Solid-State Lighting Research and Development:

Manufacturing Roadmap

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DISCLAIMER

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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. In order to effectively carryout this objective the DOE SSL Program has developed a comprehensive national strategy with three distinct, interrelated thrusts (and accompanying Roadmaps): Core Technology Research and Product Development, Manufacturing Research and Development (R&D), and Commercialization Support.

The goal of the DOE **SSL Core Technology Research and Product Development** program area is to increase end-use efficiency in buildings by aggressively researching new and evolving solid state lighting technologies. The Multi-Year Program Plan (MYPP) guides SSL Core Technology Research and Product Development and informs the development of annual SSL R&D funding opportunities.

In 2009, DOE launched a new **SSL Manufacturing Initiative** to complement the SSL MYPP which aims to accelerate SSL technology adoption through manufacturing improvements that reduce costs and enhance quality. This initiative, which included expert roundtables and two workshops, resulted in the 2009 SSL Manufacturing Roadmap. That document was updated in 2010, building on the general timelines and targets identified in 2009, and adding specific areas of priority work needed in order to achieve the ultimate goals of the program. As is the case with other SSL Roadmap documents, the Manufacturing Roadmap will continue to be updated annually to reflect progress and changing priorities. The present document is the 2011 update.

DOE has also developed a Five Year **SSL Commercialization Support Plan**.[1] The purpose of the Plan is to set out a strategic, five year framework for guiding the DOE commercialization support activities for high performance SSL products for the U.S. general illumination market.

Together, these three efforts are intended to reduce the cost and energy use for lighting. 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 2011 MYPP. We will not repeat that material here, but readers are urged to review it as background for reading this SSL Manufacturing Roadmap.

The 2011 Multi-Year Program Plan can be downloaded at:
http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mypp2011_web.pdf

[1]DOE's Five-Year SSL Commercialization Support Plan can be found at:
http://www1.eere.energy.gov/buildings/ssl/pdfs/ssl_5year-plan_09-13.pdf

1. Introduction

The goals of the SSL R&D 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 recognizes that developing new manufacturing technology, encouraging best practices, identifying common equipment needs, improving process control, and learning from manufacturing methods in other industries is the best path to achieve these goals. An important 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 about the expected evolution of SSL manufacturing. Such guidance 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.

This third annual publication of the updated 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 2011 update began March 8-9, 2011. DOE convened two expert panels for light emitting diodes (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 12-13, 2011, about 250 representatives of a broad cross-section of the SSL value chain assembled in Boston, MA for the 2011 Manufacturing Workshop[2] to provide additional feedback on program goals and the proposed task priorities.

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 will be more appropriately addressed by industry, industry consortia, or other stakeholders. It is also anticipated that each revision of the DOE SSL Manufacturing Roadmap will become more comprehensive, refined, and more detailed. This is a living document subject to continuous improvement.

The organization of this document follows the same pattern as the 2010 version and is divided into separate LED and OLED sections. The chapter describing manufacturing R&D tasks, prioritized by the work of the roundtable and the subsequent workshop breakouts, has been updated to reflect changed priorities and also to reflect progress against the various metrics for each task. Chapter 5 describes progress on SSL-related standards and identifies additional or continuing needs for standards not yet available. Appendix A provides information about

[2] Workshop presentations and handouts can be found at: http://www1.eere.energy.gov/buildings/ssl/boston2011_materials.html

existing and pending standards efforts in many areas, including testing and performance metrics not directly related to manufacturing but relevant.

1.1 Manufacturing Research Highlights

The SSL Manufacturing Initiative currently supports eight R&D research projects (see Appendix B). These projects reflect the manufacturing priorities as determined by industry leaders, research institutions, universities, trade associations, and national laboratories. Since the inception of this Initiative in 2009 there have been several major research accomplishments, some of which are highlighted below.

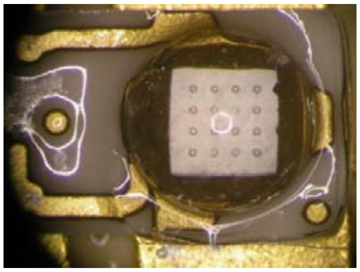
Driving Down HB-LED Costs: Implementation of Process Simulation Tools and Temperature Control Methods for High Yield MOCVD Growth – Veeco Instruments

Veeco Instruments has successfully implemented a new platform design for MOCVD growth that provides a three-fold increase in wafer throughput. In addition, Veeco Instruments has demonstrated a four-fold increase in growth rate using a newly designed input flow flange while simultaneously achieving a 35% reduction in the amount of expensive metal-organic reagent material being consumed. The new platform design, in combination with the new flow flange, will contribute to a significant lowering of manufacturing costs. Having proven significant cost reductions, the hardware is currently being finalized in preparation for beta evaluation by a customer with plans for product release. In the second year of the contract, Veeco Instruments will be adding additional hardware and process improvements in order to realize a total platform solution to demonstrate the 75% reduction in to the Cost of Ownership (COO).

Integrated Automated Yield Management and Defect Source Analysis Inspection Tooling and Software for LED – KLA-Tencor Corporation

KLA-Tencor has developed an improved inspection tool for LED manufacturing based on their existing Candela™ CS20 tool. The new tool promises to significantly improve overall process yields and minimize expensive waste. The first generation tool is currently under beta test at a number of key manufacturer's sites as part of the project evaluation stage. The tool has already achieved excellent results which have encouraged KLA-Tencor to announce in January 2011 the commercial release of this new model as the Candela™ 8620. The project also aims to develop a Yield Management Software (YMS) platform to connect inspection results in wafer and die fabrication for faster root cause analysis and automated process monitoring. KLA-Tencor is currently working to provide field validation across multiple material systems, develop recipe algorithms and ensure production robustness for its Candela™ 8620 tool, as well as to validate tool connectivity and incorporate parametric yield information into the analysis engine of the YMS platform.

Low Cost Illumination-Grade LEDs Enabled by Nitride Epitaxy on Silicon Substrates – Philips Lumileds



Currently the Philips Lumileds project has yielded thin film flip chips fabricated from 3-inch GaN-on-Si epiwafer that demonstrate an output of 437 mW of optical power at an input current of 350 mA. This work demonstrates that the GaN–on-Si LED is near the performance of state of the art LEDs produced on costly sapphire and silicon carbide. Philips Lumileds is aiming to realize illumination-grade high-power LED lamps manufactured from a low-cost epitaxy process employing 150 mm silicon substrates. Lower substrate material cost as well as improvements in epitaxial growth uniformity and yield will lead to an overall 60% reduction in epitaxy manufacturing costs by replacing industry-standard sapphire substrates with 150 mm silicon.

Creation of a U.S. Phosphorescent OLED Lighting Panel Manufacturing Facility – Universal Display Corporation (UDC) and Moser Baer Technologies (MBT)

At the Infotonics Technology Center (ITC) in Canandaigua, New York, UDC and MBT are reconfiguring a 9,400 sq ft clean room and equipping it with the necessary support facilities to implement a new, UDC-developed manufacturing process for OLED lighting panels. The 150 mm square OLED design will have an efficacy of 66 lumens per watt (lm/W) and a color rendering index (CRI) of 79. The base process flow has been set and the critical deposition equipment ordered for delivery in November 2011. Completion of the production facility is anticipated in the spring of 2012. The objective of the UDC-MBT project is to build a production line to provide prototype OLED lighting panels to U.S. luminaire manufacturers for incorporation into products to facilitate testing of design concepts and gauge customer acceptance.

1.2 Key findings and general recommendations for 2011

The 2010 Roadmap provided information on the anticipated evolution of SSL manufacturing and several suggested priority research tasks. One critical component of this year's update was to gather consensus around a very few specific tasks needed to accomplish SSL manufacturing goals and make progress along the Roadmap paths. Due to budget constraints, it has been necessary to more tightly focus priorities on a smaller number of tasks than in the past. Discussions during the March roundtables provided several suggested R&D topics which were distilled into six proposed priority tasks introduced at the workshop. These were subsequently reduced to four priority tasks in this publication as a result of workshop deliberations. A full list of tasks and descriptions identified in prior workshops but not prioritized for this year's update is found in Appendix C.

In addition, there have been some changes in the overall Roadmap, some of which were along the lines of bringing the cost estimates up to date to reflect the current status, and others to clarify and detail certain discussions in the 2010 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.

1.2.1 LED Manufacturing R&D Priorities

During the March Roundtables, the subsequent Manufacturing Workshop, and internal DOE discussions, two priority tasks for LED-based luminaire manufacturing have been selected for attention during the coming year. These choices for LED Manufacturing are listed by title and brief description in Table 1; more detail may be found in Section 4.1.1.

Table 1. LED Manufacturing R&D Priority Tasks

M.L1.	**Luminaire/Module Manufacturing** Support for the development of flexible manufacturing of state of the art LED modules, light engines, and luminaires.
M.L3.	**Test and Inspection Equipment** Support for the development of high-speed, high-resolution, non-destructive test equipment with standardized test procedures and appropriate metrics.

There were a number of additional specific recommendations that arose out of the workshop discussions relating either to individual tasks or other aspects of the Roadmap. These are 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 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 database of components and material; and
- Encourage collaboration among all participants in the value chain.

1.2.2 OLED Manufacturing R&D Priorities

Two DOE OLED Manufacturing priority tasks have been identified for 2011 as listed below in Table 2. More details may be found in Section 4.1.2.

Table 2. OLED Manufacturing R&D Priority Tasks

M.O1.	**OLED Deposition Equipment:** Support for the development of manufacturing equipment enabling high speed, low cost, and uniform deposition of state of the art OLED structures and layers.
M.O3.	**OLED Materials Manufacturing:** Support for the development of advanced manufacturing of low cost integrated substrates and encapsulation materials.

In addition to the manufacturing task recommendations, there were also a number of general recommendations for the program 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;
- Consider a repair and materials recycling strategy to minimize waste and reduce cost;
- Investigate international standards to assure compatibility with those developed here;
- Identify target markets for OLED entry to allow manufacturing costs to decline and ultimately pave the way to the general illumination market; and
- Promote collaborative projects among U.S. manufacturing lines and U.S. companies that can make OLED substrates and materials.

1.3 Overall projections/contributions to cost reduction

1.3.1 LED Lighting

One of the primary objectives of the Roadmap is to identify a practical route to cost reduction for LED-based lighting through improvements in manufacturing technologies and methods. The first step in developing a viable cost reduction strategy is to understand the sources of these costs. Once these have been identified, it is possible to focus our efforts on the critical cost elements and develop specialized goals for materials, processes, and equipment capabilities.

From a high level perspective the principal cost components of an LED-based luminaire are the LED package(s), mechanical/thermal components, driver, optics, and assembly. [3] In this context, the term 'mechanical/thermal' includes the mechanical components comprising the complete luminaire fixture and the means for mounting the LED(s), driver, optical components; and the thermal components as required for proper management of the heat produced within the fixture. The 'driver', which may be designed to operate an LED package, module or lamp, refers to the power source which provides conversion to direct current (DC) from the electrical branch circuit along with any integral control electronics.

Figure 1 shows a high-level cost breakdown projection for a typical LED-based luminaire (indoor downlight). It should be noted that the relative cost breakdown will vary depending on

[3] See RP-16-10 for definitions of LED and OLED components: http://www.iesna.org/store/product/nomenclature-and-definitions-for-illuminating-engineeringbr-rp1605-1013.cfm

the type of luminaire as discussed in Section 2.2. The initial cost split for 2010 is based on information provided by Cree, and has been projected forward based on individual price reduction targets for the LED package and LED-based replacement lamps outlined in Chapter 3 of the 2011 SSL MYPP. Such projections assume more rapid cost reductions for the LED package and less rapid reductions for the mechanical/thermal and optics components. Overall, the relative proportions change only slightly from year to year.

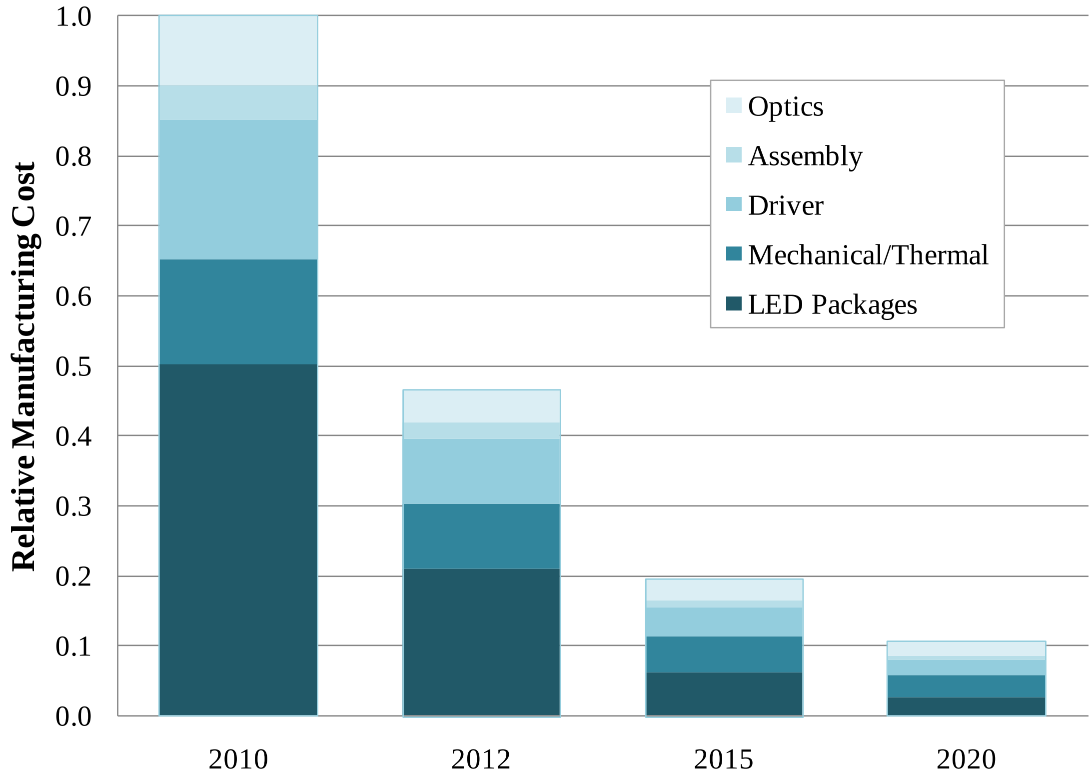


Figure 1. Projected LED-based Cost Track (Downlight Luminaire)
Source: Data provided by the 2011 Manufacturing Roundtable Attendees

The projections in Figure 1 account for potential cost savings from improved manufacturing processes, reduced materials costs, and from luminaires "designed for manufacture". While helpful to show the largest costs, this breakdown into individual cost components does not show the cost interrelationships between the components. Fully understanding potential cost reductions will require a more sophisticated systems-level approach to luminaire design with simultaneous consideration of all cost components and an analysis of their complex interactions to achieve the optimum solution for a specific application. 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 electronics 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 locating luminaire manufacturing outside the U.S. Overall goals for LED-based replacement lamps, as reflected in DOE's 2011 MYPP, project price reductions in terms of dollars per kilolumen ($/klm) by a factor of five by 2015 and a factor of ten by 2020.

Figure 2 shows a similar cost breakdown and cost reduction projection that has been developed for LED packages. Care should be exercised in comparing these *cost* projections with the *price* projections shown in Table 5. The cost projections are based on raw dollar manufacturing costs per package whereas the price projections in Table 5 are normalized to lumen output and include additional factors such as gross margin. As is evident from the figure, 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. Further details on the LED luminaire and package cost tracks can be found in Chapter 2 of this roadmap.

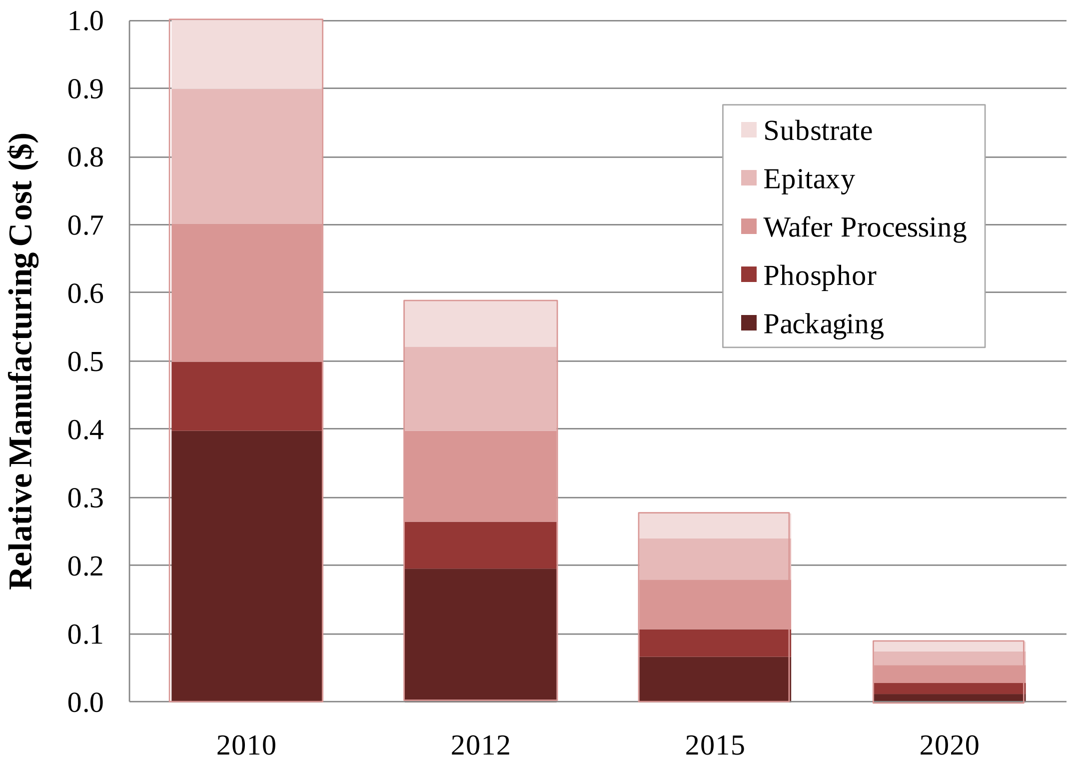


Figure 2. Projected LED Package Cost Track.
Source: Provided by the 2011 Manufacturing Workshop and Roundtable Attendees

1.3.2 OLED Lighting

OLED lighting development has evolved significantly during the past year. Laboratory research has advanced sufficiently to enable OLED products to meet the performance requirements for several lighting applications. Progress on light extraction and electrode structures has led to construction techniques that are scalable to large area and are producing panels with efficacies of 70 lm/W as well as good lifetime. Two luminaire prototypes from Acuity were demonstrated at Lightfair 2011 and commercial production is planned for 2012.

These initial products have extremely high costs, driven in part by significant capital investments and low production volumes. The price of the prototype panels and luminaires that are available on the market has been very high, when scaled to large area or high lumen output. The Lumiblade Plus, which produces about 12 lumens, was offered by Philips in April 2011 at a price of €120 ($170), corresponding to $14,000 per klm. An attractive desk lamp with six 12 lm panels from Kaneka is available at a price of ¥100,000 ($1250) or $17,000/klm. However, as OLED technology matures, manufacturing know-how is acquired, and production volumes rise, many believe the price of these panels and luminaires will dramatically decrease.

Some concern about the commercial viability of OLED lighting has arisen as the uniqueness of OLED technology in providing ultra-thin large area lighting is being challenged by the development of LED-based edge-lit panel lighting. These luminaires have emerged through adaptation of the LED backlights in LCD TVs to lighting applications and can offer both flexibility and transparency, two of the attributes expected to drive adoption of OLED lighting. The price of edge-lit LED panels was below $100/klm in 2010 and is decreasing in line with the projection shown in Section 1.3.1. While there may be other advantages to OLEDs, such as color quality, weight or simplicity, the implication of these new LED products is that an aggressive program of OLED cost reduction is essential.

Figure 3, below, shows an aggressive track for OLED cost targets, based in industry inputs, which would meet the need outlined above.

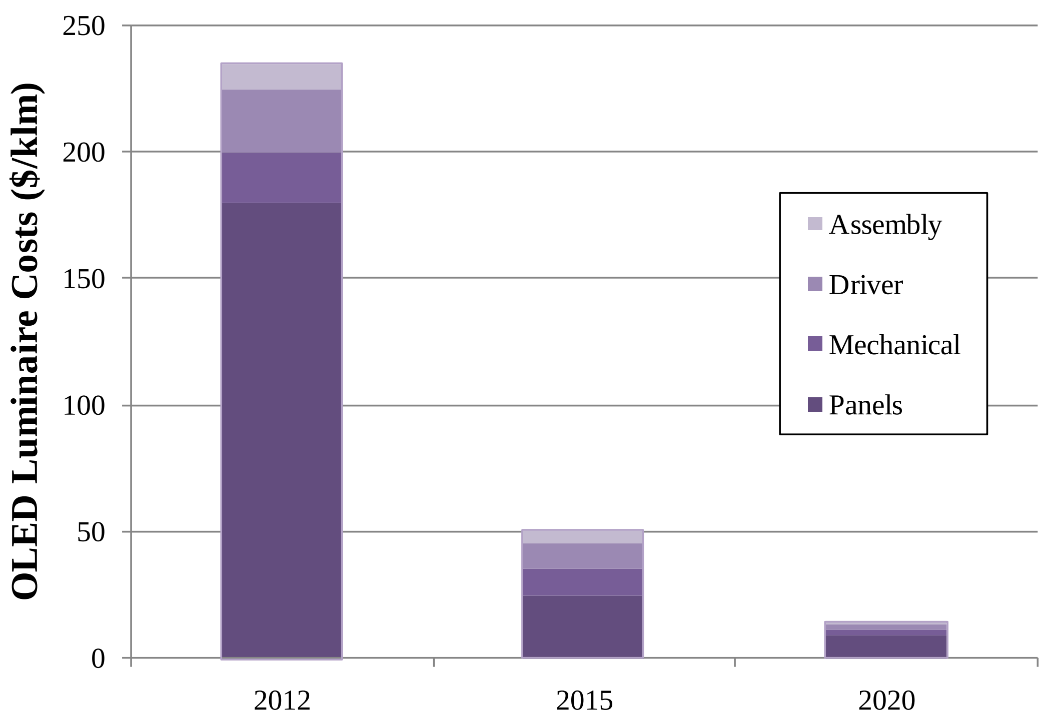


Figure 3. OLED Luminaire Cost Targets ($/klm).
Source: Provided by Luminaire Manufacturers and 2011 Manufacturing Roundtable Attendees

As depicted in Figure 3, the OLED panel is projected to remain the largest cost component in OLED luminaires. The cost of the OLED panels to the luminaire manufacturer is targeted to be $180/klm in 2012, or roughly a factor of 100 below current prototype prices. Over the next three years in this scenario, panel cost would fall to $25/klm, another factor of 7, which should make the product reasonably competitive with other SSL solutions for niche markets. The longer term target of $9/klm by 2020 would continue the goal of approaching (but not reaching) parity with LEDs. An estimated cost breakdown of production is summarized in Figure 4 and discussed in detail in Section 3.2. A key assumption in these panel cost estimates is operation at 10,000 lm/m^2 for all years which may be a near term technical challenge.

Panel costs will be dominated by equipment depreciation costs in early years and by materials costs later. The target for 2012 represents the first year of production by a new manufacturer and shows very significant depreciation costs attributable to low volumes. However, estimated depreciation and labor at this stage is somewhat speculative and not particularly meaningful, as few details of production are known and much of the initial effort will be devoted to process improvements and line adjustments. By 2015, as volumes increase, capital costs should have a more proportionate impact on the total.

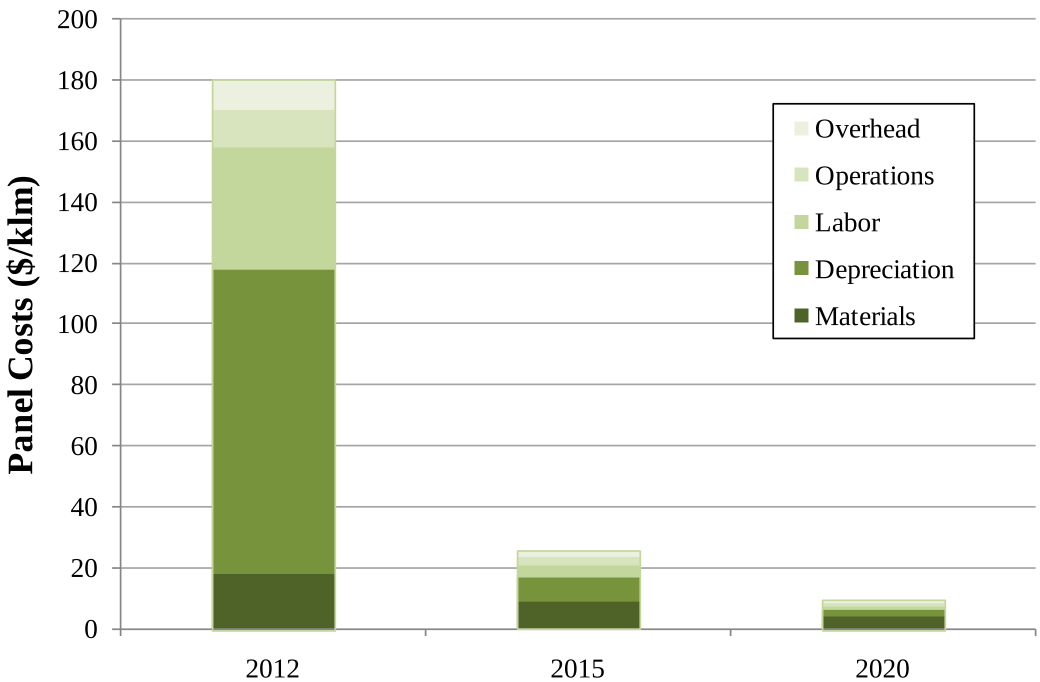


Figure 4. Targets for OLED Panel Costs ($/klm)

The major goal of this Manufacturing Roadmap is to identify one promising strategy to achieve more reasonable costs for OLED panels. It is based on five components:

1. *Radical reduction in the cost of the most expensive materials, such as substrate, electrode structures, active organic layers and encapsulation*: Considerable progress is being made through existing Product Development projects and savings of around 90% can be envisioned.

2. *Faster manufacturing processes and substrate handling*: Achievement of a 30 second cycle time (TACT) by 2015 is a critical element in the plan. This would offer substantial savings with modest increase in equipment cost. Reducing cycle time is an important focus of the UDC/Moser Baer project funded under round one of the Manufacturing Initiative.
3. *Higher brightness*: Since manufacturing costs scale more closely to substrate area rather than the light output, raising the luminous emittance has a substantial cost benefit. Though the 2011 MYPP specifies performance targets for panels operating at 6,000 lm/m^2 in 2012, and 10,000 lm/m^2 in 2015 and beyond, the use of higher brightness panels would simplify the challenge of meeting 2012 cost targets. The resulting decrease in operating lifetime is the main deterrent to immediate implementation of high brightness; therefore, lifetime enhancement remains a high-priority target for R&D.
4. *Higher yield of good panels and materials utilization*: The production of unacceptable panels is a major cause of material waste as well as inefficient use of capital equipment and labor. Rejection can result from physical defects or poor process control leading to variations in product performance. In 2010, yield improvement was prioritized in the Manufacturing Initiative and significant progress is expected in this area in the next year or two. Regarding the importance of materials utilization, several phosphorescent emitters incorporate precious metals such as iridium or platinum. Less than 1% of the metals that enter the production stream are captured in the OLED structures. The remainder is lost, either in the manufacture of emitter materials or in panel formation. Techniques to reduce these losses are available, either through more efficient processing techniques or recycling.
5. *Increased substrate area for higher throughput*: While production of OLED lighting panels has so far been restricted to substrates of size less than 0.2 m^2, OLED displays are being manufactured in Korea on substrates of area 2 m^2 and the construction of even larger lines is planned. These facilities are extremely expensive (Samsung plans to invest $4.8B on OLED facilities in 2011) and recovery of the depreciation costs from lighting applications would be extremely difficult until all the other cost saving measures have been implemented. Thus major increases in substrate area are envisaged only in the later stages of this plan, by which time lessons learned in OLED display manufacturing can be adapted for lighting applications.

Table 3. Roadmap for Addressing OLED Manufacturing Issues

Topic	Activity	2010	2011	2012	2013	2014	2015	2016
Material cost	DOE Product Development R&D							
Faster processing	DOE Manufacturing R&D							
Higher brightness	DOE Product Development R&D							
Reduced waste	DOE Manufacturing R&D							
Larger substrates	DOE Manufacturing R&D							

Existing Activities
Future Activites

2. LED Package and Luminaire Roadmap

Chapter 2 describes the current LED package and luminaire manufacturing-related issues and suggestions for manufacturing R&D tasks that were that were discussed during the 2011 DOE SSL Manufacturing Workshop in Boston, MA and the LED Manufacturing Roundtable discussion in Washington, D.C. This Chapter presents the general barriers to the adoption of LED-based products, the cost and quality drivers for LED lighting, specific LED luminaire and package manufacturing issues, as well as the need for a common cost model to describe the manufacturing of LED-based components and fixtures.

2.1 Barriers to Adoption

The barriers identified over the last two years were expanded upon and clarified and additional manufacturing issues were brought up for discussion. A full list of the LED and luminaire manufacturing issues identified at the DOE SSL Manufacturing Workshops is shown in Table 4 below. Table 4 presents the issue or suggestion that was discussed, the type of activity required, 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 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 issues can be classified as related to Manufacturing R&D, standards development, Core and Product Development R&D, and education.

The issues and opportunities related to manufacturing which could be addressed directly through the DOE SSL Manufacturing R&D Program are:

- Luminaire/Module manufacturing*
- Driver manufacturing
- Test and Inspection equipment*
- Tools for epitaxial growth
- Wafer processing equipment
- LED packaging
- Phosphor manufacturing and application

Note: An asterisk (*) indicates the current priority manufacturing R&D tasks.

Table 4. Roadmap for Addressing LED and Luminaire Manufacturing Issues

Source: Based on recommendations from the 2011 Manufacturing Workshop Attendees

Note: Current activities are shown in darker grey while future activities are shown with a hatched pattern

Issue/Suggestion	Activity	2010	2011	2012	2013	2014	2015	2016
LED Manufacturing								
Standardization of LED package 'footprint'	Standards Development							
LED Performance reporting standard	Standards Development							
LED Epitaxial growth cost and consistency	DOE Manufacturing R&D							
LED Packaging	DOE Manufacturing R&D							
LED Wafer Level Processing	DOE Manufacturing R&D							
Reduced LED Cost related to current and thermal droop	DOE Product Development R&D							
Phosphor Manufacturing and Application	DOE Manufacturing R&D							
LED Drivers								
Driver Cost	DOE Manufacturing R&D							
Driver ease of integration	DOE Manufacturing R&D							
Driver performance reporting standard	Standards Development							
Test and Inspection								
Test/validation/inspection of components	DOE Manufacturing R&D							
Testing/Qualification of luminaires within Manufacturing Process	DOE Manufacturing R&D							
LED Manufacturing Process Test and Inspection	DOE Manufacturing R&D							
Luminaire Performance Standards								
Expedited compliance testing and certification (UL, Design Lights Consortium, Energy Star)	Standards Development Bodies							
Internationally reciprocated standards (UL, Design Lights Consortium, Energy Star)	Standards Development Bodies							
Harmonization of international standards	Standards Development Bodies							
Luminaire Manufacturing								
Luminaire/Module Manufacturing	DOE Manufacturing R&D							
Color Perception/Consistency/Tolerances by lighting application	External R&D and Standards Development							
Education in Luminaire Design and LED technology	DOE Commercialization Effort							
Luminaire Reliability								
Uncertainty in luminaire reliability	DOE Product Development R&D							
Uncertainty in driver/power supply reliability	DOE Product Development R&D							

Future Activities

Existing Activities

The ‘Luminaire/Module manufacturing’ and ‘Driver manufacturing’ tasks directly address two of the 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 reduced manufacturing costs through the development of improved process control using test and inspection tools and techniques. The following four tasks primarily represent an opportunity to improve cost and consistency of LEDs for use in luminaires. The previous and current prioritization of tasks is represented in Table 4 by the timing of the supported activity. FY10 priority research areas with projects working on these topics are indicated as existing activities from FY10-FY12, FY11 priorities will with selected R&D projects are existing activities from FY11-FY13, and the current priority R&D tasks will be supported from FY12-FY14. Manufacturing research tasks, which have not been prioritized, are indicated as future activities.

Over the course of the Manufacturing R&D effort commercialization standards have been brought up for discussion. These issues are listed below and will be discussed further in Chapter 5 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; and
- Expedited and internationally reciprocated standards (UL, Design Lights Consortium, Energy Star) for compliance testing and certification.

Other manufacturing challenges, not directly related to manufacturing technology exist for LED-based luminaire manufacturing. These barriers are as follows:

- 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; and
- Understanding and manufacturing for luminaire reliability.

The issues related to standards and education is 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 and Appendix A contain 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 has been prioritized within the 2011 MYPP.

2.2 Cost and quality drivers for LED lighting

LED-based luminaires comprise a number of components which must be carefully integrated in order to achieve high quality performance at reduced cost. Viewed separately these components contribute to the final cost as illustrated schematically in Figure 5. The relative cost splits in Figure 5 are presented for three different classes of LED-based luminaires in order to illustrate how they might vary depending on the specific type. A replacement lamp is likely to have the largest LED package cost component and an outdoor area lamp the smallest. By way of contrast the outdoor lamp will have the largest mechanical/thermal cost component and the replacement lamp the smallest. Other differences are illustrated schematically in the figure. At the current time, reducing the cost of the LED package (viewed as incoming materials from the luminaire maker's perspective) offers the greatest potential for cost reductions in interior LED-based luminaries; however, the cost of the remaining components will also need to come down in order to meet cost targets. Ultimately it will be through careful application of systems level design methods and detailed cost engineering approaches that the luminaire cost targets will be met.

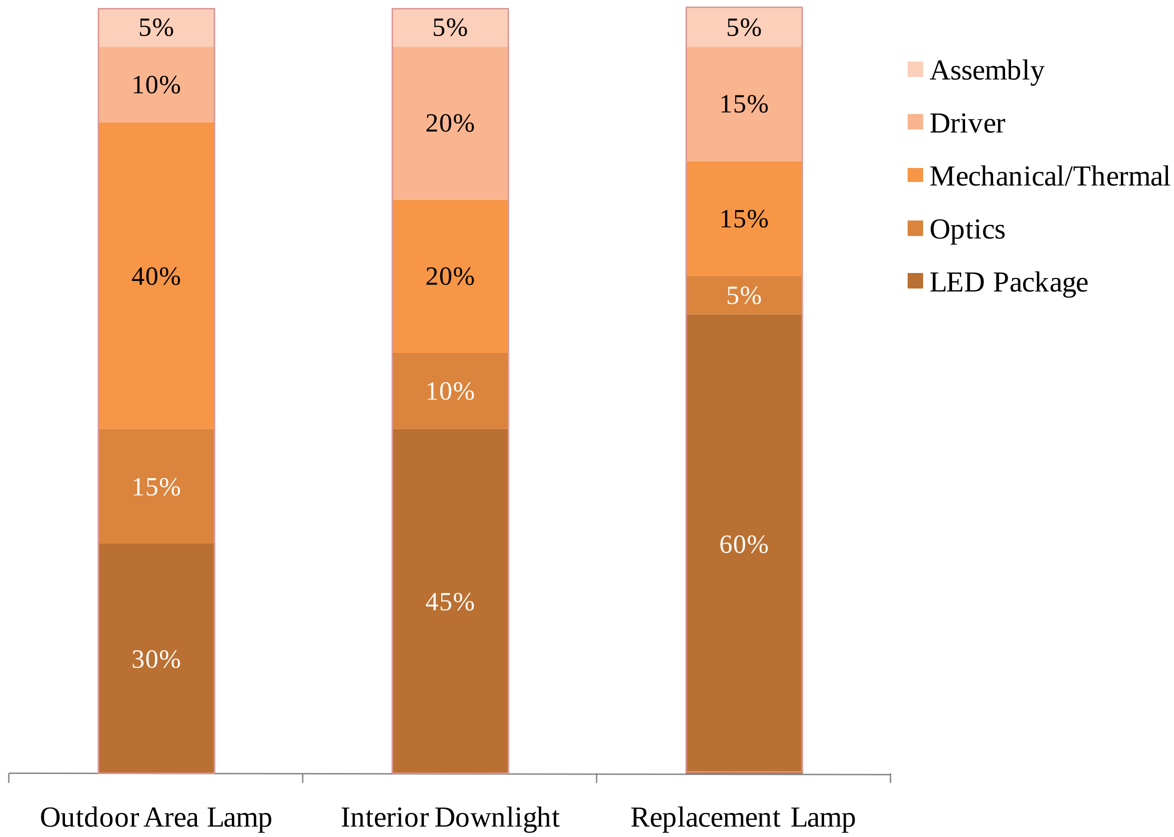


Figure 5. Approximate Cost Breakdowns for LED-based Luminaires in 2011
Source: Provided by the 2011 Manufacturing Workshop and Roundtable Attendees

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. 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 warm white pc-LED lighting sources. The analysis assumes an overall wafer yield of around 60% for the epitaxy step, and 90% for the wafer processing step.

Figure 6 indicates that a significant 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 and manufacturers will need to address die-level packaging processes or perform more of the packaging activities at a wafer level in order to realize the required cost reductions. 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 equipment throughput;
- 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); and
- Wafer scale packaging.

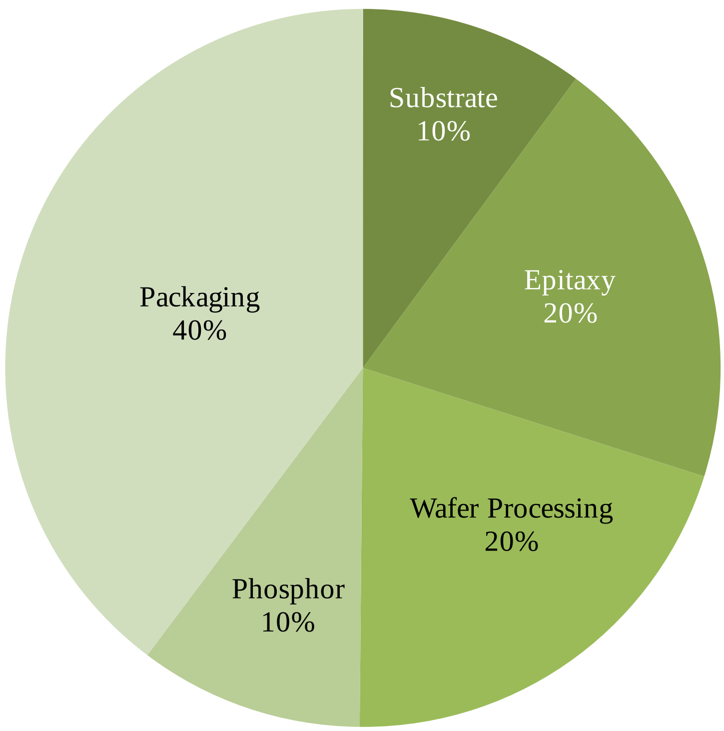


Figure 6. Typical Cost Breakdown for an LED Package in 2010
(100 mm sapphire substrate; 1 mm^2 die; phosphor converted; high power package)
Source: Provided by the 2011 Manufacturing Workshop and Roundtable Attendees

The top level metrics for LED device efficacy, LED device price, and original equipment manufacturer (OEM) lamp price are taken from DOE's 2011 MYPP.[5] These projected values are reproduced in Table 5.

[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 a warm white integrated LED lamp at reasonable volumes (several 1000s) with CRI>80 and CCT = 2700-3000K

Table 5. LED Metrics Roadmap
Source: DOE 2011 MYPP

Metric	Unit	2010	2012	2015	2020
LED Efficacy (warm white)	lm/W	96	141	202	253
LED Price (warm white)	$/klm	18	7.5	2.2	1
LED Efficacy (cool white)	lm/W	134	176	224	258
LED Price (cool white)	$/klm	13	6	2	1
OEM Lamp Price	$/klm	50	23	10	5

Note:

1. Projections for cool white packages assume CCT=4746-7040K and CRI=70-80, while projections for warm white packages assume CCT=2580-3710K and CRI=80-90.
2. All efficacy projections assume measurements at 25°C with a drive current density of 35 A/cm^2.

A review of commercially available devices[6] confirmed that the best efficacies available during 2010 for cool white[7] and warm white[8] LEDs at a current density of 35 A/cm^2 were 124 (lm/W) and 93 lm/W respectively, slightly below projections. As described in the previous report, the warm white LED efficacy has increased more rapidly than originally projected in earlier editions of the MYPP and the 2011 MYPP projections have been updated to reflect this.

Table 6. Comparison of different LED package designs from Philips Lumileds
Note: Prices are for 1000-off quantities from Future Electronics.

Product	Luxeon c	Luxeon Rebel ES	Luxeon S
Die area (mm^2)	1.0	2.0	9x2.0
Package footprint (mm^2)	2.0x1.6	3.0x4.5	13.0x14.0
CCT (K)	5700-6500	5650	3000
Price ($)	0.99	1.95	15.50
Lumens (@35 A/cm^2)	85	235	1,300
Price ($/klm)	12	8	12

Device prices in $/klm continue to decline rapidly. One route to lower cost has been to reduce the size and complexity of the package. A good example is the Luxeon c product which currently achieves a price of $12/klm (see Table 6). Another route has been to use larger die areas (multiple die or larger single die) to achieve higher lumen output in conventional package designs. Good examples of packages using large single die are the Cree XP-G (2 mm^2), Lumileds Luxeon Rebel ES (2 mm^2), Nichia NVSW219AT (2 mm^2), and Cree XM-L (4 mm^2). Such an approach has allowed the $/klm price to recently drop as low as $12/klm for warm white and $8/klm for cool white, on track with the LED metrics Roadmap shown Table 5.

[6] Values obtained during 2010 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

Examples of LED sources comprising multiple die in a single package range from the Cree MX-6 launched in 2009 which uses 6 small die (~0.25 mm^2), to the Cree MP-L launched early 2010 which uses 24 conventional die (1 mm^2), to the Cree CXA2011 introduced early 2011 which uses over 100 small area die. Other companies such as Bridgelux, Citizen and Sharp also produce LED array-based products. Recently Lumileds introduced the Luxeon S which uses nine large area die (2 mm^2) to produce 1,300 lumens at 3000 K from an 8 mm diameter aperture (see Table 6). Such products provide a large overall die area in a relatively small footprint package that results in a compact high lumen output source. Note that the die in these LED-array sources are often operated well below the 35 A/cm^2 benchmark so it is difficult in many cases to compare performance and prices.

Integration at the components level is an important consideration for lowering costs and improving product quality. Additional opportunities for simplification include the hybrid integration of components at the packaging level and the monolithic integration of components at the wafer level. The simplest example of hybrid integration is the LED array approach described above with multiple die in the same package. However, a more sophisticated example is shown in Figure 7 which combines the LED die, thermal control chip, driver chip, and primary optics into the same package. Hybrid integration schemes of this type could have a significant impact on the final luminaire costs.

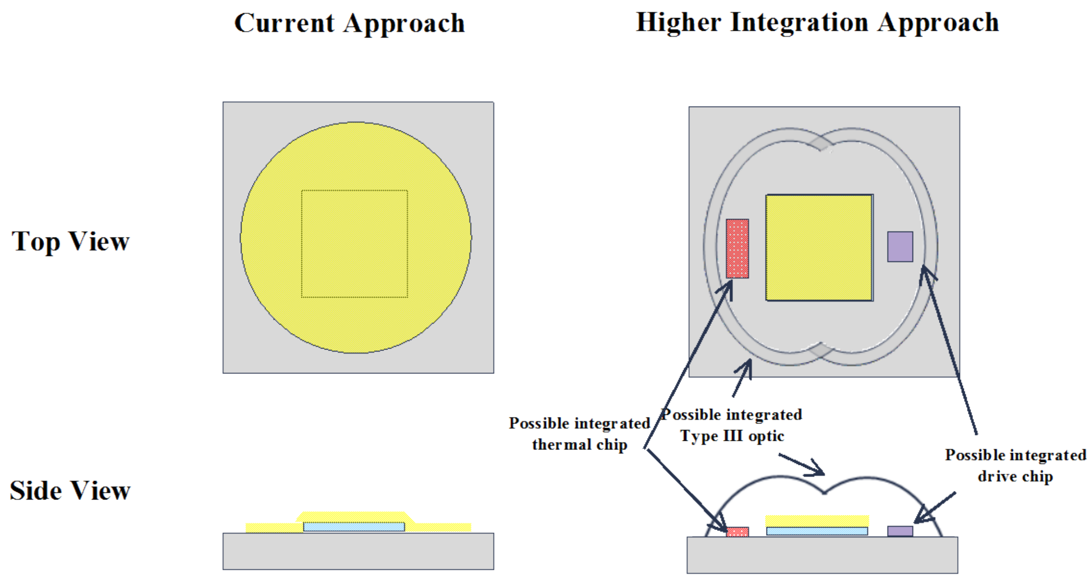


Figure 7. Schematic Representation of Possible Hybrid Integration Approach to Simplify SSL Luminaire Manufacturing and Reduce Costs
Source: Mark McClear, Cree, Inc., "An Integrated Approach to SSL Manufacturing", Vancouver, OR, June 2009

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.

2.3 LED luminaires

2.3.1 LED Packages in Luminaires

LED packages are a critical component of all current 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 2.4 along with specific suggestions for manufacturing R&D task priorities. Manufacturing workshop participants have consistently proposed that the DOE support R&D in the areas of current droop and internal quantum efficiency (IQE) as a means of reducing the relative cost contribution of LED packages within the luminaire. Improved LED efficiency and reduced droop will not necessarily reduce the cost of LED component (and may make them more expensive) but would reduce the number of expensive LED components required in a luminaire design and reduce the amount of thermal handling for a given lumen output. These LED R&D topic areas are appropriate for the Core or Product Development activities and have again been identified as priority tasks in the 2011 MYPP. While advances in LED component performance will continue to be made, luminaire manufacturers must find a way of contending with these limitations.

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. The variability in lumen output, Correlated Color Temperature (CCT), and forward voltage, is currently handled by testing each package and associating it with 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 at the 2009 SSL Manufacturing Workshop for dealing with chromaticity variations in LED packages was to have all LED manufacturers bin and label their products using a consistent set of chromaticity bins. This would enable luminaire manufacturers to more readily compare and use LED packages from different suppliers. This issue, discussed in further detail in Section 5.3, has been partially addressed with the recent publication of National Electrical Manufacturers Association (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 LED light sources.

Ultimately, the need for binning should be eliminated through LED fabrication improvements such as improved LED growth uniformity and optimized application of phosphors. LED package manufacturers have also begun to report performance under typical luminaire operating conditions to minimize variations between the specified performance and actual performance in the luminaire. While variations in LED package performance persist, binning issues can be

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

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 color within the manufacturers' bins, homogenization of the color from several LED packages using an array/module approach, and using a remote phosphor configuration that minimizes color variations. Manufacturing R&D that simplifies luminaire integration with respect to binning and LED light source performance variability will be considered under the 'Luminaire/Module manufacturing' task area.

Integration of the LED light source into the luminaire was also the subject of considerable discussion as an opportunity to reduce cost, improve performance, and optimize manufacturing of the luminaire system. The typical LED package may have layers or interfaces that can be removed or reduced when the LED light source is properly integrated into the luminaire. The removal of excess layers between the LED light source and luminaire is an obvious opportunity for thermal optimization, but improvements in electrical and optical integration would also provide system benefits. For example, certain aspects of the optical and electrical functionality of the luminaire could be integrated into the LED component or light module which could simplify luminaire manufacturing and improve luminaire performance consistency. The modifications to the LED component or light engine to improve integration may not be suitable for all general illumination applications which could lead to the development of application specific LED components and light modules. For example, some components could be optimized for use in directional lamps while other components could be optimized for omni-directional applications.

It was also suggested during the luminaire manufacturing discussions at the manufacturing workshops that the availability of components with standard form factors, and optical and electrical interfaces, particularly LED packages, would greatly expedite the luminaire design and manufacturing processes. Such standardization would positively impact LED light source cost, availability, and consistency. However, the counter-argument was also made that standardization could stifle performance and integration innovations in LED light sources and other luminaire components, and may be premature at this time. There was no consensus among the luminaire manufacturers as to when component standards should be enacted. However, it is not too early to begin the process for eventual component standardization, so that when the technology is ready component standards can be put into place. The Zhaga[10] consortium has already begun to consider component standards for luminaire manufacturing.

2.3.2 Luminaire/Module Manufacturing

At the 2011 DOE SSL Manufacturing Workshop there were 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 may lend itself to an integrated luminaire design due to the long lifetime and thermal handling demands. The long lifetime of the LED light source may mean that the light source no longer needs to be easily replaceable. Since LED components do not radiate heat, but rather, need to have the heat conducted away, luminaires need to be specifically designed for thermal conduction away from the LED components. An integrated LED-based luminaire does not easily

[10] www.zhagastandard.org

fit into the lamp-and-fixture model that exists today which could lead to a fundamental change in the lighting industry. As a result of the introduction of LED technology, the lamp portion and luminaire portion of the lighting fixture are likely to merge, and companies that can engineer the luminaire together with the source will benefit. Even within LED replacement lamp products there are opportunities to better integrate the LED die, LED package, or LED module with the lamp mechanical, electrical, and optical structures. Such advancements could simplify the design of the lamp or luminaire products, simplify the manufacturing of these products, and reduce product costs. The potential for high levels of component integration within LED-based luminaire products will have a significant impact on how such products will be manufactured. This level of integration may require automated manufacturing to bring down the assembly costs and reduce human variations in the manufacturing process. This integration also represents a challenge for existing luminaire manufacturers who may not have the necessary tools or expertise to develop the LED-based products.

While it was recognized that LED-based lighting products require a high level of integration, there was also discussion of creating a modular approach to luminaire manufacturing. The components of the luminaire, such as the LED light source, driver, thermal handling, and optics, and housing, could be developed to readily fit together in a variety of configurations. This could enable rapid manufacturing of a range of product variations, simplify inventory demands, and simplify luminaire design. All of these benefits could lead to greatly reduced luminaire costs. The modular manufacturing and design approach could also benefit smaller scale and traditional luminaire manufacturers who could more easily and rapidly design and manufacture LED-based lighting products. Different lighting applications and types of products may lend themselves to either integrated or more modular product designs. In addition, different levels of design capability for luminaire manufacturers may also encourage the use of more modular product designs. Multiple approaches to the design and manufacturing of LED-based lighting products will likely exist in parallel as the market evolves.

There are a number of additional challenges that luminaire manufacturers are currently facing as a result of this paradigm shift. These 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 LED packages, are rapidly improving in performance and new products are being introduced at a rapid rate while at the same time, high demand and limited production capacity can result in long delivery lead times. Thus, a specific LED package may become obsolete within the normal product life cycle of the luminaire. This problem is exacerbated by the lack of standardization of package footprint and performance characteristics which limits the ability to second source a particular component. This situation is particularly acute with LED packages 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.

Another fundamental change to luminaire manufacturing is how luminaire reliability is considered and how this impacts the design and sub-component selection of LED-based luminaires. The long life of the LED package has led to the expectation of longer-lived luminaires and replacement lamps. This requires not just a well-integrated long life LED package, but also long lives from all of the luminaire sub-components and reliable design and integration of the product. While consumers expect longer lifetimes from LED lighting products they also insist on low priced products. Understanding the reliability relationships between the luminaire components will allow manufacturers to make informed decisions regarding trade-offs between product cost and product reliability.[11]

The priority research task on 'Luminaire/Module manufacturing' addresses the issues discussed above. This task is focused on improving the integration and manufacturing of LED luminaires and modules. The discussions at the 2011 Roundtable and Manufacturing Workshop emphasized the need to develop LED packages and luminaire/lamp designs that are readily integrated, use fewer raw materials, and are optimized for efficient manufacturing without compromising the performance of the light source. The benefits of these improvements would be products that weigh less, have improved thermal performance, are more reliable, have more consistent color, and can be manufactured more efficiently at a lower cost.

The need for education in the new technologies required for the design and manufacturing of LED-based luminaires is also critical. Compared to conventional luminaires, an almost entirely new skill set is required to design, engineer, and manufacture LED-based lighting products. The DOE SSL Program offers 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.

2.3.3 LED Driver Manufacturing

While not identified as a current priority research task, the need for drivers with improved design for manufacturing, integration, and flexibility within the luminaire remains. 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. The manufacturing of drivers with some level of controllability and control compatibility is also a concern for driver and luminaire manufacturers. Luminaires for varying lighting applications may require different types of control. Internal electronic control of color consistency, compatibility with dimming systems, or communication with various forms of wired or wireless controls may be required for the lighting application and this functionality is typically integrated into the power supply. The need for the integration of these controls into the luminaire can impact the assembly costs of the luminaire as well as the reliability of the luminaire. Improvements to the design and manufacturing of drivers and the control systems could have a significant benefit on luminaire cost, performance, and reliability.

[11] The LED Luminaire Lifetime: Recommendations for Testing and Reporting, document can be found at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/led_luminaire-lifetime-guide.pdf

A standard report format of driver performance would also 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 also facilitate the use and development of analysis, simulation, and design tools for luminaire manufacturers. The luminaire manufacturers suggested that this reporting of performance data in a standard reporting format should be implemented in the near term. The sidebar lists the parameters the LED breakout group recommended should be included.

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

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.

2.3.4 Test and Inspection Equipment

The attendees at the 2011 workshop confirmed the need for test and inspection equipment for all levels of LED package and LED-based luminaire manufacturing. Test and inspection equipment could be used with luminaires to validate incoming components, to perform in-line testing, 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.

2.3.5 Luminaire Reliability

The lack of a thorough understanding of lifetime for LED-based luminaires continues to be a significant problem for luminaire manufacturers. While LM-79 provides a standardized protocol for measuring luminaire performance and can be performed at various points in the luminaire life, it is expensive and time consuming to perform this test, particularly at the rate new luminaire and lamps products are being developed. LM-79 also does not offer a means to accelerate life testing to allow for interpolations of lifetime within a shorter test cycle. 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 LED packages, drivers, optical components and materials used in assembly, along with accepted methods to statistically predict luminaire system lifetime. System reliability and lifetime was identified as a priority product development research task in the 2011 MYPP.

The issue of a common test protocol was initially brought up for the Core Technology R&D program under the System Reliability Methods task area. 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.[12] The luminaire discussion group at the 2011 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.

2.4 LED Packages

The following sections review progress against the four principal manufacturing barriers identified during the 2009 and 2010 SSL Manufacturing Workshops: Epitaxy Processes, Substrates, Manufacturing Equipment, and Process Control. Consideration of these barriers has focused debate over the past couple of years and has helped identify significant opportunities for manufacturing R&D. These opportunities have been discussed at subsequent roundtables and workshops. Future R&D priorities and technology Roadmaps have been molded by these discussions and are outlined in the following sections.

2.4.1 Epitaxy Processes

Epitaxial growth remains the key enabling technology for the manufacture of high brightness (HB)-LEDs. Several critical issues regarding epitaxial growth equipment and processes were originally identified as requiring attention. They are as follows:

- 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; and

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

- Need for lower cost source materials and improved source efficiencies.

All GaN-based HB-LED epiwafers are 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, the multi-quantum well (MQW) active region, and p-GaN cap. Large-capacity manufacturing equipment (up to 56 x 2 inch or 14 x 4 inch wafer capacity) that is capable of producing high quality material is readily available from companies such as Veeco Instruments (U.S.) and Aixtron (Germany). Existing projects under the manufacturing initiative are driving further improvements in uniformity, reproducibility, and equipment throughput. Preliminary work is also underway to improve the capabilities offered by in-situ monitoring and to better understand the growth chemistry. Previous concerns regarding relatively slow growth rates have been largely dispelled following the demonstration of GaN growth rates in the 15-20 μm/hr range. Nevertheless, hydride vapor phase epitaxy (HVPE) remains an alternative growth approach for thick GaN layers due to its potential for even higher growth rates, and work is underway to combine HVPE and MOCVD into a single multi-wafer growth tool to combine the best attributes of each technology.

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: Provided by the 2011 Manufacturing Workshop Attendees

Figure 8 shows the epitaxy Roadmap which remains unchanged from that shown in the 2010 Manufacturing Roadmap. Progress against this Roadmap is largely on target. The only area where there is a danger of falling behind is in the development of active process control using in-situ monitoring. Increases in wafer throughput cannot be achieved at the expense of 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. Active temperature control at the wafer surface is of particular importance 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. Therefore the focus will be on actively controlling growth temperature at the wafer surface through accurate in-situ measurement and integrated feedback control. There is no standard method to accurately monitor the wafer surface temperature and achieve this kind of active control, especially using transparent substrates such as sapphire. 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 7 describes 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 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, such as increased throughput (reduced cycle times and/or increased capacity), lower capital cost, improved materials usage efficiancy, smaller footprint, or increased yield. Process control improvements will increase yield, and equipment design changes will increase the efficiency of reagent 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 it has been decided to normalize the epitaxial layer cost to layer thickness (μm) and wafer area (cm^2), as shown in Table 7. The cost metrics have been updated based on preliminary results using the Modular Cost Model (Section 2.5) and assume the use of a Veeco Instruments 465i multiwafer reactor with an overall wafer yield of 60%. There is clearly scope for further improvements in wafer yield to further reduce epiwafer costs. The proposed Roadmap for epitaxy cost reduction in Table 7 assumes a wafer yield of 60% in 2010, increasing to around 85% by 2020.

Table 7. Epitaxy Metrics
Source: Provided by the 2011 Manufacturing Workshop Attendees

Metric	Unit	2010	2012	2015	2020
Wafer Uniformity (standard deviation of wavelength for each wafer)	nm	1.5	1.0	0.5	0.5
Wafer-to-wafer Reproducibility (maximum spread of mean wavelength for all wafers in a run)	nm	1.1	0.9	0.6	0.5
Run-to-run Reproducibility (maximum variation from run-to-run of the mean wavelength for all wafers in a run)	nm	1.5	1.1	0.9	0.75
Cost of Ownership	-	Factor of 2 reduction every 5 years			
Epitaxy Cost	$\$/\mu m \cdot cm^2$	0.45	0.28	0.14	0.05

2.4.2 Substrates

A handful of substrate options currently exist for the manufacture of high-power GaN-based LEDs covering a range of materials (sapphire, SiC, Si, and GaN) and wafer diameters (2”, 3”, 100 mm, 150 mm, etc.). Currently, GaN LED growth on sapphire and SiC typically provide the highest performance LEDs at a reasonable cost. 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.

Both sapphire and SiC substrates have been used to produce GaN-based LEDs with state-of-the-art performance, although sapphire has established itself as the dominant substrate type used in production. A general trend toward larger substrate diameters is anticipated, mimicking the silicon and GaAs microelectronics industry. Recently Philips Lumileds claimed to be the first power LED manufacturer to be in mass production on 150 mm sapphire wafers with the production of millions of GaN based LEDs weekly at the end of 2010[13]. Larger substrates provide an increase in useable area (less edge exclusion) without a proportionate increase in processing cost per wafer, resulting in a lower cost per 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

[13] Press Release: Dec 15, 2010, “Philips Lumileds Leads LED Industry with Mass Production on 150 mm Wafers”

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. Similarly, the use of GaN templates or free-standing GaN pseudo-substrates offers other alternative substrate solutions. Consequently, the investigation of alternative substrate solutions has been identified as a priority Product Development task in the 2011 MYPP.

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.

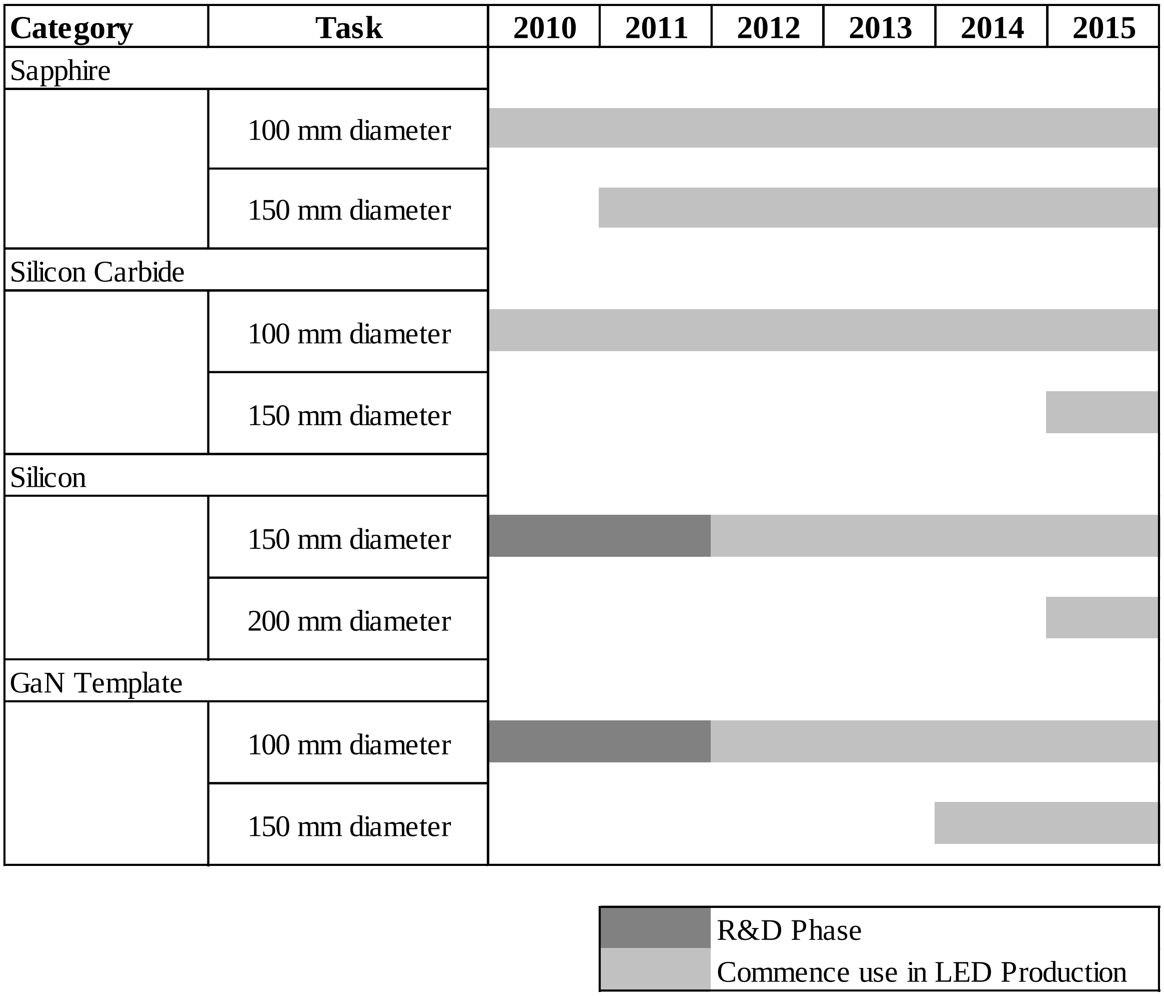


Figure 9. Substrate Roadmap
Source: Based on recommendations from the 2011 Manufacturing Workshop Attendees

2.4.3 Manufacturing Equipment

The third significant set of issues concerns the lack of availability of suitable manufacturing equipment for wafer processing, chip manufacturing, and chip packaging. To some extent this issue has become less critical as the manufacturers have migrated toward larger substrate diameters, such as 150 mm sapphire, although the lack of standardization on substrate specifications has created a whole range of additional problems for the substrate suppliers and equipment manufacturers. Significant progress has nevertheless been made in developing equipment specifically optimized for the needs of this industry such as optical inspection tools (KLA-Tencor) and lithography tools (Ultratech Inc.). Epitaxy equipment has also continued to be developed to suit industry requirements as described earlier (Section 2.3.1). Despite the good progress, further work is required to produce a complete range of manufacturing equipment that meets 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 COO. 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 earlier Roadmaps, 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 LED package cost (and ultimately the luminaire cost) is required in order to make these decisions, highlighting the need for improved 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 two times improvement in COO every five 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.

2.4.4 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.

Due to variability at various stages in the manufacturing process, manufacturers are currently required to measure all devices in order to characterize them in terms of lumen output, color coordinates (CCT and CRI), and forward voltage. Such measurements allow the end products to be placed in specific performance bins. Binning currently occurs at the end of the process and high speed testing is required to minimize the cost of this step. Until recently these measurements have been performed at a temperature of 25°C and luminaire manufacturers have been left to infer the device performance under actual operating conditions, which might be temperatures closer to 85°C. Cree has reported that typically the color shift from 25 to 85°C is around $\Delta_{u'v'} = 0.002$, or approximately 2 SDCM.[14] Lumen output is also typically reduced by 5% to 10% at the higher temperature. Consequently the device manufacturers have started to perform these measurements at a temperature of 85°C, a practice often referred to as 'hot' binning. Performing such measurements at high speed with a high degree of accuracy presents a number of challenges.

Improvements in process controls plus the application of in-line testing and inspection will tighten device performance distributions, and allow manufacturers to produce product more closely aligned with customer demand. Significant developments have been made in this sector as evidenced by the release of an increasingly wide range of products with significantly tighter color bins. Cree 'Easywhite™' was first introduced at the end of 2009 and offered 75% smaller bins (4 SDCM) than ANSI C78.377 for color temperatures of 2700, 3000 and 3500K. Over the past 18 months additional products have been introduced under the Easywhite™ label that are guaranteed to fall within either a 2 or 4 SDCM bin while covering a wider range of color temperatures. Philips Lumileds introduced their own range of products offering '*Freedom from Binning*' at the start of 2011. These products have the additional advantage that all

[14] Ralph Tuttle, Cree, "White LED Chromaticity Control—The State of the Art", San Diego, CA, 2011

measurements are performed at 85°C, so the devices are both tested and binned under real world operating conditions. Products are guaranteed to have color consistency within 3 SDCM. Bridgelux also recently commenced offering products within a 3 SDCM bin (measured at 25°C) and began reporting device performance at both 25°C and typical operating temperatures (60 or 70°C). Continuous improvements in process control are expected to allow manufacturers to offer tight binning with increased yields and reduced manufacturing costs.

While there has been a noticeable improvement in process control, further improvements are required throughout the epitaxial growth, wafer processing, chip production and chip packaging stages. There remains a strong need to develop improved in-situ monitoring and active process control for MOCVD epitaxial growth, in conjunction with rapid in-line characterization of the epitaxial wafers for rapid feedback to the manufacturing process. There is also a need for in-line testing, inspection, characterization, and metrology equipment throughout the LED package manufacturing process. Yield losses at each step in the manufacturing process have a cumulative effect so 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 from improved in-line inspection come, in roughly equal measure, from reduced R&D costs, factory ramp-up costs, and manufacturing production costs. In the case of the LED die manufacturing production process it has previously been proposed[15] that cost savings of 6-24% could arise through improvements to the baseline process yield, and 22-44% through excursion flagging. Accordingly, most reasonable estimates based on silicon industry experience suggest that the use of in-line inspection can reduce costs by roughly a factor of two (i.e. an overall cost saving of 50%). This will be the target for 2015.

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.

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 two improvements in COO over a five year timescale.

2.5 Cost Modeling

A common theme during the manufacturing workshops has been 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

[15] Richard Solarz, KLA Tencor, "In-line Process Control and and Yield Management for the HB-LED Industry", Vancouver, OR, June 2009

final device and luminaire costs. This information could then be used to help focus effort into the most profitable areas.

Conventional cost models are based on a COO analysis 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') and 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 part 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 per part is obtained by dividing the full cost of the equipment and its operation by the total number of good 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.

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 per wafer from the epitaxy and wafer processing steps must be converted into a cost per die in order to combine it with the cost per die arising from the packaging steps. A Cost Modeling Working Group was established in 2010 and has proposed a simple modular approach.

The modular approach breaks down the manufacturing process into a number of discrete process steps or modules. The contribution of each step to the final LED package cost is considered and only those steps that contribute at least one percent are considered further. Global parameters such as substrate diameter, die area, raw material costs, and factory overheads will be fixed. Costs associated with the overheads are normalized to fabrication area and apportioned based on process footprint. Each of the modules is then further analyzed to determine the most critical parameters controlling the cost of that particular process step. Finally a simple module is created with only these most critical parameters as variables.

The aim of the simple modular approach is to limit the number of variables to the bare minimum consistent with a realistic cost analysis. Modules can be repeated as often required and can be used in any order to recreate the full manufacturing process. The total number of modules is anticipated to be in the range of 20 to 25.

Figure 10 is a schematic representation of the Epitaxy module, which is one of the more complex modules. Inputs are shown on the left and outputs on the right. Different reactor selections will yield different outputs. Typical numbers are shown for a Veeco Instruments 465i multiwafer MOCVD reactor.

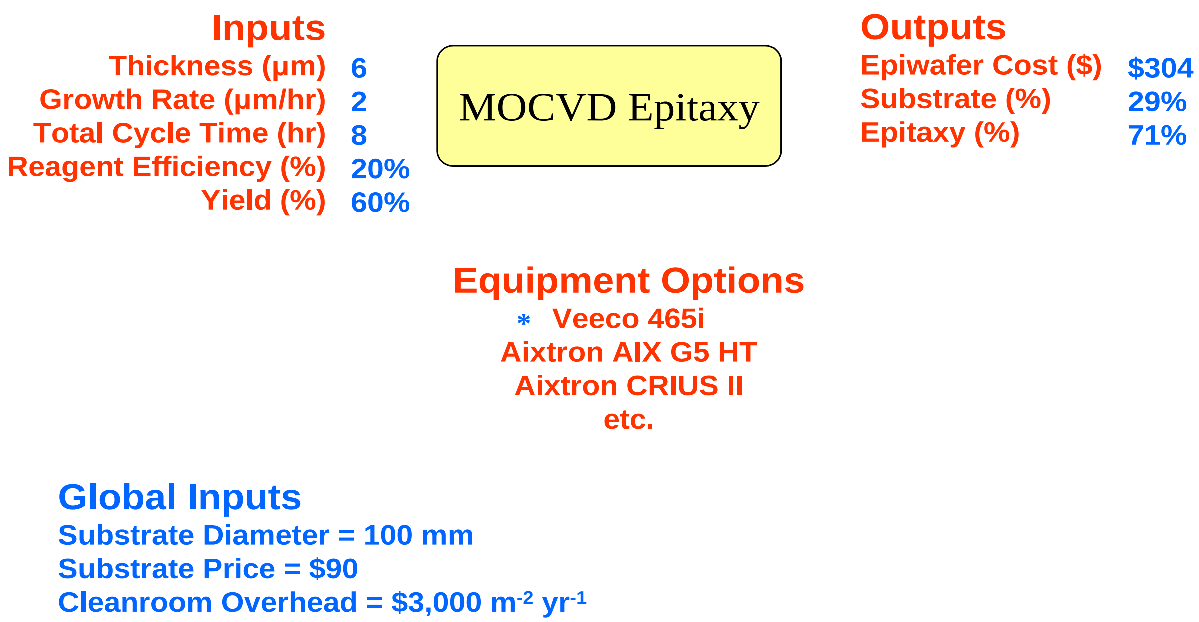


Figure 10. Schematic Representation of the Epitaxy module from the Simple Modular Cost Model
Source: Stephen Bland, SB Consulting, "Cost Engineering: How Product Evolution Can Lower Costs," Boston, MA 2011

Other modules will include lithography (combining photoresist application, photolithographic alignment and exposure, and photoresist processing into a single step), metal deposition, dielectric deposition, dielectric etching, GaN etching, wafer thinning, wafer bonding/debonding, probe testing, dicing, die attach, wire/flip-chip bonding, laser-lift-off, phosphor coating, lens attach, and final test. Also included will be test and inspection modules. The key outputs from the model will be epiwafer cost, processed wafer cost, die cost, and LED package cost.

3. OLED Roadmap

This Chapter addresses the general methods and challenges associated with manufacturing OLED luminaires as discussed during the 2011 DOE SSL Manufacturing Workshop and the OLED Manufacturing Roundtable discussion in Washington, D.C. Following a review of barriers to adoption and cost reduction strategies, some areas are identified that deserve special attention in the next year.

3.1 Manufacturing strategies

The most critical factor governing the commercial success of LED lighting is the cost of manufacturing. Near term cost reductions by a factor of about 100 from the price of today's OLED prototypes will likely be needed to make OLEDs marginally cost-competitive with present LED alternatives. As LED prices continue to decrease, substantial further reductions by 2020 in the cost of OLED luminaires will needed as shown in Figure 4**.** Similar cost reductions have been observed in other emerging technologies and substantial opportunities for cost savings are available, as outlined in Sections 1.3.2 and 3.2. Two further barriers are discussed in this section: the uncertainties in panel architecture and production volume ramp-up.

3.1.1 Uncertainties in Panel Architecture

Analyses of the relative merits of different panel designs can be found in the 2011 MYPP. This section reviews the implications of some design selections on the manufacturing processes.

- *Rigid vs. flexible panels:* Many lighting designers and market analysts have suggested that the success of OLED lighting depends on the availability of non-planar light sources, resembling lamp shades and chandeliers rather than simply imitating fluorescent troffers. This desire is counterbalanced by the relative immaturity of manufacturing methods for flexible substrates and the potential for added cost of ultra-thin glass or barrier coatings for plastic substrates. For this reason it may be that flexible substrate products will come to market somewhat later than rigid substrate implementations.
- *Color control:* Capability for the user to control the color of the emitted light can be provided through the deposition of RGB stripes, side-by-side in a single layer, or the construction of a multiple stack with separate voltage control for each emission layer. This provision clearly has significant impact on the choice of manufacturing equipment and the line lay-out. Though this is an attractive feature, color tunability could add significantly to the cost of manufacturing.
- *Size and shape of panels:* Choice of panel size is critically dependent on expectations for manufacturing yield and the consistency of panel-to-panel performance. The relatively crude patterning required to create non-rectangular shapes should be straightforward, either with vapor deposition or solution processing. Moderate challenges should arise in encapsulation, singulation and electrical connection, but these should not be insurmountable. The level of standardization adopted by the industry will also influence the evolution of manufacturing strategies. The use of larger substrate sizes provides more flexibility in the choice of panel size and shape and can lead to large, seamless emitting areas which can be attractive in certain lighting designs.

- *Single, dual or triplet stacks:* The introduction of dual or triple stack structures leads to reduced drive voltage and longer lifetimes. This appears to be a promising route to enabling high brightness on a short time scale. The added complexity could, however, result in lower yields and greater material costs, and will require additional deposition sources. There seems to be a consensus that a dual stack offers significant performance gains that may justify the extra cost, but that a third stack provides relatively little further improvement.
- *Current distribution:* It is generally accepted that for all except the smallest devices, no homogeneous sheet of transparent conductor will be able to ensure uniform distribution of current across the panel without undue absorption of light. Current spreading can be facilitated by adding metal bus lines or by using serial connections between segments of the panel. In the latter approach the anode of one segment is connected to the cathode of the neighboring segment. The choice of auxiliary conductors may increase the cost of the integrated substrate and the procedures that are used for the subsequent deposition.
- *Opaque vs. transparent panels:* The introduction of panels that are transparent when switched off offers attractive opportunities for innovative lighting products. This is feasible, since transparent cathodes and anodes are available, but rules out the use of metal foils.

3.1.2 Production Volume Ramp-Up

With the current high costs to fabricate OLED lighting panels, it has been difficult to stimulate sufficient market demand to justify the expense of developing a high-volume manufacturing capability. On the other hand, reaching attractive prices, high yields, and high material utilization to some extent can only be achieved through manufacturing experience at some meaningful volumes. To address this conundrum, the DOE SSL program is supporting R&D related to the development of pilot facilities which can produce a steady supply of panels at reasonable costs both to stimulate marketable product developments and to provide a technology base for increased capacity as demand grows. For further detail on these pilot facility projects, see Appendix B.

3.2 Cost Reduction Opportunities

3.2.1 Material Costs

Figure 11 presents targets for the cost of materials in an OLED panel, expressed in $\$/m^2$. These values are based upon the assumption of a 100% yield of good panels, but take into account that some of the materials are lost during production and are not embedded in the processed structures. The area used in the computation of these estimates is that of the active panel.

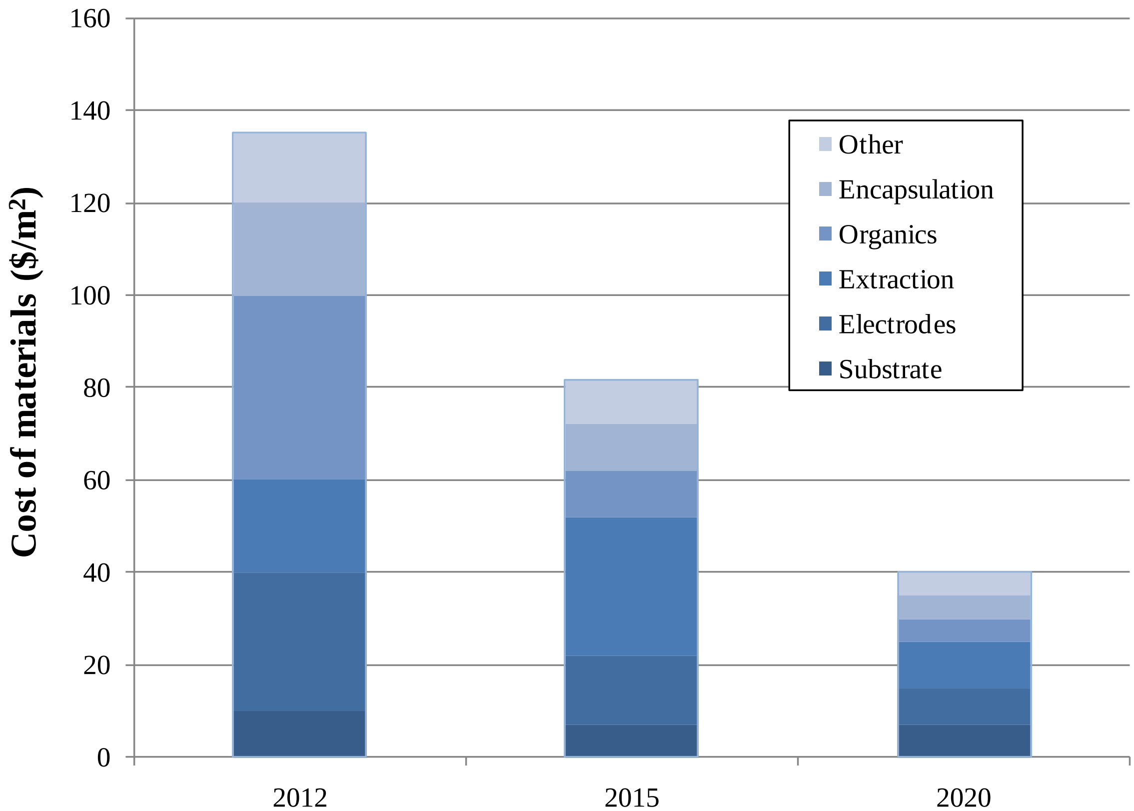


Figure 11. Cost of materials as deposited on processed substrates ($\$/m^2$)
Source: Based on data provided by the 2011 Manufacturing Roundtable Attendees

In the 2010 Manufacturing Roadmap, cost estimates were based on the material set used in OLED displays. Some refinement of those estimates is now possible as we learn more about the lighting application. Major trends anticipated in this year's projection are:

- The cost of the organic materials is expected to decrease from about $\$40/m^2$ in 2012 to approximately $\$10/m^2$ in 2015 and $\$5/m^2$ in 2020, as substantial savings through high-volume manufacturing are only partially offset by the costs of more complex structures and additional processing steps to improve material purity and stability. These improvements will be driven primarily by the display industry and so are not prioritized in current program solicitations.

- The substrate cost should fall to about $7/m^2$ in 2020 through the replacement of borosilicate glass by soda-lime glass. The product development project by PPG Industries has shown that this is feasible and is exploring the adaptation of standard float glass to meet OLED specifications, for example through the addition of a coating to prevent alkali leaching.
- The cost of light extraction materials per unit area is expected to increase in the near term as performance is improved, although the panel cost per lumen should fall. The standard procedure in 2011 is to add a film, such as a micro-lens array, to the outside of the glass substrate. This typically leads to an enhancement factor of 1.5 to 2.0. Research into more effective structures is anticipated in both core and product development projects in order to increase this factor but it seems likely that implementation of these new techniques will lead to higher costs. It is not possible to make accurate predictions of these costs, but an estimate of $30 is included in this chart for 2015. Development of the associated manufacturing methods is included in Task M.O3.
- The cost of purchasing patterned ITO from external suppliers is about $30/m^2$ currently. This can be reduced by efficient in-house processing, but only in high volumes and the purchase and maintenance of expensive equipment. Several alternative transparent conductors are under development in the product development projects by Cambrios and PPG, with significant potential for cost reduction. The anticipated savings will be partially offset by the cost of auxiliary structures, such as bus bars, and the 2015 target is $15/m^2$.
- Traditional encapsulation involves a sheet of borosilicate glass in which a cavity is etched to accommodate getters to absorb O_2 and H_2O. This might be replaced by a planar sheet of glass or metal and a thin layer of getter or by the in-situ deposition of conformal encapsulation films. Soda-lime glass or metal foils provide acceptable covers, but processes must be developed to ensure hermetic sealing and the incorporation of the getter materials without the need for cavity creation. This is one topic included in Task M.O3. Successful execution of this project should lead to reduction in the encapsulation costs to about $20/m^2$ in 2012; further reductions will be needed to meet the overall 2020 goal.

3.2.2 Materials Utilization and Yield Improvement

The high cost of materials means that minimizing waste during processing is critical. Three important elements are being addressed in SSL projects:

- *Substrate Utilization*: The foundation layers onto which the organic layers are deposited are relatively expensive and so should be used as effectively as possible. Exclusion areas near the edges of the substrate are usually necessary, but are unproductive and so should be minimized. This is being addressed for glass sheets in the design of the pilot line by UDC/Moser Baer, but is particularly important in roll-to-roll (R2R) processing. When multiple panels are produced from a single substrate, there is additional wastage between panels to allow for sealing and singulation. For small substrates, usage factors of 60% are typical, but this should be increased to 80-90% as the size increases.
- *Material Deposition*: Patterning can lead to very low utilization factors for organic materials and conductors. In OLEDs for display applications, side-by-side deposition of

the emitters of different colors has been accomplished by evaporation through masks, with typical utilization ratios less than 10%. Much of the material is deposited on the masks, leading to costly cleaning processes and increasing contamination risks. Other organics are deposited on relatively cool surfaces of the deposition chamber and delivery system. Increased material utilization in organic deposition is one of the important metrics for the Task M.O1.

- Solution processing usually leads to much higher utilization rates. The effectiveness of slot-die coating of organic materials is being investigated in the GE/DuPont project. The use of subtractive patterning for metal bus lines could also lead to over 90% waste. Metal pastes and inks are available that can be deposited only where needed, but there is currently a substantial penalty in conductivity.
  Process improvements are required to increase utilization to 50% in the short term and greater than 70% in the long term, as discussed below.
- *Defect Avoidance*: Increasing the yield of good panels is essential in reducing material, depreciation and labor costs. Many defects are caused by particulates or surface roughness in the integrated substrates onto which the thin organic layers must be deposited. Causes may include the substrates themselves, the electrode structures or the internal extraction layers, which often contain relatively large scattering particles or patterned structures. Yield improvement is a priority in the 2011 Manufacturing Initiative R&D funding opportunity.

3.2.3 Processing Speed

One key to reducing depreciation costs is to increase throughput, either through reduced processing times or increased substrate area. Faster processing has the greatest potential for cost reduction, since it does not necessarily require substantial increases in capital costs. Although increasing throughput leads to challenges in almost every step of the process, the main problems using traditional methods lie in the deposition of the cathode and the organic layers.

- Most manufacturers choose evaporation rather than sputtering to avoid damage to the underlying organic layers during deposition of the cathodes. . Evaporation is slow, however, and so the development of faster sputtering techniques that do not result in damage deserves further study.
- Cycle times for organic deposition in the manufacturing of OLED displays are usually three minutes or longer. However, much of this time is required for alignment of the fine metal masks that are not needed for lighting applications. Rates for vapor deposition are typically 1-2 nm/s and can be raised to 5 nm/s through the use of an inert carrier gas. Deposition times below 20 seconds are thus feasible for the thin internal layers, but the thicker injections layers may require faster processes. Substrate handling still presents a challenge, particularly in cluster systems, and so tools that permit the deposition of multiple layers without substrate movement could be advantageous. Cycle time is another critical metric for Task M.O1.
- R2R processing offers the prospect of rapid movement of the substrate between tools and very short cycle times. Deposition in solution can also be accomplished quickly, but solvent removal can require long residence times in an oven. Synchronization of the many processing steps is thus a challenge for this approach. Since significant

development work remains to be done on the individual processes, studies of system integration are not anticipated before 2013.

3.2.4 High Brightness

Due to the small amount of light emitted by existing OLED prototypes, luminaire manufacturers are encouraging earlier availability of panels with luminous emittance at 10,000 lm/m^2. Increasing brightness can shorten panel lifetimes, but since degradation scales strongly with current density, the use of tandem structures could alleviate this problem and meet the need higher light output. The tradeoff is that using more complex structures will increase material costs, increase cycle times, and reduce manufacturing yields. Further studies on control of the deposition process will be critical in enabling early implementation of tandem structures.

3.2.5 Substrate Size and Equipment Costs

Increasing the substrate size should improve productivity, but may lead to substantial increase in the cost of equipment and other manufacturing facilities. For example the estimated cost of the "Generation 5.5" lines (1300 mm x 1500 mm) being installed by Samsung for OLED display production is $700 million. Given the remaining performance issues and uncertain demand, such investments are not currently justified for OLED lighting. Accordingly, a rather slow increase in substrate size is planning in this Roadmap.

Although some OLED lighting applications may call for new substrate dimensions, adopting standard sizes used in the display industry may lead to cost savings. The projections below assume substrates of 370 mm x 470 mm (2012), 730 mm x 920 mm (2015) and 1300 mm x 1500 mm (2020). Costs of existing equipment can be reduced, however because of reduced patterning requirements and the absence of the TFT backplane.

The major factors that govern productivity are:

- *Cycle time*: This determines the rate at which processes are performed and controls the synchronization of the many steps. As much as possible, all processes should be accomplished within the nominal cycle time. Slower processes can be accommodated through the inclusion of multiple tools.
- *Substrate utilization*: Unproductive areas seem unavoidable, due to the difficulty of reliable processing near the edge of the substrate and the margins between multiple panels on the same substrate. The production of non-standard panel sizes or non-rectangular shapes will increase the fraction of unproductive area.
- *Uptime*: Allowance must be made for scheduled maintenance and for line modifications. Unscheduled stoppages are likely, especially in early stages of production.
- *Yield of good products*: Widening process windows can result in substantial increases in yield.

The evolution of these elements and the estimated effects on depreciation costs are shown in Table 8. A five–year straight line formula is assumed for depreciation.

Table 8. Line Productivity and Estimated Depreciation Costs
Source: Based on recommendations from the 2011 Manufacturing Workshop and Roundtable Attendees

Factor	Units	2012	2015	2020
Substrate area	m^2	0.17	0.67	1.95
Substrate utilization	%	70	80	80
Yield of good panels	%	75	90	95
Equipment uptime	%	50	75	90
Cycle time	s	120	30	20
Annual Production	1000 m^2	12	380	2100
Equipment cost	$M	60	150	250
Depreciation	$/$m^2$	1000	80	24

As stated in Section 1.3.2, calculation of depreciation costs for the first year of production is a rough approximation, since the configuration, capacity utilization, and equipment sources are uncertain. Much of the effort will be applied to equipment tuning and process improvements.

3.2.6 Panel Costs

Targets for panel costs are summarized in Table 9. These may well be refined as better understanding of the assumptions is gained with the start of volume manufacturing.

Table 9. Cost Targets for OLED Panel Fabrication
Source: Based on recommendations from the 2011 Manufacturing Workshop and Roundtable Attendees

	Units	2012	2015	2020
Materials	$/$m^2$	180	91	42
Depreciation	$/$m^2$	1000	80	24
Labor	$/$m^2$	400	40	10
Operations	$/$m^2$	120	24	8
Overhead	$/$m^2$	100	15	6
Total	$/$m^2$	1800	250	90
Total	$/klm	180	25	9

Note that the cost of materials from Figure 12 has been adjusted to allow for the assumed yields (75% in 2012, 90% in 2015 and 95% in 2020). In normalizing the cost to lumen output, the luminous emittance has been assumed to be 10,000 lm/m^2 in 2012 and beyond. The costs per kilolumen are presented in graphical form in Figure 4 (Section 1.3.2).

The high depreciation and labor costs in 2012 reflect the slow cycle times, low uptimes, and poor yield which are expected for R&D pilot lines in the introductory stage of OLED manufacturing. Significant work is being conducted by equipment developers to improve these lines and some Asian companies have put forth the investment to address these issues. Thus, there is reason to believe that between 2012 and 2015 costs will come down rapidly.

3.3 Luminaire Assembly

Most of the attention of the OLED lighting community has been focused on the architecture, manufacturing, and encapsulation of the planar panels. While OLED panels have been available for purchase for the past few years, over the past year, several new OLED luminaires, as depicted in Figure 12, have been commercially launched. Most of these have been low light output luminaires such as desk lamps and decorative chandeliers. Some higher light output designs have incorporated inorganic LEDs with OLED panels. At LIGHTFAIR 2011, Acuitiy Brands showed two OLED luminaires with planned availability in the first quarter of 2012. These luminaires, the Kindred™ and the Revel™ are suitable for indoor general illumination. The Kindred™ is an artistic luminaire with light output comparable to a fluorescent troffer while the Revel™ is a lower light output module allowing for the specific placement of individual luminaires delivering light where it is needed, thus saving energy by preventing overlighting.

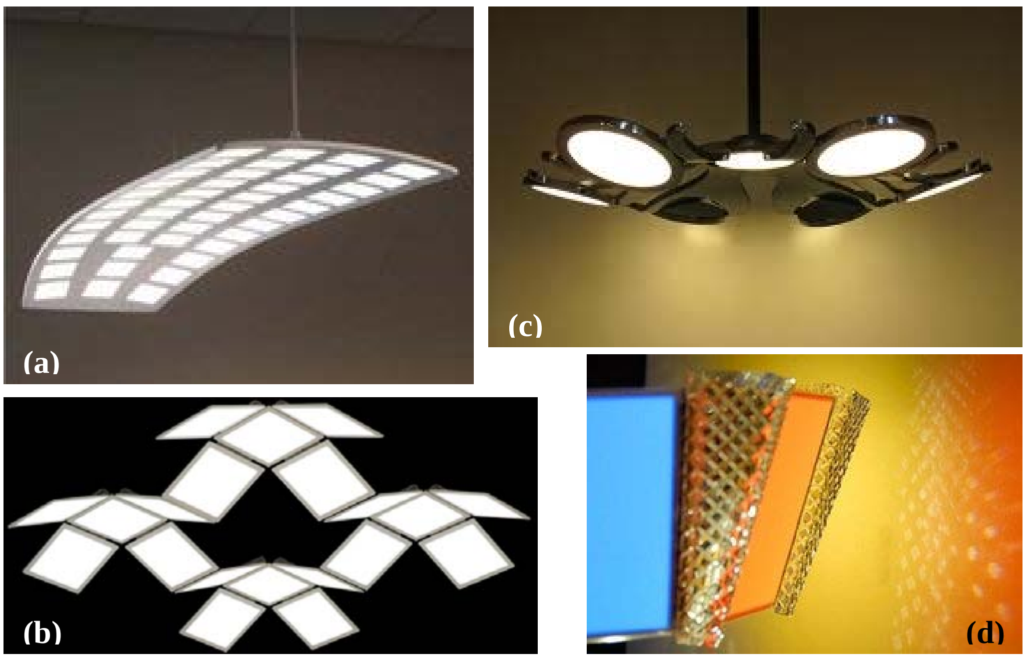


Figure 12. Recently Launched OLED Luminaires

Note:

a. The Acuity Brands Kindred™ is a slim-profile luminaire comprising 45 OLED panels made by LG Chem. It has a CRI of > 85 and delivers 3,060 lumens glare-free at 53 lm/W and with a lifetime L70 of 15,000 hours at 3,000 cd/m^2.
b. The Acuity Brands Revel™, produced by Acuity Brands, is a five panel luminaire providing 314 lumens at 48 lm/W.
c. The WAC Lighting Sol™ chandelier is a 7 panel luminaire providing around 140 lumens at up to 25 lm/W.
d. The WAC Lighting hybrid LED-OLED color tunable luminaire comprises six OLED panels and eight LEDs providing 850 lm at 35lm/W.

At LIGHTFAIR International 2011, WAC Lighting demonstrated a Sol™ chandelier comprising of seven Osram Orbeos OLED panels. The Orbeos panels used in this design deliver 25 lm/W at a brightness of around 3000 lm/m^2 and have a lifetime of around 5,000 hours. The lamp provides around 140 lumens of warm white light with a color temperature of 2800K and CRI of

80. WAC also introduced a hybrid OLED-LED luminaire comprising 6 color-tunable (RGB or white 2700-6500K) Verbatim Velve OLED panels. The OLEDs in the luminaire provide over 300 lumens at 12 watts (25lm/W) and there are eight low power LEDs providing an additional 550 lumens at 12 watts. At 3000K, the CRI of the OLEDs is 80. These new luminaires demonstrate the applicability and potential of OLED lighting for general illumination.

Although luminaire concepts have been explored and a few samples produced, the interplay between design innovation, functionality, manufacturability and cost needs further analysis. This section identifies some of the critical issues.

3.3.1 Sizing issues and brightness

OLED manufacturing costs scale more directly with panel area than light output. To achieve the desired light output in reasonably-sized luminaires, many manufacturers are targeting luminance levels of around 10,000 lm/m^2 and up to 15,000 lm/m^2 for OLED products. While it is generally accepted that higher brightness is necessary if OLEDs are to be used in low cost general illumination applications, operating at these higher luminance levels can lead to lifetime reduction, glare and thermal management issues.

Though higher brightness means more light output per area, dozens of panels are necessary to create luminaires with adequate light output for general illumination applications. In order to meet cost targets for panel manufacture and luminaire assembly, panel sizes are likely to increase. Larger panel sizes can also allow for flexibility in meeting customer preferences regarding panel size and shape, though this approach 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. While regular tile shapes are preferred in working environments, ornamental shapes can be desired in residential lighting. Production of arbitrary shapes will be difficult until fabrication using printing processes on flexible substrates becomes economic.

3.3.2 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. In the 2011 MYPP, DOE performance targets for 2020 include achieving color control within a two SDCM bin and brightness uniformity of 10% across a 200 cm^2 panel. Panel to panel variations and variations over lifetime are also concerns. In particular, color variations over lifetime can lead to major issues when replacement panels are installed adjacent to aged ones in a luminaire consisting of multiple tiles.

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 for color and efficacy 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 efficacy, color, and lifetime.

3.3.3 Light Shaping

Most OLED panels emit light uniformly in all directions, giving a Lambertian angular distribution. Lamberitian emission can work well in certain applications, such as in lighting a space with a large number of appropriately positioned, lower light output luminaires. However, for most conventional general illumination applications, Lambertian emission is not desired as it leads to glare and overlighting of the region directly beneath the luminaire. Other light distributions may be preferred which can provide even illumination on the work surface and minimize glare. 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. Unfortunately, many of these light shaping approaches lead to a small decrease in efficiency.

3.3.4 Electrical circuits

Standardized interfaces, such as connectors between the electrodes or bus lines, should be established in the panel and the external power source. Drivers should allow for voltage increase to compensate for aging, but too much headspace leads to reduced efficacy. Connections on both sides of each tile can be considered to allow for simple tile replacement. 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 and add significantly to the cost. Such enhancements, however, are beyond the scope of this Roadmap and will not be considered further here.

3.3.5 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. As brightness is increased, temperature increases. It has been observed that a 10°C rise in temperature corresponds to a reduction in lifetime of around a factor of two. 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 2011 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.

3.3.6 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.

3.3.7 Product differentiation and market expansion

The primary motivation for the DOE SSL Program is to increase overall lighting efficiency with a focus on general illumination. However, it may be necessary for emerging technologies, such as OLED lighting, to initially build their business in 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 novel, thin form factors. Much of the excitement has been caused by design concepts that are based upon thin profile, flexible or conformable substrates, arbitrary shapes and variable color. Reliable analyses of customer expectations and market forecasts would be valuable. Also competing in this space are LED-based large area light sources such as edge lit panels which may offer the thin profile panel lighting at a lower cost and longer lifetime.

3.4 Substrates and Encapsulation

When it comes to panel fabrication, which is discussed in the sub-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 and architectures. 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, as the cost of OLED products is driven down, 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 road-mapping a manufacturing evolution is not possible except in a broad outline.

3.4.1 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. Most OLED research and development has been done using display-grade borosilicate glass, but recognizing the cost constraints, more emphasis is being placed on process development on residential, soda lime float glass. In the display industry, the use of flexible glass substrates is being explored and such substrates could also be an option for OLED lighting as well, if costs targets can be achieved. Metal foil materials being explored include aluminum and stainless steel for use with top emitting OLED devices. 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.

Over the last two to three years, discussions of prototype lamps have led to suggested metrics 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 7% (transmittance 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.

3.4.2 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^{-4} cc/m^2·day·atm. The absence of pin-holes is essential, as well as the use of a material with very low bulk permeability. Unfortunately, measurement of permeation rates below approximately10^{-4} g/m^2·day requires highly specialized equipment that is not available to most manufacturers and even where available, such testing is expensive making it difficult to confirm permeation rates across large volumes of barrier layers in manufacture. Furthermore, 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. By reducing the number of layers in the barrier film or reducing the deposition time by techniques such as high throughput atomic layer deposition, barrier film costs may be reduced. Costs should be reduced to less than \$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.

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

3.4.3 Transparent Anodes

The material selection and processing of the transparent anode was identified at the Boston 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 20 Ω/square;
- Transmission: 85% across the visible spectrum;
- Work Function: preferably above 5eV and compatible with OLED materials;
- Surface Roughness: $R_{rms} < 2$ nm $R_{peak\text{-}valley} < 20$ nm;
- Chemical Migration: no escape of materials that can damage the organic layers; electrochemically stable with cathode metals;
- No undue reliance on scarce materials;
- Amenable to low cost processing; and
- Compatible with OLED processing (cleaning, patterning, deposition materials and parameters, adhesiveness).

Transparent conducting alternatives to ITO are being developed under the DOE Core and Product Development R&D programs. Doped ZnO, developed by Arkema, has demonstrated feasibility as an ITO alternative and work is underway to optimize OLED processing parameters on doped ZnO anodes. PPG is currently investigating low cost deposition of TCOs on soda lime glass substrates with good results. Other alternative transparent conductors include nanowire or nanotube approaches, such as the silver nanowire solution deposited films explored by Cambrios and Plextronics. 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 with the anode of a neighboring segment. The other is to supplement the transparent conductor by metallic bus bars or grids.

Since the grid lines should occupy only a small fraction of the area, 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. 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. Furthermore, costs should be carefully considered when choosing patterning or printing method to deposit such current spreading layers.

Adoption of either approach means that the sheet resistance requirements are relaxed. However, the lower the sheet resistance the larger the pixel or grid size can be, translating to higher fill factor and greater light output per area.

3.4.4 Outcoupling Enhancement Structures

The refractive index of OLED emitter layers and the ITO anode is typically around 1.8. Thus, most of the light is internally reflected, becoming trapped in the device layers and absorbed after multiple bounces rather than escaping 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 such that horizontal wave-guiding is reduced, incorporating scattering particles or surface plasmon enhanced structures). The design and fabrication of such solutions must be accomplished with great care so as not to degrade the current flow or light creation. Furthermore, any techniques developed should be scalable to large areas and amenable to low cost processing.

Other proposed solutions involve adding structures between the transparent electrode and/or 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 and spectral dependence on the enhancement technique should be considered in tailoring the device to achieve certain color characteristics. Whenever these structures are included inside the transparent substrate, compatibility with the neighboring layers must be considered, both in respect to fabrication and operation.

The fraction of created light that escapes from the panel should be increased to 50% (2.5x) by 2015 and 70% (3.5x) by 2020. 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.

3.4.5 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 can be reduced by printing the getter onto the cover glass. However, further product development is necessary in this area to achieve the lower cost requirements. 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.

3.5 Batch Processing on Rigid Substrates

Within the OLED display industry, vacuum processing of thin-film devices on glass substrates is relied upon for OLED fabrication. The process flow can be divided into three distinct phases, substrate preparation, deposition of the organic materials and cathode, and encapsulation. Issues concerning integrated substrates and encapsulation were addressed in Section 3.4; therefore, the emphasis within this section covers the deposition of the organic materials and cathode.

3.5.1 Deposition of Organic Layers

The requirements of deposition tools for organic materials were discussed at length in earlier versions of this Roadmap. The discussion here is concentrated on assessing recent progress and pointing out the need for further development in order to meet cost targets.

The Japanese companies Tokki and Ulvac have gained significant experience from developing deposition equipment for display applications and therefore it is necessary to examine how well their systems can be adapted for lighting applications. However, several additional companies are developing tools that may be more appropriate for lighting, including Sunic (Korea), Aixtron (Germany) and two U.S. suppliers, Applied Materials and Veeco Instruments.

Equipment from Sunic is being evaluated for lighting applications at the Fraunhofer Institute for Photonic MicroSystems (IPMS) in Dresden. Twelve panels with active area of 100 mm x100 mm are processed simultaneously on a 370 mm x 470 mm substrate. Consistency of performance of tandem structures with 12 organic layers was reported in May 2010.[16] Good process reproducibility was found comparing run-to-run and day-to-day parameter variation.

[16] Michael Eritt et al, Fraunhofer IPMS, “Up-Scaling of OLED Manufacturing for Lighting Applications”, SID Digest 2010, 699-702, paper 46.4.

The standard variation in intensity was less than 2% and color changes contained within three SDCM. However larger color variations were found between panels occupying different positions on the substrate. This demonstrates the importance of studying deposition onto multiple panels on a single substrate, even though it may be too early to extend these studies to very large areas.

Fraunhofer IPMS have used the same equipment to produce 330 mm x 330 mm panels and plan to tile nine of these together to produce a 1 m^2 OLED light source as one of the deliverables for the OLED100.eu project. Applied Materials has designed a deposition system for lighting applications based upon its vertical in-line New Aristo platform, in which the frame mask is attached to the substrate and moves with the substrate. This promises significant savings in handling time.

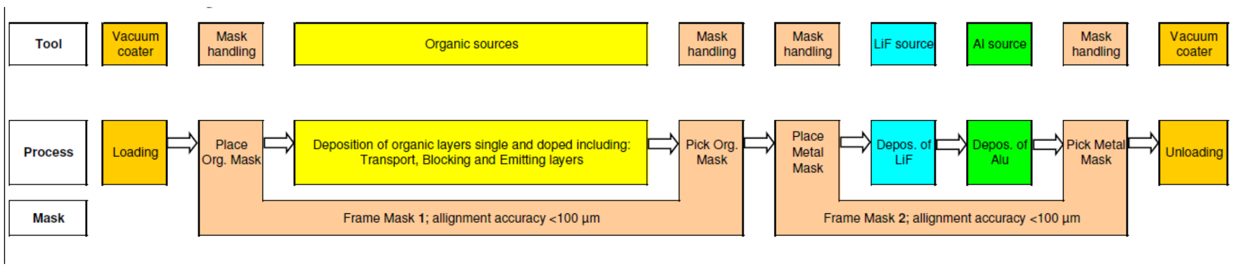


Figure 13. In-line system developed by Applied Materials for Lighting Applications
Source: Dieter Wagner, Applied Materials, Intertech-Pira OLED Summit, September 2010

This system achieves material utilization of 50%, thickness variations of less than ±3%, continuous production for up to one week, TACT time as low as 80 seconds and annual capacity of up to 220,000 m^2 per year on 730 mm x 920 mm substrates. The system is being tested within the German collaborative project Light in Line (LILi).

Although this system offers significant savings in substrate handling time, faster deposition speeds are also needed. Aixtron has shown that this can be achieved by using an inert carrier gas to transport the organic materials from source to substrate. By using a close-coupled shower head, their Organic Vapor Phase Deposition (OVPD) equipment is able to achieve high levels of material utilization and good uniformity. This approach can be used to deposit multiple organics within a chamber and to allow gradual transitions from one material to the next when graded layers are needed.

One further challenge with traditional deposition sources is to minimize the time spent by fragile organic molecules at the high temperatures required for evaporation. Flash evaporation is being explored by several companies and Aixtron feeds an evaporator with aerosol powder that is maintained at a relatively low temperature.

In addition to the testing of innovative deposition tools in Europe, Veeco Instruments has introduced a new linear source that promises high throughput and excellent control at lower cost.[17] The vapor injection source technology introduced by Kodak is capable of depositing 30 nm thick layers in 15 seconds.[18] The multiplicity of new ideas has led to including the development of improved deposition tools in Task M.O1 for the upcoming solicitation.

3.5.2 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, but may not be fast enough to meet the aggressive DOE targets for processing time. Other techniques like magnetron sputtering and ion-beam assisted deposition are also available, but greater care is needed to avoid damage. The electron injection layer can be modified to protect the more sensitive materials in the emissive layers.

3.5.3 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; and
- 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 2012 to 2015. This is one of the topics that will be studied during round two of the Manufacturing Initiative.

[17] John Patrin, Veeco, "Development of Linear Evaporation Sources for OLED Display and Lighting Manufacturing", Intertech-Pira OLED Summit, September 2010

[18] TK Hatwar et al, Kodak, "Advanced Process Technology for OLED Manufacturing", IDMC 2009, paper S05-03

3.6 Introduction of Printing Techniques

The difficulty of achieving substantial cost reduction using traditional microelectronic manufacturing methods has led many to promote the adoption of printing techniques. Some have proposed a complete transformation to R2R manufacturing using solution processing on flexible substrates. The previous editions of this Roadmap included cost projections for this approach, providing an alternative strategy for reaching panel cost targets below $10/klm. However, accurate assessment of these estimates remains elusive, and no announcements have been made of pilot production lines in the U.S.

Nevertheless, progress in SSL projects and elsewhere has confirmed that printing techniques could offer significant improvement in specific process steps. These opportunities are described in this section, but reconsideration of an integrated R2R strategy will be postponed until future Roadmap updates. The major barriers to more immediate adoption are:

- *Learning Curve*: Although solution processing with linear sources offers the promise of reduced waste of the materials to be deposited, running R2R equipment, even at modest speeds, requires substantial investment to meet the cost of integrated substrates. Unless the manufacturing processes have been tested thoroughly, the early stages of high-volume production could lead to even larger losses than are anticipated for sheet processing.
- *Control of thin layers*: Very little experience has been gained in the application of printing techniques to the formation of layers of thickness 10-50 nm. The solid content of the inks used to carry the active molecules is so low that the liquid layer must be significantly higher and the efficacy of solvent removal during drying is critical. The efficacy of cleaning and other surface preparation techniques must also be confirmed in an R2R environment. These two issues are the focus of the round one SSL manufacturing project by GE and DuPont.
- *Porosity of plastic substrates or covers*: Although metal foil can be used either for the manufacturing substrate or the cover, the second encapsulating material must be transparent. The viability of high-volume production of barriers for plastic rolls or in-situ deposition of such barrier films at acceptable costs is still unproven. Although ultra-thin glass could be used as covers for conformable panels, the current cost (>$30/m^2) is well in excess of SSL targets.

3.6.1 Solution processing of anodes and hole injection layers

Many of the alternatives to ITO as transparent conductors can be deposited in solution. For example, Cambrios has deposited silver nanowires by slot-die coating on 1100 mm x 1350 substrates mm with about 10% uniformity, achieving sheet resistance of 30 Ω/square and optical transmission over 95%. They also regularly deposit such films by R2R techniques on plastic. Cambrios has demonstrated that the nanowire layers can be patterned directly, using gravure, reverse offset or flexo-printing. Alternatively, the U.S. company nTACT has developed two methods for low resolution patterning within slot-die coating.

The major problem with the nanowire conductors is the surface roughness, which is typically around 20 nm (RMS). One goal of the SSL Product Development project by Cambrios and Plextronics is to show that the nanowire layers can be effectively planarized by the hole-injection layer (HIL). Although this approach leads to larger leakage currents, the operating voltages and lifetime appear to be similar to those obtained with ITO anodes.

Plextronics has argued that since the HIL is usually the thickest layer in the active stack, the introduction of just one solution-processed layer can result in significant cost savings. Their estimate of 35% overall cost reduction is based upon the following assumptions:[19]

- 4X improvement in throughput;
- 4-5X improvement in material utilization; and
- 25% yield improvement.

Clearly such large savings will only be possible with respect to a modest base, but this suggestion appears to offer one route to achieving process cycle times below 30 seconds. Work by Panasonic Electric Works and Tazmo Co.[20] has demonstrated that the thickness of 30 nm layers can be controlled to within ±3% with the linear coater (or substrate) moving at 0.2 m/s.

3.6.2 Solution Processing of Emission Layers

The goal of the round one manufacturing project by GE and DuPont is to improve the performance of solution-processed OLEDs. HIL and emitter materials designed by DuPont are being adapted for use in GE's R2R production line. Preliminary results have led to efficacy of 24.5 lm/W (without out-coupling enhancement) with CRI at 88. Lifetimes for red and green components are good, but the blue emitter still needs further work.

The work performed by GE in this project is focused upon yield improvement through the incorporation of better surface preparation techniques and improved control over the deposition process, primarily through the replacement of micro-gravure printing by slot-die coating.

In a separate collaboration with Dainippon Screen, DuPont is exploring the use of nozzle printing to deposit stripes of red, green and blue emitters. The nozzle head speed is 2 to 5 m/s and the use of 15 nozzles leads to a cycle time less than 3 minutes for a 730 mm x 920 mm substrate. Thickness variation is typically 2 nm. This approach has been used to create white OLED panels with color temperatures that can be controlled by the user to between 2700K and 6500K.

[19] Matthew Mathai, Plextronics, "The Role of Hole Injection Layer in Enabling OLED Device Performance and Defect Tolerant Manufacturing, CCR NIChE Workshop", June 2010

[20] Takuya Komoda, Panasonic Electric Works, "High Performance White OLEDs for Next Generation Solid State Lightings", SID 2011 Digest 1056-9, paper 72.1

3.6.3 Sheet Processing on Flexible Substrates

The potential for sheet processing on OLEDs on plastic substrates has been explored in SSL projects by Add-Vision. Their approach is based upon polymer emitters and air-stable cathodes which lead to relatively modest performance, when measured by efficacy or lifetime. Nevertheless, they have demonstrated a capability to manufacture and deliver OLED lighting at low cost on inexpensive equipment. Transfer of some of their techniques to devices with higher performance may lead to substantial savings. Their achievements include:

- Production on A4 size plastic sheets using gravure printing;
- Reduced material waste;
- 1 m/s printing speeds and rapid drying;
- Roll-based encapsulation;
- Barrier films with water vapor transmission of $<10^{-3}$ g/m^2/day;
- Product shelf lives of over 1 year;
- Yields of 90% for devices as deposited and 80% for encapsulated panels; and
- Capital costs of ~$1M and production costs of $300/m^2.

Sheet processing on flexible substrates is also being pursued by the Holst Centre in Eindhoven. Their project "Printed Organic Lighting and Signage" involves about 100 scientists and engineers from the Centre and their industrial partners and is funded partly through the European Community project Fast2Light. The main characteristics of their approach are:

- Processing on metal and plastic foils – using 3 layer barriers (SiN/polymer/SiN);
- Innovative device designs to minimize the number of process steps for OLED foils;
- Low-cost alternatives to indium-tin oxide for transparent electrodes; by using printed bus bars they have built devices using PEDOT-PSS in the anodes, despite its high resistivity;
- Top and bottom emission configurations; and
- Optimized light out-coupling.

Using slit-die coating, the team has successfully deposited organic layers with thickness between 30 and 200 nm with control to within 1 to 2%. After the methods under development have been fully tested in this format, they will be transferred in early 2012 to R2R equipment with a web width of 30 cm.

4. Manufacturing Research Priorities

As discussed in Chapter 5 of the March 2011 SSL MYPP, DOE supports research and development of promising SSL technologies. [21] 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 eight 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 2011 Manufacturing Roadmap. To develop the 2011 updated Roadmap, DOE first held SSL roundtable sessions in Washington, D.C. in March, 2011, where initial tasks were developed. The tasks were further discussed and refined in April, 2011 at the Manufacturing Workshop in Boston, MA. Using recommendations and further review, DOE further distilled the recommended tasks to a short list of four, defining the task priorities as described in below.

4.1 Current Manufacturing Priorities

The following priorities were set based upon nominations from the 2011 Manufacturing Roundtable and discussions at the 2011 Manufacturing Workshop. Where possible, task metrics and targets are listed for each of the priority research areas.

In addition to the several specific metrics related to cost called out for each task, overall 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 5 of the 2011 MYPP.

[21] http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mypp2011_web.pdf

4.1.1 LED Manufacturing Priority Tasks for 2011

DOE identified the following priority LED manufacturing R&D tasks based on discussions at the Roundtables and Manufacturing Roadmap Workshop.

M.L1. Luminaire/Module Manufacturing: Support for the development of flexible manufacturing of state-of-the-art LED modules, light engines, and luminaires. Suitable development activities will focus on advanced LED packaging and die integration (e.g. COB, COF, etc.), more efficient use of raw materials, simplified thermal designs, weight reduction, optimized designs for efficient manufacturing (such as ease of assembly), increased integration of mechanical, electrical and optical functions, and reduced manufacturing costs. The work should demonstrate higher quality products with improved color consistency, 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	$50/klm	$10/klm
Assembly Cost ($)		50% reduction every 2-3 years
Color Control (SDCM)	7	4

Industry stakeholders strongly supported bringing advanced integration and manufacturing concepts to LED luminaire manufacturing. Projects under this task should help manufacturers focus on reducing costs and waste in their processes while continuing to improve product performance.

M.L3. Test and Inspection Equipment: Support for the development of high-speed, high-resolution, non-destructive test equipment with standardized test procedures and appropriate metrics for each stage of 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-situ process monitoring, in-line process control, or final product testing/binning. Suitable projects will develop and demonstrate effective integration of test and inspection equipment in high volume manufacturing tools or in high volume process lines, and will identify and quantify yield improvements.		
Metric(s)	**Current Status**	**2015 Target(s)**
Throughput (single bin units per hour)		x2 increase
Cost of Ownership		2-3x reduction every 5 years
$/Units per hour		

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 at the wafer level 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 faster and improved measurements of LED performance at realistic operating temperatures. This information would assist luminaire manufacturers in their design of more consistent luminaires.

4.1.2 OLED Manufacturing Priority Tasks for 2011

The following priorities for OLED manufacturing R&D were identified by DOE based upon discussions at the 2011 Manufacturing Roundtable and Workshop.

M.O1. OLED Deposition Equipment: Support for the development of manufacturing equipment enabling high speed, low cost, and uniform deposition 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 under this task should be used to manufacture integrated substrates or the OLED stack. Proposals must include a cost-of-ownership analysis and a comparison with existing tools available from foreign sources.

Metric(s)		**2015 Target(s)**
Throughput	Overall	> 100,000 m^2 per year of good product
	Minimum Product Size	6”x 6”
	Area Utilization	80-90%
	Uptime of Machine	80-90%
	Speed (web)	2-10 m/min
	Cycle Time (sheet)	$\leq$ 60 s
	Yield	80-95%
Materials Utilization		Dry process on sheets: 70-80% Wet process on web: 90-95%

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, light extraction layers and encapsulation layers.

Various approaches to manufacturing equipment development can be taken such as modifying an existing tool or process, developing a novel tool compatible with the overall process for better yield/lower cost, or research into the equipment improvements necessary for a complete OLED deposition process. Deposition equipment is needed for integrated substrates, as well as the OLED stack. While encapsulation equipment is needed and can be investigated under this task area in combination with other tool development, it is not the focus of this area because large investments in this area are being made by the solar and display industries and while OLED lighting requires higher performance than these applications, current investment may be better spent in development of tools more specific to OLED lighting.

All research projects for Task M.O1 need focus on the overriding metric of cost per area of good product and total cost-of-ownership. 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 2011 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.O3. OLED Materials Manufacturing: Support for the development of advanced manufacturing of low cost integrated substrates and encapsulation materials. Performers or partners should demonstrate a state of the art OLED lighting device using the materials contemplated under this task.		
Metric(s)		**2015 Target(s)**
Substrate	Total cost – dressed substrate	$52/m^2$
	Transmission	>85%
	Surface Roughness	Rrms < 2nm; Rpv < 20nm
	Sheet Resistance	<10 ohms/square
Encapsulation	Permeability of H_2O	10^{-6} g/m^2/day
	Permeability of O_2	10^{-4}cc/m^2/day/atm
	Cost	$10/m^2

Task M.O3 focuses on the development of processes that facilitate manufacturing of high-quality materials for OLED panels. Since cost reduction is critical, establishing the optimal balance between material quality and cost should be an important component of these projects. Support is focused on the integrated substrate and encapsulation materials rather than the organic materials within the OLED stack. This is due to the potential cost reduction that can be afforded by improvements in these areas, as shown in Figure 3. Although the price and performance of the active layers needs improvement, it is hoped that research and cost reductions in this area will be driven by the display industry.

For projects focusing on the integrated substrate, DOE includes metrics that address cost while maintaining other attributes (defined in the MYPP) relating to light absorption, surface roughness, sheet resistance, and permeability to water and oxygen. 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 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 is critical.

5. Standards

This section summarizes the different types of standards that are of interest to the SSL industry as well as the progress towards developing them. This is not intended to be a complete exposition on the subject, but hopefully will provide a useful reference point in ongoing conversations about SSL standards. As noted in the first Roadmap and again in the 2010 edition, there are several uses of the term "standards" that have come up during discussions:

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

These are generally considered to be *industry* standards, but, 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”. While not always popular, the do provide a useful framework to keep unsafe or substandard products off the market. 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.

DOE works with a number of Standards Development Organizations (SDO) 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 Lighting Group (ANSLG), 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 processes/best practice and interoperability.

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 define the standard.

5.1 Definitions

5.1.1 SSL product definitions

The IES has done considerable work and service to the industry by promulgating RP-16-2010, *Nomenclature and Definitions for Illuminating Engineering*, which defines the components and products relating to LEDs for lighting. While this Roadmap may appropriately offer up suggestions for additional needs definitions, this work is best handled within 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-based 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 June 2011 release of a guide, *LED Luminaire Lifetime: Recommendations for Testing and Reporting*,[22] developed jointly with a Next Generation Lighting Industry Alliance (NGLIA) working group. An important message from this work is that more attention should be paid to more fully understand and account for the variety of failure mechanisms that can affect product lifetime. The effort will lead to more realistic claims for luminaire performance, with consequences for market acceptance and the economics of SSL. There is also an excellent discussion of the nuances of reliability and lifetime characterization for LED packages and LED-based luminaires in two DOE SSL factsheets, *LED Luminaire Reliability*[23] and *Lifetime of White LEDs.*[24]

5.2 Minimum performance specifications

EISA 2007 and other amendments to the Energy Policy and Conservation Act established mandatory minimum energy efficiency requirements for several lighting technologies such as general service fluorescent lamps, incandescent reflector lamps, general service incandescent lamps, and compact fluorescent lamps. Although currently no federal efficiency standards exist for LED and OLED lighting, effective in 2020, DOE is required to establish energy conservation standards for "general service lamps" including LEDs and OLEDs.

The implementation of minimum performance specifications has 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 of 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

[22] http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/led_luminaire-lifetime-guide_june2011.pdf
[23] http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/luminaire_reliability.pdf.
[24] http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/lifetime_white_leds.pdf

introduction of SSL products. DOE has communicated these kinds of 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 the harmonization of international standards.

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 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*, in mid-2011. While TM-21 does provide a means to estimate the luminaire lumen depreciation from multiple temperature data from LM-80 tests, DOE cautions, however, that this does not directly translate into a measurement of lifetime for a luminaire which may depend on other failure mechanisms.

Issues associated with chromaticity variations in SSL products have been discussed in previous sections. ANSI C78.377-2008, *Specifications for the Chromaticity of Solid-State Lighting Products,* was introduced as a standard for specifying LED binning ranges. In the last year NEMA published SSL 3-2010, to improve understanding on color specifications between chip manufacturers and luminaire makers. DOE is also supporting work at NIST on a new color rendering standard, the *Color Quality Scale*, which should be released soon.

In addition, the Environmental Protection Agency's (EPA) Energy Star program has defined test procedures for determining which LED products are to receive the Energy Star certification. DOE (Regulatory Group) provides ongoing technical support to the Energy Star labeling program which has been recently undergoing several procedural modifications. In order for an LED product to receive Energy Star certification, it must be tested at a laboratory holding appropriate accreditation. Qualification criteria for luminous efficacy of non-directional LED luminaires is at least 65 lm/W (prior to 9/1/2013) and greater than or equal to 70 lm/W (after 9/1/2013) in accordance with the IES LM-82-11 report (in draft as of February 2011). Lumen maintenance measurements must comply with IES LM-80-08 and are to be provided by the LED manufacturer. For LED luminaires, the IES-LM-79 approved methods and procedures are used for performing measurements of chromacity and power consumption.

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 formats

This section discusses two types of standardized reporting formats: standardized reporting of luminaire component performance and standardized reporting of end product lighting performance. Buyers of lighting components continue to ask for a standard reporting format to facilitate the comparison of alternative choices. For example, they have also asserted a need for better reporting standards for drivers. This latter issue was discussed during the November 2010 Roundtable meetings and it was agreed that standardization in the reporting of driver performance would alleviate the burden of driver testing that currently falls to the luminaire manufacturer. A standard reporting format would facilitate the use and development of analysis, simulation, and design tools for luminaire manufacturers. Section 2.3.3 provides more information on recommended driver performance data to include in a standard reporting format. A standardized reporting format is also essential for the end-product. Lighting designers, retailers and specifiers have for some time been calling for just such a standard data format for LED-based luminaires.

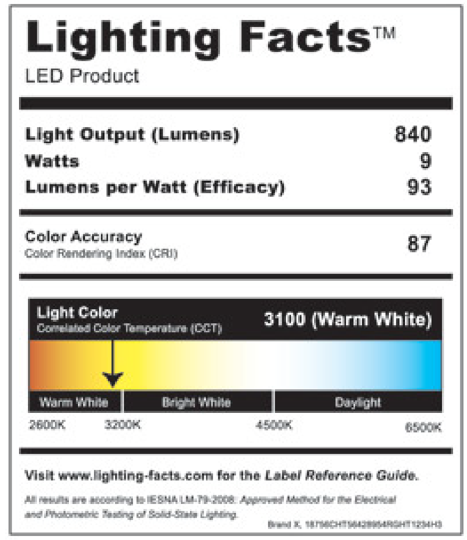


Figure 14. Example of DOE Lighting Facts Label
Source: DOE, Lighting Facts

DOE recognized the importance of introducing standardized reporting of LED-based lighting product performance for the consumer. In December 2008, Lighting Facts™, a voluntary pledge program, was created to assure that LED-based lighting products are represented accurately in the market. The Lighting Facts label provides a summary of product performance data. The label guards against exaggerated claims, and helps ensure a satisfactory experience for lighting buyers. Luminaire manufacturers who pledge to use the label are required to disclose performance data in five areas—light output (lumen), power consumption (Watts), Efficacy (lumens per Watt), correlated color temperature (CCT), and color rendering index (CRI)—as measured by the industry standard for testing photometric performance, IES LM-79-2008. Additional metrics related to reliability, product consistency, construction, and other parameters may be considered in future editions of the label.[25] Figure 14 shows an example of what the Lighting Facts™ label looks like.

In addition, the Federal Trade Commission (FTC) mandated that by January 1, 2012 all lighting manufacturers will be required to incorporate labeling on their medium screw base bulb packaging. The packaging will emphasize brightness, energy cost, life expectancy, light appearance, wattage and whether the bulb contains mercury.

DOE and the FTC have worked closely throughout this process and are both committed to assuring that products perform as claimed. The FTC label is primarily a consumer label, while the DOE label is a valuable tool for buyers. In fact, the FTC encourages stakeholders to reference

[25] http://www.lightingfacts.com/default.aspx?cp=content/about

the DOE Lighting Facts program, especially as DOE works to improve bulb life testing methodologies for LED lamps.[26]

More guidance on the DOE Lighting Facts™ label can be found at: http://www.lightingfacts.com/default.aspx?cp=content/ftclabel

5.5 Interoperability/physical standards

Similar to the standardization of reporting formats, 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. 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 challenges.

The other type includes the interfacing standards that enable complete products or component parts to be interchanged in a seamless fashion. NEMA is currently addressing this issue in part, with its issuance of NEMA LSD 45-2009, *Recommendations for Solid-State Lighting Sub-Assembly Interfaces for Luminaires.* Interconnects within an SSL luminaire have an added challenge to manage the thermal aspects of the system in order to keep the LED and electrical components cool enough such that light output and lifetime remains acceptable. The NEMA LSD 45-2009 provides the best industry information available for electrical, mechanical, and thermal SSL luminaire interconnects, and is intended to document existing and up to date industry best practices.[27]

The lighting manufacturers have also indicated a strong need for improved interoperability between solid state lighting products and conventional dimming controls. NEMA SSL-6, *Solid State Lighting for Incandescent Replacement – Dimming*, aims to address some of these issues by providing guidance on the dimming of SSL products and the interaction between the dimmer (control) and the bulb (lamp). However, additional standardization for driver controls is still necessary as discussed in Section 2.3.3.

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[26] http://www.lightingfacts.com/downloads/FTC_Guidelines_Consumer_April11.pdf
[27] LSD 45 is available as free downloads from NEMA at: http://www.nema.org/stds/lsd45.cfm#download

Furthermore, in early 2010, an international group of companies from the lighting industry initiated the formation of the Zhaga Consortium, an industry-wide cooperation aimed at the development of standard specifications for LED light engines. Zhaga aims to provide standardization within five interface areas for the different lighting applications. These include:

1. Dimensional/Mechanical (incl. "socket")
2. Power, insulation, earth for example
3. Controls
4. Photometric (lumen output, color, light distribution)
5. Thermal[28]

In February 2011, the Zhaga Consortium approved the first light engine specification for socketable LED light engines with integrated control gear. This specification describes the interfaces of a downlight engine. These specifications will be made available for public download later this year. Also, LED light engine specifications are currently being developed by Zhaga for a spotlight, streetlight, indoor lighting and compact engine.[29]

5.6 Process standards and best practices

When the DOE manufacturing initiative first began in 2009, there was a great deal of hesitation regarding the development of manufacturing or process standards for LED technology. But gradually as the industry has matured, this perspective has changed, due in large part to the efforts of Semiconductor Equipment and Materials International (SEMI) and its members who formed a HB-LED Standards Committee in November of 2010 with strong industry support among device makers, equipment manufacturers and material suppliers. Tom Morrow, EVP of the Emerging Markets Group at SEMI, summarized this activity at the Boston Workshop.[30] This section summarizes a number of his key points along with some additional observations noted during the 2011 DOE manufacturing events.

Perhaps most important for LED product manufacturers, good standards allow them to purchase equipment and materials from multiple vendors at lower cost, improved quality, and with minimum need for modification or adaptation to a particular line. As a consequence, manufacturers have more time and resources to focus on those aspects of their business that genuinely add value to their products. For suppliers to the industry, standards reduce the need for excess inventories of many similar yet slightly different materials and parts. Reduced inventory means lower costs, faster deliveries, and again more time to focus on adding value and refining the quality of the supplied materials.

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[28] Zhaga Consortium, "Consortium for the Standardization of LED Light Engines", http://www.zhagastandard.org/data/downloadables/2/0/5/20100123_zhaga_vision_-_for_website.pdf, (Accessed June 3, 2011).

[29] Zhaga Consortium, "Approved Zhaga Specifications", http://www.zhagastandard.org/method/progress.html (Accessed June 3, 2011).

[30] Copy of the presentation is available on the DOE SSL website: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/morrow_collaboration_boston2011.pdf

Obviously it is not possible to do everything at once, so the SEMI HB-LED Standards Committee has currently organized into three task forces: Wafers, Factory Automation Interfaces, and Assembly. The Wafers Task Force is focused currently on defining the physical geometry for HB-LED 150 mm diameter sapphire substrates. The Factory Automation Interfaces Task Force defines physical interfaces of substrate carriers and process and metrology tools. Finally, the Assembly Task Force is chartered with defining the physical and packaging attributes of LED die so that they might be optimized for handling and common processing or assembly equipment. Anywhere from six to eleven companies are contributing to each of these efforts.

It's worth observing that these are very detailed aspects of manufacturing that do not much affect the relative performance or quality of individual HB-LED products. Because these are "non-competitive" issues to a large extent, that makes them all very good candidates for standardization. Cooperation in this case benefits everyone. One of the early fears and impediments to standardization was the thought that competition and innovation would be inhibited. It clearly is not in such cases as these, and as this realization spreads, more projects of this type will be identified and pursued.

In addition to the work specific to HB-LEDs, SEMI also offers support for environmental health and safety standards, again something that the entire industry can profitably support.

Appendix A Standards Development for SSL

Because standards development will aid in increasing market confidence in SSL performance, to accelerate the development and implementation of needed standards for solid-state lighting products, DOE works closely with a network of standards-setting organizations and offers technical assistance and support.

Since 2006, DOE has hosted a series of workshops to bring together the key standards organizations and foster greater coordination and collaboration among related efforts. These workshops have been attended by representatives and committee members from the major standards groups: American National Standards Lighting Group (ANSLG), 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).

Below is a summary of all of the current and developing standards and white papers pertaining to SSL.

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.[31]
- **IES LM-80-2008, Approved Method for Measuring Lumen Depreciation of LED Light Sources,** defines a method of testing lamp depreciation. LED packages, like most light sources, fade over time, which is referred to as lumen depreciation. However, because LED packages have a long lifetime in the conventional sense, they may become unusable long before they actually fail, so it is important to have a sense of this mode of failure. LM-80 establishes a standard method for testing LED lumen depreciation. Note that LED source depreciation to a particular level of light, should not be construed as a measure of lifetime for luminaires, however, as other failure modes also exist which can, and in most cases will, shorten that lifetime.

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

- **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.[32]
- **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.[33]
- **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.[34]
- **NEMA SSL-1, Electric Drivers for LED Devices, Arrays, or Systems**, provides specifications for and operating characteristics of non-integral electronic drivers (power supplies) for LED devices, arrays, or systems intended for general lighting applications.
- **IES G-2, LED Application Guidelines,** presents technical information and application guidance for LED products.
- **NEMA SSL-6, Solid State Lighting for Incandescent Replacement – Dimming,** provides guidance for those seeking to design and build or work with solid state lighting products intended for retrofit into systems that previously used incandescent screw base lamps. Addresses the dimming of these products and the interaction between the dimmer (control) and the bulb (lamp).

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 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.

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[32] 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.

[33] 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.

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

- **LM-XX1, Approved Method for the Measurements of High Power LEDs**
- **LM-82-11, LED "Light Engines and Integrated Lamp" Measurements**
- **LM-XX3, Approved Method for Measuring Lumen Maintenance of LED Light Engines and LED Integrated and Non-Integrated Lamps**

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

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
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 U.S. 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.*

Appendix C DOE SSL Manufacturing R&D Tasks

The complete list of SSL Manufacturing R&D Tasks developed in 2010 and refined in 2011 is below. Priority tasks for 2011 are indicated with an asterisk. Some descriptions of non-prioritized tasks have been updated from the 2010 versions.

LED Tasks

***M.L1.**	**Luminaire/Module Manufacturing** Support for the development of flexible manufacturing of state of the art LED modules, light engines, and luminaires.
M.L2.	**Driver Manufacturing** Improved design for manufacture for flexibility, reduced parts count and cost, while maintaining performance
***M.L3.**	**Test and Inspection Equipment** Support for the development of high-speed, high-resolution, non-destructive test equipment with standardized test procedures and appropriate metrics
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** This task supports the development of improved manufacturing and improved application of phosphors (including alternative down converters) used in solid state lighting.

OLED Tasks

***M.O1.**	**OLED Deposition Equipment:** Support for the development of manufacturing equipment enabling high speed, low cost, and uniform deposition of state of the art OLED structures and layers.
M.O2.	**Manufacturing Processes and Yield Improvement:** Develop manufacturing processes to improve quality and yield and reduce the cost of OLED products.
***M.O3.**	**OLED Materials Manufacturing:** Support for the development of advanced manufacturing of low cost integrated substrates and encapsulation materials.
M.O4.	**Back-end Panel Fabrication:** Tools and processes for the manufacturing of OLED panels from OLED sheet material.