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

For several years, the SSL R&D Multi-year Program Plan (MYPP) has guided the Core and Product Development R&D programs which have greatly aided that progress. Now, as the market begins to develop, new challenges present themselves, additional planning is needed. This SSL Manufacturing Roadmap is an extension of the 2009 MYPP. It focuses on the R&D needs for achieving cost effective, high quality manufacturing capabilities for solid state lighting products, be they packaged devices, replacement lamps, or complete luminaires. As part of the 2009 MYPP, our expectation is that this roadmap will be reviewed annually by DOE in collaboration with industry partners and updated to reflect progress and resultant changes in our priorities for achieving the ultimate goals of the program.

Much of the background for the SSL program, including a summary of significant accomplishments, research highlights, the legislative framework, and financial support of the program may be found in the March, 2009 Multi-Year Program Plan. We will not repeat that material here, but readers are urged to review it as background for the SSL manufacturing roadmap.

The 2009 Multi-Year Program Plan can be downloaded at:
http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mypp2009_web.pdf

1.0 Introduction

As solid state-lighting (SSL) technology advances, lower costs and greater product consistency are two key necessities for market acceptance and, consequently, energy savings. While these needs will be addressed in part by the existing U. S. Department of Energy (DOE) SSL Core Technology and Product Development Research and Development (R&D) program, many of the issues go beyond applied research, product development, product testing, and application design and more specifically involve the state of manufacturing practice. As demonstrated by experience with the development of other technologies, most notably the silicon semiconductor industry, pre-competitive cooperation in understanding best practices, common equipment needs, process control, and other manufacturing methods and issues can yield great rewards for all. Accordingly, DOE has added a SSL manufacturing initiative to its portfolio with the twin goals of improving product consistency and quality and accelerating cost reduction. A third interest is to encourage domestic U.S. based manufacturing of SSL to the extent possible and appropriate, to encourage job creation, and to maximize the benefit to the U.S. taxpayer who has supported much SSL technology development.

This SSL Manufacturing Roadmap is intended to guide future planning for DOE R&D actions and is the end product of two workshops sponsored by DOE. On April 21-22, 2009, approximately 200 SSL leaders gathered in Fairfax, Virginia for the first event. That workshop emphasized identification of key barriers affecting SSL manufacturing and framing preliminary recommendations to address them. The April workshop had both plenary sessions of interest to all attendees as well as separate presentation and discussion tracks devoted to Light Emitting Diode (LED) and Organic Light Emitting Diode (OLED) technologies. Breakout discussions focused on either LEDs or OLEDs were interspersed with the formal presentations. The second workshop was held June 24-25, 2009 in Vancouver, Washington. The purpose of the second event was to critique a preliminary draft of this Roadmap that was developed after the April event. Again, approximately 200 participants, roughly half of whom did not attend the April workshop, participated in the June discussions. This document also incorporates some inputs received in the form of white papers from workshop participants.[1,2]

The primary goal of the roadmap is to guide the R&D program and to help direct funding solicitations. In addition, it is intended to act as a guide for equipment and material suppliers, based on industry consensus on the expected evolution of SSL manufacturing, to reduce risk, and ultimately cost of entering into SSL manufacturing. Encouraging multiple sources of key equipment and 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. In many cases the findings of the roadmap exercise will result in identifying additional R&D work, which might be carried out through the existing Core Technology and Product Development programs, as outlined in the 2009 DOE SSL Multiyear Program Plan (MYPP), or under new R&D funding directed specifically at manufacturing issues.

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[1] Information resources for the April workshop is accessible at: http://www1.eere.energy.gov/buildings/ssl/news_detail.html?news_id=12501

[2] Information resources for the June workshop is accessible at: http://www1.eere.energy.gov/buildings/ssl/news_detail.html?news_id=12674

The organization of this document is derived from the principal findings and recommendations of the workshops and is divided into separate LED and OLED sections. A third section covers SSL-related standards in general, and provides some recommendations for standards specifically related to SSL manufacturing. The appendix to this document provides information about existing and pending standards efforts in many areas, especially regarding testing and performance metrics. Because the technology may not yet be sufficiently developed, topics such as physical interface standards (either electrical or optical) may be required at a later time. . However, in consideration of the extended process of standards development, planning for future standards work is advisable. Accordingly, some recommendations on standards have been made in the main roadmap sections of this document and summarized in the standards chapter.

1.1 Key findings and general recommendations

As noted above, in both workshops there were separate tracks for OLEDs and LEDs, consisting of a number of presentations and breakout discussions. Following the track presentations on each day, participants were separated into groups. All groups at the April workshop were first charged with identifying major roadblocks to lowering costs and increasing market acceptance of SSL products. The second task was to then propose potential recommendations that the industry and DOE could pursue to obviate these barriers. At the Vancouver event, the top priorities identified at Fairfax were revisited with the objective of identifying work that could overcome the barriers and an appropriate timeline for doing so.

Many of the issues discussed in April concerned standardization and were quite wide-ranging. To help narrow the focus to manufacturing, standards are discussed in Section D of this roadmap. Many are identified as being covered by other activities outside the scope of this initiative. A panel in Vancouver further discussed the status of standards work on SSL being done outside the scope of the manufacturing workshop. In a few cases, some standardized work specifically related to manufacturing was discussed in the panels and breakouts at Vancouver. That work is covered in this document.

1.1.1 LED luminaires

The April workshop identified five primary LED luminaire manufacturing roadblocks:

- The variability and consequent binning requirement for LEDs, which leads to difficulties repeating color and lumen (lm) output performance in luminaires and limits the availability of LEDs
- The uncertainty in the long term performance of LED-based lighting and the impact on luminaire warranties
- The need for, difficulty of, and high cost of in-process and final product testing
- The difficulty of specifying and the expense of power supplies/drivers
- The lack of industry-wide design and modeling software tools across the manufacturing supply chain

Of these, four were pursued in Vancouver and are discussed in the LED roadmap section. Upon further review at the Vancouver manufacturing workshop the topic of product testing was no longer considered to be a roadblock to luminaire manufacturing due to the availability of self testing of luminaires through the NVLAP lab accreditation process. The following recommendations were made with respect to luminaire manufacturing:

- Focus on engineering solutions in the short term to accommodate color variation (long term solution is to improve LED manufacture). These include:
  - Develop a better understanding of the variability that can be tolerated;
  - Encourage all manufacturers to use the same binning criteria;
  - Differentiate binning criteria based on application because some require tighter color control than others;
  - Use LED modules or arrays to homogenize the color from several LEDs.
- Develop system reliability approaches to improve characterization of lifetime.
  - Develop a database with standardized formats for component and subsystem statistical long-term performance.
  - Develop accepted accelerated life tests for components and subsystems as well as entire luminaires.
- Encourage standardized specifications and reporting for power supplies and drivers.
- Develop software tools to simulate entire luminaire performance, including effect of component performance variability.

Beyond direct manufacturing issues, several marketing or standardization issues were raised in the LED luminaire sessions.

- Lack of uniform reporting of luminaire performance
- Light source modularity
- Standardization of the luminaire components, e.g., LEDs, drivers, and optics
- Issues with Energy Star specifications

In general, recommendations from the luminaire breakouts that emphasized standards issues are covered in Section D and are outside of the roadmap discussions.

1.1.2 Packaged LED

The packaged LED breakout group decided upon four major roadblock areas, each consisting of a number of issues:

- The need to advance the epitaxy process and equipment to improve wavelength uniformity and reproducibility, reduce variations in chip output power, increase throughput, and improve yields
- The need to address substrate-related issues, ranging from warping and defects in present materials to cost and availability of potentially better approaches such as native substrates.
- The lack of suitable manufacturing equipment. Increased automation should be introduced into the wafer processing, die packaging and testing activities. A lower cost-of-ownership for all equipment is required.

- The inadequacy of process controls. There is a need for improved inspection and testing equipment in a number of areas including epitaxial growth, wafer processing and die packaging throughout the process. Active feedback control for critical process steps such as epitaxial growth is also required.

Each of the above issues is expanded upon in subsequent sections of the report.

A primary goal for the manufacturing roadmap is to drive significant cost reductions. A cost analysis for the packaged LED device suggests that around 80% of its cost is associated with die packaging and phosphor deposition. The manufacturing roadmap should therefore reflect the need to reduce costs in this specific area. However, a note of caution was raised at the workshops regarding placing too much emphasis on individual process steps since the manufacturing process as a whole involves many complex interdependencies. It will be necessary to consider the complete LED manufacturing system when implementing cost reduction strategies. As a consequence, the impact of manufacturing improvements in specific areas on the final LED product cost was difficult to quantify and it would be necessary to develop a comprehensive cost model to establish these sensitivities and direct resources in the most efficient way.

The following recommendations were made with respect to manufacturing of packaged LEDs:

- Improve color consistency (increase binning yield).
  - Focus on epitaxial wafer uniformity and reproducibility. Improve understanding of growth processes, incorporate in-situ monitoring and improved process control.
  - Improve sapphire and SiC substrate quality and consistency, and investigate native GaN alternatives.
  - Focus on improved control of phosphor manufacturing and deposition processes.
- Improve throughput.
  - Focus on improved equipment design with higher capacities and increased use of automation.
  - Reduce epitaxial layer growth times to improve overall cycle time.
  - Incorporate improved process controls.
  - Target a factor of 2 improvement in cost-of-ownership for manufacturing equipment every 5 years.
- Reduce back-end processing costs.
  - Improve packaging equipment to increase automation and improve speeds.
  - Improve package designs and increase standardization.
  - Transfer packaging activities from die-level to wafer-level.
  - Introduce higher speed test equipment.
- Integration
  - Consider the complete integrated SSL system when developing cost reduction strategies.

  - Investigate higher levels of component integration at the packaging level and wafer level.
- Cost Model
  - Develop a cost model to describe the various cost elements within the manufactured luminaire product.
  - Use the cost model to identify the most productive use of resources to reduce overall SSL product costs.

1.1.3 OLEDs

Given the less-developed state of OLEDs as applied to lighting, the discussions at both workshops ranged over a wide range of issues. Many concerned specific technical challenges which arise in converting successful laboratory technology into viable commercial products. Others related to broader, strategic concerns which must be addressed if this transformation is to take place on an appropriate time scale.

The major strategic barriers are:

- A high level of risk is currently deterring manufacturers from making needed capital investments. Ramping production volume is essential to achieving cost goals, but is expensive to implement. Many of the elements needed to manufacture OLEDs are available. However manufacturers need to integrate these systems to achieve high volume manufacturing with reduced cycle times and high material utilization.
- There is little in-depth understanding of realistic market opportunities for OLED lamps. Few luminaire manufacturers have been involved in the development and demonstration of OLED lighting.

The recommendations concerning these strategic issues included:

- A pilot production line is needed to allow the proposed manufacturing methods to be tested and to provide products for early adopters of OLED lighting. However, some participants warned that it might be imprudent to commit to major capital investment before the relative advantages of the several manufacturing methods are clarified. The cost of the pilot line should thus be kept low. DOE can play an important role by providing incentives for US companies to work more closely together and pool resources. Companies should also consider participation in the DOE loan guarantee program
- The identification of pioneering products that can be sold in moderate volumes at premium prices would greatly facilitate the growth of the industry. A clearer definition of performance requirements for OLED luminaires would also provide guidance in the selection of manufacturing methods and future research projects. In particular, the level of customer interest in diffuse lighting on flexible or curved surfaces should be assessed more quantitatively.
- More attention needs to be paid to "design for manufacture". Researchers and innovators need to consider the manufacturability of their ideas as they strive for higher performance and greater customer appeal.

The more specific technical issues can be grouped into 3 areas:

- Manufacturing Methods:
  - The need for increased materials utilization to reduce costs. Thin active layers allow manufacturers to use relatively expensive materials if waste is controlled effectively.
  - The lack of a clear route to the manufacturing of out-coupling enhancement films that will meet the 2009 MYPP targets of 75% for light extraction
  - The need for cost effective large-area deposition techniques for the multiple layers of inorganic and organic materials in the OLED stack
  - The need to better define patterning requirements and identify appropriate techniques
  - Increasing manufacturing yields to at least the levels achieved for small OLED displays
  - The need for reduced processing times in order to increase throughput
  - Effectively using labor and implementing appropriate automation procedures
  - The need to emphasize manufacturing reproducibility in order to avoid the binning issues associated with inorganic LEDs
- Availability of Materials and Components
  - The high cost of display quality glass for use as a substrate or cover in lighting applications
  - The need for inexpensive moisture barriers for plastic substrates is hindering the production of flexible OLEDs.
  - The lack of transparent electrode materials that meet performance requirements and manufacturing cost targets
- Core Technology and Product Development Issues
  - The reduction in operating lifetime of devices when brightness of the light source is increased in order to reduce overall cost
  - The need for further core technology work and product development to determine the appropriate level of segmentation for OLED lighting panels. Important factors to consider include conduction (I2R) losses, optical uniformity and short prevention
  - Determine if presently proposed procedures to increase light extraction can be combined or enhanced to meet 2009 MYPP targets
  - Develop OLED designs that focus the light more sharply than in the usual Lambertian distribution as they may be more appropriate for lighting applications

Multiple solutions were recommended for most of the identified manufacturing barriers, as outlined in Chapter III. The design and research issues should be addressed through updates in the MYPP.

OLED discussions are complicated by a rather sharp divergence in approaches to manufacturing in this technology. Accordingly, the Manufacturing Roadmap contrasts the two fundamentally different process flow options:

- Vacuum deposition on rigid substrates in batch mode
- Roll-to-Roll solution-based processing on flexible substrates

The vacuum deposition/rigid substrate approach is modeled after OLED manufacturing for displays, the closest existing manufacturing technology. Most of the high-performance lighting prototypes have been fabricated using this approach. While the roll-to-roll approach offers many potential longer term advantages, the industry would not be able to piggy-back on current display technology being developed for near-term markets. Hybrid manufacturing options also exist, each using some of the elements of these two strategies. The dichotomy means that, at least for the present, the OLED roadmap will need to address both pathways, and consider whether eventual convergence is likely or not necessary for success.

The group recommended that DOE support manufacturing approaches that have high probability of meeting program performance and cost targets for 2015 (as defined in the 2009 MYPP) and enabling strong penetration of general illumination markets. While solution deposited OLEDs appear to have greater potential to meet the cost targets, presently vacuum deposited have higher efficacies.

OLED participants and contributors also were of the opinion that DOE support of Manufacturing R&D may need to be somewhat different than that for the other classes of R&D projects in the SSL Portfolio (Core Technology and Product Development). A typical manufacturing project may involve materials, processing, and equipment companies, and may be longer in duration and higher in total cost. This issue is but a part of the larger problem of generating capital to construct a line of sufficient capacity to gain a foothold on the lighting market. Any substantial proposal for support, however, will be greatly enhanced by the presence of a clear plan, even if initially following more than one road to the end goal. This is one of the goals of this manufacturing roadmap.

1.2 Overall projections/contributions to cost reduction

1.2.1 LED lighting

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

Figure 1 shows a high-level cost breakdown and projection for cost reductions in LED based luminaires. This figure reflects projected cost reductions based on inputs from the presentations at both workshops and discussions in the luminaire breakout sessions.

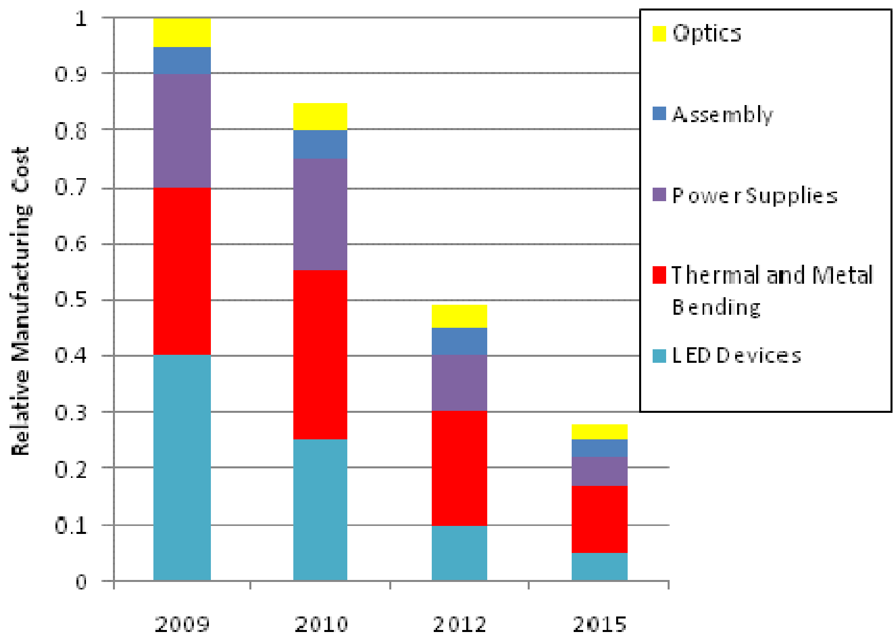

Figure 1. Projected LED Luminaire Cost Track. *Source: DOE Manufacturing Workshop consensus*

The cost projections for LED-based luminaires incorporate the LED cost targets from the SSL Multiyear Program Plan and project cost reductions of the remaining components. The projections account for potential cost savings from improved manufacturing processes and from luminaires "designed for manufacture", which would most directly affect the 'Thermal and Metal Bending' costs. In addition, there could be significant cost savings as automated assembly replaces manual processes for the manufacture of luminaires. 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 assembly of consumer electronic products. Automation could reduce the labor cost, removing one of the drivers for moving luminaire manufacturing out of the U.S. Overall goals for LED based luminaires, as reflected in DOE's 2009 Multi-year Program Plan, project cost reductions of approximately 20% per year, representing a factor of about three by 2015 and a factor of about 35 by the end of the program in 2025.

As shown in Figure 2, a similar high level cost breakdown and cost reduction projection was developed for packaged LEDs. Projected cost reductions are presented relative to the normalized 2009 cost breakdown. The packaged LED cost breakdown and projected cost reductions are based on the breakout discussions and data presented at the two manufacturing workshops. Figure 2 indicates that back end processing currently represents the largest cost associated with packaged LED manufacturing and, though the cost is projected to come down rapidly, it will remain the largest fraction of packaged LED manufacturing cost. 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 cost of the back end processing.

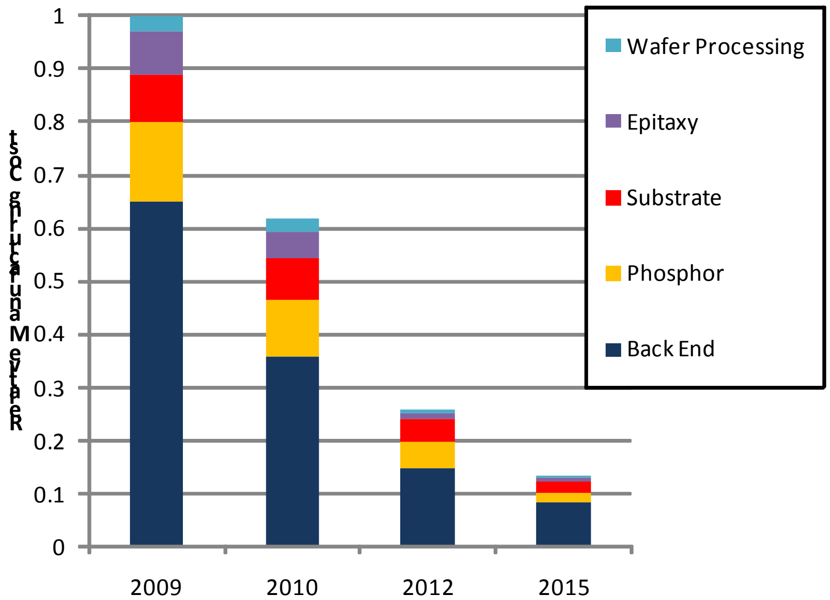

Figure 2. Projected Packaged LED Cost Track. *Source: DOE Manufacturing Workshop consensus*

A Pareto analysis of the projected combined 2010 luminaire and LED manufacturing cost breakdown is shown in Figure 3. Power supply costs will be quite significant in 2010 but are projected to come down rapidly. In 2010 LED back end processing costs will represent a significant portion of the total luminaire cost, but all of the LED costs are expected to decrease rapidly. This analysis can guide the DOE SSL Manufacturing effort and it is expected that the projections will be refined in upcoming manufacturing workshops.

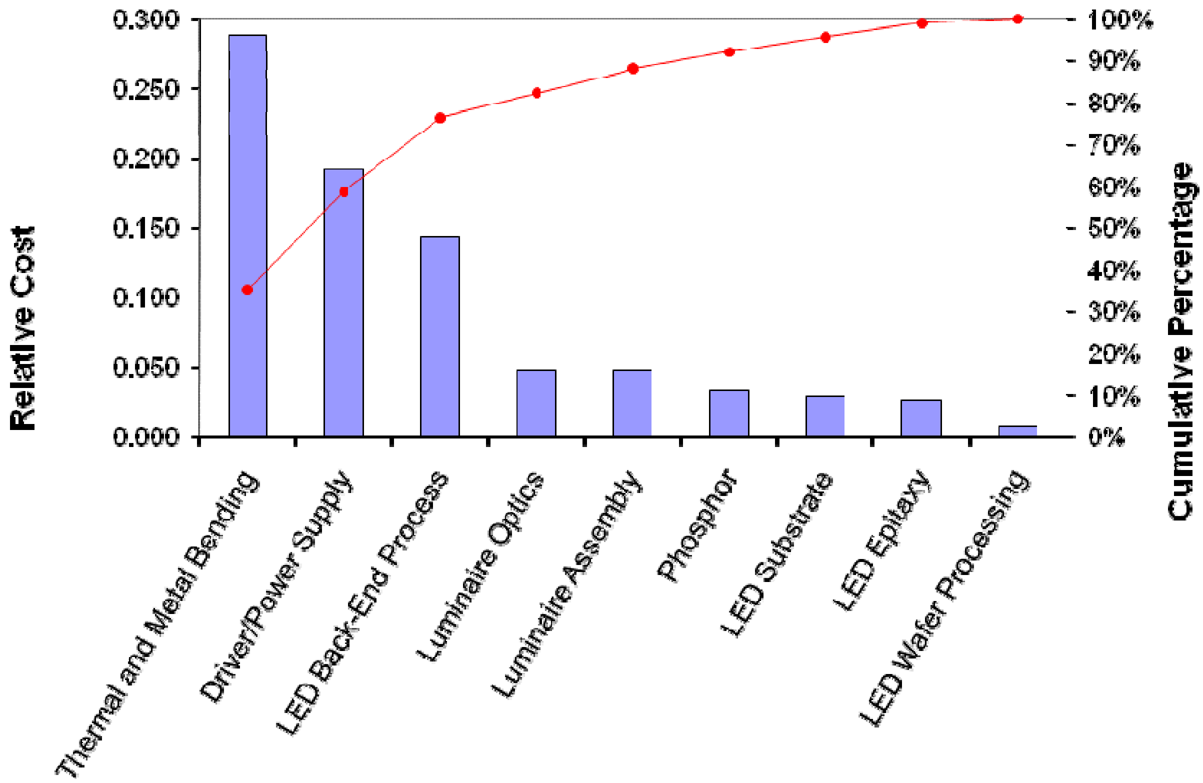

Figure 3. Pareto Analysis of SSL Manufacturing Costs. 2010 Projection[3]

1.2.2 OLED lighting

Up until this time, OLED manufacturing practices have been determined by display applications. The requirements of lighting applications are simpler in some respects but more challenging in others. One of the challenges associated with lighting applications is that the costs must be reduced by a large factor from the \$2000/m^2 typical of OLED displays. However, some of these savings can come from the elimination of expensive components not required for lighting applications, such as the thin film transistor (TFT) backplane, borosilicate glass, and patterned sheets of transparent conductors (such as ITO). Further economies can be made by implementing faster fabrication on larger substrates and by simplifying manufacturing processes.

Figure 4 presents one projection of how such savings could be achieved. This forecast was constructed to show the potential advantages of increases in substrate size in conventional evaporation manufacturing approaches, the use of solution-processing techniques, and the adoption of roll-to-roll production on flexible substrates. While various companies may favor different pathways to achieving low-cost manufacturing, all appear to support the use of large substrates. Many believe that similar savings can be achieved using vapor-deposition techniques

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

on rigid substrates in batch mode. It is too early to judge which forecasts are most accurate and several approaches are likely to be pursued in the short term.

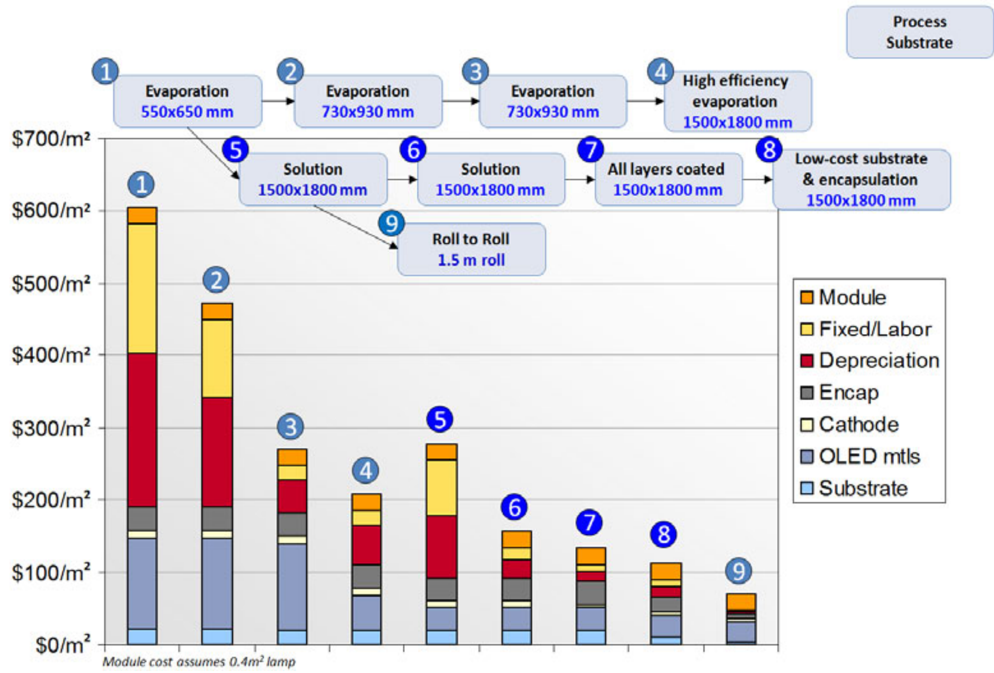

Figure 4. Sample OLED Manufacturing Cost Roadmap. *Source*: *William Feehery, DuPont, "OLED Lighting Manufacturing Cost," SSL Manufacturing Workshop, Fairfax, VA, April 2009*

Note that no time scale is indicated in this figure.

The substrate sizes used in Figure 4 are display industry standards and would facilitate the use of existing equipment for that purpose, although the specific dimensions may not be optimal for lighting applications.

As discussed below in Section 3.1.1, OLED brightness may turn out to be a critical component of meeting market-driven cost objectives. The final cost target achieved in this projection would be consistent with the 2009 MYPP price target of $10/klm, provided that the light output of the device is over 10,000 lumens/m^2. However, unless the stability of OLED devices can be improved substantially this would lead to device lifetimes that are unacceptable for most applications, suggesting that R&D to extend product life may be key to meeting long term goals.

2.0 LED roadmap

2.1 Cost and quality drivers for LED lighting

As shown in Figure 5 below, the greatest potential for LED-based luminaire cost reductions is in reducing the costs of LED packages (viewed as incoming materials from the luminaire maker's perspective). However, in addition to LED packages, the cost of the remaining components will need to come down in order to meet cost targets. Power supply cost reductions will come from standardization of the LED power requirements. In turn, this will lead to savings from higher volume manufacture of fewer subsystems. Higher efficiency LEDs will reduce costs for thermal management components, and optimization of the fixture architecture will reduce other fabrication costs. Improved optical engineering and the availability of higher efficiency LEDs (especially at higher drive currents) may allow for the use of fewer LEDs to achieve the required illuminance levels, which can result in significant cost savings. In addition to the factors shown in Figure 5, advanced manufacturing techniques, including automation, can further bring down the cost of the luminaire. Figure 1, Figure 3, and Figure 5 account for the cost of the optics in different manners, reflecting the range of data presented at the R&D workshops. In general, the cost breakdowns are in good agreement.

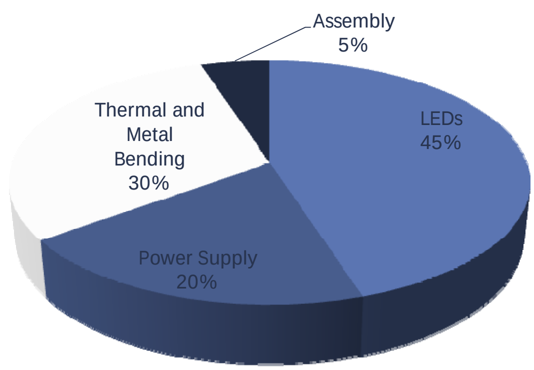

Figure 5. Approximate Cost Breakdown for LED Luminaire. *Source: Paul Pickard, Cree LED Lighting, "LED Luminaire Manufacturing Issues," SSL Workshop, Fairfax VA, April 21, 2009*

The manufacture of high power LED devices involves a number of steps; each of which contributes to the final device cost. The typical cost breakdown for a packaged LED is shown in Figure 6. In this figure 'Other FE' (Front-End) refers to front face wafer processing and 'Other BE' (Back-End) refers to substrate removal, chip separation, and packaging. Note that a very large proportion of the cost is concentrated in the die-level back-end processing stages (*i.e.*, 'Phosphor' and 'Other Back-End'). The final product is a packaged die and there are many thousands of such die on each wafer (around 5000 1 mm^2 die on a 4" diameter substrate). Therefore, costs associated with die-level activities will tend to dominate.

Manufacturers will need to address back-end processes 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 we anticipate many different approaches to cost reduction including:

- Increased automation
- Improved testing and inspection

- Improved upstream process control4
- Improved binning yield
- Optimized packages (simplified designs, multichip, etc.)
- Higher levels of component integration (hybrid or monolithic)

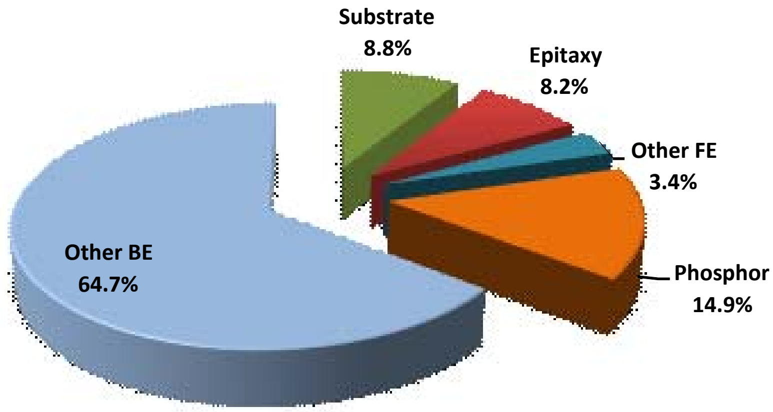

Figure 6. Typical Cost Breakdown for a Packaged LED (110k x 4" W/year Sapphire Substrates). *Source: Jeff Perkins, Yole Developpement, "LED Manufacturing Technologies and Costs," SSL Workshop, Fairfax VA, April 21, 2009*

The top level metrics for LED device efficacy, LED device price, and original equipment manufacturer (OEM) lamp price are shown in Table 1. The current and projected values for device efficacy and OEM *lamp* price are taken from DOE's 2009 MYPP[5]

A review of current, commercially available devices[6] confirmed that the best efficacy values for cool white[7] and warm white[8] LED are 117 lumens per watt (lm/W) and 65 lm/W respectively. These values are in reasonable agreement with interpolated mid-year 2009 MYPP target values of 120 lm/W and 74 lm/W. Note that there is a fairly wide range in efficacy values, with the average efficacy being around 20-25% lower than the best value. We expect this spread to narrow as the product matures and binning yields are improved.

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

[5] Assumes an integrated LED lamp at reasonable volumes (several 1000s) with CRI=70 → 80 and CCT = 4100-6500K

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

[7] CCT = 4100-6500 K; CRI = 70 → 80; 350 mA driver current at 25 C

[8] CCT = 2800-3500 K; CRI > 85; 350 mA driver current at 25 C

Table 1. LED Metrics Roadmap. *Source: DOE MYPP and survey of commercial device prices*[4]

Metric	Unit	2009	2010	2012	2015
LED Efficacy (2800-3500K, >=85 CRI)	lm/W	83	97	114	138
LED Price (2800-3500K; 350 mA)	$/klm	46	25	11	4
LED Efficacy (4100-6500K, 70-80 CRI)	lm/W	132	147	164	188
LED Price (4100-6500K; 350 mA)	$/klm	25	13	6	2
OEM Lamp Price	$/klm	130	101	61	28

The 2009 values for LED device price in Table 1 are based on best reported values for commercially available devices. The price targets for future years are consistent with the luminaire cost trends outlined in Figure 1.

2.2 LED luminaires

Several barriers to manufacturing luminaires were discussed in the luminaire breakout sessions at the DOE SSL Manufacturing Workshops in Fairfax, VA and Vancouver, WA. Four issues were identified as significant:

- LED binning
- Life testing
- Power supplies and drivers
- Software and modeling tools

These are discussed in more detail in the sections below and a roadmap for the solution of these issues is shown in Figure 7.

Although several additional issues were brought up in the luminaire break-out sessions at both DOE Manufacturing Workshops, there was no consensus as to whether these issues were significant manufacturing roadblocks for LED based luminaires. The four roadblocks listed here and discussed below did garner a consensus as being significant. Stakeholders and participants in the luminaire breakout sessions included a range of very large to small businesses with backgrounds varying from manufacturing of conventional lighting products to LED-based products. The difficulty in reaching an agreement on some of the other suggested roadblocks reflects the variety of technological approaches, business approaches, and business interests that are involved in the development of LED based luminaires for general illumination.

Category	Task	2010	2011	2012	2013	2014	2015
LED Binning							
	Define and support research into consumer tolerance for color variation in lighting	■	■				
	Develop suggested color variation tolerances based on research		■	■			
	Identify common set of chromaticity bins for common reporting	■					
	Develop standard reporting format for LED chromaticity, voltage, and lumen output	■	■				
Life Testing							
	Develop standard lifetime reporting format for components and system	■					
	Develop appropriate acceleration factors for life testing of luminaire components	■	■				
	Support R&D of luminaire system reliability modeling and methods	■	■	■	■		
Power Supplies and Drivers							
	Develop standard power supply/driver performance reporting data and format	■					
	Explore development of segmented power supply/driver standards		■	■			
Software and Modeling Tools							
	Develop standard luminaire component and system reporting formats for input into design software	■					
	Support Design Software Development		■				

Figure 7. Roadmap for Addressing Luminaire Manufacturing Issues. *Source: DOE Manufacturing Workshops*

2.2.1 Variability/binning

The diagram below (Figure 8) highlights the difficulties resulting from the performance variability and resultant binning of LEDs. As the performance requirements (wavelength, flux, and voltage) become more stringent, the availability of acceptable LEDs is significantly reduced, which can lead to higher LED costs, shortages of LEDs from the premiere bins, and long lead times. The LED manufacturers have identified this issue as a critical roadblock and hope that improvements in LED growth uniformity will reduce the variability of LED performance.

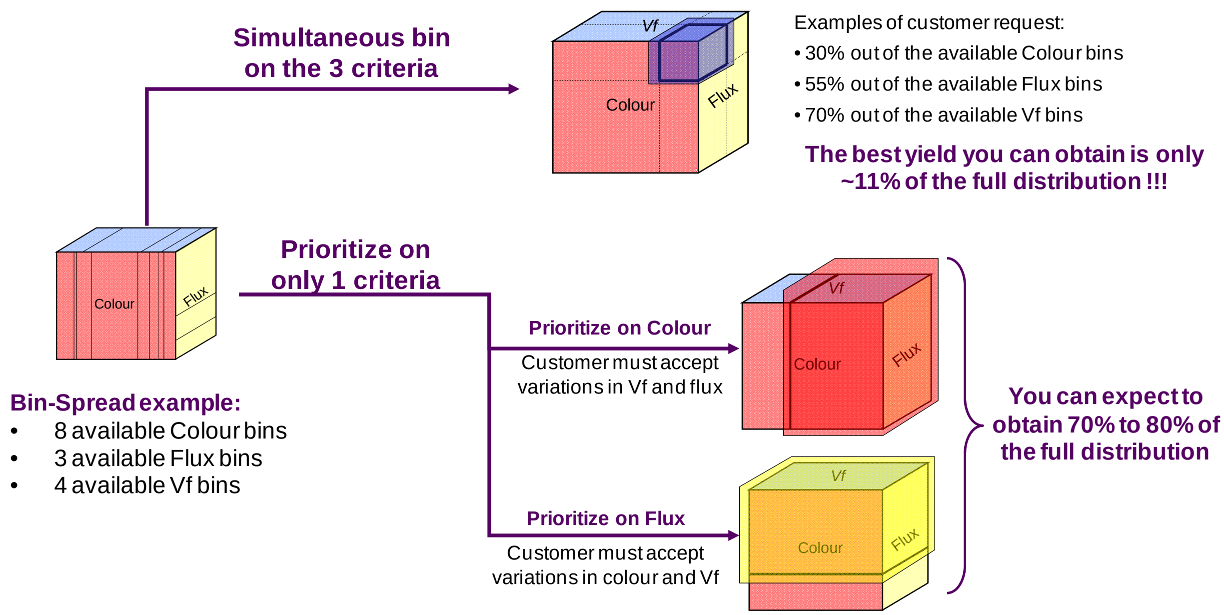


Figure 8. Binning Yield Losses for LEDs. *Source: Jeffrey Perkins, Yole Developpement, "LED Manufacturing Technologies & Costs," SSL Workshop, Fairfax VA, April 2009*

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. Color consistency of the LEDs to be used in the luminaires was seen as the most important binning issue, while voltage and lumen output variation of LEDs were seen as much less significant issues. Regarding color consistency, there was a consensus that there is 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. Existing color research is old and in need of review, summary, and validation. Research should be based on perceptual studies relating color and tolerance founded on human physiology. From this research, acceptable color and output variations could be defined which would guide the development of the LED light sources. Furthermore, the studies should differentiate between various market segments/applications and note possible different tolerances for different applications.

Many LEDs are binned for chromaticity using the American National Standards Institute (ANSI) chromaticity quadrangles. The ANSI chromaticity quadrangles are also used by some luminaire color performance standards, such as SSL Energy Star, to define acceptable color performance. There was a consensus in the luminaire breakout group that within the ANSI chromaticity quadrangles there are noticeable color differences and that the size of the bins were not perceptually scaled with respect to human vision. Although there was no consensus as to whether the ANSI chromaticity quadrangles should be resized, it was noted that there DOE-supported working group is currently looking into this question. The one clear suggestion of the group for dealing with chromaticity variations of LEDs was to have all LED manufacturers bin and label LEDs for chromaticity consistently, using the same chromaticity bins. This would enable luminaire manufacturers to more readily compare and use LEDs from different suppliers.

Ultimately, the need for binning should be eliminated through LED fabrication improvements leading to improved LED growth uniformity. The group noted that while variations in LED performance persist, binning issues can be addressed to some degree by the luminaire manufacturers through engineering techniques. These strategies include: secondary binning by the luminaire manufacturer for more consistent LED color within the manufacturers' bins and homogenization of the color from several LEDs using an LED array/module.

2.2.2 Luminaire life testing

The lack of a true lifetime test for LED-based luminaires was raised as a significant problem for luminaire manufacturers. 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 stems from the unknown long term performance of LED luminaire components, including the LEDs, in a variety of environments and the lack of an industry-wide test method based on experimental lifetime and reliability testing results.

The issue of a common test protocol is initially being addressed in the DOE Core Technology R&D program under subtask A.6.3 System Reliability Methods. The program is looking to develop experimental data and a theoretical understanding of luminaire system reliability. The lack of a common test protocol is also being addressed by a DOE-supported reliability working group which is studying the uncertainties surrounding luminaire lifetime. The breakout group did recommend that lifetime performance of luminaire components and systems should be provided by the product suppliers in some standardized data file format. This would enable the luminaire manufacturer to model lifetime performance of the luminaire system using the provided data 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 developed. 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.

2.2.3 Power supplies/drivers

Among the luminaire manufacturers there was consensus that standardized reporting and additional information is required from the power supply/driver manufacturers to facilitate the integration of the power supply/driver into the luminaire. The lack of information and inconsistent reporting of power supply/driver performance inhibits efficient and easy integration of the electronic components. The luminaire manufacturers emphasized the need to disseminate this information readily and uniformly. A standard reporting format would facilitate the use and development of analysis, simulation, and design tools for luminaire manufacturers. The luminaire manufacturers suggested that this divulgence of performance data in a standard reporting format should be implemented in the near term. The sidebar lists the parameters the breakout group recommended should be included.

Participants in the luminaire breakout group felt that developing various well-defined product categories by power range, would facilitate the matching of power supplies to the LED loads. For example, power supply segments could be defined for 4W, 8W, 14.5W, etc. The defined output power represents the output power at which the power supply would operate most efficiently. In addition, the degradation in efficiency at the edges of the ranges would be minimized. This segmentation would allow for a range of off the shelf power supplies that could be rapidly integrated into LED based luminaires for a variety of applications. While there was significant discussion of this topic, the group did not reach any consensus suggestions. It was noted that the SSL standards committee and the National Electrical Manufacturers Association (NEMA) are working on a white paper discussing possible classes of power supplies and a reporting format for LED based lighting.

Proposed power supply/driver information:

- Accurate lifetime by environment
- Operating temperature
- Efficiency with respect to power, load, and temperature
- Input voltage and output voltage variation
- Off-state power
- How driver testing is performed
- Power to light time
- Power overshoot
- Input transient (i.e. from lightning strike) and overvoltage protection/ durability for suitable environment (indoor vs. outdoor lighting) and whether additional protection is needed for certain uses
- 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
- All of the standard data provided by fluorescent ballast manufacturers (not already covered in the list above)

2.2.4 Software and modeling tools

The luminaire breakout group identified the need for industry wide software and modeling tools to aid in the design and manufacturing of luminaire products. Luminaire manufacturers discussed the need for a suite of design tools that would analyze and simulate whole luminaire performance given input data from the various luminaire components and sub-systems. Performance data related to all three of the previous sections – LED binning, luminaire life testing, and power supply/driver data reporting – if provided in a standard format could be used as input data to luminaire design and simulation software. Software tools could be developed to account for variability in performance of incoming components, particularly LEDs, allowing the luminaire manufacturer to stay within performance specifications. Software to model the reliability of the luminaire system based on component reliability could be borrowed from other, similar applications, and adapted to the luminaire system based on reliability and lifetime research. Luminaire electrical design could be aided by software with the appropriate power supply and LED data sets. The group suggested that providing the data in a text file format similar to an IES file would enable the development of the software design and simulation tools. The group suggested some additional data sets that would facilitate luminaire design and simulation: LED response to temperature; and LED spectral power density with respect to angle. The availability of all of this data in a standard format was considered an immediate need and the reporting requirements and formats could be developed under the auspices of NEMA or ANSI and supported by DOE.

2.2.5 Luminaire R&D recommendations

Based on the luminaire manufacturing related presentations and breakout discussions a number of recommendations can be made to the DOE SSL Core Technology and Product Development R&D Program that can impact the state of luminaire manufacturing. The recommendations are listed below:

- Support perceptual studies relating color and tolerance founded on human physiology. From this research, acceptable color and output variations could be defined which would guide the development of the LED light sources. Furthermore, the studies should differentiate between various market segments/applications and note possible different tolerances for different applications.
- Support development of luminaire products which are more tolerant to LED binning variations while maintaining consistent output in terms of color and flux
- Continue support of DOE Core Technology R&D subtask A.6.3 System Reliability Methods, to develop experimental data and theoretical understanding of luminaire component and system reliability
- Supported power supply/driver product development should report the items listed in section 3, above.

2.3 Packaged LED

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

2.3.1 Epitaxy processes

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

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

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

Hydride Vapor Phase Epitaxy (HVPE) is an alternative growth method which has the advantage of significantly higher growth rates and offers the prospect of much higher throughputs. While HVPE is well suited for the growth of thick GaN buffer layers, it is not well suited for the growth of the thin nanometer-scale layers and InGaN alloy compositions associated with the MQW active region. Consequently, HVPE's primary contribution could be in the growth of thick GaN layers to produce GaN templates and free-standing GaN substrates. Also, HVPE is much less advanced than MOCVD in terms of the availability of manufacturing-scale equipment. The first multiwafer HVPE reactors have only recently been announced[9].

HVPE and MOCVD can be seen as somewhat complementary processes. HVPE is able to provide high growth rates for the thick GaN layers in the device structure, and MOCVD is able to provide precise control for the thin MQW layers. Participants pointed out that some combination of the two techniques, possibly in the same tool using a cluster approach, might be a way to achieve significant throughput improvements without compromising layer quality. Figure 9 shows the agreed epitaxy roadmap.

[9] http://www.oxford-instruments.co.uk/news/Pages/news.aspx

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 9. Epitaxy Roadmap. *Source: DOE Workshop Consensus*

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

Table 2 includes a set of suitable metrics to characterize the epitaxy process. The most critical metrics are those associated with epiwafer uniformity and reproducibility. The table sets targets for in-wafer uniformity (standard deviation of wavelength for an individual wafer), wafer-to-wafer reproducibility (maximum spread of mean wavelengths of all wafers in a run), and run-to-run reproducibility (maximum drift from run to run of the mean wavelength of all wafers in a run).

Cost of Ownership (COO) is an excellent metric to describe how manufacturing equipment should evolve to reduce the cost of production. A reduced COO for epitaxy processes can be achieved in many different ways. For example, the throughput of the reactor can be increased by reducing the cycle time or by increasing the capacity, or a combination of both. Process control improvements will increase yield. In addition, equipment design changes can increase the efficiency of reagent useage. Although, it is difficult to specify at this stage which approaches will be the most effective all such actions will reduce the COO. Therefore, the group decided to simply define a COO improvement target. This COO target matches the requirements described in section 2.3.3.

The epiwafer includes the substrate and the epitaxial layers. Since the substrate cost can vary substantially a suitable metric for tracking cost reduction for an epiwafer, the ultimate goal, is the epitaxial layer cost. As a starting point assume that the cost of a 2” epiwafer using a sapphire substrate is around \$100. Assuming a price of \$15 for the substrate, the epitaxial layer cost is \$85 or 6.8 $\$/cm^2$. An extrapolation to 3” and 4” sapphire substrates is consistent with the widely accepted estimate that the substrate comprises around 30% of the epiwafer cost. The proposed roadmap for epitaxy cost reduction in Figure 9 is based on estimates provided by Veeco at the April workshop regarding projected cost reductions for spares & consumables, gases & utilites, and depreciation.

Table 2. Epitaxy Metrics. *Source: DOE Workshop Consensus*

Metric	Unit	2009	2010	2012	2015
Wafer Uniformity (STD)	nm	1.7	1.5	1.0	0.5
Wafer-to-wafer	nm	1.5	1.1	0.9	0.6
Run-to-run	nm	2.0	1.5	1.1	0.9
Intensity Uniformity	%	20	15	8	5
Cost of Ownership	-	x2 reduction every 5 years			
Epitaxy Cost	$\$/cm^2$	6.8	5.5	3.8	2.2

2.3.2 Substrates

The substrate roadmap supports two paths; (i) improved substrates for heteroepitaxial growth (sapphire and SiC), and (ii) improved substrates for homoepitaxial growth (GaN). In both cases 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 GaN substrates cost must also be dramatically reduced in order to become a viable option for LED manufacturing.

Sapphire and SiC are currently the dominant substrate types for high power GaN-based LED manufacturing. A general trend toward larger substrate diameters is anticipated, mimicking the silicon and GaAs microelectronics industry. Larger substrates provide an increase in useable area (less edge exclusion) without significantly increasing the processing cost per wafer, and provide improved access to automated wafer handling equipment. For packaged LEDs, this trend will continue despite the fact that wafer-level processing currently comprises only a small proportion of the overall cost (around 3%). As a result, any direct cost savings will be limited. In the longer term, as other cost elements are addressed, the advantages of larger substrates will become more significant.

In order to realize these advantages, a steady supply of high quality large diameter substrates at reasonable prices (typically at a slightly lower cost per cm^2) is necessary. Also necessary is significant development of epitaxial growth equipment and process controls in order to maintain the required level of epitaxial layer uniformity during heteroepitaxial growth. Problems in maintaining a uniform temperature profile over bowed substrates will be magnified for larger substrate sizes and could limit their speed of adoption.

Some R&D effort has been directed toward silicon as an alternative heteroepitaxial substrate which has the advantage of being readily available in large diameters at low cost. However, a number of significant technological challenges remain (due to increased lattice and thermal expansion coefficient mismatches) before this can be considered a viable alternative to sapphire. In addition, high efficiency GaN LEDs and good growth uniformity need to be demonstrated on Si 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 would 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 based on the use of non-polar or semi-polar substrates.

Producing GaN wafers using conventional bulk crystal growth techniques remains difficult. A promising lower cost alternative is the use of thin free-standing (FS) GaN substrates manufactured by HVPE. FS GaN substrates offer many of the same advantages as bulk crystal grown GaN substrates. However, they currently have higher defect densities and often exhibit a non-standard form factor. In the short term, the use of GaN templates comprising a thick GaN layer on a sapphire substrate might provide an intermediate solution. Templates offer a GaN surface for nucleating the MOCVD growth (saving growth time) and a lower defect density through the inclusion of a thick GaN buffer layer. However, these improvements must be demonstrated while simultaneously maintaining epilayer quality and overcoming any incompatibility with existing manufacturing processes.

Unfortunately, GaN substrates meeting practical size, cost, and quality requirements are not presently available. Bulk and free-standing GaN substrates are currently used for blue laser production. As their quality improves, substrate sizes increase, and prices continue to fall, these substrates may begin to offer a viable alternative to sapphire and SiC substrates. A significant manufacturing effort would be required to ramp up production volumes and drive down GaN substrate prices.

Substrate selection can have a significant impact on epilayer uniformity, wafer flatness and device performance. Consequently, substrate selection can impact back-end costs through changes to process yield, binning yield and device performance. Figure 10 illustrates how the choice of substrate impacts the cost balance for the final LED device. The starting point for this analysis is the cost split shown in Figure 6 with values adjusted to match 2” diameter sapphire substrates processed at today’s costs, yielding 800 die that are then individually packaged.[10]

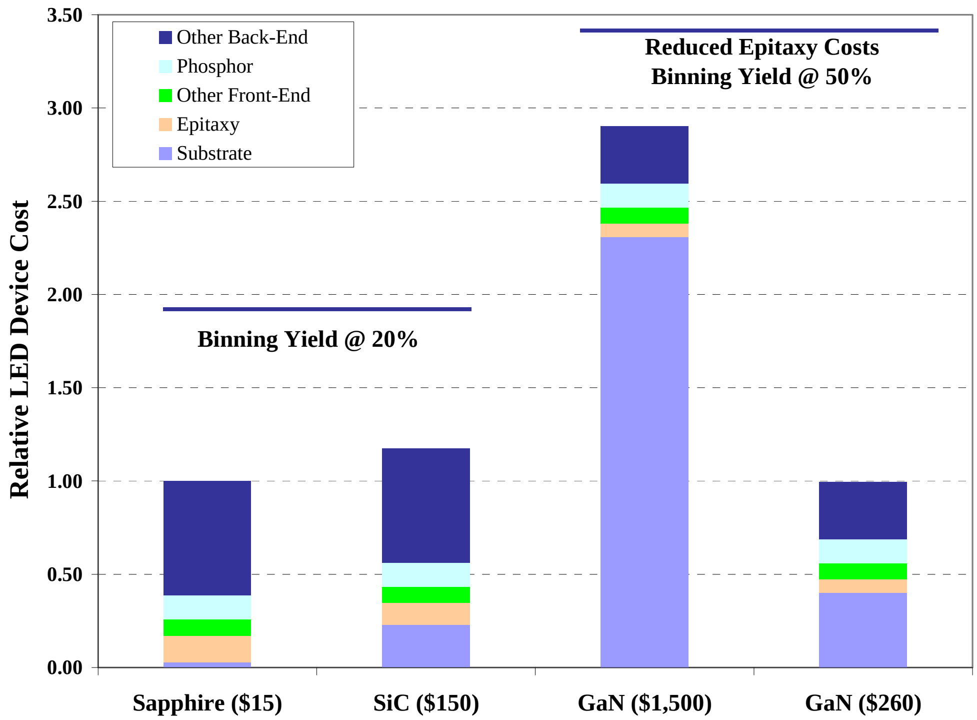


Figure 10. Impact of Substrate Selection on Relative Costs of Main Process Steps and Final Packaged LED Device. *Source: DOE Workshop Consensus*

For the GaN substrate the cost analysis assumes that the epitaxy cost is reduced due to shorter cycle times (simpler buffer layer), and the binning yield is improved due to improved uniformity and reproducibility. Figure 10 demonstrates that cost savings at the back-end can largely offset cost increases at the front-end. For example, an increase in substrate price by a factor of nearly 100 might only increase the final LED device cost by a factor of 3.

The current price for a 2” GaN substrate is cost prohibitive at around $2,000. As shown by the final bar in Figure 10, the price would need to be driven down to approximately $260 to achieve

[10] The analysis assumes: (i) epitaxy costs reduced by 20% (SiC) or 50% (GaN) compared with sapphire due to reduced buffer thickness, (ii) Other Front-End and Phosphor costs remain unchanged, and (iii) Other Back-End costs reduced by 50% for GaN compared with sapphire and SiC. Substrate costs are shown in the figure.

cost parity with a sapphire and SiC substrate. At the April workshop, Kyma predicted that GaN substrate prices will fall dramatically as production volumes increase, potentially approaching values as low as $50 for 2” wafers or $200 for 4” wafers by 2015. Additional work is needed to verify these numbers, estimate future values, and determine if other benefits associated with the use of native substrates, such as improved performance, can outweigh the higher substrate and apparent net device costs.

Figure 11 presents the substrate roadmap. The starting points of the bars in Figure 11 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.

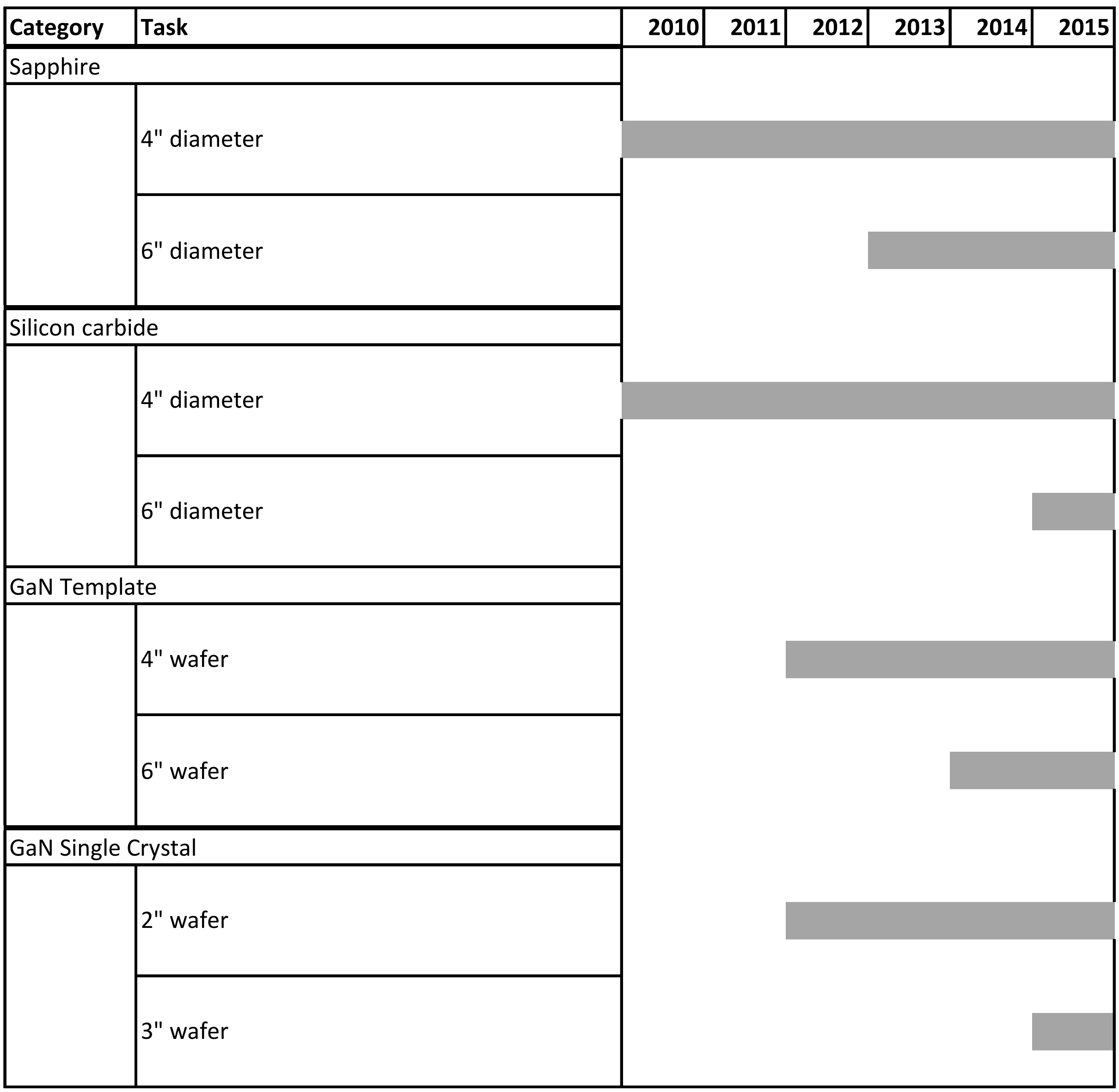


Figure 11. Substrate Roadmap. *Source: DOE Workshop Consensus*

2.3.3 Equipment

The third significant set of issues concerns a lack of availability of suitable manufacturing equipment for wafer processing, chip manufacturing, and chip packaging, especially for the smaller substrate sizes currently employed in the LED industry. Plans regarding equipment for epitaxy are included in the epitaxy roadmap (Figure 9). The group felt strongly that manufacturing equipment should be improved in several ways to better suit the requirements of the LED industry. There is a need for increased levels of automation, higher throughput, improved yields, improved equipment standards, and generally a lower cost-of-ownership. A number of the group members felt that improved communication between equipment manufacturers and end-users would help alleviate some of these issues. As equipment suppliers become more aware of manufacturing trends, it is more likely that suitable equipment will be available to the manufacturers at the appropriate time. This would help eliminate the need for each manufacturer to undertake their own customization of available equipment which often results in inefficient use of time and unreliable machinery with inadequate support.

Although it was not possible to create any kind of definitive list, there was a general agreement that equipment improvement was required to advance process control, manufacturing throughput and yield. This reluctance to focus on specific equipment, either process-related or for testing and inspection, was partly because clear cost benefits had not yet been established. Better understanding of the impact of equipment and process changes on the packaged LED cost is required in order to make these decisions, highlighting the need for better cost modeling. This need for an accurate cost model was the main take-away of the equipment discussions. Many participants stated such a model would have much wider application in identifying areas in the packaged LED process which had the largest impact on ultimate device costs. Such a model would allow the community to identify equipment and processes lying on the critical path and offer a more quantitative assessment of the beneficial cost impact of addressing each issue. Generally the most critical decision when introducing a new piece of equipment into the manufacturing operation is whether or not that equipment will reduce the overall cost of producing good parts. The total COO is a good metric for making such a decision and is widely used in the semiconductor industry (see SEMI standard E35 'Cost of Ownership for Semiconductor Manufacturing Metrics'). In fact, a key element in the successful growth of the silicon semiconductor industry was its ability to develop this common cost modeling standard.

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

As a general guideline, the participants agreed that equipment developments should exhibit at least a 2 times improvement in COO every 5 years. Thus, by 2025 the COO will have improved by at least a factor of 16, representing a significant step toward the final cost targets.

2.3.4 Process control and testing

Concerns about equipment go beyond the direct process steps discussed above, and include inspection and characterization. Table 3 shows how the process control and testing metrics might evolve. Process control associated with the epitaxy stage is included in the epitaxy roadmap (Figure 9).

Table 3. Process Control and Testing Metrics. *Source: Stan Myers, SEMI, "Driving Solid State Lighting Through Manufacturing Cost Reduction", Fairfax, April 2009; Richard Solarz, KLA Tencor, "In-line Process Control and Yield Management for the HBLED Industry*

Metric	Unit	2009	2010	2012	2015
Process Throughput	wfr/hr	50	55	70	100
Process Yield	%	60	65	75	90
Process Productivity	%	50	65	75	90
Binning Yield	%	20	25	34	50
Cost Savings through In-line Inspection	%	-	10	25	50

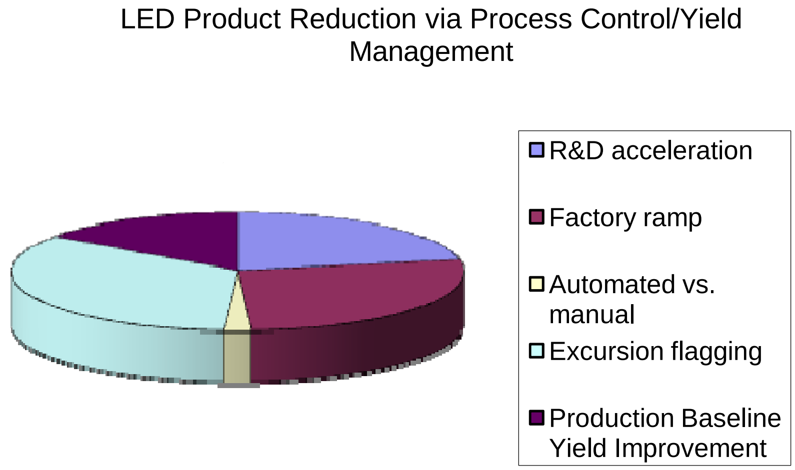
The first three items in Table 3 relate to the wafer processing stage and are common metrics in the microelectronics industry. Despite the fact that wafer processing costs currently represent only 3 percent of the packaged chip cost, due to an anticipated trend toward reducing costs through improvements in wafer-level processing, these metrics are likely to remain important.

The issue of binning yield is a little more controversial. Manufacturers are currently required to measure all devices produced in order to place them in a specific bin based on color, efficacy and forward voltage. Of these three binning criteria the most critical by far is that of color, with die from even the same wafer often falling into different bins. Since certain bins are preferred by the luminaire manufacturers, it would be most efficient to target only those bins during the manufacturing process. Unfortunately the current level of process control is such that a specific bin might only be hit with a yield of around 20%. Therefore an improvement in binning yield will have a significant impact on the final packaged LED cost and is an important target for the program.

At the present level of maturity of the SSL industry, the device manufacturers find that they are able to sell most, if not all, of the devices they produce, albeit at much lower prices for those that fall in the outer bins. Consequently the impact of binning is somewhat lessened. Devices falling in prime bins remain in short supply and these can command premium prices. Nevertheless, from the luminaire manufacturer's perspective, this lack of availability of consistent prime quality product at reasonable prices is regarded as a significant factor in the high cost of existing luminaire products (see Section 2.2.1). Improvements to the manufacturing process to better target specific bins, and allow tighter bins to be specified, would ultimately result in significant cost savings for the industry.

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

Experience from the silicon chip industry suggests that these cost savings come from, in roughly equal measure, reduced R&D costs, factory ramp-up costs, and manufacturing production costs. In the case of the LED die production process it was proposed that cost savings could range from 6% to 24% through improvements to the baseline process yield, and from 22% to 44% through the use of excursion flagging (see Figure 12). Participants felt that the cost savings impact of automating the final die inspection step would be small due to the low labor costs traditionally associated with this activity. Potential cost savings associated with R&D and factory ramp-up were estimated to be ranging from 20% to 40%. According to KLA Tencor, most reasonable estimates based on silicon industry experiences suggest that the use of in-line inspection can reduce costs by roughly a factor of 2, i.e. an overall cost saving of 50%. This will be the target for 2015.



Operation	Product Research and Development	Factory Ramp Operations	Production Automated Operations	Production Excursion Reduction	Production Baseline Yield Improvement	Overall
Improvement	**20-40%**	**30-40%**	**0.50%**	**22-44%**	**6-24%**	**79-148%**

Figure 12. Potential Cost Savings Associated with Use of In-line Inspection. *Source: Richard Solarz, KLA Tencor, "In-line Process Control and and Yield Management for the HBLED Industry", Vancouver, June 2009*

These yield improvements and cost reductions will be achieved through the introduction of in-situ and ex-situ characterization equipment with improved measurement accuracy, the linkage of these measurements to end-product performance, and the implementation of active process control. Higher throughput and more sophisticated inspection and testing equipment was required for substrates, epiwafers, processed wafers, finished die, and packaged LED devices (e.g., lm/W, correlated color temperature (CCT), color rendering index (CRI), etc.). An example of an equipment roadmap for in-line yield management is shown in Figure 13.

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

Draft roadmap for LED inspection/yield management in-line optimization

	2010	2011	2012	2013	2014
Substrate and Film monitor	install stealth channel				
(improved binning and sensitivity)		customer tests			
			product in field		
		post liftoff monitor			
			build/test wafers		
				product in field	
Diced die monitor	hardware/software mod				
(reduction of nuisance defects)		wafer demos			
			product in field		
Defect Source analysis	customer specs				
(back-front integration)	build test hardware	wafer tests			
		tune cluster red.			
		UI complete			
			product in field		
In cluster monitor	fab 10nm res. Lab				
(green LED)	hardware		tool specification		
		test/correlate to		build and test	
		device performance			product in field

Figure 13. Roadmap for In-line Yield Management. *Source Richard Solarz, KLA Tencor, "In-line Process Control and and Yield Management for the HBLED Industry", Vancouver, June 2009*

2.3.5 Packaged LED R&D recommendations

Based on the packaged LED manufacturing related presentations and breakout discussions a number of recommendations can be made to the DOE SSL Core Technology and Product Development R&D Program which can impact the state of packaged LED manufacturing. The recommendations are listed below with reference to subtasks identified in the DOE 2009 MYPP:

- Provide support for R&D on alternative substrates including bulk GaN, free-standing GaN and GaN templates (Subtask A.1.1).
- Provide support for the development of low-cost, high quality substrates (Subtask B.1.1).
- Provide support for the development of advanced package architectures including multi-chip products (Subtask B.3.6).
- Continue support for R&D on emitter materials, semiconductor materials and epitaxial growth in order to improve device efficacy and minimize droop (Subtasks A.1.2, B.1.2 & B.4.2). Expand support for epitaxial growth R&D on alternative substrates.
- Continue support for phosphor R&D to improve down conversion efficiency and color control (Subtasks A.1.3 & B.1.3).
- Continue support for optical component materials research to improve performance and stability of packaged high power LED devices (Subtasks A.5.1)

2.4 System and component integration

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

The SSL system is illustrated schematically in Figure 14 Participants suggested there is no one solution to achieving the required cost reductions and performance improvements. Rather, many aspects of the manufacturing process will need to be addressed in parallel and in an integrated manner. Disciplines such as design for manufacture and integrated product development were identified as important considerations in the drive toward improved quality, reduced cost, and rapid commercialization. Decisions made early in the product design phase can make the majority of impact on the product's cost, quality and manufacturability. Close communication and/or partnering between design engineers and manufacturing engineers will be required to optimize manufacturability. Progress can be made through several pathways including: the utilization of common parts and materials, minimizing the number of active or approved parts through standardization, designing for ease of assembly, and the creation of robust designs which avoid tight tolerances beyond the natural capability of the manufacturing processes.

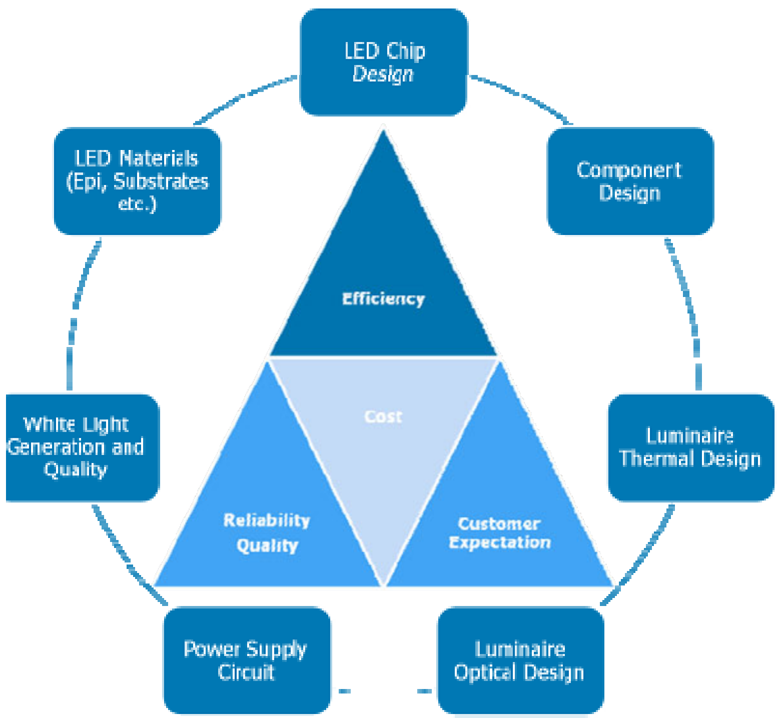


Figure 14. Integrated Systems Approach to SSL Manufacturing. *Source: Mark McClear, Cree, Inc., "An Integrated Approach to SSL Manufacturing", Vancouver, June 2009*

Ultimately, real cost reductions will be achieved through the simplification of SSL luminaires. One path to simplification is through the integrated systems design approach described above. There is significant opportunity to optimize the luminaire design and manufacturing processes to reduce costs while still continuing to meet quality, reliability, and efficiency requirements, and continuing to match customer expectations. Another path to simplification will be through increased integration at the components level. This includes hybrid integration of components at the package level and monolithic integration of components at the wafer level. The simplest example of hybrid integration would be the placing of multiple die in the same package. A more sophisticated example which better illustrates the point is shown in Figure 15 presents a more sophisticated example in which the thermal control chip, driver chip, and more sophisticated primary optics could be integrated into the same package. Hybrid integration schemes of this type could have a significant impact on the final luminaire costs.

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

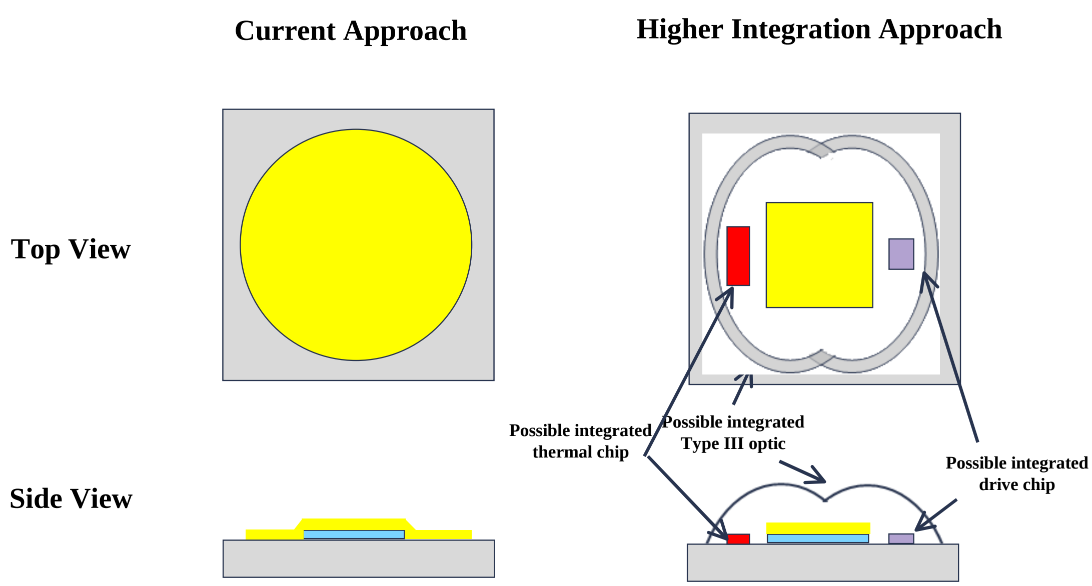


Figure 15. Schematic Representation of Possible Hybrid Integration Approach to Simplify SSL Luminaire Manufacturing and Reduce Costs. *Source: Mark McClear, Cree, Inc., "An Integrated Approach to SSL Manufacturing", Vancouver, June 2009*

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

2.5 Cost model

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

The need for a cost model was particularly important with respect to making decisions on equipment development (see section 2.3.3). The use of cost of ownership modeling was agreed to be the most suitable criterion for evaluating the impact of introducing new equipment into the manufacturing process. As discussed earlier, the same type of modeling can also be used to (i) evaluate the long-term benefit of manufacturing changes, (ii) help with decisions about materials use, equipment operations, and process improvements, (iii) identify bottlenecks in the process, and (iii) foster communication and understanding throughout the supply chain.

Hence an important outcome of the workshops was the need to develop such a model at the earliest opportunity.

3.0 OLED roadmap

3.1 Manufacturing strategies

Based on the discussions at the Manufacturing Workshops in Fairfax and in Vancouver, it is clear that there is not yet consensus on the best manufacturing strategy to meet the performance and cost targets set out in the 2009 MYPP. Some participants recommended building upon the experience gained through OLED displays by developing vacuum processing on rigid substrates, as described in Section 3.4. An alternative approach is to develop web processing (roll-to-roll) techniques on flexible substrates. This approach is discussed in Section 3.5. These two approaches represent the ends of a spectrum of processing technologies. Hybrids of these approaches, such as thermal evaporation on a flexible web combined with glass encapsulation, may provide the best combination of cost and performance.

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

Most OLED manufacturing strategies can be separated into three stages.

1) Preparation of the manufacturing substrate: The foundation onto which the organic stack is deposited consists minimally of a substrate and an electrode. However, protective coatings and layers to enhance light extraction are often added to improve the efficiency and lifetime of the devices. These combined structures will be referred to as foundation layers. The electrode may need to be patterned to ensure uniform emission of light and to minimize the effects of electrical shorts. The substrate electrode usually is in the form of

a transparent anode. The assembly of the foundation layers may be carried out by merchant suppliers who do not have access to the basic OLED intellectual property.

2) Deposition of the active organic layers: The core set of operations involve the deposition of multiple layers of organic materials that transport charge between the two electrodes and convert the electrical energy into light. The fabrication of this organic stack must be matched to the specific properties of the organic materials and so can be carried out only in close collaboration with the developers of the basic materials and architectures. The deposition of the upper electrode (usually an opaque cathode) also requires a thorough understanding of the properties of the organic layers in order to avoid damage to the fragile organics and to ensure good electrical contact and long device lifetime.

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

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

Since overall energy conservation is the primary focus of the SSL program, the emphasis must be on general illumination rather than the production of dim light sources for special applications. For planning purposes, the 2009 MYPP recommends a minimum light output of 500 lumens. For a Lambertian source with a light output of 3000 lumen/m^2, this implies an area of 0.16 m^2 or 250 sq in. In early stages of manufacturing, producing single panels of this size with acceptable yields, an appropriate voltage drop[12] and good uniformity will be very difficult. Therefore, it may be more practical to form luminaires using arrays of smaller tiles, as shown in the figure below.

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

[12] The high sensitivity of light emission to applied voltage means that voltage drops across each active area should be kept less than 0.1V. Some device designers have suggested that unless the sheet resistance of transparent conductors can be reduced to well below 1 Ω/square, it may be necessary to break each tile into segments of size around 1 cm^2. Thus, although the sub-micron resolution of OLED displays is not needed, some patterning must be accomplished. More guidance needs to be supplied to the tool-makers and substrate suppliers regarding the resolution and registration accuracy associated with this patterning.

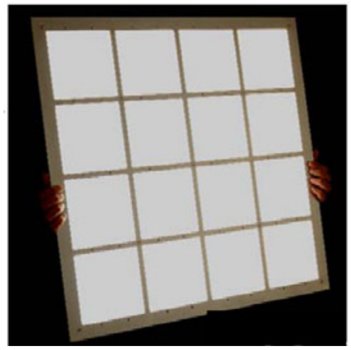


Figure 16. OLED Panel Formation with Tiles. *Source: GE*

Such tiling also greatly simplifies the uniform distribution of current across the whole panel. Until manufacturing yields reach very high levels, it may be more expedient not to fabricate such a panel monolithically, but to select and reassemble good panels from the primary manufacturing process. This tiling approach has the additional advantage that the dimensions of the luminaire need not match directly those of the manufacturing substrate.

3.1.1 Cost reduction

In most contexts, such as in comparisons with other light sources or assessing the global economic impact, cost targets for OLED lamps should be specified in terms of $ per kilolumen (klm). However, manufacturing costs scale more closely to panel area, rather than light output, so considering $\$/m^2$ is also useful. The relationship between these two metrics depends on the brightness of the panel. If the light is emitted equally in all directions, corresponding to a Lambertian distribution, a brightness of 1000 candela (cd)/m^2 will lead to a total light output of 3140 lumens/m^2. A cost of $100/klm then implies a manufacturing cost of $\$314/m^2$.[13]

As is illustrated in Figure 17, significantly higher manufacturing costs per unit area can be tolerated if the luminance is increased from 1000 cd/m^2 to 4000 cd/m^2. However, this may result in a reduction of the operating lifetime of the panel and will require more attention to glare issues and thermal management in luminaire design. Thus, in addition to the manufacturing developments described in this roadmap, continued Core and Product Development R&D to improve OLED stability is essential to meet overall objectives.

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

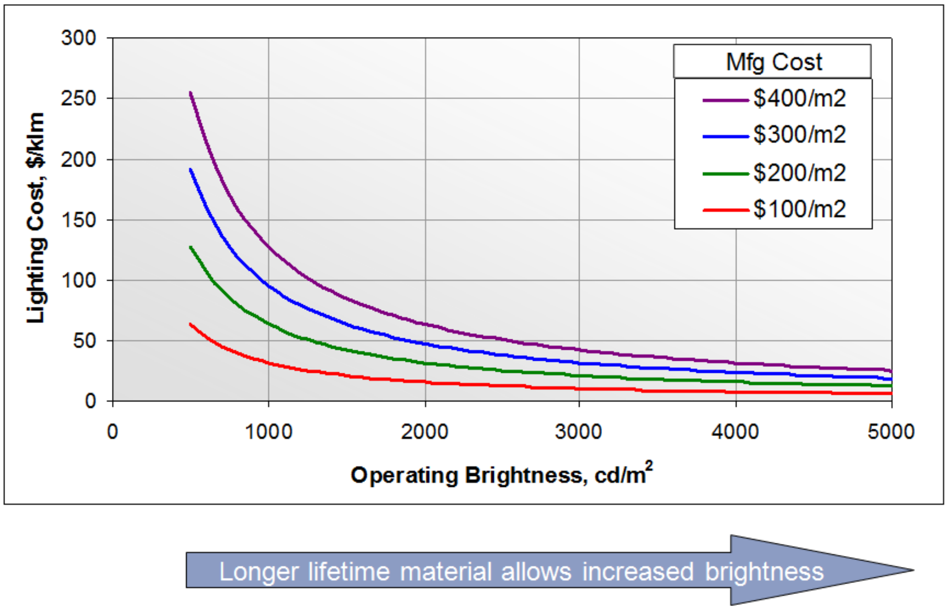


Figure 17. Influence of Luminance on Manufacturing Costs. *Source*: *William Feehery, DuPont, "OLED Lighting Manufacturing Cost," SSL Manufacturing Workshop, Fairfax, VA, April 2009*

An analysis by Acuity Brands[14] of potential solid-state replacements for fluorescent fixtures suggests that OLED panels could become competitive with inorganic LED arrays if the OEM price can be reduced to $16/klm. At a luminance of 4000 cd/m^2, this is equivalent to $200/m^2. The only manufacturing experience that has been gained so far for OLEDs is for display applications. The cost of an active matrix OLED panel for display application is at least $2000/m^2. Allowing for the replacement of expensive display substrates and the absence of the TFT backplane and high-resolution patterning, the cost of producing OLED lamps using similar equipment and materials is likely to be around $1000/m^2. Reaching cost targets as low as $200/m^2 will require significant progress in several areas. These areas are described below:

The opportunities to reduce manufacturing costs can be classified into several general areas:

- Substrate size: The area of substrate used in manufacturing OLED displays has been limited by the difficulty of aligning and maintaining high-resolution masks. Since fine patterning can be avoided in lighting applications, scaling to large areas should be simpler, bringing significant cost savings, as shown in Figure 18. Similar gains are anticipated from increases of the width of the web in roll-to-roll processing.

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

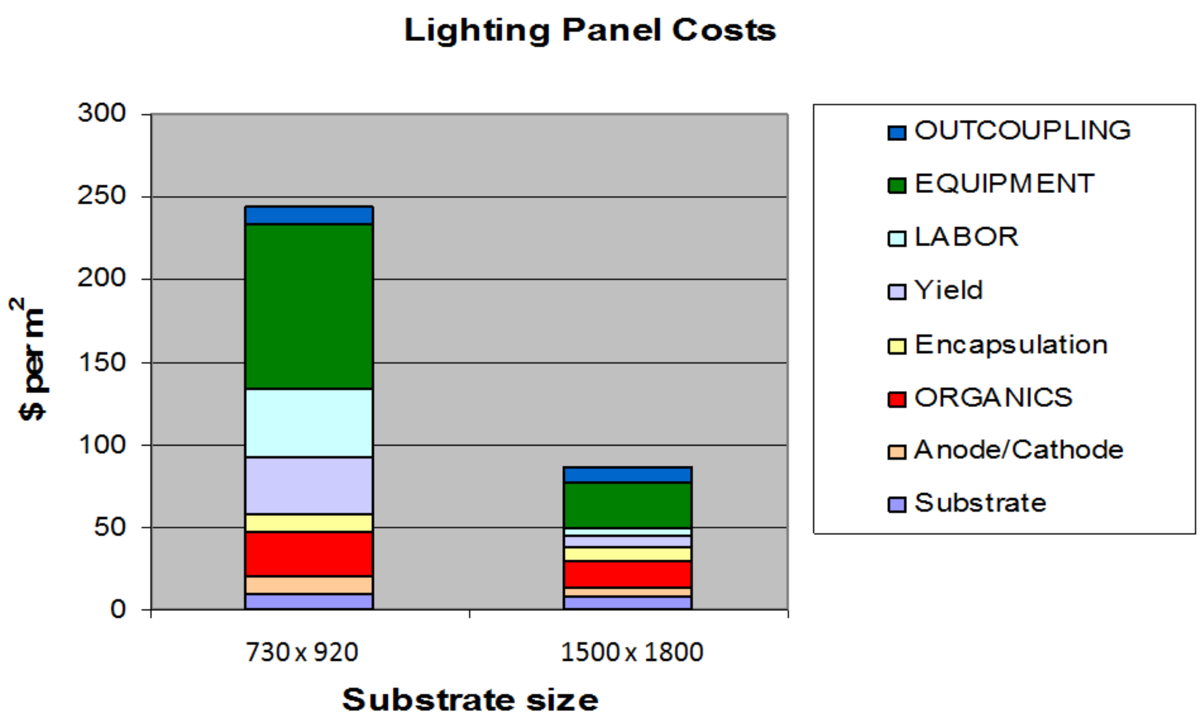


Figure 18. Dependence of OLED Manufacturing Costs on Substrate Size. *Source: Mike Hack, Universal Display Corporation, "OLED Lighting," SSL Manufacturing Workshop, Fairfax, VA, April 2009*

- The waste of critical materials, such as the active organics and transparent conductors, must be minimized. Some material utilization factors have been less than 10% but need to be increased to over 50%. Proponents of solution processing point out that extrusion coaters are available[15] which achieve material utilization rates greater than 95%. Proper design of vacuum evaporators can also lead to material utilization around 70% or higher. In addition, economic techniques should be developed to recover some rare elements, such as indium or iridium, from scrapped work pieces.
- The yield of good panels should be increased to levels in excess of 95%. Meeting this target will require experience in identifying and removing the causes of defects and the installation of effective in-line inspection tools and error recovery mechanisms.
- Processing times should be shortened to reduce depreciation and labor costs. Cycle times for batch processing should be lowered from current values of around 4 minutes and web speed increased in roll-to-roll manufacturing from today's typical values of 1 foot/min.
- Less expensive materials should be used wherever possible. For example, the replacement of display glass by window glass could reduce the cost from ~$50/m^2 to ~$5/m^2. Benefits of scale should be leveraged, especially for organic materials and transparent conductors.

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

- Manufacturing procedures should be simplified as much as possible. For example, high-resolution patterning using lithographic techniques should be avoided.
- Labor costs must be reduced through automation, increased equipment reliability and greater throughput.
- The greatest divergence in the cost forecasts presented at the Fairfax workshop concerned capital equipment. Forward-looking technology developers were more optimistic than industry analysts, who based their estimates on past experience. The impact of depreciation depends mainly on the throughput of good devices and most critically upon average cycle time or web speed.

The following four tables were constructed at the Vancouver workshop to illustrate what manufacturing targets must be achieved in order to meet 2009 MYPP cost targets. Because it is too early to decide between the main two processing methods, sheet processing and web processing, a manufacturing roadmap and projected cost targets were developed for both manufacturing techniques.

The many challenges that are faced in reducing production costs can be separated into two groups. The first relate to the costs of capital and labor associated with each manufacturing line. The contribution of these factors to the cost of each lamp can best be reduced by increasing the number of lamps produced on each line. Table 4 and Table 5 show targets for the manufacturing parameters, including capital investment and staffing levels. In both tables, the size of the substrate is steadily increased and the cycle time is reduced in order to reach the desired production levels.

With regards to light output, the targets in the 2009 MYPP assume a luminance of 1000 cd/m^2, corresponding to a luminous flux of ~3000 lm/m^2. Therefore, in order to reduce costs, both roadmaps include an increase in light output per m^2. However, as increased lumen output will likely lead to lower lifetimes, further improvements in materials performance are required such that output levels of at least 10,000 lm/m^2 can be achieved with acceptable lifetimes. Future recommendations on acceptable operating lifetimes should take into account the steadily increasing performance levels and changes in luminaire design that will reduce the demand for very long lifetimes. In addition, increased lumen output may require significant luminaire redesign.

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

With regard, the web processing manufacturing roadmap, web handling and blanket coating have already been demonstrated at the sizes and speeds depicted for many other applications. Cathode formation and optical inspection are expected to be the major challenges to reaching the speed targets. In addition, as seen in Table 4 and Table 5 the yield targets for web processing are more modest than for sheet processing due to the added difficulty of in-line inspection and repair.

Table 4. Manufacturing Roadmap for Sheet Processing of OLED Lighting Panels

Stage	Units	A	B	C
Year		**2011**	**2012/3**	**2014**
Light output	lm/m^2	3000	6000	10,000
Substrate area[16] **(example)**	m^2 m	0.2 (0.4 x 0.5)	0.67 (0.73 x0.92)	2.7 (1.5 x1.8)
Cycle Time	Sec	180	120	60
Yield	%	0.75	0.9	0.95
Annual Uptime	Hours	6000	6900	7500
Annual Production	m^2	14,000	100,000	925,000
Investment[17]	$M	30	80	150
Direct Labor	staff/shift	7	8	10
Indirect Labor	staff/shift	15	15	15
Annual Labor Costs[18]	$M	4.4	4.6	5
Other Operations[17]	$M	1	2	4

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

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

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

Table 5. Manufacturing Roadmap for Web Processing of OLED Lighting Panels

Stage	Units	A	B	C
Year		**2011**	**2013**	**2015**
Light output	lm/m^2	3000	6000	10,000
Web Width	m	0.2	0.5	2.0
Web speed	m/min	0.3	1.0	10
Product area	m^2/min	0.048	0.4	16
Yield	%	0.7	0.8	0.9
Annual Uptime	hours	6000	6900	7500
Annual Production	m^2	12,000	130,000	6,500,000
Investment[17]	$M	20	50	200
Direct Labor	staff/shift	7	8	12
Indirect Labor	staff/shift	15	15	15
Ann. Labor Costs[18]	$M	4.4	4.6	5.4
Other operations[17]	$M	1	2	10

If the capital and labor costs are spread over very many lamps, the remaining set of challenges relate to the cost of materials. These, along with the prorated costs of depreciation, labor and operations, are included in Table 6 and Table 7. All material costs are fully yielded, with allowance for materials wastage and scrapping of unacceptable panels. With regard to the sheet-processed substrate cost, the roadmap assumes the usage of tempered clear float glass. For web-processed manufacturing, the roadmap assumes plastic substrates, where most of these costs are incurred in the production of the barrier coating. In addition it is important to note that the electrode cost estimates are lower than the current prices of transparent conductors (ITO). These estimates assume more efficient production techniques or the development of less expensive alternatives. A substantial portion of current costs is associated with electrode patterning. With regard to the light extraction, meeting the performance targets of over 75% light extraction (as presented in the 2009 MYPP) within these cost estimates is very challenging and requires further research and development. Encapsulation estimates assume the use of a metal foil cover with edge sealants.

Table 6. Projected Costs of OLED Lighting Panels (sheet processed)

Stage	Units	A	B	C
Year		**2011**	**2012/3**	**2014**
Depreciation[19]	$\$/m^2$	420	160	30
Labor	$\$/m^2$	305	45	5
Other operations[17]	$\$/m^2$	70	20	4
Organic Materials[20]	$\$/m^2$	30	15	10
Substrate	$\$/m^2$	6	6	6
Electrodes	$\$/m^2$	20	15	10
Light extraction	$\$/m^2$	20	15	10
Encapsulation	$\$/m^2$	10	8	5
Other materials[17]	$\$/m^2$	20	15	10
Total direct costs	$\$/m^2$	900	300	90
Total direct cost	$/klm	300	50	9

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

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

Table 7. Projected Costs of OLED Lighting Panels (web processed)

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

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

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

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

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

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

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

3.2 Luminaire assembly

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

3.2.1 Sizing issues and brightness

As discussed in Section 3.1.1, manufacturing costs scale more directly with panel area than light output. At the Fairfax meeting, Acuity Brands recommended a luminance level of 15,000 lm/m^2, rather than the nominal value of 3000 lm/m^2, which is the reference level used in 2009 MYPP planning. This would not only reduce the cost of the panel by a factor of approximately 4, but may also reduce the lifetime by a much greater factor. It may also require more attention to glare and thermal management in luminaire design, as noted earlier. This is a critical issue that must be clarified over the next two years before large-volume production can begin.

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

3.2.2 Variability/binning

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

Until any significant differences are identified in the reproducibility of LED and OLED lamps, the recommendations in the LED section (section 2.2.1) should also be used as guidelines by OLED manufacturers.

3.2.3 Electrical circuits

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

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

3.2.4 Reliability issues

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

The 2009 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 unaddressed opportunities might deserve reconsideration for 2010.

3.2.5 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.

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

3.2.6 Product differentiation and market expansion

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

3.3 Substrates and encapsulation

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

3.3.1 Substrate and encapsulation material selection

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

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

- Smoothness: Surface roughness must be controlled at a microscopic level, with average roughness (R_{rms}) of less than 2 nm and peak-to-valley roughness less than 20 nm. Specifications for larger scale flatness are also needed. The current-carrying circuits inside the OLEDs need to be electrically isolated from the external environment.
- Mechanical and Thermal Stability: Expansion of the substrates and intermediate layers caused by thermal or mechanical stress during fabrication can cause issues with pattern registration, optical inspection accuracy, and edge seal integrity. Parameters such as

coefficient of thermal expansion (CTE) and Young's modulus are needed for all materials. Additional properties, such as shrinkage or expansion under thermal cycling and moisture absorption are important for plastics.

- Optical Properties: For transparent substrates, absorption of visible light should be less than 5% and transmittance more than 85%, with all foundation layers included. The refractive index of the glass is an important factor in the design of out-coupling enhancement structures.

3.3.2 Substrate coatings

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

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

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

3.3.3 Transparent anodes

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

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

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

3.3.4 Out-coupling enhancement structures

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

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

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

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

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

3.3.5 Encapsulation

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

For small OLEDs, such as those used in cell-phones, solid getters are available in sheet form, with pellets up to 40mm x 70mm in size and around 100 μm thick. These are inserted in cavities in the cover glass. The cost of this process (~$120/m^2) can be reduced by at least a factor of 2 by printing the getter onto the cover glass. However, further product development is necessary in this area to achieve the more than factor of ten reduction in cost required, as presented in Table 6.. Printing is advantageous because the getter can be concentrated near the seals to provide maximum protection against edge ingress. Alternatively, the development of thin-film getters that could be deposited directly onto the cathode layer could greatly facilitate the encapsulation process for large area devices.

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

3.4 Batch processing on rigid substrates

The existing OLED and Liquid Crystal Display (LCD) industries rely on vacuum processing of thin-film devices on glass substrates. LCD fabrication has been demonstrated for substrate areas as high as 5 m^2, while OLED manufacturing has evolved more recently and has been limited areas less than 0.4 m^2. In a traditional OLED system, the tools that deposit the individual layers are arranged in a cluster configuration, as shown in Figure 19.

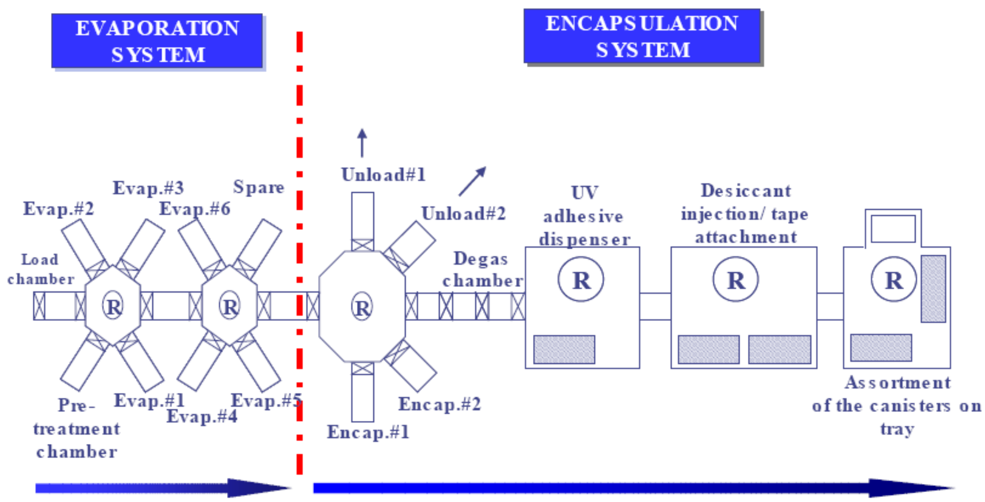


Figure 19. Vacuum Deposition Production Line with Cluster Configuration. *Source: Barry Young, OLED Association, "OLED Manufacturing", SSL Manufacturing Workshop, Fairfax, VA, April 2009*

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

It is anticipated that as OLED lighting manufacturers gain confidence in the performance of individual tools and fix device architectures, they will adopt an in-line configuration, such as that illustrated in Figure 20.

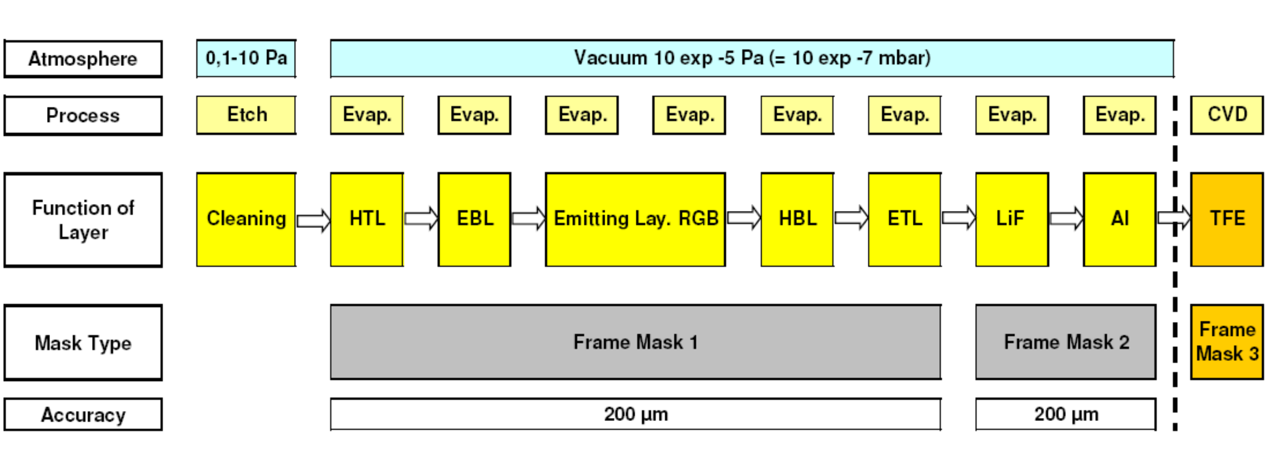


Figure 20. Vacuum Deposition Production Line with In-Line Configuration. *Source: Uwe Hoffmann, Applied Materials, "Deposition Equipment and Processes for OLED Lighting", SSL Manufacturing Workshop, Fairfax, VA, April 2009*

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

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

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

The replacement of point evaporators with linear sources and cluster configurations with in-line production has been shown[22] to lead to substantial reductions in materials costs without significant increase in the capital investment. This will result primarily from an increase in materials utilization from ~10% today up to 50-70% by 2015.

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

3.4.1 Deposition of organic layers

Deposition is usually accomplished by evaporation, with or without a flow of inert gases, preferably using a linear or areal source. Vertical orientation of the substrate has many

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

advantages, including easier particulate control and reduced substrate bending, but may lead to increased handling costs.

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

- Deposition Speed: Typical rates in mass-production tools[23] are 30 nm/min with stability of ±2% maintained over several days of operation. This should be adequate for thin layers (10-20nm), but faster deposition will be required for thicker layers to achieve cycle times below 1 minute.
- Spatial Uniformity: In OLED display applications, uniformity targets for substrates of 460 x 730mm are ±5%. Variations less than ±2% have been reported in ideal conditions. Control to ±2% or better needs to be maintained in lighting applications as substrate sizes and deposition rates are increased.
- Material Utilization: In the manufacture of high-resolution OLED displays, only 10-20% of the material is deposited in the desired position on the work piece, much of the remainder being intercepted by the mask or spread over the walls of the chamber. This fraction should rise in lighting applications, since fine masks are not needed. The usage rate should be raised to over 50% by 2012 and 80% by 2015.
- Mask Alignment: Although fine masks are not needed to create small sub-pixels[24], some patterning will be required. Accuracy targets of 5µm, typical for cell-phone displays, can be relaxed, perhaps to 100 µm. This should reduce the time required for mask alignment, which typically is 30s when high accuracy is demanded.
- Doping Control: Many layers contain dopants and hosts which should be mixed uniformly. Dopant levels are usually less than 10%, and should be controlled to better than ±1%.
- Uptime: In addition to maintenance time, evaporation equipment needs to be shut down for periodic chamber cleaning and to replenish the organic materials. Uptime needs to be increased to at least 90%. Ways to resupply organic materials without breaking the vacuum are desirable.
- Interface Control: Since OLED devices involve several thin-film layers, each with different functionality, it is important that the deposition of one layer does not degrade the structure of the layer below. No specific metrics have yet been defined to check this aspect of multi-layer formation.

3.4.2 Cathode deposition

Cathode deposition is one of the most difficult steps, both for batch and web processing, due to the fragility of the underlying organic layers. Evaporation is the preferred technique in research

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

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

environments and can be carried out at high speed for either sheet or web processing. Other techniques like magnetron sputtering and ion-beam assisted deposition are also available.

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

3.4.3 Patterning techniques

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

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

- alignment accuracy requirements for serially-connected segments
- alignment times
- cleaning frequency and associated downtime
- effect on material usage ratios
- lifetimes and costs

3.4.4 Inspection and quality control

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

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

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

The most challenging task will be to monitor the uniformity of individual layers in the stack, using either optical or electrical techniques. The fact that most layers must be optically transparent means that techniques that rely on optical absorption may be feasible.

Although immediate priority should be given to the introduction of integrated manufacturing facilities, the development of real-time inspection and process-control system should be given significant attention from 2011 to 2015.

3.5 Web processing on flexible substrates

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

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

3.5.1 Web handling

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

Throughput can be improved by increasing the web width or the speed. Currently, there seem to be no insurmountable barriers to increasing the web width from 8” in 2009 to 1 m by 2015.

Increases in web speed often lead to larger footprints for the manufacturing line. The rate limiting processes often involve drying or curing steps. Even with modest web speeds of 1 ft/min, a drying time of 30 minutes implies that a 30 foot length of web must reside in the oven at any one time. The development of rapid drying techniques would lead to greater throughput with minimal increase in plant size. Speeds of around 5 m/min would seem a reasonable target for 2015, giving throughputs equivalent to those achieved today in the flat panel display industry.

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

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

3.5.2 Deposition of organic layers

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

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

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

3.5.3 Cathode deposition

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

An innovative approach to avoid the problem of damage to the underlying organic layer, suggested at the Fairfax workshop, is to deposit the cathode on to a second substrate as shown in Figure 21[25]. This is a roll-to-roll version of the approach used for liquid crystal and plasma displays. Using this process, the manufacturer must to ensure that no oxygen, water vapor or other contaminants are trapped between the two substrates as they are brought together.

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

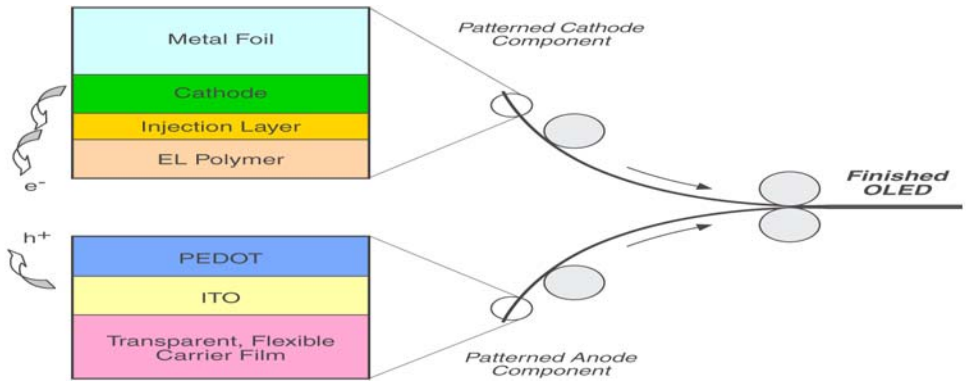

Figure 21. Dual Substrate OLED Fabrication with Lamination. *Source: Anil Duggal, General Electric, "Roll-To-Roll OLEDS", SSL Manufacturing Workshop, Fairfax, VA, April 2009*

3.5.4 Patterning techniques

Each of the methods above allows some degree of patterning during deposition. Unless the OLED architecture requires side-by-side deposition of very narrow red, green, blue (RGB) stripes, the achievable resolution should be sufficient for lighting applications. Ink-jet printing is the only one of these methods that allows patterns to be changed without the manufacture of new masks or nozzle apertures.

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

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

3.5.5 Inspection and quality control

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

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

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

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

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

3.5.6 Further research priorities

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

There is considerable evidence that the performance of polymer molecules is sensitive to the fabrication technique, in particular to the deposition and solvent-removal methods that are used. For example, material deposited by ink-jet printing can differ substantially from spin-coated layers. Also the presence of residual solvents may degrade the performance of the OLED, both with respect to efficiency and lifetime. However, there is no a-priori reason that solution processible materials cannot achieve the same efficiencies as vacuum deposited materials. Thus further work is needed to improve the effectiveness of these materials and elucidate the dependence on manufacturing techniques.

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

4.0 Standards

During the April SSL workshop, the term "standards" was widely applied to a number of quite different embodiments of the concept. Indeed, there appears to be no standard way to distinguish among types of standards. At the June workshop, this section was provided draw some distinctions and sort out which might be appropriate to consider under the manufacturing initiative and which should be considered elsewhere. There was also a separate panel at the June workshop to discuss Standards beyond manufacturing. The breakout groups did discuss manufacturing standards although only very general recommendations were forthcoming.

We can identify several different usages of "standards" that appeared during discussions in Fairfax:

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

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

Standards directly related to manufacturing, on the other hand, can be numerous and quite detailed, and often fall into the last two categories of best practices and process control, or physical interface and interoperability. Figure 22 illustrates some of the myriad standards that may apply to a semiconductor clean room.

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

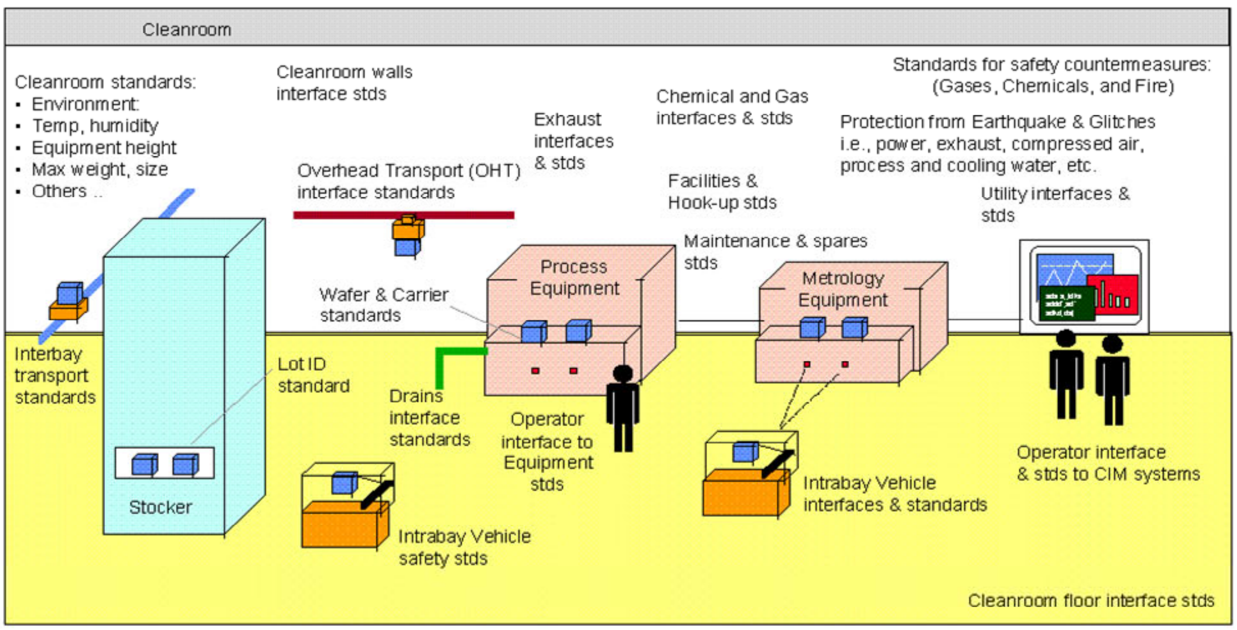

Figure 22. Manufacturing Standards for a Semiconductor Clean Room. *Source: Stanley Myers, SEMI, "Components of Supply Chain Excellence," SSL Workshop, Fairfax VA, April 2009*

4.1 Definitions

4.1.1 SSL product definitions

The IES has done considerable work and service to the industry by promulgating RP-16 addendum "a" that defines the components and products relating to SSL at least for LEDs [ref ANSI/IES RP-16-05 (Includes Addendum 2008 – LEDs)]. While this manufacturing roadmap may appropriately offer up suggestions for additional needs definitions, in general this work is probably best handled with existing standards groups.

4.1.2 Reliability characterization and lifetime definitions

Reliability potentially requires many types of standards, ranging from a basic definition to testing and performance minimums. At this point, however, even an agreed definition of "lifetime" for an SSL product does not exist.

While a standard for the measurement method for determining lumen depreciation of an LED under normal operating conditions has been published (LM-80), that is only a small part of total system reliability and lifetime, and there is still no agreed method of extrapolating lifetime from these measurements, for example. Lumen depreciation might be likened to dying of old age versus all of the other causes one may encounter along the way!

There is also a lack of agreed methods for determining most other aspects of failure of SSL products. An excellent discussion of the nuances of reliability and lifetime characterization for luminaires is available in the DOE factsheet, *LED Luminaire Reliability*.[29] While important for market acceptance of solid-state lighting products, a full understanding of these issues has not been reached. This subject was discussed at the summer SSL workshop in Chicago[30], is being addressed by the DOE in a working group under the SSL product quality initiative and is also being addressed by a number of standards development groups. It is also represented by a number of Core Technology and Product Development R&D tasks under the 2009 SSL MYPP. While some of the root causes of early failures may be related to manufacturing processes and control, there is not sufficient understanding of the major failure mechanisms at this time to warrant further recommendations in this round of the roadmap exercise.

4.2 Minimum performance specifications

Minimum performance specifications were also 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 cited lack of clarity as to which standards apply, certain legacy requirements that perhaps should not be applicable to SSL, and so forth. The DOE does have an extensive effort underway to develop appropriate Energy Star requirements for solid-state lighting, and that is the most appropriate forum for these discussions. UL, while certainly affecting SSL cost and availability, is not directly a manufacturing issue, and so again would appear to be better handled in other venues.

Color issues were referenced at least once in the context of performance requirements and outdoor lighting. Of particular significance is the increasing tendency of some jurisdictions to define a maximum CCT for outdoor lighting, which may result in higher costs or may limit potential energy savings. This is a regulatory issue best discussed apart from manufacturing.

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

[30] Highlights, presentations and materials may be found at http://www1.eere.energy.gov/buildings/ssl/news_detail.html?news_id=12706

Another color issue is the ANSI color binning specification. This is discussed above in this roadmap under the issue of product and process variability. Here, the standard is most appropriately handled by the existing standards groups, but addressing the process variability that is at the root is appropriate for the manufacturing roadmap.

4.3 Characterization and test methods

Many participants seemed to be unaware of some of the newer SSL characterization methods and standards such as LM-79 or LM-80. For example, some felt that there is not a complete or agreed upon test method for the total luminaire performance including the driver. Additionally, test methods for measuring temperature and thermal performance were described as incomplete or unclear. They correctly noted that one result can be long term performance issues, including uncertainty concerning color stability and life time ones such as incongruent driver and LED luminaire lifetimes. However, the DOE is already engaged in considerable work on characterization and test methods. Efforts include support of standard development activities for LED product and luminaire measurement standards such as the LM-79-08 (photometric and electrical testing of LED luminaires), LM-80-08 (LED lumen degradation testing), C78.377 (chromaticity of white light sources) as well as luminaire measurement standard and additional work in the context of the CALiPER product characterization program and the Gateway Demonstrations.

A recommendation coming out of the conversations was that a complete and comprehensive standards and test procedures guide book covering applicability to each end-use would help identify gaps in test methods. Such a guide might also be helpful to direct DOE research into which test methods are most useful. Summaries of current and pending standards are available among the technical publications on the DOE SSL website; one summary is included here as Appendix B.

While there may be a place for the recommended comprehensive guide at some point, at present there are many known gaps in test methods and characterization that are being addressed already. The June workshop will feature a panel to discuss the state of SSL standards development, which will be an opportunity to revisit this issue to see if more is needed.

4.4 Standardized reporting and formats

This subject is a bit controversial, but has come up at other DOE events. On the one hand, buyers of lighting components would welcome a standard report format to ease their comparison of alternative choices. Designers and specifiers have for some time been calling for a standard data format for luminaires. Luminaire manufacturers would welcome a standard specification for LEDs. However, there are many proprietary formats in place and there does not seem to be agreement among the parties at this point.

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

While these are all appropriate discussions for standards, they would seem to fit more conveniently with DOE's other market introduction activities and not with the manufacturing roadmap. We also suspect that the marketplace will sort this out eventually as buyers begin to put more weight on the benefits of formats that best meet their needs. So we note the issues that were brought up, but propose not to pursue them further under the manufacturing initiative.

4.5 Statutory/regulatory requirements

As noted, any of these types of standards could in principle become a legal requirement. Some already appear to be on track for this end. For example, the present efforts under the product quality Lighting Facts initiative may eventually result in some mandatory labeling requirements. At some point there may also be additional lighting performance requirements that will influence where certain products can be used, as has already occurred in some jurisdictions regarding incandescent and compact fluorescent lamp (CFL) sources. Again, these issues are rather removed from manufacturing and there are many venues in which they can be discussed. In fact, most regulations have a long comment period available to stakeholders before they are adopted, which allows all voices to be heard. None of this is likely to occur in the near future, either, and so will not be addressed in this roadmap.

We should point out here that there is some confusion between actual legal requirements and some Government-sponsored voluntary requirements. For example, some participants suggested that requirements on power factor for LEDs as reflected in the Energy Star specifications are too stringent and are pushing up costs. In fact, Energy Star is an entirely voluntary program, so there is no legal requirement to comply with the power factor specification. The groups recommended that DOE specifically address a plan for developing new power factor requirements. However, the Energy Star program itself does invite stakeholders to contribute to these requirements, so there does not appear to be value in duplicating that effort.

4.6 Inter-operability/physical standards

There are really two categories here. One is the end product consumer interface type of standard, such as the ANSI standards for bulb bases and sockets, or the standard wattages of incandescent lamps. These are really market-driven standards; if you want to sell into some applications, you'd better comply or you will not be successful. While such standards define the products to be manufactured, and manufacturers certainly need to be involved, they do not directly address the manufacturing process roadblocks.

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

4.7 Process standards and best practices

There was not a great deal of discussion about standardizing processes or identifying best practices. The industry is at an early stage of development and many companies consider their processes to be highly proprietary. However, this is likely to change. Equipment needs may dictate and limit the degree to which different manufacturers can use processes that differ significantly from one another. Processes in OLED manufacturing are in some cases very different and may thus limit equipment development and availability. This is certainly acceptable if the industry can live with it, but the costs should be recognized.

It is likely too early to standardize many processes in SSL at this point, but there may be some areas where it is possible. In general, these questions are considered under the various roadblock discussions in the previous Section.

4.8 Recommended standards

In some of the breakout sessions there were discussions of needed standards development to stimulate and facilitate manufacturing of SSL products. In the luminaire breakout sessions the discussions centered on reporting content and format standards. The luminaire suggestions are listed below:

- Reporting of LED chromaticity in standard chromaticity bins across all LED manufacturers.
- Development of a standard reporting format for lifetime performance data of luminaire components and systems.
- Development of standard lifetime testing protocols for all luminaire components and systems.
- Development of standardized reporting of power supply/driver performance data including all of the data listed on page 23.
- Development of an overarching text based reporting format for lifetime and performance data of luminaire components and systems for integration with software tools to model various performance parameters.

Appendix: LED Measurement Series – SSL Standards

LED Measurement Series:

Solid State Lighting Standards

Like traditional lighting products, LED-based luminaires sold in the US are subject to industry standards governing safety and performance. To accommodate LEDs, some existing standards and test procedures are being modified, while in other cases, new standards have been developed. This fact sheet lists the key performance and safety standards applicable to LED-based lighting products.

Product Performance and Measurement Standards

ANSI Standards

ANSI oversees the creation, promulgation and use of thousands of industry norms and guidelines, including the following key standards of relevance to SSL products.

C78.377-2008	Specifications for the Chromaticity of Solid State Lighting Products • Specifies the recommended chromaticity (color) ranges for white light LEDs with various correlated color temperatures (CCTs).
C82.SSL1†	Power Supply • Will specify operational characteristics and electrical safety of SSL power supplies and drivers.
C82.77-2002	Harmonic Emission Limits – Related Power Quality Requirements for Lighting • Specifies the maximum allowable harmonic emission of SSL power supplies.

IESNA Documents

IESNA is the recognized North American technical authority on illumination.

TM-16-05	IESNA Technical Memorandum on Light Emitting Diode (LED) Sources and Systems • This technical memorandum provides a general description of LED devices and systems, and answers common questions about the use of LEDs.
RP-16-05 Addendum a	Nomenclature and Definitions for Illuminating Engineering • This document provides industry standard definitions of lighting terms, including all lighting technologies. Addendum a provides definitions of solid state lighting terms.
LM-79-08	IESNA Approved Method for the Electrical and Photometric Measurements of Solid-State Lighting Products • Specifies procedures for measuring total luminous flux, electrical power, luminous efficacy, and chromaticity of SSL luminaires and replacement lamp products.
LM-80-08	IESNA Approved Method for Measuring Lumen Maintenance of LED Light Sources • Specifies procedures for determining lumen maintenance of LEDs and LED modules (but not luminaires) related to effective useful life of the product.

†*Currently under development.*

Photo credit: Labsphere

Standards Organizations

ANSI - American National Standards Institute, *www.ansi.org*

CIE - International Commission on Illumination, *www.cie.co.at*

FCC - Federal Communications Commission, *www.fcc.gov*

IEC - International Electrotechnical Commission, *www.iec.ch*

IESNA - Illuminating Engineering Society of North America, *www.iesna.org*

NFPA - National Fire Protection Association, *www.nfpa.org*

UL - Underwriters Laboratories Inc., *www.ul.com*

CIE Reference Publications

13.3-1995

Method of Measuring and Specifying Colour Rendering Properties of Light Sources

- The official document defining the CRI metric. Referenced by ANSI C78.377.

15:2004

Colorimetry, Third Edition

- The official document defining various CIE chromaticity and CCT metrics. Referenced by ANSI C78.377.

127:2007

Measurements of LEDs

- Addresses LED luminous intensity measurement; applies only to individual LEDs, not to arrays or luminaires.

S 009/E:2002

Photobiological Safety of Lamps and Lamp Systems

- Specifies measurement techniques to evaluate optical radiation hazards and eye safety risks of LEDs and LED clusters.

Safety, Installation, and Other Requirements

NFPA Requirements

70-2005	National Electrical Code • Most SSL products must be installed in accordance with the National Electrical Code.

FCC Requirements

47 CFR Part 15	Radio Frequency Devices • Specifies FCC requirements for maximum allowable unintended radio-frequency emissions from electronic components, including SSL power supplies and electronic drivers.

UL Standards

UL is currently developing a safety standard for "Light-Emitting Diode (LED) Light Sources for Use in Lighting Products," which will be designated UL standard 8750. Currently, UL has in place an "Outline of Investigation" (also numbered 8750) that references all existing UL standards applicable to LED lighting products. The purpose of the outline is to provide a comprehensive approach and listing of applicable standards for UL treatment of lighting products based on LEDs. The Outline will be used until the full LED specific document is completed. The table below lists the key UL standards referenced in the Outline.

8750	Outline of Investigation for Light-Emitting Diode (LED) Light Sources for Use in Lighting Products • Will specify the minimum safety requirements for SSL components, including LEDs and LED arrays, power supplies, and control circuitry.
1598	Luminaires • Specifies the minimum safety requirements for luminaires. The requirements in this document may be referenced in other documents such as UL 8750 or separately used as part of the requirements for SSL products.
153	Portable Electric Luminaires • Specifies the minimum safety requirements for corded portable luminaires.
1012	Power Units Other Than Class 2 • Specifies the minimum safety requirements for power supplies other than Class 2 (as defined in NFPA 70-2005).
1310	Class 2 Power Units • Specifies the minimum safety requirements for Class 2 power supplies (as defined in NFPA 70-2005).
1574	Track Lighting Systems • Specifies the minimum safety requirements for track lighting systems.
2108	Low Voltage Lighting Systems • Species the minimum safety requirements for low-voltage lighting systems.

Disclaimer: This list is not comprehensive, as other existing and future industry standards, recommended practices, and regulatory requirements may apply to specific solid state lighting products.

A Strong Energy Portfolio for a Strong America

Energy efficiency and clean, renewable energy will mean a stronger economy, a cleaner environment, and greater energy independence for America. Working with a wide array of state, community, industry, and university partners, the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy invests in a diverse portfolio of energy technologies.

For more information contact:

EERE Information Center
1-877-EERE-INF
(1-877-337-3463)
www.eere.energy.gov

For Program Information on the Web:

http://www.netl.doe.gov/ssl
DOE sponsors a comprehensive program of SSL research, development, and commercialization.

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