggregation of driver functionality into sub-modules to allow luminaire integrators to mix and match functions while maintaining high efficiency and reliability.

Proposed driver information:

- Operating temperature range
- Efficiency with respect to power, load, and temperature
- Input voltage and output voltage variation
- Off-state power
- Power to light time
- Power overshoot
- Transient and overvoltage protection specifications
- Compatibility with specific dimming protocols
- Compatibility with ambient light sensors
- Harmonic distortion in power supply
- Output current variation with temperature, voltage, etc.
- Maximum output power
- Power factor correction

Concerns were again raised by the luminaire manufacturers regarding inconsistent reporting of driver performance and it was agreed that a standard performance reporting format would facilitate driver integration into LED based luminaires. The lack of information and inconsistent reporting of driver performance inhibits efficient and easy integration of the electronic components. The luminaire manufacturers emphasized the need to disseminate this information readily and uniformly. A standard reporting format would facilitate the use and development of analysis, simulation, and design tools for luminaire manufacturers. The luminaire manufacturers suggested that this divulgence of performance data in a standard reporting format should be implemented in the near term. The sidebar lists the parameters the breakout group recommended should be included.

There were also suggestions to develop a testing protocol to better define the driver reliability. The DOE SSL Program is supporting Product Development R&D to better understand and predict driver reliability.

2.2.4 Test and Inspection Equipment

The LED roundtable group identified the need for test and inspection equipment for all levels of LED and LED based luminaire manufacturing. Test and inspection equipment could be used with luminaires to validate incoming components, to test luminaires in the midst of integration to identify potential failure mechanisms, or to test final products in a simulated installation environment. These tools could provide additional confidence in the quality of the luminaire products advancing the DOE SSL manufacturing objective of improved product consistency and quality.

2.2.5 Luminaire Reliability

The lack of a thorough understanding of lifetime for LED-based luminaires was raised as a significant problem for luminaire manufacturers. While LM-79 provides a standardized protocol for measuring luminaire performance over time, it is expensive and time consuming to do that. Uncertainty in the long-term performance of the luminaire system makes it difficult to estimate and warrant the lifetime of LED based luminaires. It also hinders manufacturers' ability to know how best to improve their product reliability. This uncertainty could be addressed by better information about long term performance of key LED luminaire components and materials, including the LEDs, drivers, optical components and materials used in assembly, along with accepted methods to statistically predict luminaire system lifetime. Several priority R&D tasks in the 2010 MYPP address this possibility.

The issue of a common test protocol was initially addressed in the DOE Core Technology R&D program under the System Reliability Methods task area and this topic is being further pursued as a research priority in the most recent DOE SSL Product Development Funding Opportunity Announcement (FOA). The program is looking to develop experimental data and a theoretical understanding of luminaire system reliability. The lack of a common test protocol has been addressed by a DOE-supported reliability working group which has recently released a guide for reporting and characterizing luminaire lifetime.[10] The luminaire discussion group at the Manufacturing Workshop recommended that lifetime performance of luminaire components and systems should be provided by the product suppliers in a standardized data file format. This would enable the luminaire manufacturer to model lifetime performance of the luminaire system using the data provided from a variety of components. The luminaire lifetime data could be used by lighting designers for lighting calculations of lumen maintenance in a variety of environments, as is done currently with conventional lighting. To enable the collection of this data, appropriate acceleration factors need to be understood for the various luminaire components and for the luminaire system. As SSL-specific understanding of the system lifetime performance is developed, testing and manufacturing best practices can be established. In addition, a common database of statistical performance of luminaire components and systems could be developed and coupled with theoretical and experimental results from the reliability R&D to develop a consistent and accurate means of estimating system lifetime.

2.3 LED Packages

The following sections address the four principal roadblocks originally identified at the April 2009 SSL Manufacturing Workshop and expanded on during the 2010 Workshop: Epitaxy Processes, Substrates, Manufacturing Equipment, and Process Control.

2.3.1 Epitaxy Processes

Epitaxial growth is the key enabling technology for high brightness. Several critical issues regarding epitaxial growth equipment and processes have been identified as requiring attention. They are as follows:

[10] http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/led_luminaire-lifetime-guide.pdf

- Insufficient wavelength uniformity and reproducibility
- Low throughput (cycle and growth times)
- Lack of in-situ monitoring/process control
- Problems managing wafer bow
- Incomplete knowledge regarding growth chemistry/mechanisms
- Need for lower cost source materials and improved source efficiencies.

All gallium nitride (GaN)-based high-brightness LED (HBLED) epiwafers are currently manufactured using Metal Organic Chemical Vapor Deposition (MOCVD). MOCVD is the only technology capable of growing the entire device structure including: the complex low temperature nucleation layer, the thick GaN buffer, and the multi-quantum well (MQW) active region. Large-capacity manufacturing equipment (up to 45x2" or 12x4" wafer capacity) that produces high quality material is readily available. The primary drawback of this growth method is its relatively slow growth rate, which results in long cycle times (typically 5-10 hours according to Veeco). Actions to increase the growth rate, reduce the overall cycle time, or expand the reactor capacity are required to raise the throughput of the epitaxial growth process.

Hydride Vapor Phase Epitaxy (HVPE) is an alternative growth method which has the advantage of significantly higher growth rates and offers the prospect of much higher throughputs. While HVPE is well suited to the growth of thick GaN layers, it is not well suited for the growth of the thin nanometer-scale layers and InGaN alloy compositions associated with the MQW active region. Therefore HVPE could provide an alternative to MOCVD for the growth of thick buffer layers and work is underway to combine HVPE and MOCVD in a single growth tool in order to combine the best attributes of each technology. However, HVPE's primary contribution is likely to be in the growth of thick GaN layers to produce GaN templates and free-standing GaN substrates. Figure 8 shows the agreed epitaxy roadmap.

Category	Task	2010	2011	2012	2013	2014	2015
MOCVD Epitaxy							
	Modeling: Apply Computational Fluid Dynamics (CFD) models to uniformity improvement and source efficiency optimization						
	Process control: Implement active control using in-situ measurements						
	Automation: Cassette-to-cassette						
	Reduce cost of ownership by factor of 2 every 5 years						
HVPE Epitaxy							
	Develop multi-wafer equipment						
	Automation: cassette to cassette						
	Reduce cost of ownership by factor of 2 every 5 years						

Figure 8. Epitaxy Roadmap
Source: DOE Workshop Consensus

Wafer throughput must increase while simultaneously improving epilayer quality. Achieving tighter control over the wavelength uniformity and reproducibility of the active MQW region will be critical. Similarly, the material quality and internal quantum efficiency (IQE) must continue to improve in order to achieve the target efficacy improvements. Therefore, a critical aspect of the epitaxy roadmap is the introduction of advanced process control measures in conjunction with sophisticated in-situ monitoring (especially wafer temperature) and accurate process modeling. The focus will be on actively controlling growth temperature at the wafer surface through integrated feedback control since temperature drives the growth process. For example, as little as a one degree Celsius change in growth temperature will produce around 1.8 nm shift in the emission wavelength for a 460 nm MQW active region. There is no standard method to achieve this kind of active control and suitable systems are not generally commercially available or in active use by manufacturers. Other in-situ tools, such as for monitoring wafer bow, are also important. However, these tools are generally used to tune a process prior to manufacture, not for active monitoring and control of the manufacturing process.

Table 4 includes a set of suitable metrics to characterize the epitaxy process. The most critical metrics are those associated with epiwafer uniformity and reproducibility. The table sets targets for in-wafer uniformity, wafer-to-wafer reproducibility, and run-to-run reproducibility. Also included is Cost of Ownership (COO) which is an excellent metric to describe how manufacturing equipment should evolve to reduce the cost of production. A reduced COO for epitaxy equipment might be achieved in many different ways. For example, the throughput of the reactor can be increased by reducing the cycle time or by increasing the capacity, or a combination of both. Process control improvements will increase yield. In addition, equipment design changes can increase the efficiency of reagent useage, such as the development of MOCVD equipment to support the use of activated growth processes that improve the efficiency of NH_3 useage. Finally, Overall Equipment Efficiency (OEE) improvements will reduce operating costs through improved preventive maintenance schedules, minimization of non-productive operations such as chamber cleaning, and introduction of cassette-to-cassette load/unload automation. Although, it is difficult to specify at this stage which approaches will be the most effective, all such actions will reduce the COO.

The epitaxial layer cost will depend to a large extent on the total layer thickness (growth time, precursor usage, etc.) and wafer yield. There is no common substrate type/diameter, epitaxial growth reactor configuration, or total layer thickness. Consequently we have chosen to normalize the epitaxial layer cost to layer thickness (μm) and wafer area (cm^2), as shown in Table 4. Overall wafer yield (total good wafers out versus wafers in) is not included here but is likely to be currently in the range 30-50%. Improvements in wafer yield will further reduce epiwafer costs.. The proposed roadmap for epitaxy cost reduction in Figure 8 is based on estimates provided by Veeco at the April 2009 workshop regarding projected cost reductions for spares & consumables, gases & utilites, and depreciation.

Table 4. Epitaxy Metrics
Source: DOE Workshop Consensus

Metric	Unit	2009	2010	2012	2015
Wafer Uniformity (standard deviation of wavelength for each wafer)	nm	1.7	1.5	1.0	0.5
Wafer-to-wafer Reproducibility (maximum spread of mean wavelength for all wafers in a run)	nm	1.5	1.1	0.9	0.6
Run-to-run Reproducibility (maximum variation from run-to-run of the mean wavelength for all wafers in a run)	nm	2.0	1.5	1.1	0.9
Cost of Ownership	-	Factor of 2 reduction every 5 years			
Epitaxy Cost	$/μm·cm^2	0.3	0.25	0.17	0.1

2.3.2 Substrates

Numerous substrate options currently exist for the manufacture of high-power GaN-based LEDs covering a range of materials (sapphire, SiC, Si, GaN, etc.) and wafer diameters (2”, 3”, 100 mm, 150mm, etc.). There is no clear ‘best’ substrate at this point in time and no attempt at standardization within the community. The substrate roadmap supports two paths; (i) improved substrates for heteroepitaxial growth (sapphire, SiC and silicon), and (ii) improved substrates for homoepitaxial growth (GaN). In the case of sapphire substrates, improvements in substrate quality (surface finish, defect density, flatness, etc.) and product consistency are required in order to meet the demands of high volume manufacturing. For SiC the issue is cost and scaling to larger diameters. For GaN substrates the major issue at this point in time is cost which must be dramatically reduced in order for them to become considered a viable option for LED manufacturing.

Sapphire and SiC are currently the dominant substrate types for high power GaN-based LED manufacturing. A general trend toward larger substrate diameters is anticipated, mimicking the silicon and GaAs microelectronics industry. Larger substrates provide an increase in useable area (less edge exclusion) without significantly increasing the processing cost per wafer, resulting in a lower cost/die. Larger wafers also provide improved access to automated wafer handling equipment originally developed for the microelectronics industry. In order to realize these advantages, a steady supply of high quality large diameter substrates at reasonable prices (typically at the same or lower cost per unit area) will be necessary. Some R&D effort is being directed toward silicon as an alternative heteroepitaxial substrate since it has the advantage of being readily available in large diameters at high quality and low cost. However, a number of significant technological challenges remain to be resolved before silicon can be considered a viable alternative to sapphire. In particular, good epitaxial layer quality and uniformity, and high efficiency GaN LEDs will need to be demonstrated on silicon substrates.

The current reliance on heteroepitaxial growth of (In)GaN layers on sapphire and SiC substrates increases process complexity and impacts costs. Complex buffer layer technologies are employed to cope with large lattice and thermal expansion coefficient mismatches, resulting in increased growth times and wafer curvature problems which can impact uniformity. In principal, the use of a GaN substrate, if it were available at reasonable cost, might simplify the buffer layer technology (thinner buffer layers with shorter growth times) and allow flat, uniform epiwafers to be manufactured. GaN might also offer improved device performance through reduced defect densities and through reduced polarization fields associated with the use of non-polar or semi-polar substrates. Further work is required to demonstrate this potential before GaN can be considered a mainstream manufacturing option and consequently GaN substrate development has been identified as a priority Product Development task in the 2010 MYPP.

In the short term, the use of GaN templates comprising a thick GaN layer on a sapphire substrate might provide an intermediate solution. Templates offer a GaN surface for nucleating the MOCVD growth (saving growth time) and a lower defect density through the inclusion of a thick GaN buffer layer. However, these improvements must be demonstrated while simultaneously maintaining epilayer quality and consistency and overcoming any incompatibility with existing manufacturing processes.

Figure 9 presents the substrate roadmap. The starting points of the light gray shaded bars in Figure 9 represent the point of initial adoption of a particular substrate type/size in manufacturing. The roadmap includes the two paths discussed earlier with heteroepitaxial substrates toward the top and homoepitaxial substrates toward the bottom.

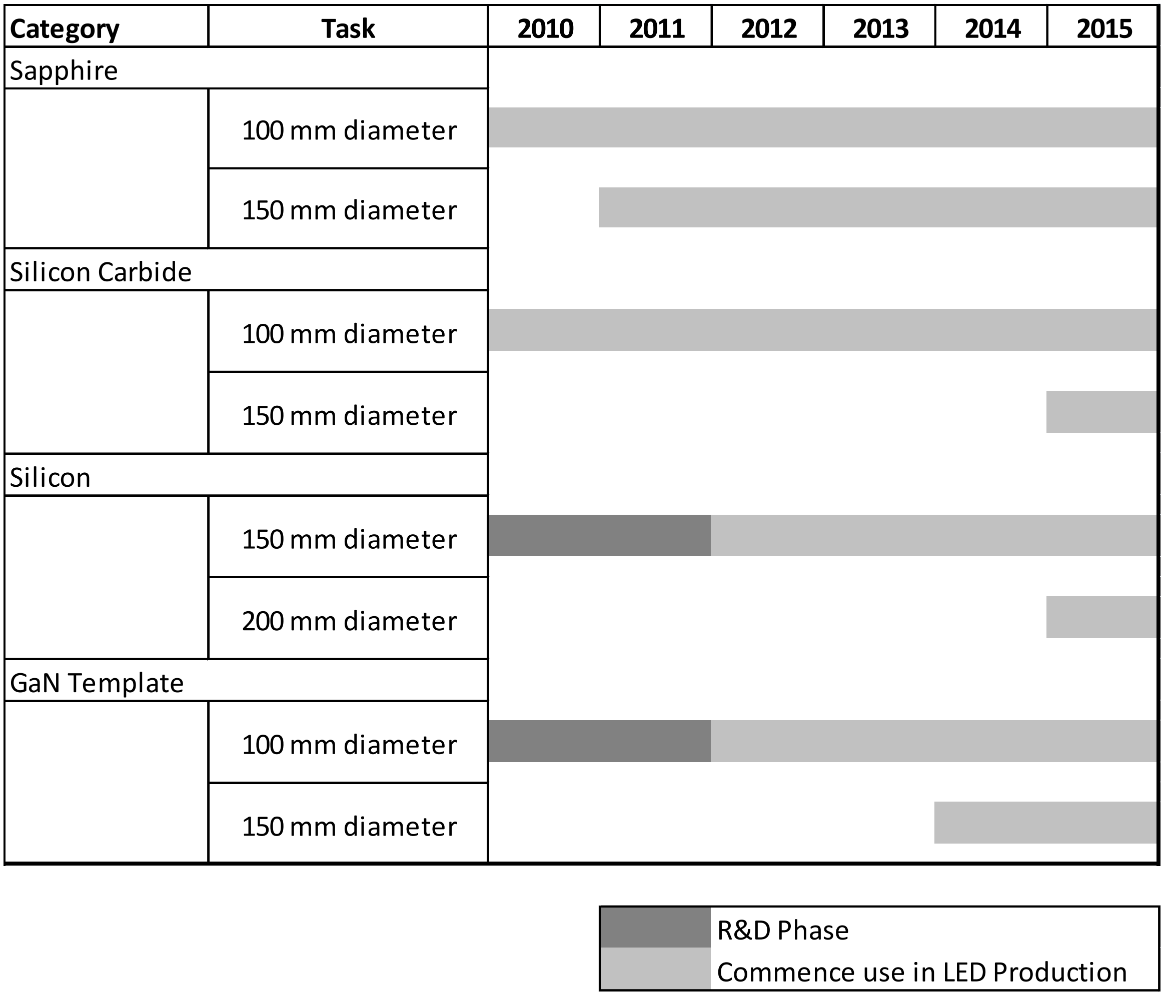

Figure 9. Substrate Roadmap
Source: DOE Workshop Consensus

2.3.3 Equipment

The third significant set of issues concerns a lack of availability of suitable manufacturing equipment for wafer processing, chip manufacturing, and chip packaging, especially for the smaller substrate sizes currently employed in the LED industry. Plans regarding equipment for epitaxy are included in the epitaxy roadmap (Figure 8). The group felt strongly that manufacturing equipment should be improved in several ways to better suit the requirements of the LED industry. There is a need for increased levels of automation, higher throughput, improved yields, improved equipment standards, and generally a lower cost-of-ownership. A number of the group members felt that improved communication between equipment manufacturers and end-users would help alleviate some of these issues. As equipment suppliers become more aware of manufacturing trends, it is more likely that suitable equipment will be available to the manufacturers at the appropriate time. This would help eliminate the need for each manufacturer to undertake their own customization of available equipment which often results in inefficient use of time and unreliable machinery with inadequate support.

In common with the 2009 Roadmap, it was not possible to create any kind of definitive list regarding equipment priorities. A better understanding of the impact of equipment and process changes on the packaged LED cost (and ultimately the luminaire cost) is required in order to make these decisions, highlighting the need for better cost modeling. It is anticipated that a clearer picture will emerge once an agreed cost model has been established. As a general guideline, the participants agreed that equipment developments should exhibit at least a 2 times improvement in COO every 5 years. Thus, by 2025 the COO will have improved by at least a factor of 16, representing a significant step toward the final cost targets. Specific wafer processing metrics are included in Table 5.

Table 5. Wafer Processing Metrics
Source: Stan Myers, SEMI, "Driving Solid State Lighting Through Manufacturing Cost Reduction", Fairfax, April 2009

Metric	Unit	2009	2010	2012	2015
Process Throughput	wfr/hr	50	55	70	100
Process Yield	%	60	65	75	90
Process Productivity	%	50	65	75	90

2.3.4 Process Control and Testing

Concerns about equipment go beyond the direct process steps discussed above, and include improved process control, in-line inspection, non-destructive testing/characterization, and high speed device testing. Process control associated with the epitaxy stage is included in the epitaxy roadmap (Figure 8).

Due to variability at various stages in the manufacturing process, manufacturers are currently required to measure all devices produced in order to place them in a specific bin based on correlated color temperature and lumen output. Binning currently occurs at the end of the process and high speed testing is required to minimize the cost of this step. Binning also affects the LED selling price because of potential limited availability of specific codes. Improvements in process controls plus the application of in-line testing and inspection will tighten these distributions, and allow manufacturers to produce product more closely aligned with customer demand. Therefore an improvement in binning yield is an important target for this program and will have a significant impact on the final packaged LED price and on the availability of consistent quality product.

Many felt there was a general lack of process control throughout the wafer processing, chip production and chip packaging stages, and there was a need to introduce improved in-line testing, inspection, characterization, and metrology equipment. In-line inspection is used to provide rapid feedback throughout the manufacturing process. The ability to detect manufacturing problems at an early stage (excursion flagging) enables problems to be corrected or non-compliant product to be excluded from further processing. Both actions can have a significant impact on overall production yield and provide significant cost savings.

Experience from the silicon chip industry suggests that these cost savings come from, in roughly equal measure, reduced R&D costs, factory ramp-up costs, and manufacturing production costs. In the case of the LED die production process it was proposed that cost savings could range from 6% to 24% through improvements to the baseline process yield, and from 22% to 44% through the use of excursion flagging (see Table 6). Participants felt that the cost savings impact of automating the final die inspection step would be small due to the low labor costs traditionally associated with this activity. Potential cost savings associated with R&D and factory ramp-up were estimated to be ranging from 20% to 40%. According to KLA Tencor, most reasonable estimates based on silicon industry experiences suggest that the use of in-line inspection can reduce costs by roughly a factor of 2, i.e. an overall cost saving of 50%. This will be the target for 2015.

Table 6. Potential Cost Savings Associated with Use of In-line Inspection
Source: Richard Solarz, KLA Tencor, "In-line Process Control and and Yield Management for the HBLED Industry", Vancouver, OR, June 2009

Operation	Product Research and Development	Factory Ramp Operations	Production Automated Operations	Production Excursion Reduction	Production Baseline Yield Improvement
Improvement	20-40%	30-40%	0.50%	22-44%	6-24%

These yield improvements and cost reductions will be achieved through the introduction of in-situ and ex-situ characterization equipment with improved measurement accuracy, the linkage of these measurements to end-product performance, and the implementation of active process control. Higher throughput and more sophisticated inspection and testing equipment was required for substrates, epiwafers, processed wafers, finished die, and packaged LED devices (e.g., lm/W, correlated color temperature (CCT), color rendering index (CRI), etc.). An example of an equipment roadmap for in-line yield management is shown in Figure 10.

There was also a need expressed for improved characterization equipment offering higher levels of sensitivity to enable rapid and effective incoming materials qualification throughout the supply chain, and assure the quality and consistency of LED products.

Similar to Section II.C.3, a full list of equipment needs was not developed during the workshop. It was agreed that these decisions should be made with respect to a full COO analysis, and with reference to a suitable cost model (section 2.5). The common metric for COO improvements identified earlier would set the basis for all equipment development, requiring a factor of 2 improvements in COO over a 5 year timescale.

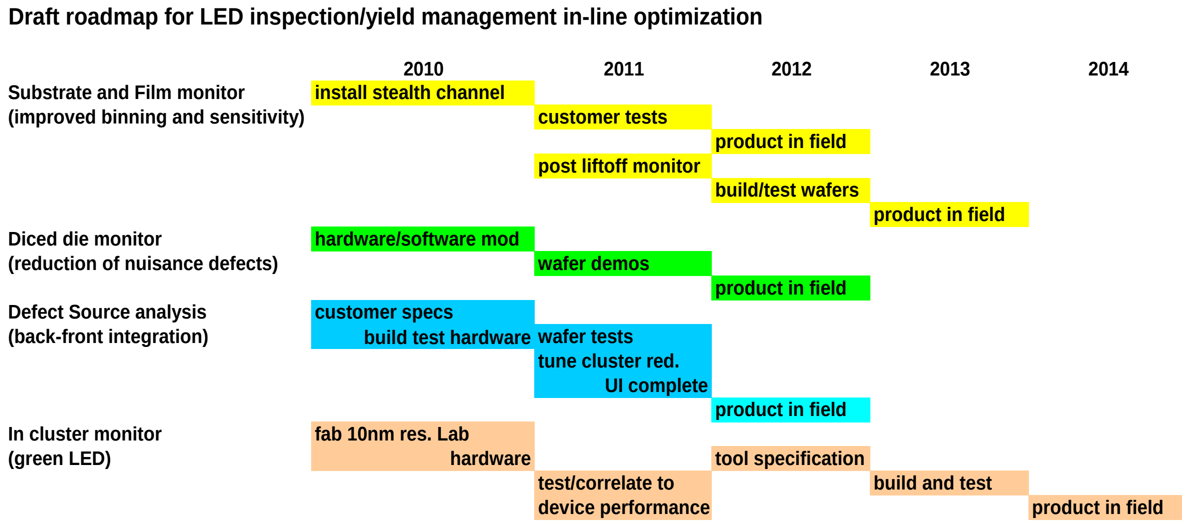

Figure 10. Roadmap for In-line Yield Management
Source: Richard Solarz, KLA Tencor, "In-line Process Control and and Yield Management for the HBLED Industry", Vancouver, OR, June 2009

2.3.5 LED Package R&D Recommendations

The Manufacturing R&D Roadmap maintains a close link to the MYPP which describes the Core Technology and Product Development activities. Certain tasks proposed at the manufacturing workshops were believed to be better suited to the scope of the Core Technology and Product Development activities and were recommended for inclusion as priority tasks in the 2010 MYPP.

Subtask B.1.1 (Substrate development) was prioritized following recommendations from the manufacturing initiative due to the potential for alternative high quality substrates such as GaN to enable the growth of higher quality epitaxial layer structures which should lead to significantly enhanced LED performance.

Support was also provided for:

- Subtask B.1.2 (Semiconductor materials) due to the positive impact that reduced droop and reduced thermal sensitivity would have on manufacturing costs.
- Subtask B.3.6 (Package architecture) since the development of LED components and modules optimized for integration into general illumination products is expected to feed very rapidly into the manufacturing of improved low cost luminaires.

Similarly subtasks A4.4 (Manufacturing Simulations), B4.1 (Yield and Manufacturability), B4.2 (Epitaxial Growth), and B4.3 (Manufacturing Tools) originally included in the MYPP will now be addressed in the Manufacturing R&D Roadmap.

2.4 System and Component Integration

Integration at both the systems level and components level is an important consideration for lowering costs and improving product quality. It was argued that a focus purely on isolated individual topic areas would not address the overall cost reduction targets and that a more integrated or holistic approach to manufacturing was required. Similarly there is a need for simplification throughout the process in order to lower costs. Opportunities for simplification include the integration of components at the systems level (standardized sub-assemblies), the hybrid integration of components at the packaging level, and the monolithic integration of components at the wafer level.

The SSL system is illustrated schematically in Figure 11 Participants suggested there is no one solution to achieving the required cost reductions and performance improvements. Rather, many aspects of the manufacturing process will need to be addressed in parallel and in an integrated manner. Disciplines such as design for manufacture and integrated product development were identified as important considerations in the drive toward improved quality, reduced cost, and rapid commercialization. Decisions made early in the product design phase can make the majority of impact on the product's cost, quality and manufacturability. Close communication and/or partnering between design engineers and manufacturing engineers will be required to optimize manufacturability. Progress can be made through several pathways including: the utilization of common parts and materials, minimizing the number of active or approved parts through standardization, designing for ease of assembly, and the creation of robust designs which avoid tight tolerances beyond the natural capability of the manufacturing processes.

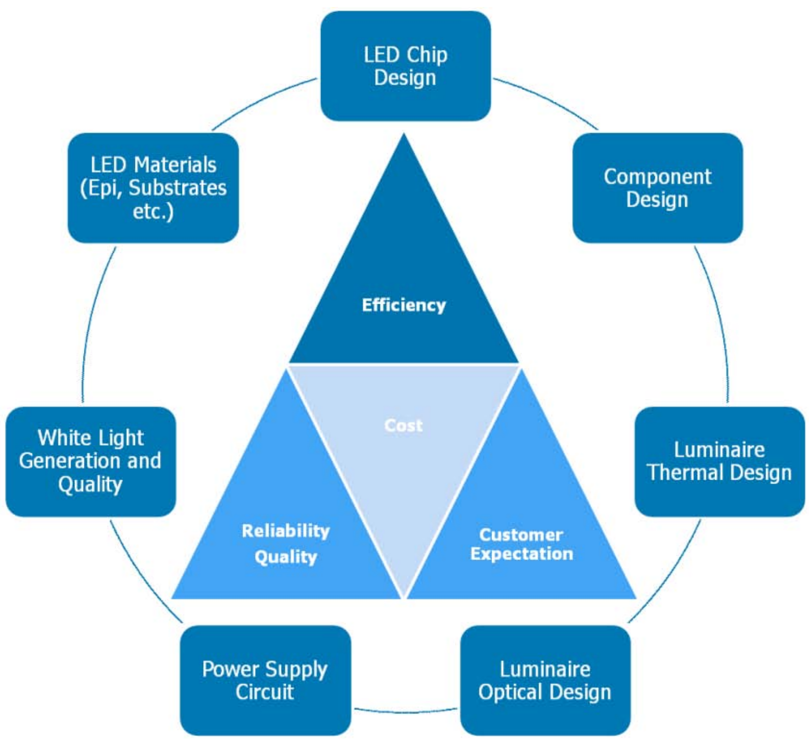

Figure 11. Integrated Systems Approach to SSL Manufacturing
Source: Mark McClear, Cree, Inc., "An Integrated Approach to SSL Manufacturing", Vancouver, OR, June 2009

Ultimately, real cost reductions will be achieved through the simplification of SSL luminaires. One path to simplification is through the integrated systems design approach described above. There is significant opportunity to optimize the luminaire design and manufacturing processes to reduce costs while still continuing to meet quality, reliability, and efficiency requirements, and continuing to match customer expectations. Another path to simplification will be through increased integration at the components level. This includes hybrid integration of components at the package level and monolithic integration of components at the wafer level. The simplest example of hybrid integration would be the placing of multiple die in the same package. A more sophisticated example which better illustrates the point is shown in Figure 12 presents a more sophisticated example in which the thermal control chip, driver chip, and more sophisticated primary optics could be integrated into the same package. Hybrid integration schemes of this type could have a significant impact on the final luminaire costs.

Taking this integration approach one step further, it might also be possible to monolithically integrate the thermal control circuitry and driver electronics onto the same semiconductor chip as the LED. A monolithically integrated chip would offer significant simplification with regard to chip packaging, luminaire design, and luminaire assembly. The cost savings associated with such high levels of integration could be very significant.

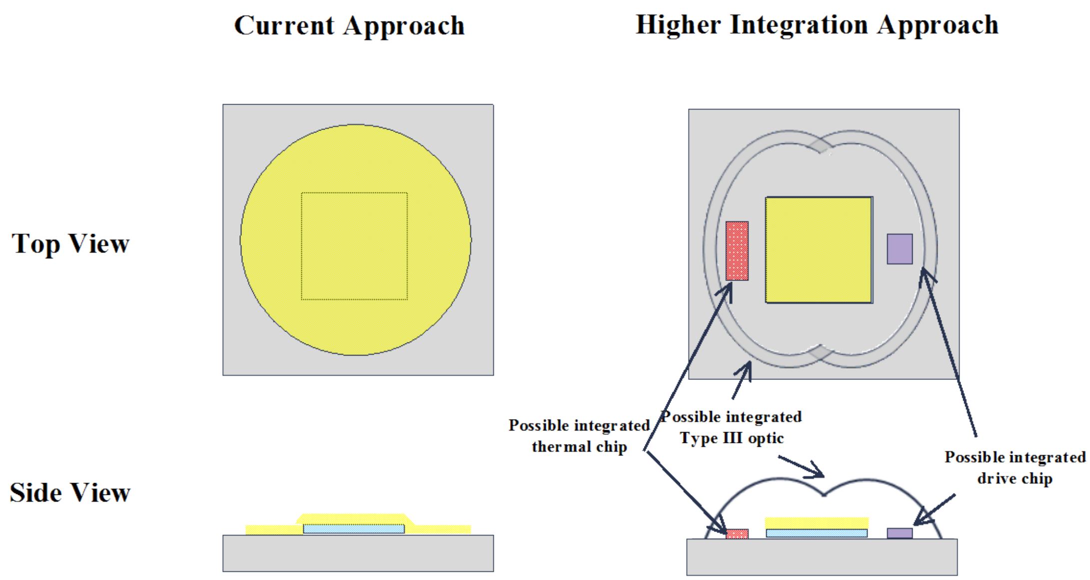

Figure 12. Schematic Representation of Possible Hybrid Integration Approach to Simplify SSL Luminaire Manufacturing and Reduce Costs
Source: Mark McClear, Cree, Inc., "An Integrated Approach to SSL Manufacturing", Vancouver, OR, June 2009

Monolithic integration described in the previous paragraph is just one example of how cost reduction can be achieved through moving processes from die-level to wafer-level; the more that can be achieved before the wafer is diced up, the less that will need to be accomplished at an individual chip level where the cost per die will be much higher. One good example of process simplification would be the deposition of a phosphor layer prior to wafer dicing and separation. Another example might be the use of wafer-level packaging techniques developed in other semiconductor technology areas such as in the production of complementary metal-oxide semiconductor (CMOS) cameras for cell phones. Such methods might allow a significant proportion of the packaging to be completed at the wafer-level, and could offer the prospect of highly automated optical and electrical testing prior to final assembly.

2.5 Cost Modeling

A common theme during the manufacturing workshops was the need to establish a common cost model to describe the manufacturing of LED-based components and fixtures. Such a model would allow industry and government to identify those areas which had the largest impact on final device and luminaire costs. This information could then be used to help focus effort into the most profitable areas.

The cost model will depend on an analysis of Cost of Ownership (COO) for each piece of equipment in the manufacturing process. COO is a widely used metric in the semiconductor industry (see SEMI standard E35 'Cost of Ownership for Semiconductor Manufacturing Metrics'). COO was originally developed for wafer fabrication tools. COO can be defined as the full cost of embedding, operating and decommissioning, in a factory environment, a system needed to accommodate a required volume. In its simplest form it is the total cost of producing a good part from a piece of equipment. The cost per wafer for an item of semiconductor processing equipment can be determined from a knowledge of the fixed cost (purchase, installation, etc.), variable cost (labor, materials, etc.), cost due to yield loss, throughput, composite yield, and utilization (proportion of productive time). The cost/wafer (cost/part) is obtained by dividing the full cost of the equipment and its operation by the total number of good wafers (parts) produced over the commissioned lifetime of the equipment.

COO can also be applied to non-process equipment such as test and inspection tools. The purpose of these tools is to identify good product from bad product and generally results in some level of scrappage. Scrap caused by the inspection method, such as destructive testing, is part of the test equipment COO (increases the yield loss). Scrap identified by the inspection method is part of process tool COO for the tool causing the scrappage.

An important application of COO is in evaluating new equipment purchases. However, COO is also used to evaluate the long-term benefit of manufacturing changes. Hence, COO can help with decisions about materials use, equipment operations and process improvements. It can help identify any bottlenecks in the process, and it can foster communication and understanding throughout the supply chain.

COO considerations are central to the development of a cost model for a particular manufacturing process. A COO analysis is performed for each piece of equipment at each step in the process flow. This analysis produces a cost per good part for each process step. The overall cost per good part for a simple serial process is then calculated by combining each of these individual cost contributions. In the case of an LED package the cost/wafer from the epitaxy and wafer processing steps must be converted into a cost/die in order to combine it with the cost/die arising from the packaging steps. A Cost Modeling Working Group has been established to coordinate efforts to develop a suitable model following the recommendation of the 2009 Roadmap. The initial focus of the group will be on developing a model to describe the LED package cost breakdown.

3.0 OLED Roadmap

3.1 Manufacturing strategies

Based on the discussions at the Manufacturing Workshops in 2009 and 2010, it is clear that there is not yet consensus on the best manufacturing strategy to meet the performance and cost targets set out in the 2010 MYPP. Some participants recommended building upon the experience gained through OLED displays by developing vacuum processing on rigid substrates, as described in Section 3.4. Because the substrates move along the manufacturing line as separate sheets, this approach is often called “sheet processing”. An alternative approach, discussed in Section 3.5, is to develop roll-to-roll techniques on flexible substrates, often referred to as “web processing.” In addition, hybrids of these two approaches, such as thermal evaporation on a flexible web combined with glass encapsulation, may provide the best combination of cost and performance.

In this roadmap, analyses of the current and anticipated future costs of these two specific approaches are outlined. However, these costs depend on uncertain assumptions about manufacturing parameters, such as yields, materials utilization, processing times and future cost of equipment suitable for high-volume manufacturing. At this time, there is no sound basis on which to make reliable predictions of these factors. Therefore, choosing to support one manufacturing strategy over another based solely on these estimates is inappropriate. The most prudent procedure is to examine at what rate each approach can be pursued, to define the criteria by which the various process flows can be assessed and to set a provisional schedule for deciding on the optimal production techniques.

Most OLED manufacturing strategies can be separated into three stages.

1) *Preparation of the manufacturing substrate:* The foundation onto which the organic stack is deposited consists minimally of a substrate and an electrode. The electrode may need to be patterned to ensure uniform emission of light and to minimize the effects of electrical shorts. To reduce costs, this patterning should preferably not require sub-micron resolution. The substrate electrode is usually in the form of a transparent anode. Protective coatings and layers to enhance light extraction may also be added to improve the efficiency and lifetime of the devices. These combined structures (substrate, electrode, protective coatings, and light extraction layers) will be referred to as “foundation layers.” The assembly of the foundation layers may be carried out by merchant suppliers who do not have access to the basic OLED intellectual property.

2) *Deposition of the active organic layers and second electrode:* The core set of operations involve the deposition of multiple layers of organic materials that transport charge between the two electrodes and convert the electrical energy into light. Design of the stack should be optimized to avoid electrical shorts and to minimize transfer of energy from the photons to the metal electrode. The fabrication of this organic stack must take account of the specific properties of the organic materials and so can be carried out only in close collaboration with the developers of the basic materials and architectures. The deposition of the upper electrode (usually an opaque cathode) also requires a thorough

understanding of the properties of the organic layers in order to avoid damage to the fragile organics and to ensure good electrical contact and long device lifetime.

3) *Encapsulation and Panel Formation:* After the organics and upper electrode are deposited, the top surface of the device must be protected from the environment through encapsulation. This is usually accomplished by the addition of a cover and an edge sealing process.[11] The resulting product at this stage will be a thin sheet containing one or more OLED devices. These devices must then be separated and tested, ready for luminaire assembly.

The issues involved in foundation, construction, and encapsulation are discussed in section 3.4.

Despite many years of research, it now seems clear that it will not be possible to ensure good uniformity across a large area OLED panel using a homogenous sheet of transparent conductor. Most solutions to this problem involve separating the panel into segments with opaque boundaries. The segment boundaries can be made so thin as to be invisible to the user or can be integrated into the design, as in the desk lamp shown in Figure 13.

Figure 13. Desk lamp incorporating two segmented OLED panels
Source: GE 2010

3.1.1 Cost Reduction

In most contexts, such as in comparisons with other light sources or assessing the global economic impact, cost targets for OLED lamps should be specified in terms of $/klm. However,

[11] The cover and seal must still allow power to be delivered to the OLED segments.

manufacturing costs scale more closely to panel area, rather than light output, so considering $/m^2 is also useful. The relationship between these two metrics depends on the brightness of the panel. If the light is emitted equally in all directions, corresponding to a Lambertian distribution, a luminance of 1000 candela per square meter (cd/m^2) will lead to a luminous emittance of 3140 lm/m^2. A cost of $100/klm then implies a manufacturing cost of $314/m^2.[12]

As is illustrated in Figure 14, significantly higher manufacturing costs per unit area can be tolerated if the luminance is increased from 1000 cd/m^2 to 4000 cd/m^2. However, this may result in a reduction of the operating lifetime of the panel and will require more attention to glare issues and thermal management in luminaire design. Thus, in addition to the manufacturing developments described in this roadmap, continued Core and Product Development R&D to improve OLED stability is essential to meet overall objectives.

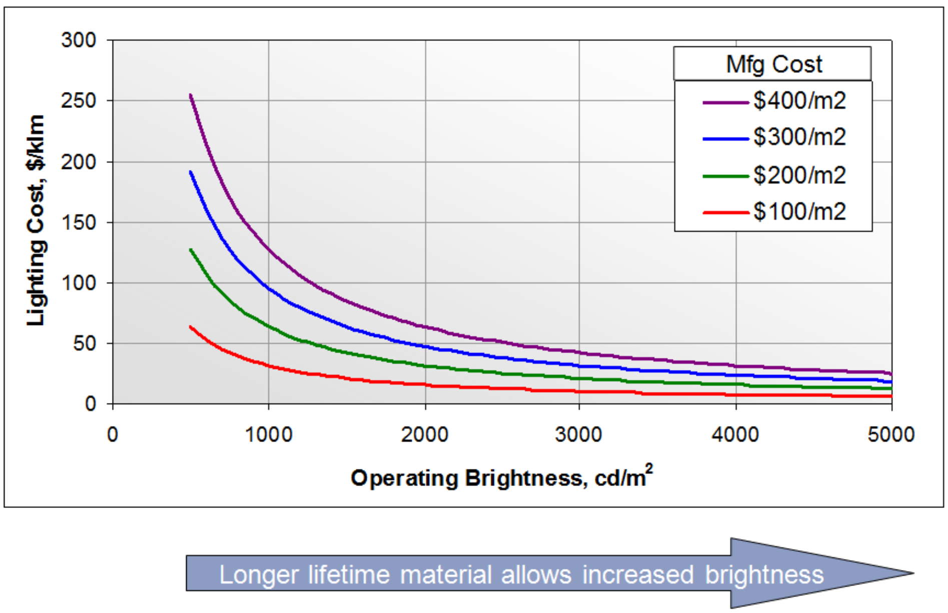

Figure 14. Influence of Luminance on Manufacturing Costs
Source: William Feehery, DuPont, "OLED Lighting Manufacturing Cost," SSL Manufacturing Workshop, Fairfax, VA, April 2009

An analysis by Acuity Brands[13] of potential solid-state replacements for fluorescent fixtures suggests that OLED panels could become competitive with inorganic LED arrays if the OEM price can be reduced to $16/klm. At a luminance of 4000 cd/m^2, the manufacturing cost is equivalent to $200/m^2. The cost of an active matrix OLED panel for display application, the only OLED manufacturing experience, is at least $2000/m^2. Allowing for the replacement of expensive display substrates and the absence of the TFT backplane and high-resolution

[12] In the SSL MYPP the performance targets for OLED brightness are expressed in terms of the luminance in units of cd/m^2. Luminaire manufacturers at the Vancouver workshop suggested strongly that the total light output from each unit area (measured in lm/m^2) would be of more value to users. Assuming a Lambertian distribution of the emitted light, the luminance in cd/m^2 should be multiplied by 3.14 to obtain the light output in lm/m^2.

[13] Peter Ngai, Acuity Brands, DOE SSL Manufacturing Workshop, Fairfax, VA, April 2009

patterning, the cost of producing OLED lamps using similar equipment and materials is likely to be approximately $1000/m^2. Reaching cost targets as low as $200/m^2 will require significant progress in several areas. These areas are described below:

In addition to increasing luminous emittance, other opportunities to reduce manufacturing costs can be classified into several general areas:

- Substrate size: If sub-micron patterning can be avoided, the cost of adapting manufacturing equipment to process large substrates scales more closely to the linear dimensions of the equipment, rather than the area processed, resulting in substantial savings in depreciation costs. Furthermore, larger tools need not lead to a commensurate increase in total labor costs, as shown in Figure 4. Similar gains are anticipated from increases of the width of the web in roll-to-roll processing.
- The waste of critical materials, such as the active organics and transparent conductors, must be minimized. The replacement of point sources by linear or planar sources in evaporation equipment has led to increase in the material utilization factor from less than 10% to around 70%.[14] Proponents of solution processing point out that extrusion coaters are available for OLED manufacturing[15] which achieve material utilization rates greater than 95%. The development of economically viable methods to recover rare elements, such as indium or iridium, from scrapped work pieces could reduce costs.
- The yield of good panels should be increased to levels in excess of 90%. Meeting this target will require experience in identifying and removing the causes of defects and the installation of effective in-line inspection tools and error recovery mechanisms.
- Processing times should be shortened to reduce depreciation and labor costs. Cycle times for batch processing should be lowered from current values in OLED display production of around 4 minutes. Avoiding the need for precise positioning of masks will help reduce cycle times. Values of 80 seconds have been demonstrated for evaporation sources on substrates of 760 x 980 mm. In roll-to-roll manufacturing, the web speed needs to be increased from today's typical values of 1 foot/min. The curing of films and the removal of solvents may be the rate limiting processes when wet processing techniques are used.
- Less expensive materials should be used wherever possible. For example, the replacement of display glass by window glass could reduce the cost from ~$50/m^2 to ~$5/m^2. Benefits of scale should be leveraged, especially for organic materials and transparent conductors.
- Manufacturing procedures should be simplified as much as possible. For example, high-resolution patterning using lithographic techniques should be avoided.
- Labor costs must be reduced through automation, increased equipment reliability and greater throughput.

[14] Uwe Hoffman et al (Applied Materials) SID 2010 Technical Symposium paper 46.1.

[15] Miguel Friedrich (NextTech FAS), submission to the Vancouver workshop.

The following four tables were constructed at the 2009 Vancouver, OR workshop and reviewed at the 2010 San Jose, CA workshop to illustrate what manufacturing targets must be achieved in order to meet MYPP cost targets. Due to the limited progress thus far made on the existing integrated manufacturing line projects, there was no rationale to change the cost estimates. DOE will reevaluate these targets once the manufacturing lines are in operation or substantial simplifications have been demonstrated in processing methods.

The many challenges that are faced in reducing production costs can be separated into two groups. The first relate to the costs of capital and labor associated with each manufacturing line. The contribution of these factors to the cost of each lamp can best be reduced by increasing the number of lamps produced on each line. Table 7 and Table 8 show targets for the manufacturing parameters, including capital investment and staffing levels. In both tables, the size of the substrate is steadily increased and the cycle time is reduced in order to reach the desired production levels.

With regards to light output, the targets in the 2009 MYPP assumed a luminance of 1000 cd/m^2, corresponding to a luminous emittance of ~3000 lm/m^2. Therefore, in order to reduce costs, both roadmaps include an increase in light output per m^2. However, as increased lumen output will likely lead to lower lifetimes, further improvements in materials performance are required such that output levels of at least 10,000 lm/m^2 can be achieved with acceptable lifetimes. In the 2010MYPP, the targets for luminous emittance were raised to 6000 lm/m^2 in 2012 and 10,000 lm/m^2 in 2015.

Regarding substrate area in sheet processing, due to the experience gained in the display industry, no formidable barriers to increasing the substrate size to at least 6 m^2 are anticipated. Substrate sizes can be chosen either to fit the anticipated product sizes or the manufacturing equipment already developed for other applications. The relative importance of these two factors has yet to be determined. Concerning the cycle time in sheet processing, factors that limit cycle time may include cathode deposition, mask handling and optical inspection.

With regard, the web processing manufacturing roadmap, web handling and blanket coating have already been demonstrated at the sizes and speeds depicted for many other applications. Cathode formation and optical inspection are expected to be the major challenges to reaching the speed targets. In addition, as seen in Table 9 and Table 10 the yield targets for web processing are more modest than for sheet processing due to the added difficulty of in-line inspection and repair.

Table 7. Manufacturing Roadmap for Sheet Processing of OLED Lighting Panels

Stage	Units	Year		
		2011	**2013**	**2015**
Light output	lm/m^2	3000	6000	10,000
Substrate area[16]	m^2	0.2	0.67	2.7
Cycle Time	Sec	180	120	60
Yield	%	0.75	0.9	0.95
Annual Uptime	Hours	6000	6900	7500
Annual Production	m^2	14,000	100,000	925,000
Investment[17]	$M	30	80	150
Direct Labor	staff/shift	7	8	10
Indirect Labor	staff/shift	15	15	15
Annual Labor Costs[18]	$M	4.4	4.6	5
Other Operations	$M	1	2	4

[16] It is assumed that 80% of the total substrate area will be devoted to light production, leaving margins between tiles or panels and around the edge of the substrate.

[17] More detailed process flows and cost-of-ownership models for the required tools are needed to refine these estimates. These must include all processes for substrate preparation and back-end assembly, as well as the deposition of the organic materials.

[18] Four shifts are assumed for direct labor and two for indirect. Average FTE costs of $50,000 per year are assumed for direct labor and $100,000 for indirect.

Table 8. Manufacturing Roadmap for Web Processing of OLED Lighting Panels

Stage	Units	Year		
		2011	**2013**	**2015**
Light output	lm/m^2	3000	6000	10,000
Web Width	m	0.2	0.5	2.0
Web speed	m/min	0.3	1.0	10
Product area	m^2/min	0.048	0.4	16
Yield	%	0.7	0.8	0.9
Annual Uptime	hours	6000	6900	7500
Annual Production	m^2	12,000	130,000	6,500,000
Investment	$M	20	50	200
Direct Labor	staff/shift	7	8	12
Indirect Labor	staff/shift	15	15	15
Ann. Labor Costs	$M	4.4	4.6	5.4
Other operations	$M	1	2	10

If the capital and labor costs are spread over very many lamps, the remaining set of challenges relate to the cost of materials. These, along with the prorated costs of depreciation, labor and operations are included in Table 9 and Table 10. All material costs are fully yielded, with allowance for materials wastage and scrapping of unacceptable panels. With regard to the sheet-processed substrate cost, the roadmap assumes the usage of tempered clear float glass. For web-processed manufacturing, the roadmap assumes plastic substrates, where most of these costs are incurred in the production of the barrier coating. In addition it is important to note that the electrode cost estimates are lower than the current prices of transparent conductors (ITO). These estimates assume more efficient production techniques or the development of less expensive alternatives. A substantial portion of current costs is associated with electrode patterning. With regard to the light extraction, meeting the performance targets of over 75% light extraction (as presented in the MYPP) within these cost estimates is very challenging and requires further research and development. Encapsulation estimates assume the use of a metal foil cover with edge sealants.

Table 9. Projected Costs of OLED Lighting Panels (sheet processed)

Stage	Units	Year		
		2011	**2013**	**2015**
Depreciation[19]	$\$/m^2$	420	160	30
Labor	$\$/m^2$	305	45	5
Other operations	$\$/m^2$	70	20	4
Organic Materials[20]	$\$/m^2$	30	15	10
Substrate	$\$/m^2$	6	6	6
Electrodes	$\$/m^2$	20	15	10
Light extraction	$\$/m^2$	20	15	10
Encapsulation	$\$/m^2$	10	8	5
Other materials	$\$/m^2$	20	15	10
Total cost	$\$/m^2$	900	300	90
Total cost	$/klm	300	50	9

[19] 5-year depreciation is assumed with annual charges equal to 20% of invested capital.

[20] Initial estimates are based upon costs of $1000/gm for dopants and $100/gm for host materials. It is assumed that material utilization will improve from 50% in 2011 to 70% in 2015, and that further cost reductions will accrue from the increased sales volume for materials suppliers.

Table 10. Projected Costs of OLED Lighting Panels (web processed)

Stage	Units	Year		
		2011	2013	2015
Depreciation	$\$/m^2$	360	60	6
Labor	$\$/m^2$	365	37	1
Other operations	$\$/m^2$	80	15	2
Organic Materials[21]	$\$/m^2$	50	30	20
Substrate	$\$/m^2$	70	35	20
Electrodes	$\$/m^2$	20	15	10
Light extraction	$\$/m^2$	20	15	10
Encapsulation	$\$/m^2$	10	8	5
Other materials	$\$/m^2$	20	15	10
Total cost	$\$/m^2$	970	230	85
Total cost	$/klm	320	38	8.5

Although the specific numbers in these tables need to be refined as more experience is gained, several conclusions can be drawn:

- The prorated cost (per lamp) associated with capital expenditures and labor will be very high until large volume production is achieved. This will seriously impact profitability for general illumination until annual production from each line approaches 1 million klm. The identification and capture of appropriate specialty lighting markets will be essential to the financial health of manufacturers during the ramp-up phase.
- In high volume production, materials costs will dominate, just as for OLED displays. It will be essential to control the costs of the structural materials, inorganic films, and specialty organic materials. In addition, minimizing waste of materials will be critical to controlling costs.
- The current expectation is that the bill of materials will be higher for web processing due to the additional cost of solution-processable organic materials and of encapsulation. However, anticipated capital costs are less because of the simpler handling equipment in roll-to-roll fabrication. Labor costs are assumed to be similar.

The analysis also confirms that the potential advantage of the web processing approach comes from the high throughput that can be attained through speeds of around 10 m/min. With such throughput, materials account for approximately 90% of total costs. The major risk arises from the difficulty of detecting, identifying and correcting processing errors, both in the barrier

[21] It is assumed that the greater complexity of solution–processed materials will lead to relatively higher costs.

coatings and in the processed panels. For these reasons, the time scale for web processing has been extended to allow time for development and testing of improved process control techniques.

With either approach, gauging the right pace at which to scale up in size and speed will be critical to the commercial viability of OLED lighting. Many of the problems will become apparent only after attempting rapid processing on large area tools. However, installing such equipment too early will lead to large financial losses through material waste and unrecovered depreciation expense. Prior experimentation with critical processes, such as the deposition of the organic multi-layers and cathode materials could be very prudent.

3.2 Luminaire Assembly

Most of the attention of the OLED lighting community has been focused on the architecture, manufacture, and encapsulation of the planar panels. Although luminaire concepts have been explored and a few samples produced, the interplay between design innovation, functionality, manufacturability and cost has not been analyzed. This section identifies some of the critical issues. Most of these, given the state of the art, may not be amenable to incorporation into the manufacturing roadmap at this time, and some need additional R&D. The luminaire issues listed here have received little discussion in the OLED community so far, but have been identified by comparison with inorganic LEDs, for which far more experience has been gained.

3.2.1 Sizing issues and brightness

As discussed in Section 3.1.1, manufacturing costs scale more directly with panel area than light output. At the 2009 Fairfax meeting, Acuity Brands recommended a luminance level of 15,000 lm/m^2, rather than the nominal value of 3000 lm/m^2, which was the reference level used in the MYPP. This would not only reduce the cost of the panel by a factor of approximately four, but may also reduce the lifetime by a much greater factor. It may also require more attention to glare and thermal management in luminaire design. A compromise was reached resulting in the revision of the MYPP targets for 2012 and 2015.

Allowing flexibility to meet customer preferences regarding panel size and shape conflicts with the economic benefits of standardized substrate sizes and waste minimization. Tiling may provide a partial solution with respect to size selection and standardization. Production of arbitrary shapes will be difficult until fabrication using printing processes on flexible substrates becomes economic.

3.2.2 Variability/binning

Whether luminaires are built around single or multiple tiles, similar to LEDs, issues will arise from the variability in the performance of manufactured panels. It will be economically unacceptable to discard all panels with observable deviations in brightness or color from the intended values. Variations in luminous emittance can usually be corrected through changes in the drive voltage, but the testing procedures and drive circuits must be designed to allow such adjustments, an additional expense both in materials and assembly. Variations in color are more difficult to correct, and manufacturers offering a family of products with different color mixes may be appropriate. Ultimately, variability tolerances need to be established and specified by luminaire manufacturers. Also, production schemes need to be developed to ensure uniform, repeatable color and luminance.

Until any significant differences are identified in the reproducibility of LED and OLED lamps, the recommendations in the LED section (section 2.2.1) should also be used as guidelines by OLED manufacturers. Most developers of OLED technology have assumed that greater control can be achieved over OLED processing than in traditional LED fabrication, so that binning can be avoided. However, initial experience with OLED panel prototypes suggests that some binning may be necessary. Further research is needed to determine the effects of process tolerance at each of the manufacturing process on the performance of the resulting panels, particularly with respect to brightness, color, and lifetime.

3.2.3 Light Shaping

Most OLED panels emit light uniformly in all directions, giving a Lambertian angular distribution. This can lead to annoying glare and customers often prefer to focus the light to some extent. The angular distribution of the light emerging from the OLED stack can be modified using micro-cavity effects, but this will often result in variations of color with angle. One solution is to add an exterior film to the panel, or to use the luminaire to redirect the light. As with conventional light sources, reflectors or other optical components might also be used to shape the light. Diffusing films or components might be incorporated within the luminaire to improve the spatial uniformity of light or to mask the appearance of thick grid-lines or tile boundaries.

3.2.4 Electrical circuits

Standardized interfaces, such as connectors between the electrodes or bus lines, should be established in the panel and the external power source. While making firm recommendations may be premature, preparing draft specifications as they will affect the power supplies and driver circuits that must be designed to match the chosen configuration would be useful.

As with LEDs, various performance options might make OLEDs more attractive in the market. Customer controlled dimming might be incorporated into the design of the driver circuits. Color adjustments are more challenging with most of the architectures envisaged for OLED lighting. Such enhancements, however, are beyond the scope of this manufacturing roadmap and will not be considered further here.

3.2.5 Reliability Issues

Much R&D effort has been focused on identifying the basic degradation issues that limit the operational lifetime of OLED devices and on the effectiveness of the various encapsulation procedures. However, the demand for increased brightness will lead to accelerated degradation and increase the importance of thermal management. Substantial uncertainties remain, since materials and architectures are rapidly evolving. Almost all lifetime predictions are based on accelerated testing methods that may not give accurate results. Also, measurements made on devices fabricated in the laboratory and operated in tightly controlled conditions may not be appropriate for OLEDs built on mass-production lines and operated in a variety of uncontrolled environments.

The 2010 MYPP identifies several tasks, both in Core and Product Development related to extending the lifetime of OLED materials and products and also to the characterization of long term performance. Given the critical importance of lifetime to meeting the cost goals as outlined in this roadmap, not to mention the difficulty for manufacturers to establish appropriate warranties, any progress in this area needs to be implemented in manufacturing as rapidly as possible.

3.2.6 Physical Protection

OLED displays are built on very thin glass and must be protected against external shocks. Thicker sheets can be used in lighting applications, but stress protection through tempering or covering with a plastic film will be essential, so that damage is not incurred during transport and installation. Edges are particularly prone to damage in transit or in installation.

One of the potential advantages of flexible OLEDs is that they need not incorporate fragile glass sheets. Although impressive demonstrations have been made to show that physical stress does not lead to immediate failure for flexible OLEDs, the effect on the integrity of barrier layers has not been thoroughly checked.

3.2.7 Product differentiation and market expansion

The primary motivation for the DOE SSL Program is to increase overall lighting efficiency and the focus is on general illumination. However, it may be necessary for emerging technologies, such as OLED lighting, to initially build their business on niche applications, such as architectural and decorative lighting. Part of the reason for the interest in OLED lighting from potential integrators and customers is the promise of new form factors that go well beyond those that are amenable to fluorescent tubes. Much of the excitement has been caused by design concepts that are based upon flexible substrates, arbitrary shapes and variable color. Reliable analyses of customer expectations and market forecasts would be valuable.

3.3 Substrates and Encapsulation

When it comes to panel fabrication, which is discussed at length in the sections below, many of the issues are sensitive to the choice of the active materials or device architecture. As a result, issues can be pursued effectively only in close collaboration with the holders of basic intellectual property relating to specific light emitting and conducting organic materials. In contrast, the preparation of the substrate and the encapsulation of the whole device require expertise that is most likely found outside these companies. Furthermore, these aspects of manufacturing OLED lamps are likely to account for the majority of expenditure, both in materials and processing cost. Thus, as the OLED lighting effort moves from research to high-volume production, more attention needs to be paid to these packaging issues. Again, as with the luminaire issues above, many of these issues are still in the R&D phase, and roadmapping a manufacturing evolution is not possible except in a broad outline.

3.3.1 Substrate and Encapsulation Material Selection

Most R&D has been focused on three material types for both the fabrication substrate and cover – glass, metal foil and plastic. For glass and metal foils, materials that have been developed for other applications seem to be well suited to OLED lighting. The many years of effort that have been expended on the development of plastic substrates for OLED displays has resulted in materials that are adequate for OLED lighting in all respects but one: The porosity of all commercially-available plastic materials to water vapor and oxygen is too high (by several orders of magnitude) to protect OLED light panels over the required operational and storage lifetimes. Thus, barrier coatings are needed to provide added protection.

Following studies on prototype lamps, metrics have been suggested for each of the important characteristics of substrate materials. These aid in material selection and give guidance to potential suppliers, but should be refined as manufacturing experience is gained and products are tested by customers. The metrics include:

- Smoothness: Surface roughness must be controlled at a microscopic level, with average roughness (R_{rms}) of less than 2 nm and peak-to-valley roughness less than 20 nm. Specifications for larger scale flatness are also needed. The current-carrying circuits inside the OLEDs need to be electrically isolated from the external environment.
- Mechanical and Thermal Stability: Expansion of the substrates and intermediate layers caused by thermal or mechanical stress during fabrication can cause issues with pattern registration, optical inspection accuracy, and edge seal integrity. Parameters such as coefficient of thermal expansion (CTE) and Young's modulus are needed for all materials. Additional properties, such as shrinkage or expansion under thermal cycling and moisture absorption are important for plastics.
- Optical Properties: For transparent substrates, absorption of visible light should be less than 2% and transmittance more than 85%, with all foundation layers included. Very low absorption is particularly important when extraction enhancement solutions lead to multiple passes of light across the substrate or transparent conductor. The refractive index of the glass is an important factor in the design of out-coupling enhancement structures.
- Physical protection: Hardcoats are often needed to strengthen glass and plastic substrates and edges need to be protected. Damage must be avoided in transporting the substrate to the OLED manufacturer, during OLED fabrication and in the delivery, installation and operation of the finished panel or luminaire.

3.3.2 Substrate Coatings

As noted above, the most difficult coating challenge is to provide a barrier layer for plastic substrates that limits the permeation of water vapor to less than 10^{-6} g/m^{2}day and oxygen to less than 10^{-6} cc/m^{2}day. The absence of pin-holes is essential, as well as the use of a material with very low bulk permeability. Unfortunately, measurement of such low permeation rates requires highly specialized equipment that is not available to most manufacturers, and direct lifetime tests can only be performed on a reasonable time scale using accelerated degradation techniques. Therefore, until real experience is obtained with working lamps, uncertainties will remain concerning the adequacy of barrier layers.

It has been clearly demonstrated that multi-layer barriers containing alternate layers of organic and inorganic materials can provide almost any desired level of protection provided that enough layers are used and that they are fabricated without defects. However, the cost of manufacturing these barrier films can be high. Costs should be reduced to less than $20/m^2 by 2013 and $10/m^2 by 2015. It should also be shown that these multi-layer films can be deposited reliably over large areas.

For plastic and metal foil substrates, deleterious effects of residual roughness can be minimized by adding a planarization layer, for example using a polymer material or "Spin-on Glass". This layer can also serve other functions, such as an insulation layer for metal foils, or a hole injection layer if placed on top of the anode.

Barrier coatings may even be needed with some forms of glass, for example to restrict the egress of sodium or other potential contaminants. Quantitative criteria need to be developed in this respect.

3.3.3 Transparent Anodes

The material selection and processing of the transparent anode was identified at the Fairfax workshop as being critical to achieving reliable, cost-effective OLED manufacturing. The metrics that need to be applied to the processed anode include:

- Sheet Resistance: preferably less than 20Ω/square
- Work Function: preferably above 5V and compatible with OLED materials
- Surface Roughness: as for substrates
- Chemical Migration: no escape of materials that can damage the organic layers
- No undue reliance on scarce materials

If any alternatives to ITO emerge from the R&D program, processing techniques consistent with these metrics need to be developed.

As discussed above, the use of a homogeneous sheet of transparent conductor across a large panel would result in intolerable voltage drops, leading to non-uniform emission of light and significant energy loss. Two solutions have been suggested. One is to divide the panel into several segments, with the cathode of one segment connected in series to the anode of a neighboring segment. The other is to supplement the transparent conductor by a metallic grid.

The grid lines should occupy only a small fraction of the area and so their thickness may be larger than the total thickness of the organic stack. Care must be taken in the formation of these grids to avoid shorting or other problems along line edges.

Adoption of either approach means that the requirements on sheet resistance in the 2009 Manufacturing Roadmap can be relaxed. The implications of these additional structures upon the operation and integrity of the device must be thoroughly checked and the optimal fabrication techniques need to be identified.

3.3.4 Out-coupling Enhancement Structures

The refractive index of OLED emitter layers is typically around 1.8. Thus, most of the light is internally reflected, becoming trapped in the device layers and absorbed after multiple bounces before it can escape into the air. Unless steps are taken to enhance out-coupling of the light, roughly 80% of the light is lost.

Researchers have suggested many techniques to increase the fraction of light that escapes through the transparent substrate, but little experience has been gained in manufacturing OLEDs using these methods. Some of the techniques involve modifications in the stack structures between the electrodes (e.g., creating an optical cavity to such that horizontal wave-guiding is reduced). The design and fabrication of such solutions must be accomplished with great care so as not to degrade the current flow or light creation.

Other proposed solutions involve adding structures between the transparent electrode and the associated substrate, or on the outside of the transparent substrate. These structures can be designed and fabricated by the substrate supplier. Three types of these structures are:

- Surface Profiling: The escape of light from the transparent substrate can be enhanced if the microscopic orientation of the external substrate surface is modified, for example by adding prism sheets or micro-lens arrays.
- Scattering Layers: As the addition of one or more scattering layers can result in multiple scattering with minimal absorption, it is likely that the angle of incidence on one of the many approaches to the external surface will be small enough such that the light escapes.
- Low Index Layers: The interleaving of layers with low and high indices can act as a band-pass filter. This approach may be especially effective when combined with a scattering layer.

Care must be taken that the introduction of these structures does not lead to undesirable anomalies in the emitted light, such as variations in color with the angle of emission. Whenever these structures are included inside the transparent substrate, compatibility with the neighboring layers must be considered, both in respect to fabrication and operation.

Support for manufacturing implementation of these techniques should be given high priority. The fraction of created light that escapes from the device should be increased to 50% by 2012 and 70% by 2015. Low-cost fabrication techniques that are scalable to large area substrates and are consistent with average cycle times given above need to be found.

The problem of light extraction could be simplified greatly if the refractive index of all the layers through which light passes could be matched to that of the emission layer, which is typically around 1.8. Developers of small devices have recommended the use of high-index glass or plastic as a substrate material. The present cost of such materials prohibits their use in large panels, but the development of an inexpensive high-index substrate would be a major contribution to this effort. A cost target of $\$10/m^2$ would be appropriate.

3.3.5 Encapsulation

Porosity requirements for the cover material are similar to those for the fabrication substrate. The two substrates must be brought together in a dry, oxygen-free environment. In addition, desiccants or getters may be needed to absorb any H_2O or O_2 that is either trapped during encapsulation or enters at a later time. Sealing the edges is also critical, and can be especially challenging when two different substrate materials are used. The presence of electrical connections must not degrade the integrity of the edge seals. Some seals need to be cured in-situ, either thermally or by ultraviolet (UV) irradiation.

For small OLEDs, such as those used in cell-phones, solid getters are available in sheet form, with pellets up to 40 mm x 70 mm in size and around 100 µm thick. These are inserted in cavities in the cover glass. The cost of this process (~$120/$m^2$) can be reduced by at least a factor of 2 by printing the getter onto the cover glass. However, further product development is necessary in this area to achieve the more than factor of ten reduction in cost required, as presented in Table 9. Printing is advantageous because the getter can be concentrated near the seals to provide maximum protection against edge ingress. Alternatively, the development of thin-film getters that could be deposited directly onto the cathode layer could greatly facilitate the encapsulation process for large area devices.

The need to cut the processed substrate into tiles and reassemble the tiles to make the OLED panels complicates the encapsulation process. Manufacturers need to decide whether to encapsulate all the tiles before testing or to add covers and encapsulation only to defect-free tiles, either before or after panel assembly.

3.4 Batch Processing on Rigid Substrates

The existing OLED and Liquid Crystal Display (LCD) industries rely on vacuum processing of thin-film devices on glass substrates. LCD fabrication has been demonstrated for substrate areas as high as 5 m^2, while OLED manufacturing has evolved more recently and has been limited areas less than 0.4 m^2. In a traditional OLED system, the tools that deposit the individual layers are arranged in a cluster configuration, as shown in Figure 15.

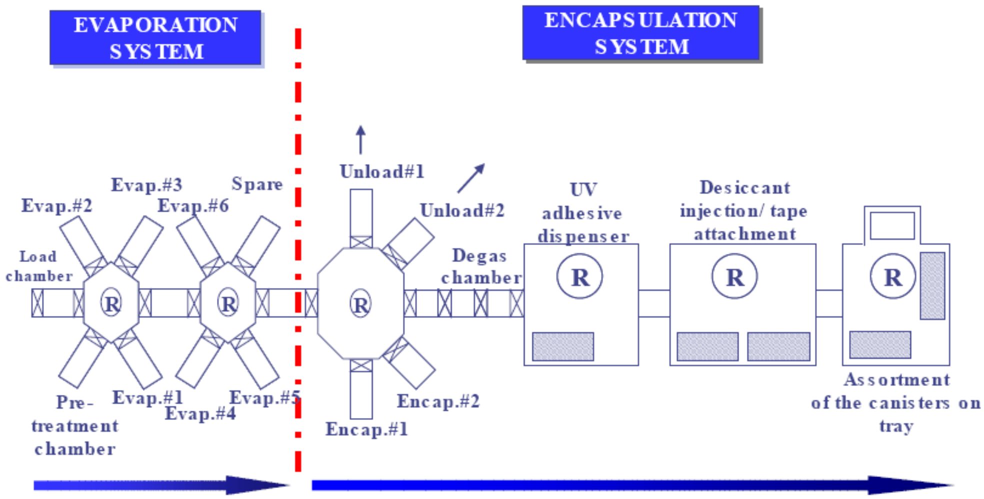

Figure 15. Vacuum Deposition Production Line with Cluster Configuration
Source: Barry Young, OLED Association, "OLED Manufacturing", SSL Manufacturing Workshop, Fairfax, VA, April 2009

The cluster approach allows greater flexibility; for example, multiple evaporation sources can be used for layers that require longer deposition times. However, the transfer of substrates from one chamber to the next is time consuming and may limit the cycle time.

It is anticipated that as OLED lighting manufacturers gain confidence in the performance of individual tools and fix device architectures, they will adopt an in-line configuration, such as that illustrated in Figure 16.

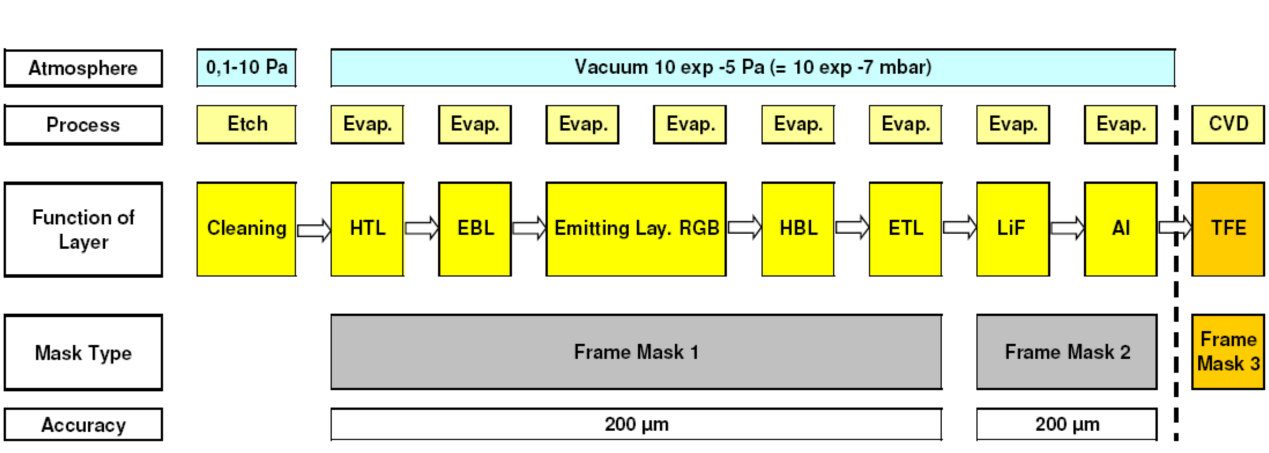

Figure 16. Vacuum Deposition Production Line with In-Line Configuration
Source: Uwe Hoffmann, Applied Materials, "Deposition Equipment and Processes for OLED Lighting", SSL Manufacturing Workshop, Fairfax, VA, April 2009

In this particular process, it is assumed that the transparent anode layer and other foundation structures have been added to the substrates before processing. The last step involves the deposition of a thin-film cover by chemical vapor deposition (CVD).

Conveyors can be used to transport the substrates between tools, replacing robots. This reduces the cost and processing time, but may require more floor space.

For both cluster and in-line manufacturing techniques, the efficiency of evaporation sources is critical to the batch processing vapor deposition strategy. There are several types of deposition sources and geometry. Although point sources were used initially, these lead to low material utilization and significant variations in uniformity across the substrate. Linear or area sources give much better results and are more easily scaled to larger substrates and shorter cycle times. The substrates can be either vertically or horizontally oriented.

The replacement of point evaporators with linear sources and cluster configurations with in-line production has been shown[22] to lead to substantial reductions in materials costs without significant increase in the capital investment.

The remainder of this section will address some of the critical issues associated with this approach and identify metrics to gauge progress. Issues concerning light out-coupling, encapsulation and luminaire formation will be deferred until later sections. Other steps, such as substrate acceptance and preparation can be accomplished using standard industrial procedures and need not be discussed here.

3.4.1 Deposition of Organic Layers

Deposition is usually accomplished by evaporation, with or without a flow of inert gases, preferably using a linear or areal source. Vertical orientation of the substrate has many advantages, including easier particulate control and reduced substrate bending, but may lead to increased handling costs.

The metrics that should be used to gauge the progress of deposition techniques are:

- Deposition Speed: Typical rates in mass-production tools[23] are 30 nm/min with stability of ±2% maintained over several days of operation. This should be adequate for thin layers (10-20nm), but faster deposition will be required for thicker layers to achieve cycle times below 1 minute.
- Spatial Uniformity: In OLED display applications, uniformity targets for substrates of 460 x 730mm are ±5%. Variations less than ±2% have been reported in ideal conditions. Control to ±2% or better needs to be maintained in lighting applications as substrate sizes and deposition rates are increased.
- Material Utilization: In the manufacture of high-resolution OLED displays, only 10-20% of the material is deposited in the desired position on the workpiece, much of the remainder being intercepted by the mask or spread over the walls of the chamber. This fraction should rise in lighting applications, since fine masks are not needed. The usage rate should be raised to over 70% by 2012 and 80% by 2015.

[22] Uwe Hoffman, Applied Materials, DOE SSL Manufacturing Workshop, Fairfax, VA, April 2009

[23] Eiichi Matsumoto, Tokki Corporation, 2008 OLED Summit, Pira-International

- Mask Alignment: Although fine masks are not needed to create small sub-pixels[24], some patterning will be required. Accuracy targets of 5µm, typical for cell-phone displays, can be relaxed, perhaps to 100 µm. This should reduce the time required for mask alignment, which typically is 30s when high accuracy is demanded.
- Doping Control: Many layers contain dopants and hosts which should be mixed uniformly. Dopant levels are usually less than 10%, and should be controlled to better than ±1%.
- Uptime: In addition to maintenance time, evaporation equipment needs to be shut down for periodic chamber cleaning and to replenish the organic materials. Uptime needs to be increased to at least 90%. Ways to resupply organic materials without breaking the vacuum are desirable.
- Interface Control: Since OLED devices involve several thin-film layers, each with different functionality, it is important that the deposition of one layer does not degrade the structure of the layer below. No specific metrics have yet been defined to check this aspect of multi-layer formation.

3.4.2 Cathode Deposition

Cathode deposition is one of the most difficult steps, both for batch and web processing, due to the fragility of the underlying organic layers. Evaporation is the preferred technique in research environments and can be carried out at high speed for either sheet or web processing. Other techniques like magnetron sputtering and ion-beam assisted deposition are also available.

Metrics must be set and further tests made so that the appropriate tools can be selected and integrated into the production line. Deposition rate, yield and surface properties are the major criteria to be used in selection.

3.4.3 Patterning Techniques

Although lighting applications do not require the fine pixilation of OLED displays, some patterning is desirable in both the organic and conducting layers to define the active regions within the substrate and perhaps to permit segmentation of the OLED devices. Patterning will also be needed if bus lines are used to aid current distribution. It is generally agreed that photolithography, as used in the microelectronics industry, is too expensive for this application.

If patterning is achieved by deposition through masks, metrics need to be set with respect to:

- Alignment accuracy requirements for serially-connected segments;
- Alignment times;
- Cleaning frequency and associated downtime;
- Effect on material usage ratios; and

[24] Because of the reduced need for fine masks, the cost of the masks should be much less than those used for OLED displays.

- Lifetimes and costs.

3.4.4 Inspection and Quality Control

Quality control will be needed at all stages in the manufacturing process, beginning with the acceptance of materials and components from suppliers. For example, checking the purity of organic materials and the integrity of barrier coatings for plastic substrates are formidable tasks.

Real-time inspection systems will be essential if yield targets are to be reached and material waste minimized. These systems can be used in several ways.

- To identify errors in one set of devices and prevent recurrence of the same defects in future devices; the problem may be solved by changes in process control settings or by temporary line closure.
- To check progress at critical stages of production and avoid further processing on defective devices.
- As part of automatic process control systems; for example, on-line thickness measurements can be used in the control of deposition times.

Equipment developed for other applications may be suitable for inspection of the coated or treated substrates before organic deposition begins. Optical detection of particulates or scratches is relatively straightforward for defects above 1 µm in size. However, since conducting particles as small as 10 nm may cause shorts, special techniques to detect, prevent or ameliorate local shorting may be needed.

The most challenging task will be to monitor the uniformity of individual layers in the stack, using either optical or electrical techniques. The fact that most layers must be optically transparent means that techniques that rely on optical absorption may be feasible. Although immediate priority should be given to the introduction of integrated manufacturing facilities, the development of real-time inspection and process-control system should be given significant attention from 2011 to 2015.

3.5 Web Processing on Flexible Substrates

The major advantage of web processing (roll-to-roll manufacturing) lies in the ease of handling and potential for faster processing. This strategy requires the use of flexible substrates and essentially eliminates the option of cluster tool configurations used in batch processing. Coordination of processing times becomes more critical, as does quality control and equipment reliability, since a failure in one tool means that the whole line has to be shut down.

Roll-to-roll fabrication is compatible with vacuum deposition techniques in which many years of experience have been gained for other applications, ranging from food packaging to photovoltaics. However, many proponents of this approach for organic electronics prefer to use solution-processing techniques wherever possible, believing that these will be less expensive when scaled to high-volume production. The best combination of cost and performance may involve both technologies, where solution processing is used for some layers to reduce cost and thermal evaporation is used for other layers to maximize performance.

3.5.1 Web Handling

In roll-to-roll manufacturing, most tools remain stationary while the substrate is moved, either continuously or in discrete steps. Many steps can be carried out while the web moves at a constant speed. These include substrate cleaning, roll or slot die coating, gravure and inkjet printing, dry and wet lamination. Others require step and repeat operation in which the substrate motion is halted temporarily. These include screen printing and many optical imaging procedures. The use of accumulators makes it possible for some of the processes to be carried out while the web is moving while the web is stopped for others.

Throughput can be improved by increasing the web width or the speed. Currently, there seem to be no insurmountable barriers to increasing the web width from 20 cm in 2009 to 1 m by 2015.

Increases in web speed often lead to larger footprints for the manufacturing line. The rate limiting processes often involve drying or curing steps. Even with modest web speeds of 30 cm/min, a drying time of 30 minutes implies that a 9 m length of web must reside in the oven at any one time. The development of rapid drying techniques would lead to greater throughput with minimal increase in plant size. Speeds of around 5 m/min would seem a reasonable target for 2015, giving throughputs equivalent to those achieved today in the flat panel display industry.

Accurate deposition and patterning requires careful control of the position of the web with respect to the tools and the tension in the web. Both can be affected by variations in temperature and humidity, which must be tightly controlled. The position of the web can be monitored using charge-coupled device (CCD) cameras or ultrasonic detectors. Maintaining a tight web is essential as the depth of view of optical detection equipment can be as low as 3 µm. Thus metrics must be defined and met for positional control in all three dimensions.

Many processing steps need to be carried out in dry, oxygen-free atmospheres, and some may require vacuum conditions because of the sensitivity of the active organic materials to water and oxygen.. Additionally, special valves and adequate pumping procedures are needed so that the web can move between chambers of varying pressures and gas constituents while unrolled..

3.5.2 Deposition of Organic Layers

There are several methods of depositing organics during web-processing. These include screen printing, flexographic and gravure printing, slit-coating, and ink-jet printing. Relatively little experience has been gained in the application of these methods to print OLED materials on moving webs. Thus, high priority should be given to more rigorous testing of the techniques so that the best ones can be identified before high-volume production begins.

Irrespective of the method used to deposit the inks, the solvents need to be removed leaving a uniform layer of functional organic material, before the next layer is deposited. Thermal drying has typically been used to drive off the solvent, but this is a slow process requiring large ovens. The development of effective rapid-drying techniques could be of great value in facilitating faster web speeds and greater throughput in mass production.

There have been reports that the solvent used in the deposition of one layer can damage underlying layers or degrade their performance. Thus the compatibility of solvents used in multi-layer stacks must be checked thoroughly.

Nozzle printing has been shown to be very effective for large area OLED televisions where the creation of red, green and blue stripes is required. Although separate color stripes are not necessary for lighting applications, this technique may also prove to be viable for lighting applications. Cycle times of 2 minutes have been reported.

3.5.3 Cathode Deposition

Although conducting inks can be used to print metals, the resulting layers are relatively thick, so that the method is better suited to bus lines rather than thin-film electrodes. Thus even in polymer OLEDs, the cathode metal is usually deposited in vapor phase, either by evaporation, sputtering or ion-beam aided deposition. These techniques can be used on moving webs as well as on stationary substrates.

An innovative approach to avoid the problem of damage to the underlying organic layer, suggested at the Fairfax Workshop, is to deposit the cathode on to a second substrate as shown in Figure 17[25]. This is a roll-to-roll version of the approach used for liquid crystal and plasma displays. Using this process, the manufacturer must to ensure that no oxygen, water vapor or other contaminants are trapped between the two substrates as they are brought together.

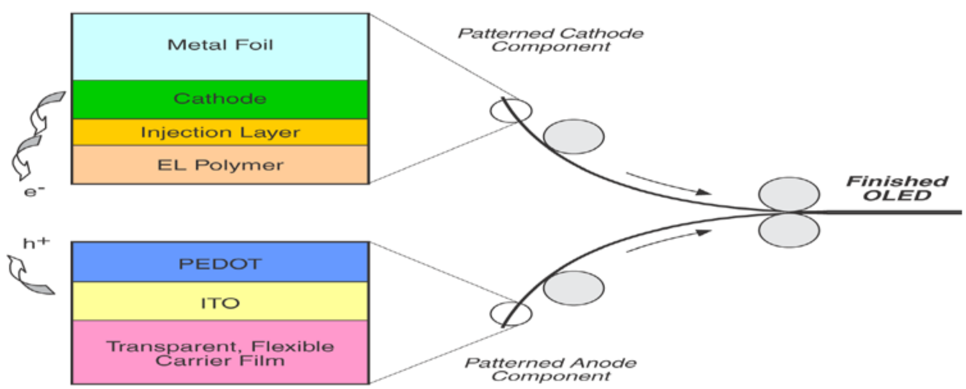

Figure 17. Dual Substrate OLED Fabrication with Lamination
Source: Anil Duggal, General Electric, "Roll-To-Roll OLEDS", SSL Manufacturing Workshop, Fairfax, VA, April 2009

3.5.4 Patterning Techniques

Each of the methods above allows some degree of patterning during deposition. Unless the OLED architecture requires side-by-side deposition of very narrow red, green, blue (RGB)

[25] Anil Duggal, General Electric, DOE SSL Manufacturing Workshop, Fairfax, VA, April 2009

stripes, the achievable resolution should be sufficient for lighting applications. Ink-jet printing is the only one of these methods that allows patterns to be changed without the manufacture of new masks or nozzle apertures.

For the removal of small strips of material around the edges of tiles or between segments, a subtractive approach, such as laser ablation may be appropriate. A special technique has been developed[26] for use with solution-processed OLED materials, called "Solvent Assisted Wipe". In this method, polymer materials are first weakened using a solvent and then the mixture is removed by a wiping head.

Laser ablation is another subtractive patterning technique that has been tested on polymer layers as well as ITO and cathode metals. Single layers can be removed using a small number of pulses, each of nanosecond duration, so that web motion is minimal. The method has been proposed[27] to expose contact pads or wire bond pads and for isolation or singulation of individual panels or device segments.

3.5.5 Inspection and Quality Control

In-line inspection tools are even more critical in web processing than in batch mode, since it is not possible take panels out of the line during fabrication. Some inspection procedures require stationary substrates, so that step-and-repeat mode must be used.

Dark-field scattering systems are available from Integral Vision and others[28] to detect particles and scratch defects of sizes as low as 1 µm, using 5 µm-resolution optics. However, the field of view of these systems is restricted, so that multiple cameras may be needed for wide webs.

3.5.6 Further Research Priorities

The production of OLED lamps using roll-to-roll techniques will be restricted to niche applications unless the efficiency and lifetime of solution-processable materials can be substantially improved. For example, the commercial offerings of the leading developer of light-emitting polymers include no white emitters with efficacy greater than 5 lm/W. The situation is better with solution-processable small molecules, for which efficacies of ~30 lm/W have been reported.

There is considerable evidence that the performance of polymer molecules is sensitive to the fabrication technique, in particular to the deposition and solvent-removal methods that are used. For example, material deposited by ink-jet printing can differ substantially from spin-coated layers. Also the presence of residual solvents may degrade the performance of the OLED, both with respect to efficiency and lifetime. However, there is no *apriori* reason that solution processable materials cannot achieve the same efficiencies as vacuum deposited materials. Thus,

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[26] Anil Duggal, General Electric, DOE SSL Manufacturing Workshop, Fairfax, VA, April 2009

[27] http://www.resonetics.com/pdfs/OLED.pdf; http://www.tamsci.com/products/Excimer.html

[28] Vincent Cannella, ECD Ovonics, Flextech Flexible Electronics Conference, 2008

further work is needed to improve the effectiveness of these materials and elucidate the dependence on manufacturing techniques.

One of the major advantages in using polymer materials is that the resulting OLED structures are often simpler. This has only been confirmed in systems of modest efficacy. It remains to be proven that simple structures can be used in very efficient devices and that this advantage also holds when small molecules are used in solution-processed form.

4.0 Manufacturing Research Priorities

4.1 Introduction

As discussed in Chapter 5 of the March 2010 SSL MYPP, DOE supports research and development of promising SSL technologies. In order to achieve the LED and OLED projections presented in Chapter 2 and Chapter 3, respectively, progress must be achieved in several research areas. Last year, DOE issued a Manufacturing Support competitive solicitation. In response to the proposals received, DOE engaged in 8 cooperative agreement awards, six related to LED manufacturing and two related to OLED manufacturing. The awarded projects are briefly described in Appendix B.

Because of the continuing progress in the technology and better understanding of critical issues, DOE engaged members of the lighting field, from industry representatives to academic researchers, to revise the manufacturing priority tasks for the 2010 Manufacturing Roadmap. In updating the 2010 Roadmap, DOE first held SSL roundtable sessions in Washington, D.C. in March, 2010, where initial tasks were developed. The tasks were further discussed and refined in April, 2010 at the Manufacturer's Workshop in San Jose, CA. Using recommendations and further review, DOE defined the task priorities as described in section 4.3.

4.2 Current Manufacturing Priorities

The following priorities were set based upon discussions at the 2010 roundtable and 2010 Manufacturing Workshop, taking into account the projects already funded in 2009. For each task metrics and targets are listed.

In addition to the several specific metrics related to cost called out for each task, overall cost of ownership (COO) should be considered a metric for every task (see section 2.5 for further discussion of COO).

Also, all manufacturing efforts intended to reduce overall COO should not result in product performance degradation. Performance attributes should be consistent with those outlined in Chapter 4 of the 2010 MYPP.

4.2.1 LED Manufacturing Priority Tasks for 2010

M.L1. Luminaire/Module Manufacturing: Support for the development of flexible manufacturing of state of the art LED modules[29], light engines, luminaires, and luminaire components. This work could include the development of automation tools for luminaire manufacturing in the U.S. The work should demonstrate higher quality products with lower system costs and improved time-to-market through successful implementation of integrated systems design, supply chain management, and quality control.		
Metric(s)	**Current Status**	**2015 Target(s)**
Downtime		50% reduction
Manufacturing Throughput		x2 increase
OEM Lamp Price	$113/klm	$28/klm
Book-to-Build time (weeks)[30]	10	5

Industry stakeholders strongly supported bringing advanced manufacturing concepts to LED luminaire manufacturing. Projects under this task should help manufacturers focus on reducing costs and waste in their processes. This work could include manufacturing tools and automation which allow for more efficient manufacturing of high quality luminaires. The development of small-scale tools optimized for smaller scale, more customizable manufacturing with low cost of ownership could also be supported. Manufacturing R&D into processes and approaches which accelerate the integration of components and reduce the design cycle time, such as manufacturing of integrated components or design software which reduces design cycle time could also be supported. Any work which generally makes the LED based luminaire manufacturing process more efficient while maintaining state-of-the-art luminaire performance may be considered.

Industry standardization would also support efficient manufacturing as it promotes compatibility between components and thus helps to eliminate waste. Though many agreed that it is too early to actually develop LED standards, it is the right time to begin to plan for future standards. Projects under this task could support this work and could include developing top form factors at the module level being used today, identifying the standard building blocks for luminaires and drivers, and defining the technologies on which the industry cooperates (standardizable) and competes (non-standardizable).

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[29] "LED Array or Module. Several LED packages may be assembled on a common substrate or wiring board (possibly with additional optical components and mechanical, thermal, or electrical interfaces) to be connected to the LED driver." 2010 SSL MYPP http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mypp2010_web.pdf.

[30] This is meant to increase responsiveness to design changes. Flexibility is essential to provide customer driven changes.

M.L2. Driver Manufacturing: Improve design for manufacture and flexibility in the system design in order to improve consistency of driver performance, lower cost, and improve integration into the luminaire. Develop a driver more amenable to lighting products while not degrading the driver performance (particularly lifetime) and reducing luminaire system cost.

Metric(s)	Current Status	2015 Target(s)
Luminaire Cost reduction through driver integration ($/klm)		50% reduction in luminaire cost over non-integrated driver approaches
Driver cost ($/klm)	22	4

The driver is currently estimated to be approximately 20% of the LED luminaire cost and offers a logical target for potential cost reductions. Beyond just the first cost of the driver, improvements can be made in the form factor and integration of the driver with other luminaire components which could enable reduced luminaire cost. With increased flexibility in the form factor and functionality of the driver, luminaires could be more readily designed for manufacture and significant cost savings could be realized through reduced thermal and mechanical costs in the luminaire. Manufacturing R&D in this topic should not degrade the reliability or efficiency of state of the art drivers, but may have the side benefit of improving reliability through more thoughtful luminaire integration.

M.L3. Test and Inspection Equipment: Support for the development of high speed non-destructive optical test equipment, standardized test procedures and appropriate metrics for each stage in the value chain for semiconductor wafers, epitaxial layers, LED die, packaged LEDs, modules, luminaires, and optical components. Equipment might be used for incoming product quality assurance, in-line process control, or final product testing/binning.		
Metric(s)	**Current Status**	**2015 Target(s)**
Throughput		x2 increase

Testing and inspection is an enabling mechanism fundamental to process and performance improvements. One specific area of interest regarding testing LED performance is the high-speed monitoring of color quality and color consistency in order to improve the back end quality and lower overall costs. Such test equipment would facilitate the automation of LED and phosphor matching and speed up final device binning. Also of particular value would be improved measurements of LED performance at realistic operating temperatures. This information would assist luminaire manufacturers in their design of more efficient luminaires. Another area of interest for testing and inspection is in improving the measure of the low defect density ($< 10^8$) substrate materials.

M.L4. Tools for Epitaxial Growth: Support for the development of manufacturing tools, processes, and precursors for lower cost of ownership and more uniform epitaxy.		
Metric(s)	**Current Status**	**2015 Target(s)**
Throughput (wafers/hr)	5 (for 2" equivalent wafers)	10 (for 2" equivalent wafers)
Wafer Uniformity [1σ] (nm)	1.7	0.5
Wafer-to-Wafer Reproducibility (nm)	1.5	0.6
Run-to-Run Reproducibility (nm)	2.0	0.9
Epitaxy Growth Cost ($/μm.cm^2)	0.3	0.1

Epitaxial growth is the key enabling technology for high brightness LEDs. While work in the product development program, conducted under subtasks A1.2 and B1.2 , will focus on the actual development of new epitaxial structures to achieve specific performance improvements, the manufacturing projects will focus on how better to execute these designs through process and equipment improvements. The two techniques drawing the most attention in this roadmap are MOCVD and HPVE. The large expected growth in the LED market means that scalable, advanced equipment for these techniques is needed.

Research projects could include the development of crystal growth tools and support for in-situ metrology equipment which can improve growth uniformity, yield, and/or materials usage efficiency. Additional areas of research include projects aimed to improve overall equipment efficiency, such as preventive maintenance recovery, development of cassettes for larger substrates, automation of cassette loading and unloading.

M.L5. Wafer Processing Equipment: Support is required for the development of improved manufacturing equipment for LED wafer level processing. This activity covers processing equipment used to create individual LED from an epitaxial wafer. Equipment must offer significant improvements in cost of ownership or throughput, over existing equipment, resulting in lower cost LED packages.

Metric(s)	Current Status	2015 Target(s)
Overall Wafer Throughput (wafers/hr)	50 (for 2" equivalent wafers)	100 (for 2" equivalent wafers)
Overall Wafer Yield (%)	60	90
Overall Process Productivity (%)	50	90

Wafer processing currently accounts for about 10-20% of the LED package cost, and improvement in this category can have a significant impact on both cost and device performance. The availability of manufacturing equipment purpose designed for LED wafer processing would likely lead to lower costs and higher yields. One way to catalyze the introduction of advanced equipment would be to improve the transfer of information between equipment manufacturers and end-users. Manufacturing R&D in lithography, etch, deposition of metals and dielectrics, polishing, singulation, substrate removal, or wafer bonding equipment developed specifically for LED production with a lower cost of ownership would be suitable for this task area. Development of entirely new equipment for wafer processing which yield reduced LED package cost could also be considered in this task area. One example might be wafer level packaging equipment that allows packaging processes to be moved to the wafer level prior to dicing and separation of the wafers.

M.L6. LED Packaging: Identify critical issues associated with back-end processes for packaged LEDs and develop improved processes and/or equipment to optimize quality and consistency, and reduce costs.		
Metric(s)	**Current Status**	**2015 Target(s)**
Packaged LED Throughput		2x increase per year
Assembly Cost ($/klm)		50% reduction every 2-3 years
Cost of Packaging ($/mm^2)		50% reduction every 2-3 years
Cost of Package ($/klm)		50% reduction every 2-3 years

Packaging accounts for approximately 65% of the packaged LED cost, or approximately 25% of the entire luminaire cost today. It is also an area where innovative research projects can be impactful, and are expected. Research proposals could include equipment development projects that aim to increase the level of automation in packaging, or that allow for high-speed inspection and testing. More potentially game-changing research could look into relocating packaging processes to the wafer level. Examples of this research include developing silicon with Via technology to acquire the electrical connection on the wafer; developing wafer bonding for the light emitting layer to substrate connection, which would serve as the electrical interface to the PC board; and developing methods to apply phosphors on the wafer level.

M.L7. Phosphor Manufacturing and Application: This task supports the development of improved manufacturing of phosphors used in solid state lighting in terms of quality, performance variation, and volume. This task also supports the development of phosphors materials, applications materials, and techniques which improve color consistency of the packaged LEDs and reduce the cost of LEDs without degrading LED efficacy or reliability.

Metric(s)		Current Status	2015 Target(s)
Phosphor Manufacturing			
	Batch Size (kg)	1-5	>20
	Cost ($/kg)		50% reduction every 2-3 years
	Materials Usage Efficiency (%)	50	90
	PSD-range Uniformity (μm)	30	10
Phosphor Application			
	Duv Control	0.012	<0.003
	Thickness Uniformity [1σ] (%)	5	2
	Cost ($/klm)		50% reduction every 2-3 years
	Device-to-Device Reproducibility (MacAdam Ellipse steps)	7	2

Phosphors have large implications to both the cost and quality of the LED package. At the roundtable, it was asserted that high volume manufacturing of high performance, high purity phosphors would result in reductions in LED package cost. Phosphors greatly affect the LED package color quality and consistency, and price. Potential projects might address the development of improved manufacturing, binder materials, and application processes including remote phosphors in order to lower materials costs, reduce the variation in color, and improve color stability. Developing tools to automate the process of matching an LED die and phosphor to achieve a specific color point could also be considered. Potential cost savings include reducing or eliminating the need for binning.

4.2.2 OLED Manufacturing Priority Tasks for 2010

The following priorities were set based upon discussions at the 2010 Manufacturing Roundtable and Workshop.

M.O1. OLED Deposition and Patterning Equipment: Support for the development of manufacturing equipment enabling high speed, low cost, uniform deposition, and/or patterning of state of the art OLED structures and layers. This includes the development of new tool platforms or the adaptation of existing equipment to better address the requirements of OLED lighting products. Tools can fit into any stage of the manufacturing process – substrate, OLED stack formation, and encapsulation. The proposed process must address concerns of compatibility and adhesion between neighboring layers; thus, proposals relating to solution-processing should discuss solvent removal and drying issues.

Metric(s)			2015 Target(s)
Throughput	Overall		> 100,000 m^2 per year of good product
	Web Width		1-2 m
	Substrate Area (sheet)		1-3 m^2
	Area Utilization		80-90%
	Uptime of Machine		80-90%
	Speed (web)		2-10 m/min
	Cycle Time (sheet)		≤ 60 s
	Yield		80-95%
Uniformity	Luminous Emittance Uniformity	Panel to Panel	±10% of nominal value
		Within Panel	20% (max to min) over 200 cm^2
	Duv (Panel to Panel)		< 0.01
Materials Utilization			Dry process on sheets: 70-80% Wet process on web: 90-95%
Integrity of Encapsulation	Shelf Lifetime		10-20 years
	Operating lifetime		50,000 hours
Patterning	Registration and resolution		~10 µm
	Patterning time		< 60 s

There is a large opportunity for cost reduction in the deposition and patterning steps of OLED manufacturing. Specific needs have been identified for the organic layers, electrodes (anode or cathode), short-prevention layers and light extraction layer.

The accuracy required in registration and resolution of patterning varies widely, depending on the design of the device. For example, some structuring will be essential in the current distribution system. If visible structures are accepted by the customer, variations in excess of 10 µm may be acceptable. Tighter control may be needed if the structures are to be imperceptible. A similar dichotomy pertains if the RGB emitters are laid down side-by-side in a single patterned layer. A further uncertainty arises from the selection of emission enhancement layer. Some approaches rely on random scattering of light, while others embody structures that would require fine patterning at the sub-micron level.

All research projects for Task M.O1 need focus on the overriding metric of cost per area of good product. In high-volume production, the total capital cost of all deposition and patterning tools should be less than $100 for each square meter of good product produced each year. Other critical factors in processing cost include throughput, yield and materials utilization. However, the cost reduction targets must be met without sacrificing performance metrics identified in the 2010 MYPP, such as uniformity of luminous emittance and color, efficacy and lifetime. The value of the proposed work will be greatly enhanced if tool developers work with potential OLED manufacturers to demonstrate the relationship between the characteristics of the deposited layers and the performance of the resultant devices.

M.O2. Integrated Manufacturing and Quality Control: Support for the development of methods to integrate the many process steps, to check the compatibility of materials, or for the development of testing and inspection tools. Tools and procedures must demonstrate cost reduction and/or improved quality and yield of the OLED products.

Metric(s)		**2015 Target(s)**
Reliability	Yield of Good Product	80-90%
	Catastrophic Failure in Use	1 in 10,000
Waste Reduction	Material loss due to defects	<10%
Panel to Panel Reproducibility	Luminous Emittance Control	±10% of nominal value
	Color control Duv	<0.01

Task M.O2 focuses on the support for integrated manufacturing and quality control. Projects under this task should focus on improvements in reliability, waste reduction, and reproducibility Improvements should be made while maintaining OLED panel performance (e.g. luminous emittance, efficacy, CRI, and lifetime) and costs as defined in the MYPP. DOE is currently funding two integrated manufacturing projects. Both are ongoing and substantial work remains. Projects under this task should focus on researching quality control tools, and should consider collaborating with the existing projects through potentially integrating and testing their tools or procedures in the pilot lines under development.

The quality control research could involve in-line monitoring tools as well as off-line techniques. Rapid response is critical for both in-line and off-line measurements. The in-line tools should provide instant feedback of the manufacturing process. Such equipment could include optical monitoring for defect detection and layer deposition uniformity, or tools to rapidly measure barrier coating performance.

Off-line techniques must also be developed to provide quality control between participants in the supply chain. For example, manufacturers need to be able to check the purity of incoming organic materials, the effectiveness of barrier films, the surface condition of substrates, and the effectiveness of edge seals.

Incorporation of proposed changes in design or process flow that have been shown to improve performance or reliability may also be appropriate. Procedures are also needed to provide tight control of the performance of manufactured panels, so that binning is minimized.

M.O3. OLED Materials Manufacturing: Support for the development of advanced manufacturing of organic and inorganic OLED materials to increase material production volume while reducing costs and improving consistency and purity. Materials, tools and processes should demonstrate compatibility with state of the art OLED lighting device structures and with existing OLED manufacturing approaches.

Metric(s)		**2015 Target(s)**
Substrate	Total cost – dressed substrate	$25/m^2
Organics	Thermal stability	> 80 C
	Total cost – all organic layers	<$20/m^2
Encapsulation	Permeability of H_2O & O_2	10^{-6} g/m^2/day
	Cost	$5-10/m^2

Task M.O3 focuses on the development of processes that facilitate manufacturing of high-quality materials for OLED panels. Since cost control is critical, establishing the optimal balance between material quality and cost should be an important component of these projects. Also important to this task is the scaling up of materials production from laboratory volumes to mass production volumes. Materials could include multi-layer structures, such as coated substrates, as well as bulk chemicals. Support could be focused on three components of the OLED panel: 1) substrate, 2) organic materials, and 3) encapsulation.

For projects focusing on the coated substrate, DOE includes metrics that address cost while maintaining other attributes (defined in the MYPP) such as light absorption, surface roughness, permeability to water and oxygen, and sheet resistance. Substrate proposals should focus upon the integration of the several elements in the composite structure; those concerning tools to deposit a single layer should be submitted under Task M.O1.

In the production of transparent substrates, such as glass or plastic, high efficiency of light extraction is the most critical performance issue. Low optical absorption is essential, but the metric for transmittance should be based upon passage from the high index organic layers into air, rather from air to air, as is usually measured. Effective transmission of current across the panel is also important to ensure uniform emission of light. The resistance of the electrode structure should be low enough that voltage differences across the panel can be kept within 0.1 V. For the organic materials, there are five main areas of interest: thermal stability, purity, scalability of the chemical process, cost, and the sustainability of the manufacturing process. Regarding the thermal stability, a target of stability at greater than 80° C was set in order to potentially allow faster deposition of cathode, a rate-limiting manufacturing process. Improving purity is critical to achieving the Manufacturing Roadmap goals for OLED panels and is currently hindered by uncertainty in the appropriate method to assay purity and the necessary level of organic material purity; interaction between suppliers and OLED manufacturers will thus be essential to the success of a project. In addition, the manufacturing sustainability, process safety, adequate supply of raw materials, and the environmental footprint should be considered.

For encapsulation, cost and the lifetime of the resulting OLED (measured through accelerated testing) are the major factors determining success. The extreme sensitivity of OLED materials to contaminants such as O_2 and H_2O means that porosity of the encapsulant material, the absence of pin-holes and edge-seal integrity are all critical.

M.O4. Back-end Panel Fabrication: Support the development of tools and processes for the manufacturing of OLED panels from OLED sheet material. This includes singulation, packaging, testing and repair. The goal is to ensure fabrication of robust OLED panels with consistent color quality, yield, reliability, and lifetime while maintaining a path to low cost. The proposed work should be compatible with the other portions of the OLED manufacturing process and with the creation of OLED panels with state of the art performance and lifetime. The methods used must be able to support the production of different panel sizes and to incorporate electrical connectors that match customer requirements and local regulations.

Metric(s)		2015 Target(s)
Yield	Yield of Good Panels	90%
Reproducibility	Variation in Luminous Emittance	±10%
	Color Variation Duv	< 0.01
Adaptability	Time to Change Panel Dimensions	<10 minutes

Task M.O4 incorporates all the back-end activities that are needed after the several thin films are deposited onto the substrate, patterned and processed. The processed sheets must be cut to the desired panel size and the panels connected to the electronic drivers and power supplies, sealed and protected against damage in transit.

Manufacturing lines should be capable of producing a variety of products. The appropriate balance needs to be determined between standardization to lower costs and adaptation to individual customer requirements and local regulations.

Since there has been so little experience with this stage of OLED manufacturing for lighting applications, DOE does not wish to overly constrain proposal in this task area. The overall goals are to facilitate the market introduction of OLED luminaires at acceptable prices in the 2013-14 time-frame and to provide a basis for rapid expansion of production and sales in later years. Collaboration between luminaire manufacturers and OLED producers is encouraged to propose viable routes to achieving these objectives.

5.0 Standards

In the course of manufacturing discussions in 2009, it became apparent that there was considerable confusion when referring to "standards". The following discussion is taken from the 2009 roadmap, where we tried to address that confusion.

There are several uses of the term "standards" that have come up during the workshop discussions:

- Standardized technology and product definitions
- Minimum performance specifications
- Characterization and test methods
- Standardized reporting and formats
- Process standards or "Best Practices"
- Physical dimensional, interface or interoperability standards

Most often, such standards and test methods are developed by various industry organizations in order to provide the industry and its consumers with the tools to fairly evaluate and compare products or the confidence in quality of design and production. However, *any* of these general types may eventually become a *regulatory or statutory requirement* having the force of law. They are then variously called "rules", "regulations", or "codes", and maybe a few other things not printable. Examples might be a safety requirement such as UL type labeling that is generally required for electrical products, or a minimum efficiency requirement as may be required by Federal Appliance Efficiency legislation. Usually, such legal standards only appear after some period of maturity in the industry; to enforce them too early may mean stifling beneficial further innovation of the technology. Thus, essentially the first four types of standards and regulatory requirements fall outside the scope of the manufacturing roadmap.

DOE has been working closely with a network of standards-setting organizations to accelerate the development and implementation of needed SSL standards. DOE provides standards development support to the process, which includes hosting ongoing workshops to foster coordination and collaboration on related efforts. These workshops are attended by representatives and committee members from the major standards groups: American National Standards Institute (ANSI), Illuminating Engineering Society of North America (IES), National Electrical Manufacturers Association (NEMA), National Institute of Standards and Technology (NIST), Underwriters Laboratories Inc. (UL), Commission Internationale de l'Eclairage (CIE), CSA International, and International Electrotechnical Commission (IEC). DOE will continue to provide updates on standards progress in this section because of the strong interest on the part of those involved with manufacturing. Standards directly related to manufacturing can be numerous and quite detailed, and often fall into the last two categories of best practices and process control, or physical interface and interoperability. Figure 18 illustrates some of the myriad standards that may apply to a semiconductor clean room.

During a panel presentation at the San Jose, CA Workshop, Tom Morrow of SEMI specifically identified a number of current activities in that organization that are related to manufacturing of LEDs:

- SEMI Standards (Compound Semiconductor Committee)
    - Specification for Compound Semiconductor Epitaxial Wafers
    - Specifications for Sapphire Substrates to use for Compound Semiconductor Epitaxial Wafers
    - Specification for Polished Monocrystalline Silicon Carbide Wafers
    - FPD Metrology (Backlight measurement)
- LED Fab Database
- HB-LED Steering Committee

Many more specific standards will be needed over time.

Since most work on standards is and will be done by independent industry groups, the objective of developing this Roadmap was simply to identify likely needs for such standards for SSL manufacturing as specifically as possible without trying to actually define the standard.

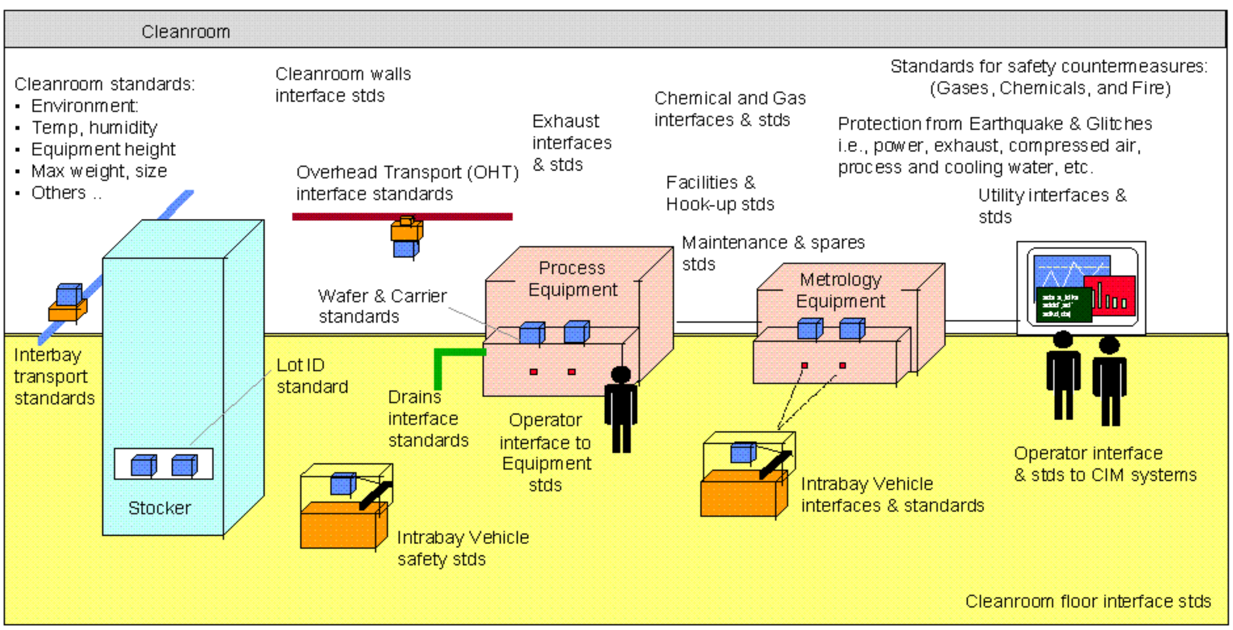

Figure 18. Manufacturing Standards for a Semiconductor Clean Room
Source: Stanley Myers, SEMI, "Components of Supply Chain Excellence," SSL Workshop, Fairfax VA, April 2009

5.1 Definitions

5.1.1 SSL product definitions

The IES has done considerable work and service to the industry by promulgating IES RP-16 Addenda a and b, *Nomenclature and Definitions for Illuminating Engineering*, which defines the components and products relating to LEDs for lighting. While this manufacturing roadmap may appropriately offer up suggestions for additional needs definitions, this work is best handled with existing standards groups.

5.1.2 Reliability characterization and lifetime definitions

The lack of an agreed definition of LED package or luminaire lifetime has been a continuing problem because of unsubstantiated claims of very long life for LED luminaire products. Often these are simply taken from the best-case performance of LED packages operating under moderate drive conditions at room temperature. DOE has attempted to address this lack of clarity (and understanding) with the recent release of a guide, *LED Luminaire Lifetime: Recommendations for Testing and Reporting*,[31] developed jointly with a NGLIA working group. There is also an excellent discussion of the nuances of reliability and lifetime characterization for luminaires in the DOE factsheet, *LED Luminaire Reliability*.[32]

While not directly related to manufacturing, an understanding of the causes of luminaire failure can lead to improved product design and more accurate claims on the part of manufacturers which will help to avoid customer disaffection with the technology. The issue is further addressed through several Core and Product Development tasks identified in the 2010 Multi-Year Product Plan.

5.2 Minimum performance specifications

Minimum performance specifications have also been mentioned under the umbrella of standards. These may be either mandatory or voluntary, as noted above, and some may morph from one classification to the other. The most commonly mentioned were ENERGY STAR (voluntary) and UL (mandatory for many applications). Participants have cited lack of clarity as to which standards are applicable because certain legacy requirements that perhaps should not be applicable to SSL. Above all, the long time taken to get appropriate approvals for both mandatory and voluntary standards has been frequently cited as slowing down the market introduction of SSL products. DOE has communicated these issues to the responsible organizations, and will continue to do so, but it will take time to establish more streamlined procedures for the new technologies. There was also concern about possible lack of coordination with standards being developed in other countries. DOE is aware of this and supports harmonization of international standards which is expected due course.

5.3 Characterization and test methods

Over the past year, there has been increasing industry awareness of recommended standard measurement methods such as IES LM-79-2008, *Approved Method for the Electrical and Photometric Testing of Solid-State Lighting Devices* and IES LM-80-2008, *Approved Method for Measuring Lumen Depreciation of LED Light Sources*, for measurement of initial performance and lumen depreciation in LEDs, respectively. An ongoing issue has been how to extrapolate limited LM-80 lumen depreciation measurements to predict LED package lifetime, a very

[31] http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/led_luminaire-lifetime-guide.pdf.

[32] http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/luminaire_reliability.pdf.

difficult proposition because of widely varying performance of different designs. An IES subcommittee, with DOE support, has been working for some time on this issue, and anticipates releasing their recommendations in the form of a technical memorandum, IES TM-21, *Method for Estimation of LED Lumen Depreciation as a Measure of Potential LED Life*, later in 2010. This group is also separately considering options for accelerated testing. DOE cautions, however, that this work applies to LED packages and does not directly translate into a measurement of lifetime for a luminaire.

An ongoing color issue has been the ANSI color binning specification, ANSI C78.377-2008, *Specifications for the Chromaticity of Solid-State Lighting Products*. This is discussed above in this roadmap under the issue of product and process variability. While this standard provides a basis for specifying LEDs, it is often not tight enough for many lighting applications, with the result that manufacturers developed sub-bins and not all to the same specifications. This issue has been addressed in the last year with the publication of NEMA SSL 3-2010, which provides a consistent formulation for binning. The need for binning results from the variability in the CCT of the emitted light of LED packages. Several identified task priorities address this root cause, either directly or indirectly.

DOE is also supporting work at NIST on a new color rendering standard, the *Color Quality Scale*, which should be released soon.

Summaries of current and pending standards related to SSL are available among the technical publications on the DOE SSL website. Appendix A lists current standards as well as several related white papers and standards in development.

5.4 Standardized reporting and formats

Buyers of lighting components continue to ask for a standard report format to ease their comparison of alternative choices. Designers and specifiers have for some time been calling for a standard data format for luminaires. Luminaire manufacturers would welcome a standard specification for LED packages. Although there was considerable discussion of the topic at the Roundtables and the Workshop, no agreements have been reached at this time. NEMA is addressing this issue, and has recently issued NEMA LSD 45-2009, *Recommendations for Solid-State Lighting Sub-Assembly Interfaces for Luminaires.* Also, new industry group, Zhaga, has been formed to attempt to reach agreement on some common interfaces for light engines, but that work has only just begun and little information is available on their website.[33]

Luminaire makers specifically asserted that there needs to be better reporting standards for drivers. The burden currently falls on the manufacturer to test drivers because of significant differences across drivers and insufficient reporting of performance. The control side of drivers also needs to be more compatible – it is becoming increasingly difficult to purchase and stock the large number of proprietary devices.

[33] http://www.zhagastandard.org/

Issues of this sort are being addressed in DOE's other market introduction activities and not within the Manufacturing Roadmap.

5.5 Statutory/regulatory requirements

As noted, any of these types of standards could in principle become a legal requirement. Some already appear to be on track for this end. For example, the present efforts under the product quality Lighting Facts initiative may eventually result in some mandatory labeling requirements. At some point there may also be additional lighting performance requirements that will influence where certain products can be used, as has already occurred in some jurisdictions regarding incandescent and compact fluorescent lamp (CFL) sources. Again, such issues are not directly related to the SSL Manufacturing Initiative, and are being addressed elsewhere.

5.6 Interoperability/physical standards

There are two categories of interoperability/physical standards. One type is the end product consumer interface standard, such as the ANSI standards for bulb bases and sockets, or the standard wattages of incandescent lamps. These are market-driven standards; compliance with these standards is necessary for success in certain lighting applications. While such standards define the products to be manufactured, and manufacturers certainly need to be involved, they do not directly address the manufacturing process roadblocks.

The other type includes the interfacing standards present in the manufacturing process, which may or may not directly apply to the product itself or a component part. They are generally developed over time as the technology matures; however, it is never too early to begin contemplating such standards. Waiting too long will result in investments that may have to be written off, making agreement much more difficult.

5.7 Process standards and best practices

The industry as a whole remains reluctant to consider standardizing processes or identifying best practices. However, many industry participants seemed more receptive to this idea during the San Jose, CA Workshop as compared to the 2009 events. Several of the manufacturing tasks address processes, and continued attention to these issues is likely to result in some degree of standardization over time.

Appendix A: Standards Development for SSL

Standards Development Increases Market Confidence in SSL Performance

Like traditional lighting products, LED-based luminaires sold in the United States rely on industry-developed standards and test methods to characterize their performance and safety. The use of national standards and test methods is critical to user design and bolsters consumer confidence in the performance capabilities of the products. However, the unique attributes of LEDs, or light-emitting diodes, necessitate the development of new standards to effectively measure and characterize this technology.

Until recently, the lack of sufficient standards for solid-state lighting (SSL) generated a great deal of confusion and frustration in the market. Variations in testing methods and terminology from one manufacturer to another made it difficult to compare new LED products to other light sources as well as to other LED products.

The U.S. Department of Energy (DOE) has been working closely with a network of standards-setting organizations to accelerate the development and implementation of needed SSL standards. DOE provides standards development support to the process, which includes hosting ongoing workshops to foster coordination and collaboration on related efforts. These workshops are attended by representatives and committee members from the major standards groups: American National Standards Institute (ANSI), Illuminating Engineering Society of North America (IES), National Electrical Manufacturers Association (NEMA), National Institute of Standards and Technology (NIST), Underwriters Laboratories Inc. (UL), Commission Internationale de l'Eclairage (CIE), CSA International, and International Electrotechnical Commission (IEC).

Current SSL Standards and White Papers

- **IES LM-79-2008, Approved Method for the Electrical and Photometric Testing of Solid-State Lighting Devices,** enables the calculation of LED luminaire efficacy (net light output from the luminaire divided by the input power and measured in lumens per watt). Luminaire efficacy is the most reliable way to measure LED product performance, measuring luminaire performance as a whole instead of relying on traditional methods that separate lamp ratings and fixture efficiency. LM-79 helps establish a foundation for accurate comparisons of luminaire performance, not only for solid-state lighting, but for all sources.[34]
- **IES LM-80-2008, Approved Method for Measuring Lumen Depreciation of LED Light Sources,** supports an assessment of expected LED lifetime by defining a method of testing lamp depreciation. Unlike traditional filament-based sources, which usually fail completely, LEDs typically don't fail;

[34] Electronic copies of LM-79, LM-80, and RP-16 may be purchased online through IES at www.ies.org/store.

they simply fade over time, which is referred to as lumen depreciation. LM-80 establishes a standard method for testing lumen depreciation.

- **ANSI C78.377-2008, Specifications for the Chromaticity of Solid-State Lighting Products,** specifies recommended color ranges for white LEDs with various correlated color temperatures. Color range and color temperature are metrics of critical importance to lighting designers.[35]
- **IES RP-16 Addenda a and b, Nomenclature and Definitions for Illuminating Engineering,** provides industry-standard definitions for terminology related to solid-state lighting.
- **NEMA LSD 45-2009, Recommendations for Solid-State Lighting Sub-Assembly Interfaces for Luminaires,** provides guidance on the design and construction of interconnects (sockets) for solid-state lighting applications.[36]
- **NEMA LSD 49-2010, Solid-State Lighting for Incandescent Replacement—Best Practices for Dimming,** provides recommendations for the application of dimming for screw-based incandescent replacement solid-state lighting products.
- **NEMA SSL 3-2010, High-Power White LED Binning for General Illumination,** provides a consistent format for categorizing (binning) color varieties of LEDs during their production and integration into lighting products.
- **UL 8750, Safety Standard for Light Emitting Diode (LED) Equipment for Use in Lighting Products,** specifies the minimum safety requirements for SSL components, including LEDs and LED arrays, power supplies, and control circuitry.[37]

Standards in Development

- **CIE TC1-69, Color Quality Scale,** provides a more effective method for relating the color characteristics of lighting products including LEDs.
- **IES G-2, LED Application Guidelines,** presents technical information and application guidance for LED products.
- **IES TM-21, Method for Estimation of LED Lumen Depreciation as a Measure of Potential LED Life,** is a proposed method for taking LM-80 collected data and estimating an effective life for LEDs.
- **LM-XX1, Approved Method for the Measurements of High Power LEDs**
- **LM-XX2, LED "Light Engines and Integrated Lamp" Measurements**
- **NEMA SSL-1, Electric Drivers for LED Devices, Arrays, or Systems**

Over time, these and other standards will remove the guesswork about comparative product performance, making it easier for lighting manufacturers, designers, and specifiers to select the best product for an application. As industry experts continue the painstaking work of standards development, they are contributing to a growing body of information that will help support solid-state lighting innovation, as well as market adoption and growth.

For more information on SSL standards, see www.ssl.energy.gov/standards.html

[35] The C78.377 standard is available for hard copy purchase or as a free download from NEMA at www.nema.org/stds/ANSI-ANSLG-C78-377.cfm#download. Hard copies can also be purchased from ANSI at www.webstore.ansi.org.

[36] LSD 45 and LSD 49are available as free downloads from NEMA at http://www.nema.org/stds/lsd45.cfm#download and http://www.nema.org/stds/lsd49.cfm#download. SSL 3 is available for purchase at http://www.nema.org/stds/ssl3.cfm.

[37] UL customers can obtain the outline for free (with login) at www.ulstandards.com or for purchase at www.comm-2000.com.

Appendix B: Funded Projects

Recipient: Applied Materials Inc.
Title: Advanced Epi Tools for Gallium Nitride LED Devices
Summary: *This project seeks to develop a multichamber Metalorganic Chemical Vapor Deposition (MOCVD) and Hydride Vapor Phase Epitaxy (HVPE) system, which is an advanced epitaxial growth system for LED manufacturers that has the potential to decrease operating costs, increase efficiency of LEDs, and improve binning yields. The approach builds upon the successful Centura platform which is used for growing low-cost, high-quality epitaxial wafers in the integrated circuit industry.*

Recipient: GE Lumination
Title: Development of Advanced Manufacturing Methods for Warm-White LEDs for General Lighting
Summary: *This project seeks to develop precise and efficient manufacturing techniques for GE Lumination's "remote phosphor" platform of warm-white LED products named Vio™. The approach drives significant materials, labor, and capital productivity to achieve approximately 53% reduction in overall cost, while minimizing color variation in the Vio platform.*

Recipient: KLA-Tencor Corporation
Title: Automated Yield Management and Defect Source Analysis Inspection Tooling and Software for LED Manufacturing
Team Members: Philips Lumileds
Summary: *This project seeks to improve the product yield for high-brightness LEDs by developing an automated optical defect detection and classification system that identifies and distinguishes harmful defects from benign defects. The proposed approach allows for traceability in defect origin and includes the hardware and correlated software package development.*

Recipient: Philips Lumileds Lighting Company, LLC
Title: Low-Cost Illumination-Grade LEDs
Summary: *This project seeks to realize a 30% yield improvement and 60% reduction in epitaxy manufacturing costs for high-power LEDs through the implementation of GaN-on-Si epitaxial processes on 150 mm substrates. The use of silicon replaces the industry-standard sapphire substrates. The process will be developed using Philips Lumileds' proven thin film flip chip capabilities on the company's LUXEON® Rebel lamp.*

Recipient: Ultratech Inc.
Title: A Low-Cost Lithography Tool for High-Brightness LED Manufacturing
Team Members: SemiLEDs
Summary: *This project seeks to develop a lithographic manufacturing tool having the benefits of higher throughput, greater yields, lower initial capital cost, and lower cost of ownership. A projection stepper process will be modified and optimized for LED manufacturing. The proposed system will be able to accommodate a variety of wafer sizes and thicknesses and handle the wafer warpage typically associated with larger-diameter substrates.*

Recipient: Veeco Instruments
Title: Implementation of Process-Simulation Tools and Temperature-Control Methods for High-Yield MOCVD Growth
Team Members: Sandia National Laboratories and Philips Lumileds
Summary: *This project seeks to develop a complementary set of high-resolution short-wavelength and infrared in-situ monitoring tools for accurate substrate temperature measurement and growth rate monitoring. Philips Lumileds will test the resulting tool in the processing of LEDs. The approach is anticipated to result in a 100% improvement in wavelength yield and a 75% cost reduction for LED epitaxy.*

Recipient: GE Global Research
Title: Roll-to-Roll Solution-Processable Small-Molecule OLEDs
Team Members: Dupont Displays Inc.
Summary: *This project seeks to integrate the following with GE's pre-pilot roll-to-roll (R2R) manufacturing infrastructure: high-performance phosphorescent small-molecule OLED materials, advanced OLED device architectures, plastic ultra-high barrier films, and an advanced encapsulation scheme. The project proposes to eliminate the differences in OLED performance between idealized laboratory-scale batch process and pre-pilot production, and to demonstrate, by 2012, R2R-manufactured OLEDs that have the same luminous efficacy as their laboratory-scale counterparts.*

The goal of this project is to show that roll-to roll (R2R) processing can be used to manufacture high-performance OLEDs on flexible substrates. The approach has been used successfully by GE in an R&D environment using polymer materials. DuPont will adapt their small-molecule materials and solution processing techniques to be compatible with R2R manufacturing on plastic substrates. The project will also test the efficacy of ultra-high barrier films and advanced encapsulation schemes.

Recipient: Universal Display Corporation (UDC)
Title: Creation of a U.S. Phosphorescent OLED Lighting Panel Manufacturing Facility
Team Members: Moser Baer Technologies
Summary: *This project seeks to design and set up two pilot phosphorescent OLED (PHOLED) manufacturing lines. The team will implement UDC's PHOLED technology and provide prototype lighting panels to U.S. luminaire manufacturers for incorporation into products in order to facilitate testing of design and to gauge customer acceptance.*

The goal of this project is to establish the first US manufacturing line for phosphorescent OLED lighting panels within a 2 year time frame, using known and proven procedures. The aim is to produce panels of size 150mm x 150mm that meet the MYPP performance targets, with luminance >76 lm/W, and to demonstrate a path towards meeting cost targets of $27/klm by 2013. The team will deliver panels to enable luminaire manufacturers to produce lighting products that will test design concepts and gauge consumer acceptance.

The pilot line manufacturing technology will be implemented as an integrated process using up to three separate equipment clusters with intermediate substrate transfer capability:

- *i) substrate technology including light extraction layers and transparent conducting oxide*
- *ii) phosphorescent emitters and matched transport layers*
- *iii) encapsulation layers, seals and electrical connections.*