Solid-State Lighting Research and Development:

Manufacturing Roadmap

August 2012

Prepared for:

Lighting Research and Development
Building Technologies Program
Office of Energy Efficiency and Renewable Energy
U.S. Department of Energy

Prepared by:

Bardsley Consulting
Navigant Consulting, Inc.
Radcliffe Advisors, Inc.
SB Consulting
SSLS, Inc.

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

DISCLAIMER

ACKNOWLEDGEMENTS

The Department of Energy (DOE) would like to acknowledge all of the participants for their valuable input and guidance provided to develop this Manufacturing Roadmap. DOE would like to thank those individuals who participated in the Solid-State Lighting (SSL) Roundtables of April 2012 in Washington, D.C.:

DOE LED and OLED Roundtable Participants

Thomas Albrecht	EMD Chemicals
Dave Bartine	Lighting Science Group Corp
Rainer Beccard	Aixtron
Ravi Bhatkal	Cookson Electric
Iain Black	Philips Lumileds
Michael Boroson	OLEDWorks LLC
Dennis Bradley	GE Lighting Solutions, LLC
Nick Colaneri	Arizona State University
Mark D'Evelyn	Soraa, Inc
Jim Dietz	Plextronics
Craig Fenske	Philips Lighting
Miguel Friedrich	nTact
David Gotthold	Pacific Northwest National Laboratory
Scott Grimshaw	Colnatec
Mark Hand	Acuity Brand Lighting
Eric Haugaard	Cree, Inc
Abdul Lateef	Plasma-Therm, LLC
Jerry Liu	GE Global Research
Jeff Meth	DuPont Displays Inc
David Newman	Moser Baer Technologies
Dennis O'Shaughnessy	PPG Industries, Inc
Steve Paolini	Lunera Lighting
Florian Pschenitzka	Cambrios Technologies Corporation
Bill Quinn	Veeco Instruments
Rich Solarz	KLA Tencor
Nikhil Taskar	WAC Lighting
Mark Taylor	Corning
Tom Trovato	Trovato Manufacturing, Inc
James Zahler	GT Advanced Technologies

COMMENTS

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

James R. Brodrick, Ph.D.
Lighting Program Manager
EE-2J
U.S. Department of Energy
1000 Independence Avenue SW
Washington D.C. 20585-0121

Table of Contents

List of Figures

List of Tables

List of Acronyms

$/klm	Dollars per kilolumen
ALD	Atomic Layer Deposition
AMAT	Applied Materials
AMOLED	Active-Matrix Organic Light Emitting Diode
ANSI	American National Standards Institute
ANSLG	American National Standard Lighting Group
ARRA	American Recovery and Reinvestment Act
BMBF	Federal Ministry of Education and Research (Germany)
CCT	Correlated Color Temperature
CFD	Computation Fluid Dynamics
CIE	Commission Internationale de l'Eclairage
COMEDD	Center for Organic Materials and Electronic Devices Dresden
COO	Cost of Ownership
CRI	Color Rendering Index
CSA	Canadian Standards Association
DC	Direct Current
DOE	Department of Energy
EISA 2007	Energy Independence and Security Act of 2007
EML	Emissive Layer
EPA	Environmental Protection Agency
EPACT 2005	Energy Policy Act of 2005
FTC	Federal Trade Commission
FY	Fiscal Year
GaAs	Gallium Arsenide
GaN	Gallium Nitride
Gen	Generation
HB-LED	High Brightness LED
HIL	Hole Injection Layer
HTL	Hole Transport Layer
HTM	Hole Transport Materials
HVPE	Hydride Vapor Phase Epitaxy
IEC	International Electrotechnical Commission
IES	Illuminating Engineering Society of North America
InGaN	Indium Gallium Nitride
IQE	Internal Quantum Efficiency
ITO	Indium Tin Oxide
klm	Kilolumen
LED	Light Emitting Diode
LILi	Light In Line
lm	Lumens
lm/w	Lumens per Watt
mBAR	Millibar
MOCVD	Metal Organic Chemical Vapor Deposition
MQW	Multiple Quantum Well

MYPP	Multi-Year Program Plan
NEMA	National Electrical Manufacturers Association
NIST	National Institute of Standards and Technology
NOPR	Notice of Proposed Rulemaking
OEE	Overall Equipment Efficiency
OEM	Original Equipment Manufacturer
OLED	Organic Light Emitting Diode
OPV	Organic Photovoltaic
OVPD	Organic Vapor Phase Deposition
PECVD	Plasma Enhanced Chemical Vapor Deposition
R&D	Research and Development
R2R	Roll-to-roll
SDCM	Standard Deviation of Color Matching
SDO	Standards Development Organizations
SEMI	Semiconductor Equipment and Materials International
Si	Silicon
SiC	Silicon Carbide
SSL	Solid State Lighting
TCO	Transparent Conductive Oxide
TFT	Thin Film Transistor
TMG	Tri-Methyl Gallium
UL	Underwriters Laboratories
UV	Ultra Violet
ZnO	Zinc Oxide

Preface

The Energy Policy Act of 2005 (EPACT 2005) directed the Department of Energy (DOE) to carry out a "Next Generation Lighting Initiative" to include support of research and development of solid-state lighting (SSL) with the objective of lighting that would be more efficient, longer lasting, and have less environmental impact than incumbent lighting technologies. In order to effectively carryout this objective the DOE SSL Program has developed a comprehensive national strategy with three distinct, interrelated thrusts (and accompanying Roadmaps): Core Technology Research and Product Development, Manufacturing Research and Development (R&D), and Commercialization Support.

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

In 2009, DOE launched an **SSL Manufacturing Initiative** to complement the SSL Core Technology Research and Product Development Program which aims to accelerate SSL technology adoption through manufacturing improvements that reduce costs and enhance quality. This initiative, which included expert Roundtables and two Workshops, resulted in the 2009 SSL Manufacturing Roadmap. That document was updated in 2010 and 2011, building on the general timelines and targets identified in 2009, and adding or changing specific areas of priority work needed in order to achieve the ultimate goals of the Program. As is the case with other SSL Roadmap documents, the Manufacturing Roadmap will continue to be updated annually to reflect progress and changing priorities. The present document is the 2012 update.

DOE has also developed an SSL **Multi-Year Market Development Support Plan.**[1] Last updated in May of 2012, the purpose of the Plan is to set out a strategic, framework for guiding the DOE market development support activities for high performance SSL products for the U.S. general illumination market.

Together, these three efforts are intended to reduce the cost and energy use for lighting. Much of the background for the SSL Program, including a summary of significant accomplishments, research highlights, the legislative framework, and financial support of the Program may be found in the 2012 MYPP. This material will not be repeated here, but readers are urged to review the other SSL Program documents as background for reading this SSL Manufacturing Roadmap.

The 2012 Multi-Year Program Plan can be downloaded at:
http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mypp2012_web.pdf

[1]DOE's SSL Multi-Year Market Development Support Plan can be found at:
http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_5year-plan_2012-16.pdf

1. Introduction

The goals of the SSL R&D Manufacturing Initiative are to:

- Reduce costs of SSL sources and luminaires;
- Improve product consistency while maintaining high quality products; and
- Encourage the growth, leadership, and sustainability of domestic U.S. manufacturing within the SSL industry.

DOE recognizes that developing new manufacturing technology, encouraging best practices, identifying common equipment needs, improving process control, and learning from manufacturing methods in other industries is the best path to achieve these goals. While one important purpose of the Roadmap is to guide the R&D Program and to help direct funding solicitations, as the industry grows the size of DOE's R&D funding in relationship to overall R&D spending diminishes. Accordingly a second and more important purpose of the Roadmap is to provide guidance for equipment and material suppliers based on industry consensus about the expected evolution of SSL manufacturing. Such guidance reduces risk, and ultimately the cost, of undertaking SSL manufacturing. Supporting the development of multiple sources of key equipment and standardized components can also improve quality and lower costs. At the same time, identifying best practices, to the extent firms are willing to share their experiences, can reduce product variability and increase yields. As we recognized in last year's edition, many of the activities discussed in this document are beyond the scope of the DOE SSL Manufacturing Initiative and, in some cases, beyond the scope of the DOE SSL Program in general. The DOE SSL Program will endeavor to address all of the issues which fall within the Program charter, but some are more appropriately addressed by industry, industry consortia, or other stakeholders.

One objective and a central theme of the Manufacturing Roadmap is and has been the reduction of costs. However, a few words of caution: the majority of these discussions within the Roadmap concern *manufacturing costs*, that is, the costs incurred by the manufacturer of the product or the "cost of goods sold." Therefore, it is emphasized that *cost* is not the same as *price*, and great effort is taken to distinguish this difference throughout the Roadmap. Although, the selling price is considered the *cost* to the buyer, this document only considers the manufacturing perspective. Price does strongly influence the adoption of SSL technology, and ultimately the objective of manufacturing cost reduction is to enable competitive pricing in order to take full advantage of the energy savings that SSL offers. What is a competitive price? It is one that fairly reflects the value of the product. And that includes the value of the energy saved, the extended lifetime, the reduced cost of maintenance, and additional features such as dimming or instantaneous control of the light, excellent color and light distribution, and aesthetic features. Reducing manufacturing costs, at the start of a product's pathway through the market, can make all this possible while still maintaining profitability, but buyers expecting to see the cost reductions forecasted in this Roadmap fully reflected in a price which matches that of incumbent technologies may be overlooking the significant economic added value of the new technology.

> ***What is a competitive price? It is one that fairly reflects the value of the product. And that includes the value of the energy saved, the reduced cost of maintenance, and additional features . . .***

Similar to prior versions, this fourth annual publication of the updated SSL Manufacturing Roadmap guides future planning for DOE R&D actions including funding of solicited cooperative R&D projects. Furthermore, this Roadmap is intended to guide R&D strategy beyond that which is funded by DOE in order to more rapidly advance the overall state of manufacturing technology. This SSL Manufacturing Roadmap is the result of a highly collaborative and participative effort that has taken place during the course of this year. The work for the 2012 Roadmap update began on the 17th and 18th of April with the convening of two expert panels for light emitting diodes (LEDs) and organic light emitting diodes (OLEDs), to recommend specific tasks to be accomplished in the near term, as well as other updates to the Roadmap. Then, on June 12th to the 14th about 200 representatives from a broad cross-section of the SSL value chain participated in the 2012 SSL Manufacturing Workshop[2] to provide additional feedback on Program goals and the proposed task priorities.

In somewhat of a departure from earlier editions of the Roadmap we have retained in this document most of the descriptions of those tasks identified as priorities by the Roundtable gatherings and supported by the Workshop. While DOE may not be able to issue a solicitation that covers all of them, the valuable inputs we have received will thus be available to others to guide SSL manufacturing R&D.

The organization of this document follows a similar pattern to the previous 2011 version and is divided into separate LED and OLED sections. This year, however, descriptions of the priority manufacturing R&D tasks have been incorporated, as determined by the Roundtable and the subsequent Workshop discussions, into the LED and OLED Roadmap sections, rather than putting them into a separate section. There are changes in the priorities, of course, and in the various metrics for each task, as dictated by progress towards the DOE SSL Program goals. Section 4 describes progress on SSL-related standards and identifies additional or continuing needs for standards not yet available. Appendix A provides information about existing and pending standards efforts in many areas, including testing and performance metrics not directly related to manufacturing but still relevant.

1.1 Manufacturing Research Highlights

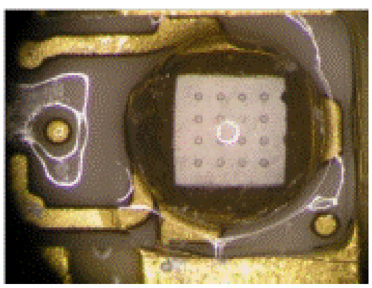
The SSL Manufacturing Initiative currently supports six R&D research projects and three new project selections are in the contract negotiation process (see Appendix B). These projects reflect the manufacturing priorities as determined by industry leaders, research institutions, universities, trade associations,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

[2] Workshop presentations and handouts can be found at: http://www1.eere.energy.gov/buildings/ssl/sanjose2012_materials.html

Ultratech Develops an Improved Lithography Tool for LED Wafer Manufacturing

Ultratech modified a lithography tool used for semiconductor manufacturing to better meet the cost and performance targets of the high brightness LED manufacturing industry. The goal was to make the equipment compatible with the wide range of substrate diameters and thicknesses prevalent in the industry while reducing the capital cost and the overall cost of ownership (COO). The project has been very successful and the yield and throughput benefits have been demonstrated through a recent comparison between the new tool and conventional contact lithography based on the operation of two parallel manufacturing lines within a commercial wafer fabrication facility. This practical comparison demonstrated very significant yield benefits using the Ultratech lithography tool which resulted in the new tool achieving a return-on-investment in only three months. (June 2012)

Philips Lumileds Demonstrates LED Device Grown on Silicon Substrate

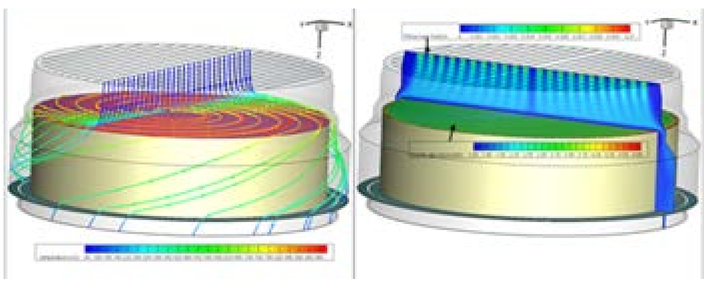


Philips Lumileds developed an illumination grade high-power LEDs on low cost silicon substrates. The development of GaN-on-silicon technology using 150 mm diameter substrates offers the prospect for a 60% reduction in epitaxy manufacturing costs and a 20% improvement in wavelength uniformity in comparison to their baseline technology using 75 mm diameter sapphire substrates. Once established, this technology offers a low risk path to 200mm wafer sizes and the prospect for further cost reduction. Epitaxy and device performance for GaN-on-silicon has been demonstrated to be within 10% of standard GaN-on-sapphire production technology, and on-wafer wavelength uniformity shows a 5% improvement. Blue LED devices have recently been fabricated on silicon substrates with a light output of 484 mW at a current of 350 mA (current density ~35 A/cm^2), wavelength of 445 nm, and packaged LED wall plug efficiency of 40%. This project received funding under the American Recovery and Reinvestment Act. (June 2012)

Veeco Instruments Demonstrates Improved Yield with MaxBright™ Multireactor System

Veeco has been working with Sandia National Laboratories and Philips Lumileds to decrease the cost of high-brightness LEDs by reducing the COO of the deposition equipment. One recent development has been the introduction of a heated flow flange which reduces the consumption of the expensive reagents by 40%. Another development has been the introduction of an advanced wafer carrier design offering a 14in x 4in configuration to increase capacity, and optimized pocket shaping to improve wavelength uniformity/reproducibility. The pocket shaping has resulted in a within-wafer wavelength uniformity improvement of 24%, and the wafer yield for a 5 nm wavelength bin has consequently increased from 82 to 92%. These and other developments have resulted in a cumulative reduction of 66% in the COO for Veeco's Metal Organic Chemical Vapor Deposition (MOCVD) equipment and have identified a clear path to achieving a 77% reduction based on the introduction of larger scale architectures. All these features are being incorporated into Veeco's new MaxBright™ multireactor system and helped promote Veeco to the position of top MOCVD equipment supplier worldwide in 2011. This project received funding under the American Recovery and Reinvestment Act. (May 2012)

Sandia Establishes Improved Process Modeling in Support of Veeco Instruments' Reactor Development



Sandia is collaborating with Veeco Instruments on the development of improved deposition equipment (see previous highlight) using Computational Fluid Dynamics (CFD) and CHEMKIN process modeling. The image illustrates the application of 3D CFD/CHEMKIN modeling to the Veeco K465i reactor geometry. As part of its reactor development, Veeco observed enhanced growth rates as the gas inlet temperature was increased from 50 to 200°C using a heated flow flange. Such behavior offers an excellent opportunity to increase throughput and reduce costs but was at odds with current theoretical models which predicted precisely the opposite behavior. Recently it succeeded in replicating this behavior by introducing a temperature dependent reaction into the process model, whereby the formation of parasitic gas-phase particles that would ordinarily reduce the growth rate was effectively reversed at higher inlet temperatures leading to a net increase in the growth rate. Such detailed analyses help advance the state of the art in process modeling and facilitate the design of more efficient MOCVD reactors, which will lower the cost of future SSL products (May 2012).

DuPont Displays Develops Low-Cost Method of Printing OLED Panels

DuPont Displays Inc. has developed a novel way of printing color-tunable OLED lighting panels that keeps manufacturing costs low. DuPont's 50 cm^2 prototypes were incorporated into task-lighting luminaires that were tunable from a CCT of 2700K to 6500K. Panels achieved an efficacy of 35 lm/W at ~2700K (expected to improve to 40 lm/W with minor optimization). Operating lifetimes easily met the 5,000-hour target. Uniformity of the printed layers was demonstrated to be high, giving excellent luminance uniformity. A detailed cost model of next generation manufacturing predicts that module costs will drop to ~$25 for a 1,000 cm^2 panel ($25 per klm), based on a realistic evolution of materials costs and performance improvements over the next few years. (April 2012)

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

At the Infotonics Technology Center (ITC) in Canandaigua, New York, UDC and MBT are reconfiguring a 9,400 sq. ft. clean room and equipping it with the necessary support facilities to implement a new, UDC-developed manufacturing process for OLED lighting panels. The goal is to process 150mm x 150mm panels with an efficacy of 80 lm/W and CRI > 80. The base process flow has been set and the critical deposition equipment ordered for delivery. The production facility is ready for equipment installation. The objective of the UDC-MBT project is to build a production line to provide prototype OLED lighting panels to U.S. luminaire manufacturers for incorporation into products to facilitate testing of design concepts and gauge customer acceptance.

1.2 Key Findings and General Recommendations for 2012

The previous 2011 Manufacturing Roadmap provided information on the anticipated evolution of SSL manufacturing and several suggested priority research tasks. One critical component of this year's update was to gather consensus around a very few specific tasks needed to accomplish SSL manufacturing goals and make progress along the Roadmap paths. Similar to the previous Roadmap edition in 2011, due to budget constraints it has been necessary to tightly focus priorities on a small number of tasks. Discussions during the April 17th and 18th Roundtables provided suggested R&D topics which were distilled into seven proposed priority tasks introduced at the June Manufacturing Workshop. These were subsequently reduced to six priority tasks in this publication as a result of Workshop deliberations. A full list of tasks and descriptions identified in prior Workshops, including those not prioritized for this year's update, is found in Appendix C.

In addition, changes have been made to the overall Roadmap document. These include updating cost estimates to reflect the current status, and others to clarify and detail certain discussions in the 2011 edition. The next sections summarize the priority tasks as well as some of the additional changes to be found detailed in subsequent sections of this report.

1.2.1 LED Manufacturing R&D Priorities

During the Roundtables, the subsequent Manufacturing Workshop, and internal DOE discussions, four priority manufacturing R&D tasks for LED-based luminaire manufacturing were identified. These choices for LED Manufacturing are listed by title and brief description in Table 1-1; more detail may be found in Section 2.6.1.

Table 1-1. LED manufacturing R&D priority tasks

M.L1	**Luminaire/Module Manufacturing** Support for the development of flexible manufacturing of state of the art LED modules, light engines, and luminaires.
M.L3	**Test and Inspection Equipment** Support for the development of high-speed, high-capability, non-destructive test equipment with standardized test procedures and appropriate metrics.
M.L6	**LED Packaging** Identify critical issues with back-end processes for packaged LEDs and develop improved processes and/or equipment to optimize quality and consistency and reduce costs.
M.L7	**Phosphor Manufacturing and Application** Development of efficient manufacturing and improved application of phosphors (including alternative down converters) used in solid-state lighting.

There were a number of specific recommendations that arose out of the Workshop discussions relating either to individual tasks or other aspects of the Roadmap. These are discussed throughout the document. In addition to specific recommendations for manufacturing R&D, participants at the Roundtables and at the Workshop emphasized some more general thoughts about the evolution of the industry:

- Collaboration between equipment makers and manufacturers; among manufacturers, perhaps even to the level of a cooperative SEMATECH-like manufacturing laboratory could accelerate manufacturing cost reductions;
- Developing interface and process standards (i.e., for substrate wafers, package and subsystem interchangeability, and common processes) could also accelerate manufacturing developments and reduce costs.

1.2.2 OLED Manufacturing R&D Priorities

Last year, three OLED tasks were identified as priority manufacturing research areas: 1) OLED Deposition Equipment (M.O1); 2) Manufacturing Processes and Yield Improvement (M.O2); and 3) OLED Materials Manufacturing (M.O3). The Roundtable participants retained all three priority tasks, but upon further consideration by Workshop attendees, it was deemed that M.O1 and M.O3 are more critical now for the development of OLED manufacturing technology. Thus, only two DOE OLED Manufacturing priority tasks have been identified for 2012 as listed below in Table 1-2. More details may be found in Section 3.6.1.

Table 1-2. OLED manufacturing R&D priority tasks

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

In addition to the manufacturing task recommendations, there were also a number of general recommendations pertaining to OLED manufacturing:

- Develop specifications for component interfaces, processes, tools and packaging;
- Identify an evaluation OLED stack that can be used in the development of OLED equipment and substrates to assess and compare performance;
- OLED testing standards development;
- Increased effort in product development and design of novel/breakthrough luminaires (market and manufacture specifications);
- Standardization of panel footprint and electrical and mechanical connectors to facilitate luminaire design;
- Identify target markets for OLED entry to allow manufacturing costs to decline and ultimately pave the way to the general illumination market; and
- Promote collaborative projects among U.S. manufacturing lines and U.S. companies that can make OLED substrates and materials.

1.3 Overall Projections/Contributions to Cost Reduction

1.3.1 LED Lighting

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

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

Figure 1-1 shows a high-level cost breakdown projection for an LED-based A19 60 W replacement lamp. It should be noted that the relative cost breakdown will vary depending on the type of luminaire as discussed in Section 2.2. The initial cost breakdown for 2011 reflects the consensus view of the 2011 and 2012 Manufacturing Roundtable attendees and was corroborated by information reported during the recent Workshops (e.g. Cannacord Genuity[4], Cree[5], etc.). The manufacturing cost has been projected forward based on price reduction targets for the LED

[3] See RP-16-10 for definitions of LED and OLED components: http://www.iesna.org/store/product/nomenclature-and-definitions-for-illuminating-engineeringbr-rp1605-1013.cfm
[4] http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/baribeau_transform_2012rdworkshop.pdf
[5] http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/negley_costs_boston2011.pdf

package and LED-based replacement lamps outlined in Section 3 of the 2011 SSL MYPP, and the assumption that margins will reduce over time. Such projections assume more rapid cost reductions for the LED package and less rapid reductions for the mechanical/thermal and optics components. The rapid cost decrease in Figure 1-1 reflects the significant price reduction projected for integrated lamps in DOE's 2012 MYPP, with a reduction in terms of dollars per kilolumen ($/klm) of 66% by 2015 and 80% by 2020.

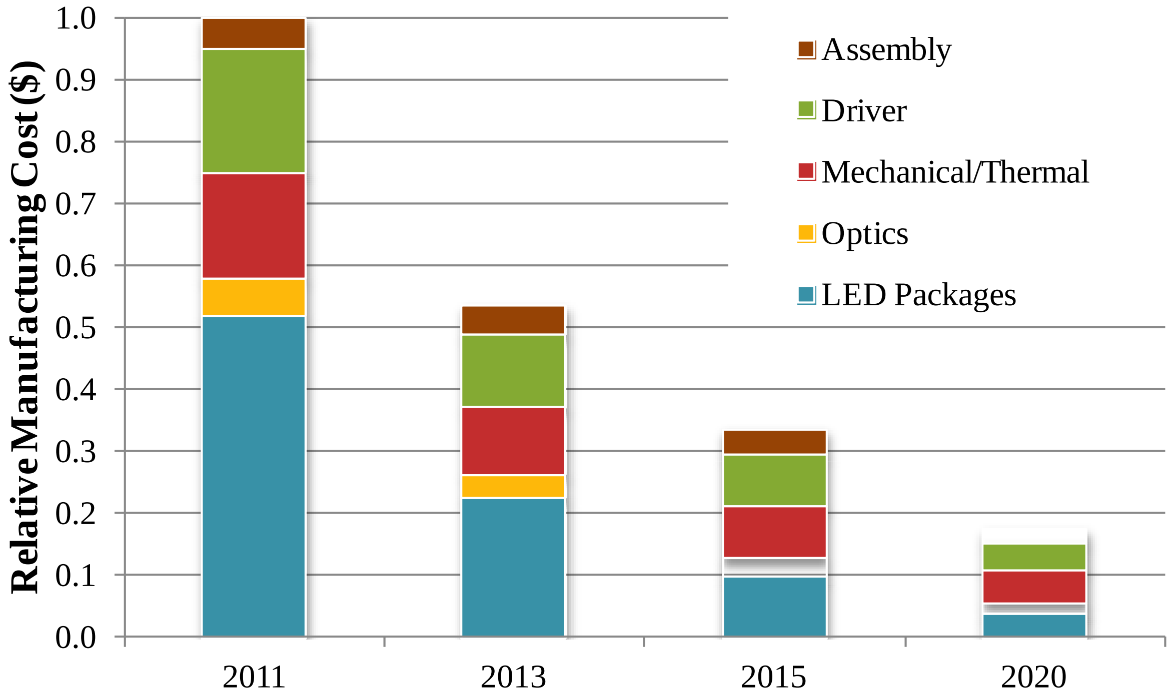


Figure 1-1. Projected cost track for an LED-based A19 60W replacement lamp
Source: data provided by the 2011 Manufacturing Roundtable attendees

The projections in Figure 1-1 account for potential cost savings from improved manufacturing processes, reduced materials costs, and from luminaires "designed for manufacture". While such an analysis is helpful in identifying the largest cost components, it does not show the cost interrelationships between the components. Fully understanding potential cost reductions will require a more sophisticated systems-level approach to luminaire design with simultaneous consideration of all cost components and an analysis of their complex interactions to achieve the optimum solution for a specific application. In addition, there could be cost savings as automated manufacturing and assembly operations replace manual processes for the manufacture of luminaires and the sub-components. Since this new lighting technology is based on semiconductor technology and manufacturing processes, the final luminaire products may be able to take advantage of automation technologies developed for the manufacturing and assembly of consumer electronics products. Automation could reduce the labor cost for the full luminaire and for the sub-components of the luminaire, removing one of the drivers for locating luminaire manufacturing outside the U.S.

Figure 1-2 shows a similar cost breakdown and cost reduction projection that has been developed for LED packages. Care should be exercised in comparing these *cost* projections with the *price* projections shown in Table 2-2. The cost projections are based on raw dollar manufacturing costs per package whereas the price projections in Table 2-2 are normalized to lumen output and include additional factors such as gross margin. As is evident from the figure, packaging costs represent the largest contribution to the overall cost of an LED package. Though not reflected in the cost projection, improvements in an earlier part of the manufacturing process, such as improved uniformity in the epitaxial process, will have a “lever” effect and can greatly impact the final device cost and selling price through improved binning yields. Further details on the LED luminaire and package cost tracks can be found in Section 2 of this Roadmap.

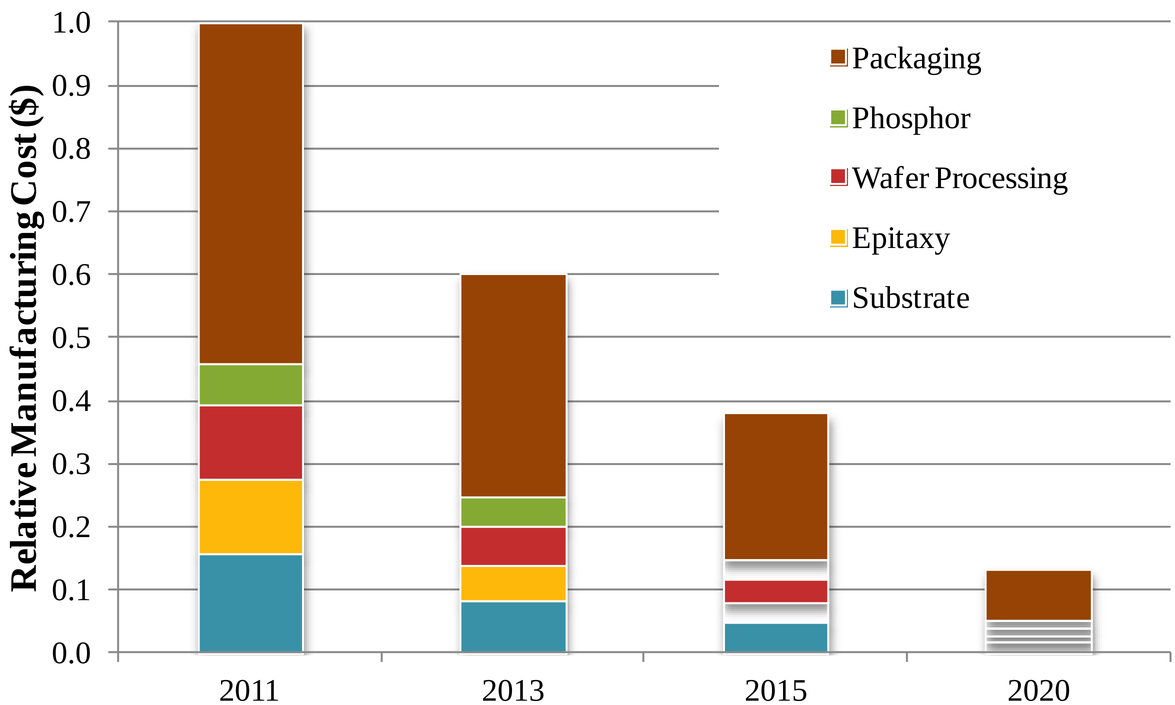


Figure 1-2. Projected LED package cost track
Source: compiled from data provided by the 2011 and 2012 Manufacturing Workshop and Roundtable attendees

1.3.2 OLED Lighting

During the past year, the potential that OLED technology brings in innovative luminaire design has been confirmed with many new concepts shown on company websites, at exhibitions and in high-profile promotional installations, as illustrated in Section 3. Performance is improving steadily and is on track to meet the requirements of several key market sectors. However, the cost of the panels and luminaires that are available as samples is still extremely high, at over $1000/klm. Most producers have aggressive strategies to reduce costs, but uncertainties in the choice of manufacturing technique and in the price sensitivity of the market have led to the postponement of plans for investment in high volume manufacturing.

Within the U.S., the prototype production line at Canandaigua, New York, has been delayed by over one year and only one other company (OLEDWorks) has announced a clear commitment to manufacture OLED panels.

The rapid progress that has been made by LED manufacturers in performance improvements and cost reduction and the emergence of diffuse LED luminaires with innovative form factors mean that OLED developers cannot relax their long-term cost targets if they wish to impact general service lighting markets. The anticipated competition from LEDs has led to a wide divergence in the forecasts of market researchers concerning the size of the OLED market in the period 2015-20. Some believe that the market will remain below $300 million, while others project sales of over $6 billion by 2018. The key to market success seems to be in achieving substantial cost reductions.

Thus in this edition of the Roadmap the cost targets begin with the year 2015, by which time efficient manufacturing should be underway, mainly through the conversion of R&D lines to volume production. The assumptions that have been made in estimating the cost of panel manufacturing are described in Section 3.

Figure 1-3 shows the projections for the costs of luminaire manufacturing.

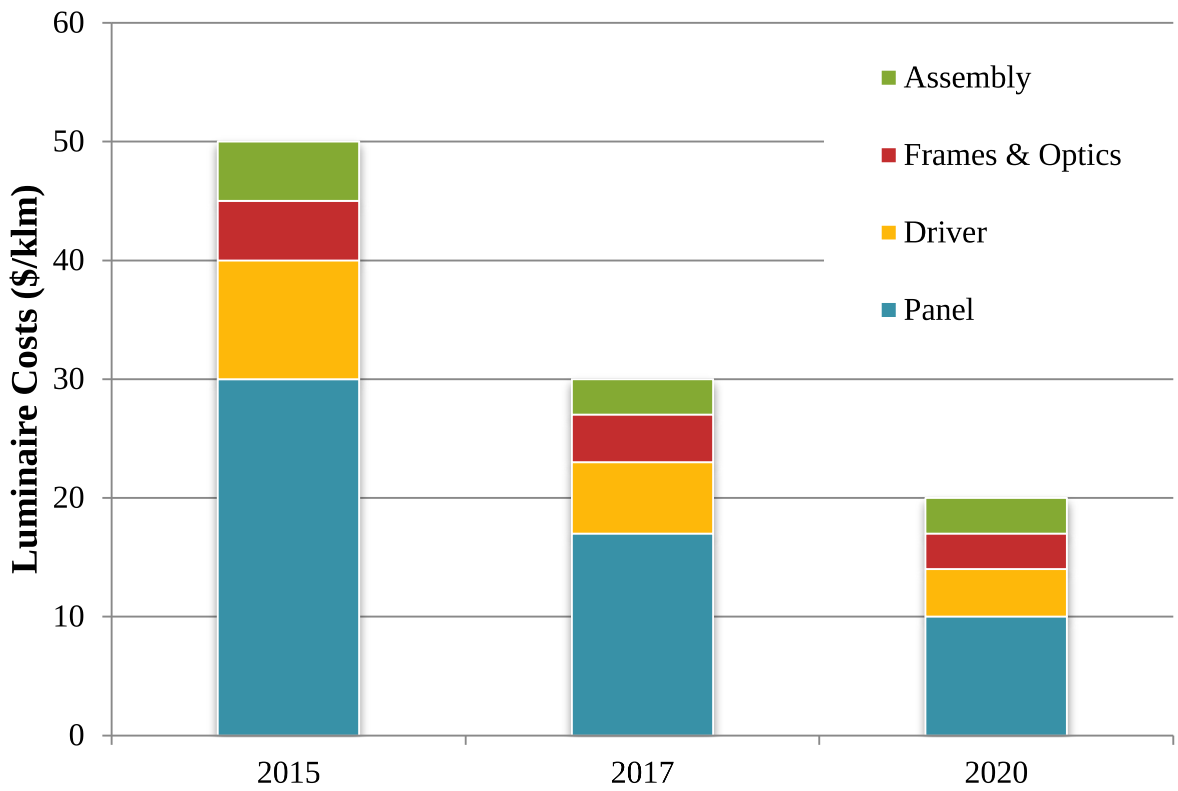


Figure 1-3. Projected cost track for OLED luminaires ($/klm)

The cost of fabricating panels is broken down further in Figure 1-4.

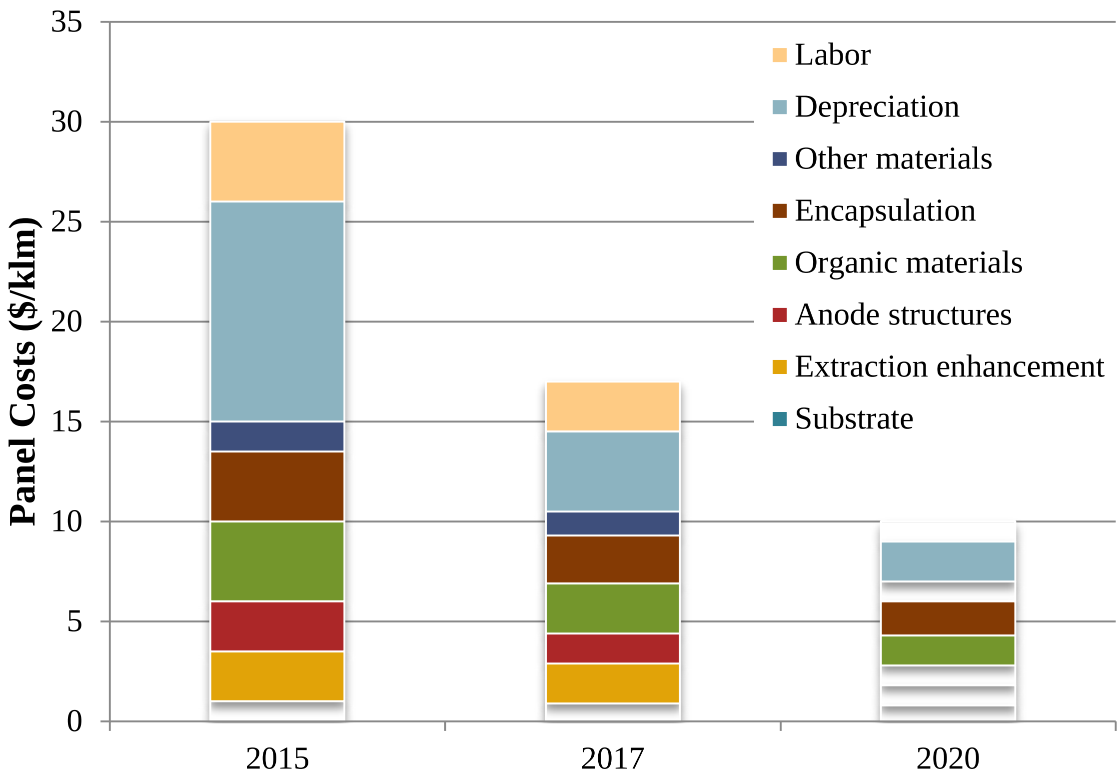


Figure 1-4. Projected cost track for OLED panels ($/klm)

The targets for 2015 are based on estimates by Moser Baer, whose strategy is to minimize cycle time while using relatively small substrates. The reduction in the impact of labor costs and depreciation by 2020 is expected to come from faster processing or modest increases in substrate size. Experience in the display industry suggests that the cost of equipment rises in proportion to the linear dimension of the tools, while the throughput scales with their area. It seems unlikely that the lighting market will be able to support the use of the very large substrates (over 5 m^2 in area) used in the display industry.

The cost targets for 2015 are much less than the current price per kilolumen of sample panels. As described more fully in Section 3, the major short term challenges are:

- To reduce the cycle time for batch of substrates to around 1 minute;
- To increase the material utilization to more than 70%;
- To increase the yield of good panels to about 80%;
- To increase the fraction of substrate used for light emission to approximately 80%; and
- To reduce the fraction of manufacturing downtime to around 20%.

Given the uncertainty in the size of the attainable market, it seems prudent to attempt to reach these goals with modest total substrate area (about 0.2 m^2) before making the large capital investments that would be necessary for larger equipment. Developing simpler tools that can be scaled at lesser expense would also be of great value. Many believe that the key to doing this is the adoption of solution processing to replace the vapor processing techniques that have been used to make OLED displays. These alternative methods are described in Section 3.2.2.

2. LED Package and Luminaire Roadmap

Section 2 describes the current LED package and luminaire manufacturing-related issues and suggestions for manufacturing R&D tasks that were that were discussed during the 2012 DOE SSL Manufacturing Workshop in San Jose, CA and the LED Manufacturing Roundtable discussions in Washington, D.C. and by teleconference. This section presents the general barriers to the adoption of LED-based products, the cost and quality drivers for LED lighting, specific LED luminaire and package manufacturing issues, as well as the development of a simple modular cost model to describe the manufacturing of LED packages.

2.1 Barriers to Adoption

The manufacturing barriers identified over the last three years continue to be expanded and clarified as the industry gains experience in manufacturing. A list of the LED and luminaire manufacturing issues identified at the DOE SSL Manufacturing Workshops is shown in Table 2-1. Table 2-1 presents the issue or suggestion that was discussed, the type of activity required, and a suggested timeline for the activity to be started and completed. As noted in the introduction, some of the identified issues/suggestions may be more appropriately addressed by the LED industry, industry consortia, or other stakeholders. The Roadmap below is meant to identify manufacturing related barriers to the adoption and production of LED-based luminaires, regardless of the appropriate entity to address the barriers. These SSL luminaire manufacturing issues can be classified as related to Manufacturing R&D, standards development, Core and Product Development R&D, and education.

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

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

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

Table 2-1. Roadmap for addressing LED and luminaire manufacturing issues

Source: based on recommendations from the 2009 – 2012 Manufacturing Workshop attendees

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

Existing Activities Future Activities

The 2012 prioritized R&D task, 'Luminaire/module manufacturing', directly addresses the need for new manufacturing technology to achieve flexible, consistent, and reliable integration of luminaire components and need to the reduce cost of LED-based luminaires. 'Test and Inspection equipment' addresses the manufacturing goal of improved quality of LED-based luminaires and reduced manufacturing costs through the development of improved process control using advanced test and inspection tools and techniques. R&D in this task area could occur in any portion of the manufacturing process, from substrate testing to monitoring of the epitaxial growth process to in-line testing of LED modules and luminaires. 'LED Packaging' addresses the need for high performance packages that use lower cost materials and manufacturing processes. And 'Phosphor Manufacturing and Application' addresses the role of phosphors within the LED package and luminaire.

While the four priority tasks were identified as the most critical, the remaining three (listed in Appendix C) manufacturing R&D task areas are still considered important for the ongoing development of energy saving, cost effective lighting. All of the manufacturing R&D task areas represent an opportunity to reduce cost and improve consistency of LEDs for use in luminaires and develop a U.S. manufacturing base for these products. The previous and current prioritization of tasks is represented in Table 2-1 by the timing of the supported activity. Previous and ongoing priority research areas with projects working on these topics are indicated as existing activities from 2010-2016, recent project selections and current R&D priorities are represented as existing activities as well. Manufacturing research tasks, which have not been prioritized, are indicated as future activities.

Over the course of the Manufacturing R&D effort, commercialization standards have been consistently brought up for discussion. These issues are listed below and will be discussed further in Section 4 of this document:

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

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

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

- Understanding and manufacturing for luminaire reliability.

The issues related to standards and education is outside the direct scope of the DOE SSL Manufacturing R&D initiative. However, there are numerous other DOE SSL initiatives that are addressing these topics. Section 4 and Appendix A contain discussions on the various DOE supported standardization efforts. In addition, DOE is developing programs to educate stakeholders on all aspects of LED and LED-based luminaire performance and design. It should also be noted that several LED manufacturers offer training and certification on the design of LED-based luminaires.

The development of the manufacturing infrastructure for efficient manufacturing of LED-based luminaires can be accelerated through DOE support. However, ongoing industry and stakeholder support of all of the research areas will be necessary for solid-state lighting to reach its full energy saving potential.

2.2 Cost and Quality Drivers for LED Lighting

There is an extensive hierarchy of LED-based luminaire product types with varying requirements, ranging from large outdoor area lights to small MR16 spotlights. Most current LED-based product offerings closely follow the form factors established for more conventional light sources. In particular, the replacement lamp closely matches current form factors and utilizes existing sockets. Other lighting products such as downlights, troffers, and outdoor lamps are designed to completely replace existing fixtures although they still tend to retain the same overall form factor. This situation is beginning to change as the unique attributes of LEDs are exploited and completely new form factors are established. It is believed that the development of novel form factors and applications is where the real benefits afforded by solid-state lighting will be realized.

Irrespective of the type of product, the LED-based luminaire comprises a number of common components which must be carefully integrated in order to achieve the required optical, electrical, and thermal performance while meeting the need for reduced costs. Viewed separately these components contribute to the final cost as illustrated schematically in Figure 2-1. The relative cost breakdown in Figure 2-1 has been presented for three different classes of LED-based luminaires in order to illustrate how they might vary depending on the specific product type. An A19 replacement lamp is likely to have its largest LED package cost component whereas this is a less significant cost component for an outdoor area lamp. By way of contrast the outdoor lamp will have the largest mechanical/thermal cost component and the replacement lamp the smallest. Other differences are illustrated schematically in the figure. At the current time, reducing the cost of the LED package (viewed as incoming materials from the luminaire maker's perspective) offers the greatest potential for cost reductions in interior LED-based luminaries; however, the cost of the remaining components will also need to come down in order to meet cost targets (see Figure 2-1). Ultimately it will be through careful application of systems level design methods and detailed cost engineering approaches that the luminaire cost targets will be met.

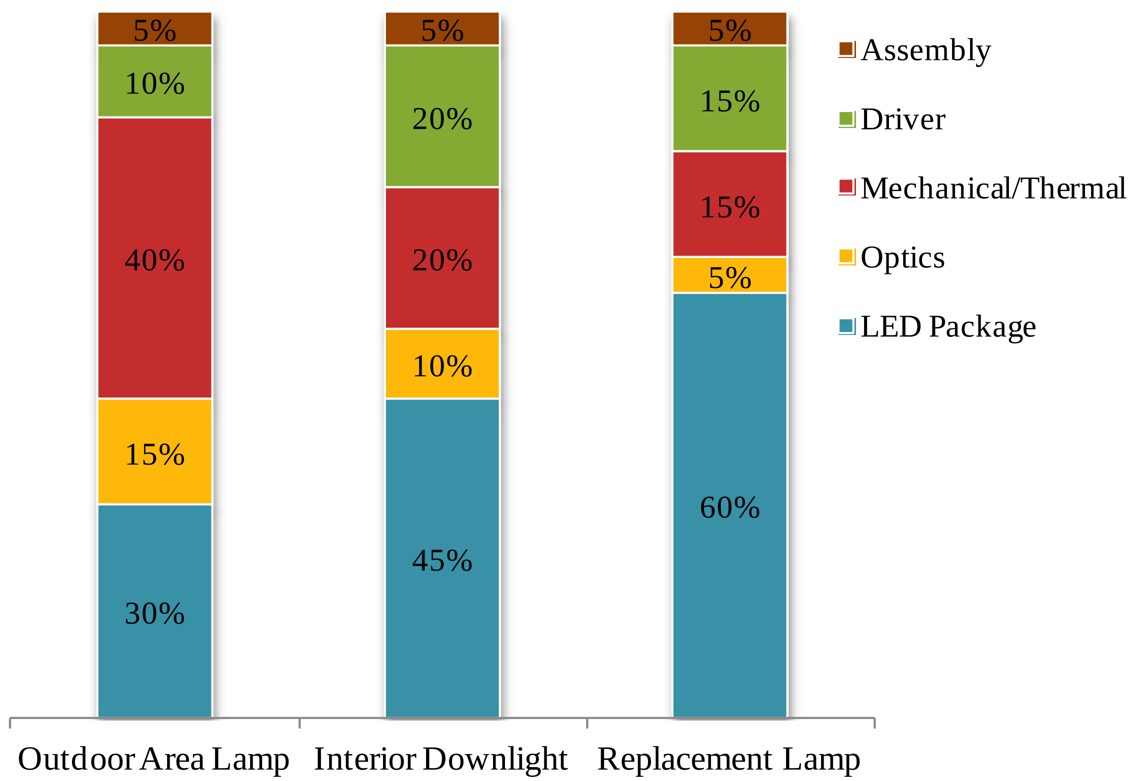


Figure 2-1. Approximate cost breakdowns for LED-based luminaires in 2012
Source: consensus of the 2011/2012 Manufacturing Workshop and Roundtable attendees

The manufacture of high power LED packages involves a number of steps, each of which contributes to the final device cost. The typical cost breakdown for an LED package is shown in Figure 2-2. The data represents high volume manufacturing of 1 mm^2 die on 100 mm diameter sapphire substrates and packaging of the die to produce high power warm white phosphor-converted LED lighting sources. The analysis was performed using the cost model described in Section 2.5. In this model the yield for each process step defines the cost of that step and a cumulative overall wafer yield is calculated after each step to reflect the percentage of good product progressing to the next step or, in the case of the final step, the percentage of good product produced. For example, the model illustrated in Figure 2-11 on page 48 assumes an overall wafer yield of 85% following the epitaxy step, and 48% at the completion of wafer processing.

Figure 2-2 indicates that a significant proportion of the cost is concentrated in the die-level packaging stage. This result is not too surprising since the final product is a packaged die and there are many thousands of such die on each wafer (around 5,000 1 mm^2 die on a 100 mm diameter substrate). Therefore, costs associated with die-level activities will tend to dominate and manufacturers will need to address die-level packaging processes or perform more of the packaging activities at a wafer level in order to realize the required cost reductions. The optimum packaging approach is difficult to define and will depend on the precise application and performance requirements. Medium power LED packages can use smaller die, simpler phosphor deposition methods, cheaper packaging materials (plastics), and a smaller footprint. High power LED packages require larger die (or die arrays), more sophisticated phosphor deposition methods, ceramic sub-mounts with good thermal properties, and a larger footprint. In both cases, a high efficacy can be achieved and the optimum design approach depends on the ultimate application. In most cases, manufacturers produce a wide range of LED package products based on different packaging options but using largely the same die manufacturing process.

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

- Increased equipment throughput;
- Increased automation;
- Improved testing and inspection;
- Improved upstream process control;[6]
- Improved binning yield;
- Optimized packages (simplified designs, multichip, etc.);
- Higher levels of component integration (hybrid or monolithic); and
- Wafer scale packaging.

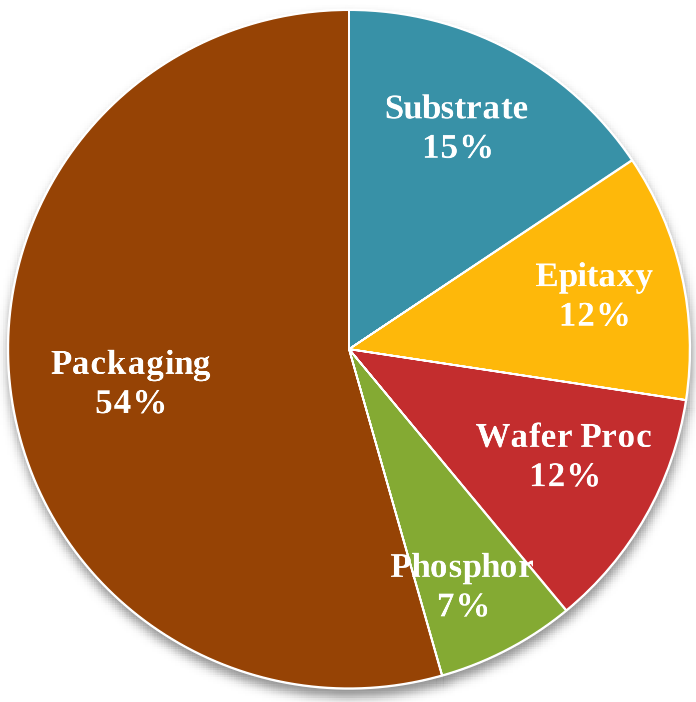


Figure 2-2. Typical cost breakdown for an LED package in 2011
(100 mm sapphire substrate; 1 mm^2 die; phosphor converted; high power package)
Source: provided by the 2011/2012 Manufacturing Workshop and Roundtable attendees with support from the Cost Model

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

The top level metrics for LED package efficacy, LED package price, and original equipment manufacturer (OEM) lamp price are taken from DOE's 2012 MYPP.[7] These projected values are reproduced in Table 2-2.

Table 2-2. LED metrics roadmap
Source: DOE 2012 MYPP

Metric	Unit	2011	2012	2013	2015	2020
LED Package Efficacy (warm white)	lm/W	97	113	129	162	224
LED Package Price (warm white)	$/klm	12.5	7.9	5.1	2.3	0.7
LED Package Efficacy (cool white)	lm/W	135	150	164	190	235
LED Package Price (cool white)	$/klm	9	6	4	2	0.7
OEM Lamp Price	$/klm	33	23	16.5	10	5

Notes:
1. Projections for cool white packages assume CCT=4746-7040K and CRI=70-80, while projections for warm white packages assume CCT=2580-3710K and CRI=80-90.
2. All efficacy projections assume measurements at 25°C with a drive current density of 35 A/cm^2.
3. Note that MYPP projections are based price, not cost.

A review of commercially available LED packages[8] confirms that the best efficacies currently available for cool white[9] and warm white[10] LEDs at a current density of 35 A/cm^2 are 144 and 113 lm/W respectively, in good agreement with the projections. The performance and price differential between cool white and warm white LED packages are anticipated to disappear by 2020.

LED package prices in $/klm continue to decline rapidly. One of the most effective approaches to lowering prices has been to use larger die areas (multiple die or larger single die) to achieve higher lumen output with respect to packaging costs. Such approaches have allowed the $/klm price to recently drop as low as $7/klm for warm white and $5/klm for cool white, on track with the LED metrics Roadmap shown in Table 2-2.

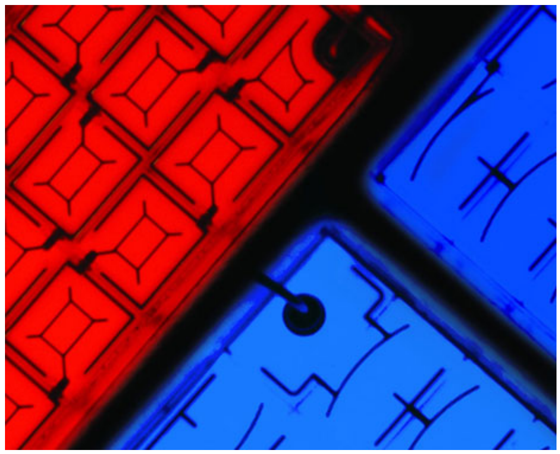
Good examples of LED packages using large single die are the Cree XP-G (2 mm^2 die in an 11.9 mm^2 area package), Lumileds Luxeon Rebel ES (2 mm^2 die in a 13.5 mm^2 area package), and Cree XM-L (4 mm^2 die in a 25 mm^2 area package). Examples of LED packages using multiple die range from the Cree MX-6 launched in 2009 which uses 6 small rectangular die (thought to be 0.35mm x 0.47mm in area)) in a simple plastic leaded chip carrier (PLCC) package, to the Cree MP-L launched in early 2010 which uses 24 conventional 1 mm^2 power die, to the Cree CXA2011 introduced in early 2011 which uses over 100 small area die. Other companies such as Lumileds, Bridgelux, Citizen and Sharp also produce LED array-based products. Note that the die in these LED-array sources are often operated well below the 35 A/cm^2 benchmark so it is difficult in many cases to compare performance and prices with single die packages.

---

[7] Assumes a warm white lamp through commercial outlets with CRI>80 and CCT = 2700-3000K
[8] Values obtained during 2011/2012 for quantities of 1000 units from various suppliers including Future Electronics and Digi-Key for power LEDs manufactured by Cree, Lumileds and OSRAM.
[9] CCT = 4746-7040K; CRI = 70-80; 35 A/cm^2 current density at 25°C
[10] CCT = 2580-3710K; CRI = 80-90; 35 A/cm^2 current density at 25°C

Integration at the components level is an important consideration for lowering costs and improving product quality. Additional opportunities for simplification include the hybrid integration of components at the packaging level and the monolithic integration of components at the wafer level. The simplest example of hybrid integration is the LED array approach described above with multiple die in the same package. However, more sophisticated examples are shown in Figure 2-3. The first of these combines a red, green, blue, and white LED into the same package to achieve a widely color tunable source. The second example combines white LED die with red die to produce a high efficiency warm white source with tunable color temperature.

Cree MC-E Color



Epistar High Voltage R+B Chipset
(prior to phosphor application)

Figure 2-3. Examples of mixed multi-die packages reported by Cree and Epistar
Note: the Epistar device is a laboratory prototype.

Hybrid integration of other types of components within the same package is an interesting option with drivers, sensors, and control systems being examples. Taking this integration approach one step further, it might also be possible to monolithically integrate the control circuitry and driver electronics onto the same semiconductor chip as the LED. A monolithically integrated chip would offer significant simplification with regard to chip packaging, luminaire design, and luminaire assembly. The cost savings associated with such high levels of integration could be very significant.

2.3 LED Luminaires

2.3.1 LED Packages in Luminaires

LED packages are a critical component of all current LED-based luminaires, and luminaire manufacturing is profoundly affected by LED package cost, performance, color consistency, form factor, and availability. These LED manufacturing-related issues are addressed in detail in Section 2.4 along with specific suggestions for manufacturing R&D task priorities. Since the beginning of the DOE SSL Manufacturing R&D effort, Workshop participants have consistently proposed that the DOE support R&D in the areas of current droop and internal quantum efficiency (IQE) as a means of reducing the relative cost contribution of LED packages within the luminaire. Improved LED efficiency and reduced droop will not necessarily reduce the cost of LED components (and may make them more expensive) but would reduce the number of expensive LED components required in a luminaire design and reduce the amount of thermal handling for a given lumen output. In addition, consistent, efficient, and stable emitters are desired across the visible spectrum. These LED R&D topic areas are appropriate for the Core or Product Development activities and have again been identified as priority tasks in the 2011 MYPP. While advances in LED component performance continue to be made, luminaire manufacturers must, make do with the LED packages that are currently available.

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. LED variability in lumen output, correlated color temperature (CCT), and forward voltage, is currently handled by testing each package and associating it with a specific performance bin. Color consistency of the LED package is seen as the most important binning issue. Regarding color consistency, there is an ongoing need for research into the sensitivity of the market for color variation – what is humanly visible and what is the tolerance for variations in color and output with respect to the lighting application? Color and output shift with time and temperature for different color LEDs must also be dealt with in the product design and manufacturing processes.

One clear proposal from the 2009 SSL Manufacturing Workshop to assist with chromaticity variations in LED packages was to have all LED manufacturers bin and label their products using a consistent set of chromaticity bins. This would enable luminaire manufacturers to more readily compare and use LED packages from different suppliers. This issue, discussed in further detail in Section 4.3, has been partially addressed with the recent publication of National Electrical Manufacturers Association (NEMA) SSL 3-2010[11] which provides consistent formulation for sub-binning. This creates a consistent set of sub-bins which LED manufacturers and luminaire manufacturers can use when describing the color of LED light sources.

Ultimately, the need for binning should be eliminated through LED fabrication improvements such as improved LED growth uniformity and optimized application of phosphors (both of which could be improved through improved process test and inspection). LED package manufacturers have also begun to report performance under typical luminaire operating conditions to minimize variations between the specified performance and actual performance in the luminaire. While variations in LED package performance persist, binning issues can be addressed, to some degree, by the luminaire manufacturers through engineering and integration techniques. These strategies include: secondary binning by the luminaire manufacturer for more consistent color within the manufacturers' bins, homogenization of the color from several LED packages using an array/module approach, and using a remote phosphor configuration that minimizes color variations. Manufacturing R&D that simplifies luminaire integration with respect to binning and LED light source performance variability will be considered under the 'Luminaire/Module Manufacturing' task area.

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

2.3.2 Luminaire/Module Manufacturing

At the 2012 DOE SSL Manufacturing Workshop and Roundtable meetings there were presentations and inputs by luminaire manufacturers about the challenges of manufacturing LED-based luminaires, and how luminaire manufacturing has fundamentally changed. The term 'luminaire' is used to describe fully integrated luminaires as well LED-based replacements lamps, which have the same level of integration but a standard electrical interface for use within conventional lighting fixtures. The introduction of LED-based lighting technology has significantly complicated the lamp and luminaire manufacturing process compared to conventional lighting products. In particular, testing requirements have become much more significant due to the fact that each LED-based luminaire is a unique fixture comprising a number of sub-components. Each fixture therefore has its own distinct electrical and photometric performance characteristics and must be separately tested. Conventional lighting technologies tend to be based around the fixture-plus-bulb paradigm which allows for simple and rapid testing with readily anticipated results. LED-based lighting, on the other hand, has a high degree of performance uncertainty due to the variable performance of the sub-components, particularly the LED. However, as the LED manufacturing components and processes become more mature, and manufacturers gain experience, the LED luminaire manufacturing process may no longer be considered quite so 'complicated' and much of the uncertainty (and cost) will be removed from the process.

All of the stakeholder inputs to the luminaire manufacturing R&D task related to the increased design and manufacturing complexity of the system and most of the R&D discussion revolved around simplifying the manufacturing process. Two distinct simplification themes emerged from discussions. The first theme was the simplification of testing of the luminaire products. Several stakeholders suggested this could be partially achieved by changes to testing policies and standards. In terms of manufacturing R&D, testing simplification could be accomplished through a more consistent supply of incoming components, particularly LED packages. Testing the luminaires at critical points in the manufacturing process and relating the test results to final luminaire performance could also simplify testing. Lastly, design modeling software could enable more rapid product design with a range of incoming components and anticipate product performance. In-line testing and design software could also expedite the development of similar products within a product family enabling a more flexible manufacturing process. For example, common sub-components to a range of final products could be tested before the manufacturing process diverges.

The next theme from stakeholders to simplify the manufacturing process was to simplify the integration of the luminaire by simplifying interfaces between the sub-components of the luminaire. Two divergent approaches were proposed for simplifying interfacing between luminaire components. Within the LED luminaire products there are opportunities to better integrate the LED die, LED package, or LED module with the lamp mechanical, electrical, and optical structures. Such advancements could simplify the design of the lamp or luminaire products, simplify the manufacturing of these products, and reduce product costs. The potential for high levels of component integration within LED-based luminaire products will have a significant impact on how such products will be manufactured. This level of integration may require automated manufacturing to bring down the assembly costs and reduce human variations in the manufacturing process. This integration also represents a challenge for existing luminaire manufacturers who may not have the necessary tools or expertise to develop the LED-based products. For example, the LED chip could be mounted directly to the luminaire heat-sink removing several layers of material and thermal interfaces, if an appropriate manufacturing method could be developed. This would remove the distinction between the LED package or light module and the luminaire. This is just one example, but the thermal, mechanical, optical, and electrical interfaces could all be considered for enhanced integration. Novel materials could also be considered which could simplify manufacturing and reduce the complexity, cost, and weight of the luminaire. Luminaire manufacturing would benefit from lighter weight and lower cost heat-sinks and thermal handling materials. Luminaire and LED modules could also benefit from lower cost but similarly robust optical materials.

The second approach is to standardize form factors and interfaces between sub-components, which would allow for a consistent integration process regardless of the supplier of the sub-component. This approach is being considered and supported by an industry consortium – the Zhaga Consortium. While it was recognized that LED-based lighting products require a high level of integration, there was also discussion of creating a modular approach to luminaire manufacturing. The components of the luminaire, such as the LED light source, driver, thermal handling, and optics, and housing, could be developed to readily fit together in a variety of configurations. This could enable rapid manufacturing of a range of product variations, simplify inventory demands, and simplify luminaire design. All of these benefits could lead to greatly reduced luminaire costs. The modular manufacturing and design approach could also benefit smaller scale and traditional luminaire manufacturers who could more easily and rapidly design and manufacture LED-based lighting products. Different lighting applications and types of products may lend themselves to either integrated or more modular product designs. In addition, different levels of design capability for luminaire manufacturers may also encourage the use of more modular product designs. Multiple approaches to the design and manufacturing of LED-based lighting products will likely exist in parallel as the market evolves.

Another fundamental change to luminaire manufacturing is how luminaire reliability is considered and how this impacts the design and sub-component selection of LED-based luminaires. The long life of the LED package has led to the expectation of longer-lived luminaires and replacement lamps. Maximizing product lifetime requires not just a well-integrated long life LED package, but also long lives from all of the luminaire sub-components and reliable design and integration of the product. While consumers expect longer lifetimes from LED lighting products they also insist on low priced products. Understanding the reliability relationships between the luminaire components will allow manufacturers to make informed decisions regarding trade-offs between product cost and product reliability.[12]

The priority research task on ‘Luminaire/Module Manufacturing’ addresses the issues discussed above. This task is focused on improving the integration and manufacturing of LED luminaires and modules. The discussions at the 2012 Roundtable and Manufacturing Workshop emphasized the need to develop LED packages and luminaire/lamp designs that are readily integrated, use

[12]The LED Luminaire Lifetime: Recommendations for Testing and Reporting, document can be found at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/led_luminaire-lifetime-guide_june2011.pdf

fewer raw materials, and are optimized for efficient manufacturing without compromising the performance of the light source. The benefits of these improvements would be products that weigh less, have improved thermal performance, are more reliable, have more consistent color, and can be manufactured more efficiently at a lower cost.

2.3.3 LED Driver Manufacturing

The driver manufacturing discussion group at the Workshop did not recommend prioritization of driver manufacturing as a manufacturing R&D topic. Drivers remain a critical component of all LED-based luminaires that can significantly impact luminaire performance. They are often the cause of failure of luminaires, and features built into the driver such as controls can add value to LED lighting products. Even with these considerations the driver group felt that these issues are more related to product performance and cost trade-offs than manufacturing technology. The manufacturing of drivers is well understood and can be done at low cost if the product performance requirements are well understood. There is still manufacturing R&D that needs to be done but it may not be the most critical manufacturing issue for the moment.

Proposed driver information:

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

While basic driver manufacturing technology is understood, the need for drivers with improved integration, reliability, and flexibility within the luminaire remains. Approaches for the development of flexible, high efficiency, low cost drivers could include the disaggregation of driver functionality into sub-modules to allow luminaire integrators to mix and match functions while maintaining high efficiency and reliability. The manufacturing of drivers with some level of controllability and control compatibility is also a concern for driver and luminaire manufacturers. Luminaires for varying lighting applications may require different types of control. Internal electronic control of color consistency, compatibility with dimming systems, or communication with various forms of wired or wireless controls may be required for the lighting application and this functionality is typically integrated into the power supply. The need for the integration of these controls into the luminaire can impact the assembly costs of the luminaire as well as the reliability of the luminaire. Improvements to the design and manufacturing of drivers and the control systems could have a significant benefit on luminaire cost, performance, and reliability.

A standard report format of driver performance would also facilitate driver integration into LED-based luminaires. The lack of information and inconsistent reporting of driver performance inhibits efficient and easy integration of the electronic components. The luminaire manufacturers as well as the driver manufacturers emphasized the need to disseminate this information readily and uniformly. A standard reporting format would also facilitate the use and development of analysis, simulation, and design tools for luminaire manufacturers. The luminaire manufacturers suggested that this reporting of performance data in a standard reporting format should be implemented in the near term. The sidebar, on the previous page, lists the parameters the LED breakout group recommended should be included.

There were also suggestions to develop a testing protocol to better define the driver reliability. The DOE SSL Program is supporting product development R&D to better understand and predict driver reliability. A CALiPER[13] type program is being considered by DOE for driver performance but has not yet been finalized.

2.3.4 Test and Inspection Equipment

The attendees at the 2012 Manufacturing Workshop confirmed the need for test and inspection equipment for all levels of LED package and LED-based luminaire manufacturing. Test and inspection equipment for LED production is discussed in Section 2.4.6. For luminaires, test and inspection equipment could be used to validate incoming components, to perform in-line testing, to identify potential failure mechanisms, or to test final products in a simulated installation environment. These tools could provide additional confidence in the quality of the luminaire products advancing the DOE SSL manufacturing objective of improved product consistency and quality. Within this R&D task it is important to not just perform the testing within the manufacturing process but to demonstrate the impact of the testing at the specific point in the manufacturing process. At certain points in the manufacturing process, test or inspection could have a greater impact on yield, cost, or performance of the final product. These critical testing points need to be identified and exploited for their benefits to the manufacturing process.

2.3.5 Luminaire Reliability

The lack of a thorough understanding of lifetime for LED-based luminaires continues to be a significant problem for luminaire manufacturers. While LM-79 provides a standardized protocol for measuring luminaire performance and can be performed at various points in the luminaire life, it is expensive and time consuming to perform this test, particularly at the rate new luminaire and lamps products are being developed. LM-79 also does not offer a means to accelerate life testing to allow for interpolations of lifetime within a shorter test cycle. Uncertainty in the long-term performance of the luminaire system makes it difficult to estimate and warrant the lifetime of LED-based luminaires. It also hinders manufacturers' ability to know how best to improve their product reliability. This uncertainty could be addressed by better information about long term performance of key LED luminaire components and materials, including the LED packages, drivers, optical components and materials used in assembly, along with accepted methods to statistically predict luminaire system lifetime.

---

[13] DOE's Commercially Available LED Product Evaluation and Reporting (CALiPER) program: http://www1.eere.energy.gov/buildings/ssl/caliper.html

The issue of a common test protocol was initially brought up for the Core Technology R&D Program under the System Reliability Methods task area. The lack of a common test protocol has been addressed by a DOE-supported reliability working group which has recently released a guide for reporting and characterizing luminaire lifetime.[14] The luminaire discussion group at the Workshop recommended that lifetime performance of luminaire components and systems should be provided by the product suppliers in a standardized data file format. This would enable the luminaire manufacturer to model lifetime performance of the luminaire system using the data provided from a variety of components. The luminaire lifetime data could be used by lighting designers for lighting calculations of lumen maintenance in a variety of environments, as is done currently with conventional lighting. To enable the collection of this data, appropriate acceleration factors need to be understood for the various luminaire components and for the luminaire system. Subsequent to that discussion, a new LED Systems Reliability Consortium facilitated by DOE has begun to explore ways to identify and characterize the physics of failure of LED lighting systems. The group is working in concert with a DOE-funded project, under the Core Technology initiative, at Research Triangle Institute and is developing the software and database needed to characterize LED systems. As SSL-specific understanding of the system lifetime performance is developed, testing and manufacturing best practices can be established. In addition, a common database of statistical performance of luminaire components and systems could be developed and coupled with theoretical and experimental results from the reliability R&D to develop a consistent and accurate means of estimating system lifetime.

2.4 LED Packages

The LED package remains a key component within the LED-based luminaire and represents a significant cost element. Efforts to reduce costs while continuing to improve performance will require concerted action throughout the manufacturing supply chain. Such efforts will focus on higher quality and lower cost raw materials, improved epitaxial growth equipment and processes, optimized wafer processing equipment, and more flexible packaging methods and equipment. Various raw materials feed into the manufacturing process such as substrates, phosphors, gases, and chemicals. Of these, substrates have assumed a high level of strategic importance due to the lack of an obvious best candidate and the impact of substrate selection on virtually all subsequent process steps. Another critical raw material is the phosphor or down-converter which controls the efficiency and color quality of the white light emission.

The following sections review these requirements in more detail and highlight specific problems and barrier to progress that have been identified during recent Manufacturing Roundtables and SSL Manufacturing Workshops.

2.4.1 Substrates

A handful of substrate options currently exist for the manufacture of high-power Gallium Nitride (GaN)-based LEDs covering a range of materials (sapphire, Silicon Carbide (SiC), Silicon (Si), and GaN) and wafer diameters (2inch, 3inch, 100mm, 150mm, etc.). Currently, GaN LED

[14] http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/led_luminaire-lifetime-guide_june2011.pdf

growth on sapphire and SiC provide the highest performance LEDs at a reasonable cost but significant progress has been reported using both Si and GaN substrates. The substrate Roadmap supports two paths; (i) improved substrates for heteroepitaxial growth (sapphire, SiC and Si), and (ii) improved substrates for homoepitaxial growth (GaN). In the case of SiC and sapphire substrates, improvements in substrate quality (surface finish, defect density, flatness, etc.), product consistency, and size are required in order to meet the demands of high volume manufacturing. For GaN substrates the major issue impacting adoption is the very high substrate cost, consistency, limited supply, and the lack of availability of larger diameters.

Both sapphire and SiC substrates have been used to produce GaN-based LEDs with state of the art performance, although sapphire has established itself as the dominant substrate type used in production. A general trend toward larger substrate diameters is anticipated, mimicking the Si and GaAs microelectronics industry. Philips Lumileds has been manufacturing LEDs on 150 mm sapphire wafers since the end of 2010[15]and Osram Opto started moving its standard production of GaN-based LEDs to 150 mm diameter sapphire substrates early in 2012.[16]

Beyond this, a number of manufacturers such as Bridgelux and Azzuro are already developing capabilities based on 200 mm Si substrates. Toshiba, in partnership with Bridgelux, recently announced that it would begin mass production of GaN-based LEDs on 200 mm Si wafers in October 2012 (Figure 2-4). According to Toshiba, the fabrication process will depend on "the combination of Bridgelux’s crystal growth and LED chip structure and Toshiba’s advanced Si process and manufacturing technology." Larger substrates provide an increase in useable area (less edge exclusion) without a proportionate increase in processing cost per wafer, resulting in a lower cost per die. Larger wafers also provide improved access to automated wafer handling equipment originally developed for the microelectronics industry. In the case of 200 mm silicon the hope is to use existing unused 200 mm wafer fabrications originally established for silicon microelectronics. In order to realize these advantages, a steady supply of high quality large diameter substrates at reasonable prices (typically at the same or lower cost per unit area) will be necessary.

[15] Press Release: Dec 15, 2010, “Philips Lumileds Leads LED Industry with Mass Production on 150 mm Wafers”
[16] “Osram Opto expands LED capacity with 6-inch conversion”, March 2011, http://ledsmagazine.com/news/8/3/6

Figure 2-4. GaN-based LEDs on a 200 mm silicon wafer as demonstrated by OSRAM

The current reliance on heteroepitaxial growth of (In) GaN layers on sapphire, SiC, and Si 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. As bulk GaN substrates continue to increase in size and reduce in price they may become a practical alternative to sapphire, SiC and Si substrates. In principal, the use of a GaN substrate offers to simplify the buffer layer technology (thinner buffer layers with shorter growth times) and allow flat, uniform epiwafers to be manufactured. GaN might also offer improved device performance through reduced defect densities and through reduced polarization fields associated with the use of non-polar or semi-polar substrates. The first products using LEDs manufactured on GaN substrates were launched recently by Soraa, Inc. The product is an MR16 replacement lamp and takes advantage of the good thermal characteristics and low current droop for such devices which allow a small area chip to be used to achieve a narrow beam at high efficacy.

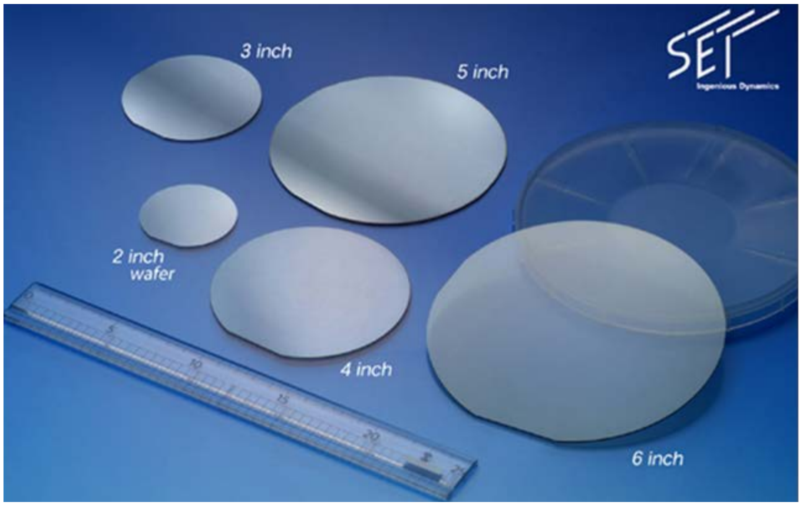


Figure 2-5. Bulk GaN substrates produced by Sumitomo Electric Industries

Figure 2-6 presents the Substrate Roadmap. The starting points of the blue shaded bars 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.

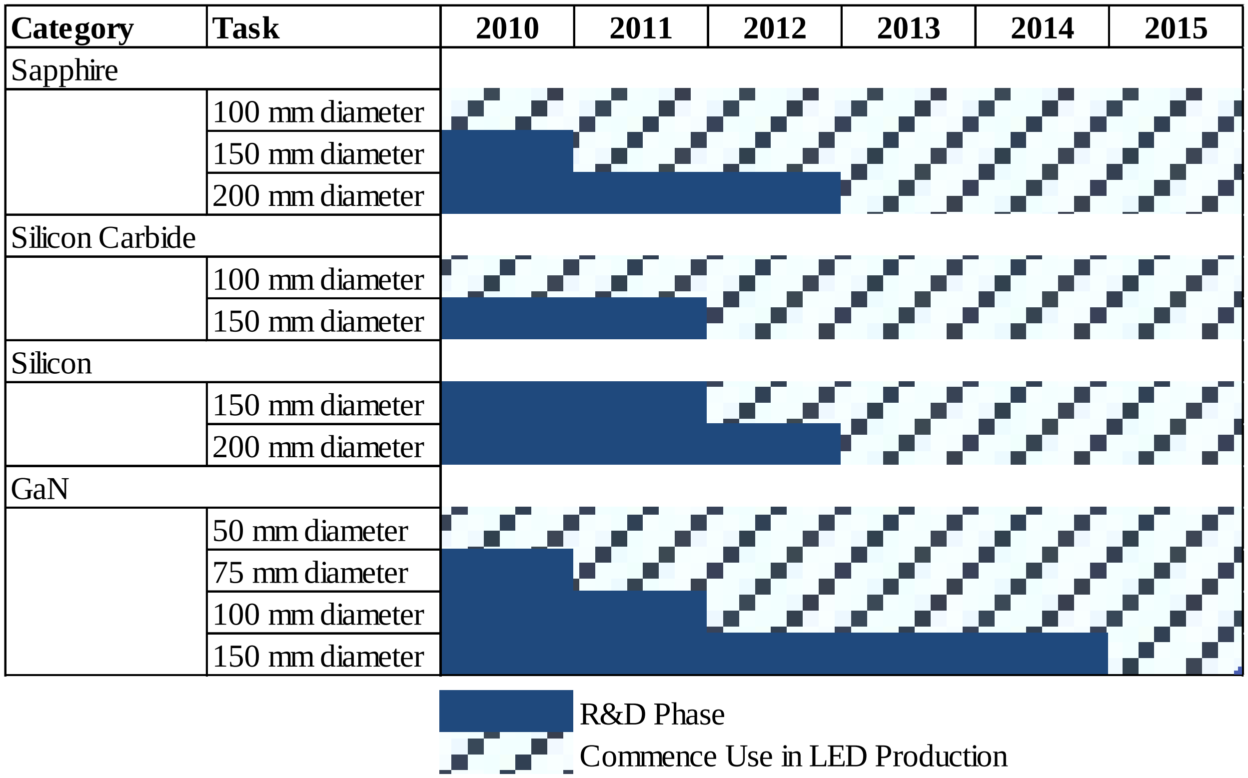


Figure 2-6. Substrate Roadmap
Source: based on recommendations from the 2012 Manufacturing Roundtable and Workshop attendees, and progress reported elsewhere (e.g., Sumitomo[17], Soitec/Sumitomo[18]).

It should be noted that epitaxial growth equipment to handle the wide variety of substrate sizes is readily available with both Veeco and Aixtron supply MOCVD reactors able to handle from 2 inch all the way up to 200 mm. For example, Azzuro Semiconductors recently purchased a Veeco TurboDisc K465i MOCVD to extend its GaN-on-Si work to 200 mm substrates, and Aixtron recently introduced the AIX G5+ as a 5mm x 200mm GaN-on-Si technology package for its AIX G5 Planetary Reactor platform.

2.4.2 Epitaxy Processes

Epitaxial growth remains the key enabling technology for the manufacture of high brightness (HB)-LEDs. GaN-based HB-LED epiwafers are currently manufactured using Metal Organic

[17] “Sumitomo Electric Industries, Ltd. has successfully developed the world’s first 6-inch diameter GaN (gallium nitride) substrates to be used for white LEDs (light emitting diodes).”, Press Release, November 16, 2010
[18] “Soitec and Sumitomo Electric announce major milestone in strategic joint development of engineered gallium nitride substrates”, Press Release, January 24, 2012

Chemical Vapor Deposition (MOCVD). MOCVD is the only technology capable of growing the entire device structure including the complex low temperature nucleation layer, the thick GaN buffer, the multi-quantum well (MQW) active region, and p-GaN cap. Nevertheless, hydride vapor phase epitaxy (HVPE) remains an alternative growth approach for thick GaN layers due to its potential for significantly higher growth rates and less expense, and work is underway to combine HVPE and MOCVD into a single multi-wafer growth tool to combine the best attributes of each technology.

Significant progress has been made over the past few years on many of the critical issues identified in earlier versions of the Roadmap. Existing projects under the SSL Manufacturing Initiative are driving further improvements in uniformity, reproducibility, and equipment throughput. Preliminary work is also underway to improve the capabilities offered by in-situ monitoring and to better understand the growth chemistry. This progress is summarized as follows:

- Insufficient wavelength uniformity and reproducibility-
  Achieving tighter control over the wavelength uniformity and reproducibility of the active MQW region will be critical in order to improve color point consistency in the final product and overall product yield. Similarly, the material quality and internal quantum efficiency (IQE) must continue to improve in order to achieve the target efficacy improvements. Both requirements will be met by improved equipment design, process optimization, and process control.

- Low throughput (cycle and growth times)-
  Large-capacity manufacturing equipment (up to 56 x 2 inch or 14 x 4 inch wafer capacity) that is capable of producing high quality material is readily available from companies such as Veeco Instruments (U.S.) and Aixtron (Germany). Developments in cluster tool technology, such as the Veeco MaxBright™ platform, offer the prospect of even higher throughputs and reductions in overall cost of ownership. Equipment design modifications and process improvements has allowed the GaN growth rate to reach 15-20 μm/hr, which essentially eliminates growth time issues for the thicker GaN layers.

Figure 2-7. Veeco MaxBright™ 14 x 14 inch wafer carrier

- Lack of in-situ monitoring/process control-
  The demanding reproducibility and uniformity requirements suggest the need for advanced process control measures in conjunction with sophisticated in-situ monitoring

(especially wafer temperature) and accurate process modeling. Active temperature control at the wafer surface is of particular importance since temperature drives the growth process. Developments in the use of ultraviolet (UV) pyrometery to measure temperatures at the wafer surface rather than remotely via the carrier surface offer a more direct route to active control. Initial experiments reported by Veeco suggest an improvement in run-to-run reproducibility from 2.33 to 1.4 nm could be possible[19]. Other in-situ tools, such as for monitoring wafer bow are routinely incorporated into most production reactors, although they are not generally used in active monitoring and control of the manufacturing process.

- Problems managing wafer bow-
  Monitoring of the wafer bow leads to an insight as to the stresses incurred at each step in the process. The critical stage is the growth of the Indium Gallium Nitride (InGaN)/GaN MQW active region, where the temperature uniformity must be extremely good. The presence of any residual wafer bow at this stage results in variations in contact between the wafer and the carrier, and hence differences in temperature. One elegant solution, being developed by Veeco, is to create an advanced engineered wafer carrier where the pockets are carefully designed to provide uniform heating to the wafer at this critical stage in the process. The results indicate that the uniformity can be significantly improved with the proportion of the wafer falling within a 5 nm bin rising from 73% to >90% as reported by Veeco.

- Incomplete knowledge regarding growth chemistry/mechanisms-
  CFD-based modeling is used extensively in the development of improved equipment and processes. However more work is required in this area. A good example of this imperfect knowledge of the growth chemistry was the observation of an increased GaN growth rate using a heated inlet flange by Veecowhile the model suggested just the opposite effect. Subsequent detailed experimental and theoretical analysis by Sandia[20] determined the cause of the discrepancy and the model was refined in order to replicate the observed behavior.

- Need for lower cost source materials and improved source efficiencies -
  High purity metalorganic alkyl sources and hydride gases are expensive. For example, the high cost of Tri-Methyl Gallium (TMG) is an issue since a large amount of the material is used to produce an LED epitaxial structure. The usage efficiency is only 20-25%; so much of the material is wasted. Work is therefore required to lower the cost of the source or improve the source efficiency. The use of larger sources helps but the equipment design largely determines how efficiently the TMG can be converted to GaN and improvements are required in this area.

[19] http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/montgomery_costs_sanjose2012.pdf
[20] http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/coltrin_costs_sanjose2012.pdf

Category	Task	2010	2011	2012	2013	2014	2015
MOCVD Epitaxy							
	Modeling: Apply Computational Fluid Dynamics (CFD) and chemical reaction models to uniformity improvement and source efficacy 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						

Present and Expected Activity

Figure 2-8. Epitaxy Roadmap
Source: provided by the 2012 Manufacturing Workshop attendees

Figure 2-8 shows the epitaxy Roadmap which remains unchanged from that shown in previous Manufacturing Roadmaps. Progress against this Roadmap remains largely on target. The main area where there is a danger of falling behind remains the development of active process control using in-situ monitoring. The focus on uniformity and reproducibility improvements must continue along with the focus on reducing costs. One area that was highlighted was the high cost of raw materials, and the need to improve the efficiency of use of such materials to reduce overall costs. There will need to be a focus on improved materials manufacturing to reduce raw materials costs but also a focus on systems design and process optimization to improve source usage efficiency.

Table 2-3 describes a set of suitable metrics to characterize the epitaxy process. The most critical metrics are those associated with epiwafer uniformity and reproducibility. The table sets targets for in-wafer uniformity, wafer-to-wafer reproducibility, and run-to-run reproducibility. Also included is cost of ownership[21](COO) which is an excellent metric to describe how manufacturing equipment should evolve to reduce the cost of production. A reduced COO for epitaxy equipment might be achieved in many different ways, such as increased throughput (reduced cycle times and/or increased capacity), lower capital cost, improved materials usage efficiancy, smaller footprint, or increased yield. Process control improvements will increase yield, and equipment design changes will increase the efficiency of reagent useage. Finally, Overall Equipment Efficiency (OEE) improvements will reduce operating costs through improved preventive maintenance schedules, minimization of non-productive operations such as

[21] See section 2.5 for a broader description of the concept of cost of ownership.

chamber cleaning, and introduction of cassette-to-cassette load/unload automation. Although, it is difficult to specify at this stage which approaches will be the most effective, all such actions will reduce the COO.

The epitaxial layer cost will depend to a large extent on the total layer thickness (growth time, precursor usage, etc.) and wafer yield. There is no common substrate type/diameter, epitaxial growth reactor configuration, or total layer thickness. Consequently it has been decided to normalize the epitaxial layer cost to layer thickness (μm) and wafer area (cm^2), as shown in Table 2-3. The epitaxy metrics are unchanged from the 2011 Roadmap. The cost metrics anticipate ongoing improvements in wafer throughput (shorter cycle times and increased numbers of wafers/run) and in epiwafer yield (improved wavelength uniformity and wafer-to-wafer/run-to-run reproducibility).

Table 2-3. Epitaxy metrics
Source: provided by the 2011/2012 Manufacturing Workshop attendees

Metric	Unit	2010	2012	2015	2020
Wafer uniformity (standard deviation of wavelength for each wafer)	nm	1.5	1.0	0.5	0.5
Wafer-to-wafer reproducibility (maximum spread of mean wavelength for all wafers in a run)	nm	1.1	0.9	0.6	0.5
Run-to-run reproducibility (maximum variation from run-to-run of the mean wavelength for all wafers in a run)	nm	1.5	1.1	0.9	0.75
Cost of ownership (COO)	-	Factor of 2 reduction every 5 years			
Epitaxy cost	$/μm·cm^2	0.45	0.28	0.14	0.05

2.4.3 Wafer Processing

Earlier problems associated with the lack of suitable manufacturing equipment for wafer processing have receded to some extent. Partly this is due to a general migration toward larger substrate diameters, such as 150 mm sapphire, but also to the fact that equipment manufacturers have responded to the growing demand and introduced more flexible platforms to cope with the different substrate types and diameters. Significant progress has been made in the development of equipment specifically optimized for the needs of this industry such as optical wafer inspection tools (KLA-Tencor) and lithography tools (Ultratech Inc.). Many manufacturers place a premium on low acquisition cost and still tend to modify their own equipment so, despite the good progress; further work is required to produce a complete range of manufacturing equipment that meets the requirements of the LED industry. Communication between equipment manufacturers and end-users has steadily increased and more focus is being placed on standards activities (especially for sapphire substrates), but there is still room for improvement.

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

2.4.4 Die Packaging

Die packaging is heavily based on equipment and processes developed for the general semiconductor die packaging industry. Certain customization has been required but to a large extent existing equipment is already suitable. There is a high degree of commonality with regard to packaging materials such as ceramic packages and sub-mounts, and surface mount technology. Similarly, the industry has been able to employ many of the existing processes and equipment for die-attach, wire bonding, flip-chip, encapsulation, and lens attach. Probably the most critical difference occurs in the controlled application of a phosphor or other down-conversion material to the die to create a phosphor-converted white LED.

There are a multitude of options regarding the packaging of LED die in terms of the package design and packaging materials employed. Ultimately the packaging method reflects the target application, and the end result is a wide range of different types of package in terms of physical dimensions and light output characteristics. Traditionally the focus has been on the manufacture of high power 1 W packages comprising a single 1 mm^2 die and producing around 80-100 lumens of white light. Such packages use relatively expensive ceramic materials on account of their superior thermal properties. A more recent trend has been to utilize lower power LED packages originally developed for the backlighting industry. Such products use cheap plastic packaging materials resulting in very low cost packages, and while the lumen output per package is much lower it is possible to use many more packages to achieve similar overall light output levels in a cost effective manner. Cheap plastic packages are well suited to the manufacturing of diffuse lighting sources, while compact high power packages are well suited to the manufacturing of high intensity point sources. In this context it is common to refer to medium power and high power packages to distinguish between plastic packages with power dissipations of around 0.5 W or less, and ceramic packages with power dissipations of over 0.5 W.

Die packaging remains a major source of cost for the final packaged LED. The challenge will be to make more efficient use of raw materials (either using less material or finding more affordable alternatives) to enable the manufacturing of lower cost LED packages without forsaking performance.

2.4.5 Phosphor Manufacturing and Application

Phosphor and associated matrix materials comprise a significant cost for various package designs. Part of the cost is associated with the raw materials themselves, especially for the more specialized red phosphors that are required for warm white LED packages. A second part of the cost is associated with the need to provide uniform and reproducible application of phosphors to achieve a high level of control over the final color coordinates, and hence the ultimate device yield/cost.

Improvements are required in the manufacturing of the phosphor or down-conversion materials in order to lower costs and produce more uniform and reproducible materials characteristics. Areas for materials improvement include the realization of more uniform particle sizes, better controlled morphology, better chemical stability, better thermal stability, and more consistent excitation characteristics. In terms of manufacturing improvements, the introduction of continuous processing methods (as opposed to a batch processing methods) has the potential to significantly reduce phosphor manufacturing costs. In addition, the development of materials compatible with manufacturing at lower temperatures and pressures would help simplify the manufacturing process.

Figure 2-9. Examples of LED phosphors available at Intematix Corp.

The application of phosphors to achieve high quality white light of the specified color quality and color point requires careful control of material composition and layer thickness. As the color coordinate tolerance is tightened it is often necessary to employ a tunable phosphor application process where each die is tested prior to phosphor application to achieve the target color point. The availability of more uniform and reproducible phosphor materials would help eliminate such matching processes and reduce costs.

There are many different methods to apply the phosphor to the die ranging from the relatively simple “dam & fill” method, through conformal methods such as electrophoretic deposition or the use of phosphor loaded ceramic discs (e.g. Lumiramic), to remote methods. Different package types suit different application methods with the simpler and cheaper “dam & fill” being largely confined to medium power LEDs using plastic packages and the more expensive conformal methods used for high power LEDs using ceramic packages. Remote phosphors are generally applied as a coating to optical elements positioned above and around the semiconductor die. Further improvements in application flexibility to meet the wide range of demands for current and new package designs is required along with suitable equipment to meet that demand.

2.4.6 Test and Inspection Equipment

Concerns about equipment go beyond the direct process steps discussed above, and include improved process control, in-line inspection, non-destructive testing/characterization, and high speed device testing.

Due to variability at various stages in the manufacturing process, manufacturers are currently required to measure all devices in order to characterize them in terms of lumen output, color coordinates (CCT and CRI), and forward voltage. Such measurements allow the end products to be placed in specific performance bins. Binning currently occurs at the end of the process and high speed testing is required to minimize the cost of this step. Until recently these measurements have been performed at a temperature of 25°C and luminaire manufacturers have been left to infer the device performance under actual operating conditions, which might be temperatures closer to 85°C. Cree has reported that typically the color shift from 25 to 85°C is around $\Delta_{u'v'} = 0.002$, or approximately 2 SDCM.[22] Lumen output is also typically reduced by 5% to 10% at the higher temperature. Consequently the device manufacturers are now performing these measurements at a temperature of 85°C for their new product introductions, a practice often referred to as 'hot' binning. Performing such measurements at high speed with a high degree of accuracy presents a number of challenges which remain to be solved.

Improvements in process controls plus the application of in-line testing and inspection will tighten device performance distributions, and allow manufacturers to produce product more closely aligned with customer demand. Significant developments have been made in this sector as evidenced by the release of an increasingly wide range of products with significantly tighter color bins. Cree's Easywhite™ product range was first introduced at the end of 2009 and offered 75% smaller bins (4 SDCM) than ANSI C78.377 for color temperatures of 2700, 3000 and 3500K. More recently, products introduced under the Easywhite™ label are guaranteed to fall within either a 2 or 4 SDCM bin while covering a wider range of color temperatures. Philips Lumileds introduced their own range of products offering '*Freedom from Binning*' at the start of 2011. These products are guaranteed to fall within a 3 SDCM bin and have the additional advantage that all measurements are performed at 85°C, so the devices are both tested and binned under real world operating conditions. Most new product introductions over the year or so are being tested at the de-facto standard of 85°C. The quest for tighter control of the end product color coordinates is driving the need for equivalent hot testing at the wafer level to determine the LED emission wavelength under simulated operating conditions.

While there has been a noticeable improvement in process control, further improvements are required throughout the epitaxial growth, wafer processing, chip production and chip packaging stages. There remains a strong need to develop improved in-situ monitoring and active process control for MOCVD epitaxial growth, in conjunction with rapid in-line characterization of the epitaxial wafers for rapid feedback to the manufacturing process. There is also a need for in-line testing, inspection, characterization, and metrology equipment throughout the LED package manufacturing process. Yield losses at each step in the manufacturing process have a cumulative effect so the ability to detect manufacturing problems at an early stage (excursion flagging)

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

enables problems to be corrected, or non-compliant products to be excluded from further processing. Both actions can have a significant impact on overall production yield and provide significant cost savings.

As tighter tolerances continue to be introduced there is a need for improved characterization equipment offering higher levels of sensitivity and accuracy to enable rapid and effective incoming materials qualification throughout the supply chain, and assure the quality and consistency of LED products.

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

2.5 Cost Modeling

A common theme during previous Manufacturing Workshops was the need for a common cost model to describe the manufacturing of LED-based components and fixtures. Such a model would allow industry and government to identify those areas which had the largest impact on final device and luminaire costs. This information could then be used to help focus effort into the most profitable areas. A working group was formed to consider how best to develop a suitable model for the community which would prove easy to use while providing a good indication of the major cost elements. A simple modular cost model has now been developed to describe the manufacturing of an LED package and was demonstrated at the 2012 Manufacturing Workshop.

Conventional cost models are based on a cost of ownership (COO) analysis for each piece of equipment in the manufacturing process. COO is a widely used metric in the semiconductor industry (see SEMI standard E35 ‘Cost of Ownership for Semiconductor Manufacturing Metrics’) and was originally developed for wafer fabrication tools. COO can be defined as the full cost of embedding, operating and decommissioning, in a factory environment, a system needed to accommodate a required volume. In its simplest form it is the total cost of producing a good part from a piece of equipment. The cost per part for an item of semiconductor processing equipment can be determined from a knowledge of the fixed cost (purchase, installation, etc.), variable cost (labor, materials, etc.), cost due to yield loss, throughput, composite yield, and utilization (proportion of productive time). The cost per part is obtained by dividing the full cost of the equipment and its operation by the total number of good parts produced over the commissioned lifetime of the equipment. COO can also be applied to non-process equipment such as test and inspection tools. The purpose of these tools is to identify good product from bad product and generally results in some level of scrappage. Scrap caused by the inspection method, such as destructive testing, is part of the test equipment COO (increases the yield loss). Scrap identified by the inspection method is part of process tool COO for the tool causing the scrappage.

The Simple Modular LED COst Model (LEDCOM) focuses on only those process steps contributing more than 1% to the final LED package cost. For these process steps it performs a simple cost analysis based on the equipment employed and the yield. These costs are accumulated along with the yields to establish a final manufacturing cost/wafer or cost/die.

The Simple Modular Cost Model breaks down the manufacturing process into a number of discrete process steps or modules. It focuses on only those process steps contributing more than 1% to the final LED package cost. For these process steps it performs a simple cost analysis based on the equipment employed and the yield. These costs are accumulated along with the yields to establish a final cost per wafer or cost per die. Global parameters such as substrate type, substrate diameter, die area, and factory overheads can be fixed. The first version of the model limits the number of process steps to 17 for wafer processing, including epitaxy, and 13 for die packaging. Each step can be repeated as many times as necessary.

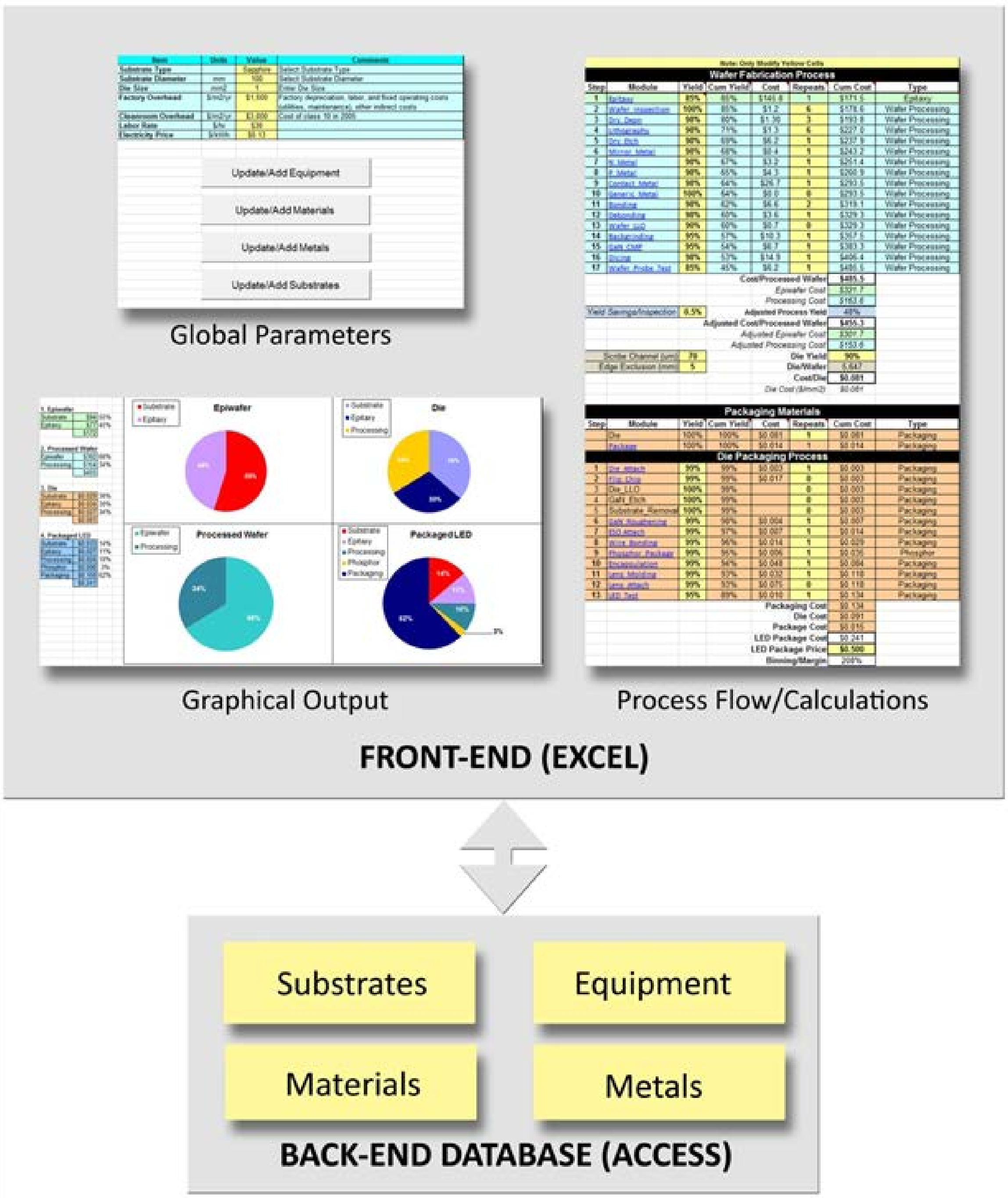


Figure 2-10. Schematic representation of the Simpler Modular Cost Model
Source: Stephen Bland, SB Consulting, "A Simple Modular Cost Model for LED Packages," Poster Session, San Jose, CA 2012

Figure 2-10 is a schematic representation of the LEDCOM model. The Global module includes global variables and provides a link to the underlying data. The Process module allows the process steps to be identified. The Output module provides a simple graphical representation of the final cost breakdowns. All equipment and materials data is held in a central database.

Note: Only Modify Yellow Cells							
Wafer Fabrication Process							
Step	**Module**	**Yield**	**Cum Yield**	**Cost**	**Repeats**	**Cum Cost**	**Type**
1	Epitaxy	85%	85%	$175.4	1	$206.4	Epitaxy
2	Wafer_Inspection	100%	85%	$1.2	6	$207.6	Wafer Processing
3	Dry_Depn	98%	80%	$1.30	3	$228.4	Wafer Processing
4	Lithography	98%	71%	$1.3	6	$262.1	Wafer Processing
5	Dry_Etch	98%	69%	$6.2	1	$303.5	Wafer Processing
6	Mirror_Metal	98%	68%	$0.4	1	$310.0	Wafer Processing
7	N_Metal	98%	67%	$3.2	1	$319.6	Wafer Processing
8	P_Metal	98%	65%	$4.3	1	$330.5	Wafer Processing
9	Contact_Metal	98%	64%	$26.7	1	$364.5	Wafer Processing
10	Generic_Metal	100%	64%	$0.0	0	$364.5	Wafer Processing
11	Wafer Bonding	98%	62%	$6.6	2	$379.5	Wafer Processing
12	Wafer Debonding	98%	60%	$3.6	1	$394.6	Wafer Processing
13	Wafer LLO	90%	60%	$0.7	0	$395.3	Wafer Processing
14	Backgrinding	95%	57%	$10.3	1	$416.1	Wafer Processing
15	GaN_CMP	95%	54%	$6.7	1	$445.1	Wafer Processing
16	Wafer Dicing	98%	53%	$14.9	1	$469.4	Wafer Processing
17	Wafer_Probe_Test	85%	45%	$6.2	1	$559.6	Wafer Processing
					Cost/Processed Wafer	**$559.6**	
					Epiwafer Cost	*$387.1*	
					Processing Cost	*$172.5*	
Yield Savings/Inspection		**0.5%**			Adjusted Process Yield	48%	
					Adjusted Cost/Processed Wafer	**$524.8**	
					Adjusted Epiwafer Cost	*$363.0*	
					Adjusted Processing Cost	*$161.8*	
Scribe Channel (um)		**70**			**Die Yield**	**90%**	
Edge Exclusion (mm)		**5**			**Die/Wafer**	5,647	
					Cost/Die	**$0.093**	
					Die Cost ($/mm 2)	*$0.093*	
Packaging Materials							
Step	**Module**	**Yield**	**Cum Yield**	**Cost**	**Repeats**	**Cum Cost**	**Type**
	Die	100%	100%	$0.093	1	$0.093	Packaging
	Package	100%	100%	$0.014	1	$0.014	Packaging
Die Packaging Process							
1	Die_Attach	99%	99%	$0.003	1	$0.003	Packaging
2	Flip_Chip	99%	99%	$0.017	0	$0.003	Packaging
3	Die_LLO	100%	99%		0	$0.003	Packaging
4	GaN_Etch	100%	99%		0	$0.003	Packaging
5	Substrate_Removal	100%	99%		0	$0.003	Packaging
6	GaN_Roughening	99%	98%	$0.004	1	$0.007	Packaging
7	ESD Attach	99%	97%	$0.007	1	$0.014	Packaging
8	Wire_Bonding	99%	96%	$0.014	1	$0.029	Packaging
9	Phosphor_Package	99%	95%	$0.009	1	$0.038	Phosphor
10	Encapsulation	99%	94%	$0.048	1	$0.087	Packaging
11	Lens_Molding	99%	93%	$0.032	1	$0.121	Packaging
12	Lens_Attach	99%	93%	$0.075	0	$0.121	Packaging
13	LED_Test	95%	89%	$0.010	1	$0.137	Packaging
					Packaging Cost	$0.137	
					Die Cost	$0.105	
					Package Cost	$0.015	
					LED Package Cost	$0.258	

Figure 2-11. The Process module from the Simpler Modular Cost Model

Figure 2-11 shows the main process module of the model where the process steps are summarized. Changes here are limited to defining the number of times each step is repeated and the yield for each step. Drilling down to a specific process step allows the user to change the equipment and modify other key variables. Inspection steps are included in the model and will have a cost associated with them however there is also the provision to allow for an improvement in the overall yield due to inspections.

2.6 Current LED Manufacturing Priorities

As discussed in Section 5 of the April 2012 SSL MYPP, DOE supports research and development of promising SSL technologies.[23] In order to achieve the LED projections presented in Section 2, progress must be achieved in several research areas. Last year, DOE issued a Manufacturing Support competitive solicitation. In response to the proposals received, DOE engaged in cooperative agreement awards related to LED manufacturing. The awarded projects are briefly described in Appendix B.

Because of the continuing progress in the technology and better understanding of critical issues, DOE engaged members of the LED lighting industry to revise the manufacturing priority tasks for the 2012 Manufacturing Roadmap. To develop the 2012 updated Roadmap, DOE first held SSL Roundtable sessions in Washington, D.C. in April, 2012, where initial tasks were developed. The tasks were further discussed and refined in June, 2012 at the Manufacturing Workshop in San Jose, CA. Using recommendations and further review, DOE further distilled the LED recommended tasks to a short list of four, defining the task priorities as described in below. Where possible, the task metrics and targets are listed for each of the priority research areas.

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

Also, all manufacturing efforts intended to reduce overall COO should not result in product performance degradation. Performance attributes should be consistent with those outlined in Section 5 of the 2012 MYPP.

2.6.1 LED Manufacturing Priority Tasks for 2012

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

[23] http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mypp2012_web.pdf

M.L1. Luminaire/Module Manufacturing: **M.L1. Luminaire/Module Manufacturing**: Support for the development of flexible manufacturing of state of the art LED modules, light engines, and luminaires. Suitable development activities would likely focus on one or more of the following areas:

1. Advanced LED package and die integration (e.g. COB, COF, etc.) into the luminaire,
2. More efficient use of components and raw materials,
3. Simplified thermal designs,
4. Weight reduction,
5. Optimized designs for efficient and low cost manufacturing (such as ease of assembly),
6. Increased integration of mechanical, electrical and optical functions, and/or
7. Reduced manufacturing costs through automation, improved manufacturing tools, or product design software.

The work should demonstrate increased manufacturing flexibility (processes or designs that can work for multiple products) and higher quality products with improved color consistency, lower system costs, and improved time-to-market through successful implementation of integrated systems design, supply chain management, and quality control.

Metric(s)	Current Status	2015 Target(s)
Manufacturing Throughput		x2 increase
OEM Lamp Price	\$50/klm	\$10/klm
Assembly Cost (\$)		50% reduction every 2-3 years
Color Control (SDCM)	7	4

With respect to M.L1., workshop participants also noted that luminaire testing requirements may be overly burdensome and add significant additional cost to LED-based lighting products that do not apply to conventional lighting products. Participants further claimed that LED lighting technology has matured to the point where luminaire performance can be accurately extrapolated based on known luminaire and LED information. Work in this R&D area could focus on a specific portion or sub-component of the luminaire manufacturing process (while still demonstrating a full luminaire), but the work should demonstrate and describe the impact (in terms of throughput, cost, or quality) within the context of the entire luminaire manufacturing process.

M.L3. Test and Inspection Equipment: Support for the development of high-speed, high-resolution, non-destructive test equipment with standardized test procedures and appropriate metrics within each stage of the value chain for semiconductor wafers, epitaxial layers, LED die, packaged LEDs, modules, luminaires, and optical components. Equipment might be used for incoming product quality assurance, in-situ process monitoring, in-line process control, or final product testing/binning. Suitable projects will develop and demonstrate effective integration of test and inspection equipment in high volume manufacturing tools or in high volume process lines, and will identify and quantify yield improvements.

Metric(s)	Current Status	2015 Target(s)
Throughput (single bin units per hour)		x2 increase
Cost of Ownership		2-3x reduction every 5years
\$/Units per hour		

Testing and inspection is an enabling mechanism fundamental to process and performance improvements. One specific area of interest regarding testing LED performance is the high-speed monitoring of light output, color quality, and color consistency at the wafer level at LED operating temperature. Such test equipment would facilitate the automation of LED and phosphor matching and speed up final device binning. This information would assist luminaire manufacturers in their design of more consistent luminaires.

Workshop attendees also suggested that collaboration between the test inspection equipment manufacturers and the tool users is critical for the development of optimized, ultimately useful systems.

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

The Roundtable discussion of LED package manufacturing revolved around using lower cost materials and manufacturing processes within the LED package.

M.L7. Phosphor Manufacturing and Application: This task supports the development of improved manufacturing and improved application of phosphors (including alternative down converters) used in solid-state lighting. This could include projects focused on continuous processing of phosphors to increase production volume and manufacturing techniques to improve quality, reduce performance variation, and control particle size and morphology. This task also supports the developments of phosphor materials, application materials, and techniques which improve color consistency of the packaged LEDs and reduce the cost of LEDs without degrading LED efficacy or reliability.		
Metric(s)	**Current Status**	**2015 Target(s)**
Batch size (kg)	1-5	>20
Cost ($/kg)		50% reduction every 2-3 years
Material Usage Efficiency	50%	90%
PSD-range Uniformity	30	10
Duv Control	0.012	<0.002
Thickness Uniformity (1 sigma)%	5	2
Cost ($/klm)		50% reduction
Device to Device Reproducibility(SDCM)	4	2

3. OLED Panel and Luminaire Roadmap

In the past year, the number of OLED panel and luminaire manufacturers has risen and many luminaires have been demonstrated by OLED developers, luminaire manufacturers and lighting designers. These have confirmed the potential of OLED technology to create innovative lighting designs. For example, as shown in Figure 3-1A, Acuity Brands has designed the Revel lighting module. The idea behind these low light output luminaires (370 lumens per module) is that they can be appropriately positioned to direct light where it is needed and improve the application efficiency by preventing over-lighting. Acuity Brands has also created the Trilia luminaire, shown in Figure 3-1B, which comes in tri- and straight- line modules and can be pieced together to form organic-like network designs. The Canvis luminaire, illustrated in Figure 3-1C-D, is a flexible “sheet of pure luminance” whose shape can be controlled remotely through hand gestures. Figure 3-2 illustrates another example of “kinetic” lighting, the Manta Rhei by Selux and design studio ART+COM, is powered by 140 Tridonic OLED modules. The Manta Rhei has several programmed choreographies and integrates mechanical movement with the light experience. Other manufacturers are looking at using transparent OLED panels to make interesting luminaires. Liternity, Novaled’s luminaire manufacturing division, is offering a luxury lamp using transparent panels. At Light + Building 2012, Fraunhofer IPMS showed the OBranch luminaire comprising transparent panels fabricated at COMEDD (Figure 3-3). Another approach in luminaire design that has been explored by luminaire manufacturers such as Blackbody and WAC is to pair LEDs and OLEDs together. In such configurations, features of LEDs such as higher efficacy, lower cost, and directionality can be utilized in conjunction with high quality, diffuse light from OLED panels.

A) B) C) D)

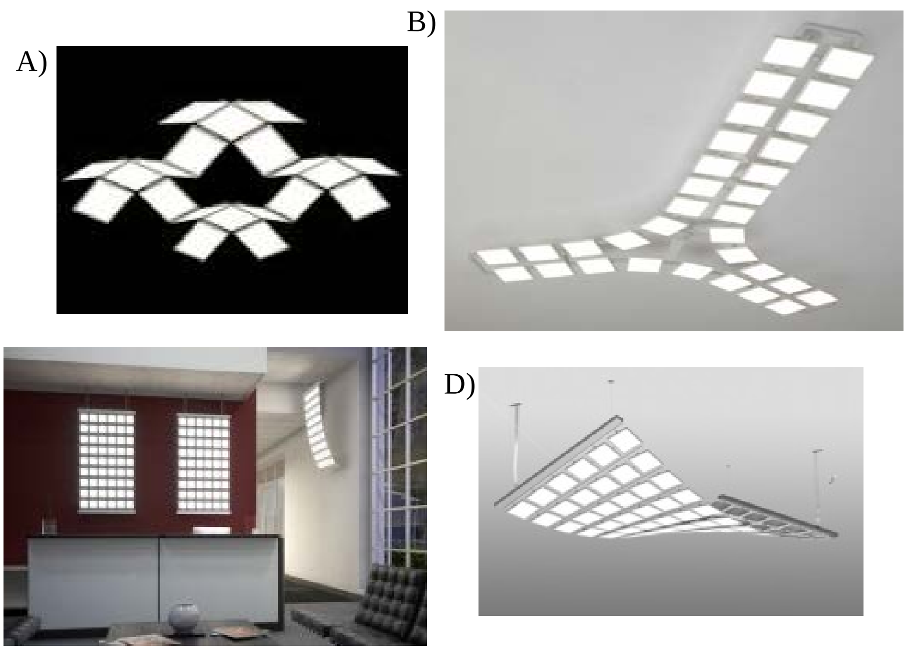


Figure 3-1. Acuity Brands OLED luminaires
A) Revel (370 lumens); B) Trilia (1810 lumens) which can be pieced together with other modules to form interesting designs; C) Canvis in vertical mount; D) Canvis in horizontally mounted position

Figure 3-2. Tridonic Manta Rhei

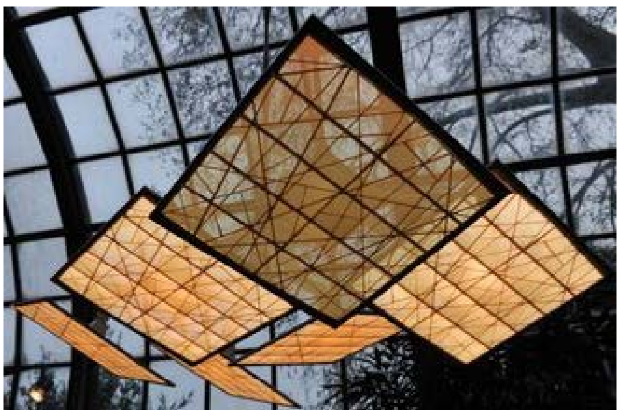


Figure 3-3. Fraunhofer IPMS's OBranch
Source: Light and Building 2012 using transparent panels fabricated at COMEDD

While there is great potential value for OLEDs in architectural and decorative lighting, the major concern of the DOE SSL Program is whether the technology can contribute to energy savings in general service lighting applications. It may be necessary for emerging technologies, such as OLED lighting, to initially build their business in niche applications. With the promise of novel design concepts based upon thin profile, flexible or conformable substrates, arbitrary shapes, variable color, transparency, and kinetic lighting OLEDs have gained interest from a variety of luminaire manufacturers. Novel, breakthrough luminaires are desired to launch the development of this technology. If the functionality of OLEDs can be developed further and the costs reduced, the innovations in styling could encourage more customers to adopt solid-state lighting.

In order to get the efficacy and light output desired for general illumination applications, the manufacture of high efficacy OLED panels is crucial and developments in panel performance are continually being made. Presently, luminaires are being offered using panels with efficacy of 60 lm/W at 10,000 lm/m^2, CRI > 80, and L_{70} 15,000 hours.

While much work remains to improve the performance of OLED panels, manufacturing cost is the top concern for OLED developers. Although the prices of prototype panels have been reduced by a factor of 10 in the past two years, they are still far too high to encourage wide adoption. The typical price for samples is now $1500 to $2000 per klm and Philips has indicated that panels can be purchased in modest volumes for $800 per klm. Meanwhile, LED-based diffuse luminaires as troffer replacement products or thin profile edge-lit designs are being developed and rapidly decreasing in price and improving performance. Thus, the challenge faced by OLED manufacturers is to reduce the production cost by a factor of 20 to 100. Such savings were achieved in the LED industry over less than a decade and possible opportunities to achieving similar cost savings for OLEDs will be outlined in this section.

3.1 Barriers to Adoption

As OLED technology is brought to market, it will have to face many of the same problems that are now being addressed by LED manufacturers. The OLED industry will need to meet the expectations of lighting designers, contractors, installers, regulators and utilities as well as end customers. However, the most urgent barriers to market acceptance all relate to manufacturing cost. The general issues are outlined in this section and specific examples of critical expenses will be cited in later sections of Section 3. Table 3-1 provides a summary of the barriers and shows which ones are being addressed within the DOE SSL Program.

Table 3-1. Roadmap for addressing OLED panel and luminaire manufacturing issues

Barriers to Adoption	Activity	2010	2011	2012	2013	2014	2015	2016
Equipment Cost & Throughput	Manufacturing R&D							
Yield & Process Reliability	Manufacturing R&D							
Materials (cost, robustness, utilization efficiency)	Manufacturing R&D							
Standards and Testing	Commercialization Support							
Marketability	Commercialization Support							

Existing Activities   Future Activities

3.1.1 Equipment Costs

The manufacturing of OLED displays has been very successful in small panels in smart phones and tablet computers and is now being scaled up for large-screen televisions. However, the price of these panels is $5000/m^2, indicating that their manufacture has proved profitable despite the need for a capital investment of approximately $5 billion. Fortunately, much of this equipment is not needed for lighting applications. Active matrix displays require a complex backplane with millions of thin-film transistors to provide independent control of the emission of light from each pixel. The control structure for OLED lighting is much simpler. Display applications also demand the production of red, green and blue light within each pixel. This requires either the creation of separate sub-pixels emitting the primary colors, or the use of uniform white light with patterned color filters.

Much of the reason for the high outlay required for manufacturing equipment for displays comes from the rapid increase in substrate size that has occurred over the past decade. The industry refers to distinct "generations" in indicating the size of the substrates used. Unfortunately, the definition of each generation (Gen) varies from one company to another, but a rough guide is given in Table 3-2.

Table 3-2. Substrate sizes (mm) corresponding to each display production generation

Gen	1	2	3	4	5	5.5	6	7	8	9	10
Short	300	370	550	730	1100	1300	1500	1870	2200	2500	2880
Long	400	470	650	920	1300	1500	1850	2200	2500	2800	3130

Most OLED panels for displays are produced on lines of Gen 4, 5.5 and 8. If the market for OLED displays does not meet expectations, some of the equipment from Gen 4 and Gen 5.5 display lines may become available for conversion to production of OLED lighting.

Achieving substantial reduction in the cost of the equipment used for OLED lighting is made more difficult by uncertainty about the device structures. Improvements are continually being made in stack structure, materials, extraction approaches, substrates, and encapsulation techniques, and these changes affect the manufacturing equipment and processes employed. When the SSL Manufacturing Initiative was first developed, two OLED Manufacturing projects were funded with the objective to determine and compare the costs associated with production of OLED panels via roll-to-roll (R2R) solution deposition techniques and batch processing using vacuum evaporation. As these projects are nearing completion, it appears that the near-term approach will involve batch processing, but in the future, as the technology and materials become more robust, R2R solutions may be used for price reductions. In the meantime, further research can be performed on solution processing methods in batch mode.

Another debate within the OLED community is whether panel manufacturers should bring cost down by utilizing high volume, high throughput equipment, or whether low cost equipment should be utilized to make small volumes of panels. Currently, the panels intended for lighting are being manufactured on lines of generation 2, with substrate area less than 0.2 m^2, that were designed initially for R&D. The cost of these lines is typically in the range of $20 to $50 million, but the throughput is low, since little automation is used. In 2011 Philips announced the investment of $50 million on their line in Aachen, Germany to make it more suitable for production. The company anticipates that the production cycle will be reduced from 30 minutes to two minutes and that this will reduce the manufacturing cost to $1,250/$m^2$ or $125/klm by the end of 2013. Osram has committed $25 million to upgrade a similar line in Regensburg, Germany with a staff of over 200 engaged in production as well as R&D. In Japan, Panasonic and Idemitsu Kosan set up a joint venture with capital of $40 million.

Although further gains can be made by reducing the cycle time to less than one minute, most companies expect that the next stage will involve substrates of area between 0.5 and 1.5 m^2. Several manufacturers have shown designs of appropriate equipment and have made some design adjustments to limit the cost, but the price at which these tools will be available is unclear. It was suggested at the 2012 Manufacturing Workshop that the total capital cost of equipment should be kept within \$100 for each m^2 of annual throughput.

Although the absolute size of the required investment is important while the size of the market is uncertain, the long term impact on production also depends on the throughput that is achieved. The critical factors include:

- Cycle time – target 1 minute;
- Area of substrate that is converted into product – target 80%;
- Yield of good product – target 80%; and
- Downtime for repairs or maintenance – target 20%.

If these targets are attained, the annual capacity of a Gen 5 line (1100mm x 1300mm) would be 380,000 m^2. The capital expenditure guideline of \$100/m^2·yr would be equivalent to an investment of \$38 million for a Gen 5 system. Proponents of solution processing and simple OLED structures argue that this will be possible by a change in manufacturing strategy, as described in Section 3.2.2.

3.1.2 Material Costs

Materials constitute the majority of the manufacturing cost in flat panel displays and most other forms of large area electronics. It is anticipated that this will also pertain to OLED lighting once automation is introduced, more cost-effective tools are available, and the production lines are operating smoothly.

The primary route to reducing material costs will be to eliminate waste. For example, it has been estimated that less than 1% of the precious metals, such as iridium or platinum, that enter the supply chain are actually embedded in the final OLED product. Some of the factors that contribute to low materials usage are:

- Low production yields;
- Deposition of material on the walls and other surfaces inside tools; and
- The use of subtractive patterning techniques.

Most equipment vendors are aware of this situation and have developed tool designs that will lead to substantial improvements in material usage. Meanwhile panel manufacturers are developing techniques for in-line quality control to increase yields. This has been the focus of the last two SSL Manufacturing solicitation awards.

A substantial fraction of the material cost lies outside of the organic stack and is associated with the external layer structures that are required to provide structural integrity, distribute current across the panel, extract light, and encapsulate the device. Up until recently, it was hoped that commonality with the materials need for organic photovoltaic (OPV) systems would lead to price reductions for both applications. However, the progress in OPV systems has not been as fast as anticipated.

One material for which significant progress has been made in the past two years is the glass sheets that are used as substrates and covers in rigid panels. Through an SSL Product Development project, PPG Industries has demonstrated that soda-lime float glass can be used instead of the borosilicate glass used in OLED displays. This replacement for display grade glass could lead to a five-fold reduction in costs, from around $35/m^2 to $7/m^2. This would bring the cost close to that of alternative substrates, such as metal foils or polyester (without a barrier coating).

3.1.3 Standards and Testing

Very few standards or common practices have yet been adopted within OLED manufacturing. This leads to unattractive business propositions for potential tool makers, slows the evolution from panel designs to manufactured products and increases costs. Participants at the Manufacturing Roundtables proposed that that an evaluation stack be identified by panel manufacturers. Such a stack could be used to demonstrate the ability of the tool in relevant processes and allow panel manufacturers to compare alternative tools in such terms as throughput and uniformity with relevant materials and processes. Similarly, such a stack could be used by OLED substrate and encapsulation manufacturers to demonstrate and compare the performance of their products. The variety of OLED lighting architectures that have emerged from laboratory R&D is so great that it may be difficult for the whole community to agree on a single structure. Nevertheless, it may be possible to define just two or three baseline designs that would enable most of the critical steps to be evaluated.

Test and inspection processes for OLED manufacturing also need to be developed further. Progress has been made in the past year to control layer thickness in the deposition of organic materials. One unsolved challenge is to develop effective ways to confirm the reliability of the barrier coatings and/or edge seals used in the encapsulation of panels produced in high volume.

3.1.4 Market Timing

A high level of excitement regarding OLED technology has been generated by the success of OLED panels in smart phones, the image quality of large OLED televisions, and the prototype OLED luminaires shown at lighting fairs. However, the very high cost of OLED manufacturing and the substantial market penetration of LEDs require aggressive innovations for OLED products and manufacturing approaches.

High first cost was also an issue for LED luminaire manufacturers and recently significant cost reductions have been achieved for these products. In addition, there are clear economic benefits in terms of total life-cycle costs for adopting LED-based lighting rather than traditional light sources. Currently, there seems to be no similar economic arguments in favor of OLEDs over LEDs. The perceived value is one of light quality and style and it is difficult to ascribe a dollar value to those attributes.

Corporate reports suggest that about fifteen Gen 2 lines (370mm x 470mm) might be in production by 2015. With capacity utilization as described above, the total annual production from these lines would be 0.7 million m^2 or seven million kilo-lumens. This global total would represent a small fraction of the five billion kilo-lumen capacity base installed in U.S. homes or the six billion kilo-lumen base in U.S. commercial buildings.

3.2 OLED Stack Formation

The OLED manufacturing process can be divided into three phases, substrate preparation, deposition of the organic materials and cathode, and encapsulation. The production line currently used by LG Chem in Korea is shown in Figure 3-4. The front end processes are carried out in two cluster tools, seen in the foreground of this picture. The straight in-line section contains the deposition chambers for the organic materials and can be extended almost arbitrarily to accommodate a large number of layers. The substrates then pass through the metal chamber for cathode formation, and the process is completed in the panel separation and encapsulation tools.

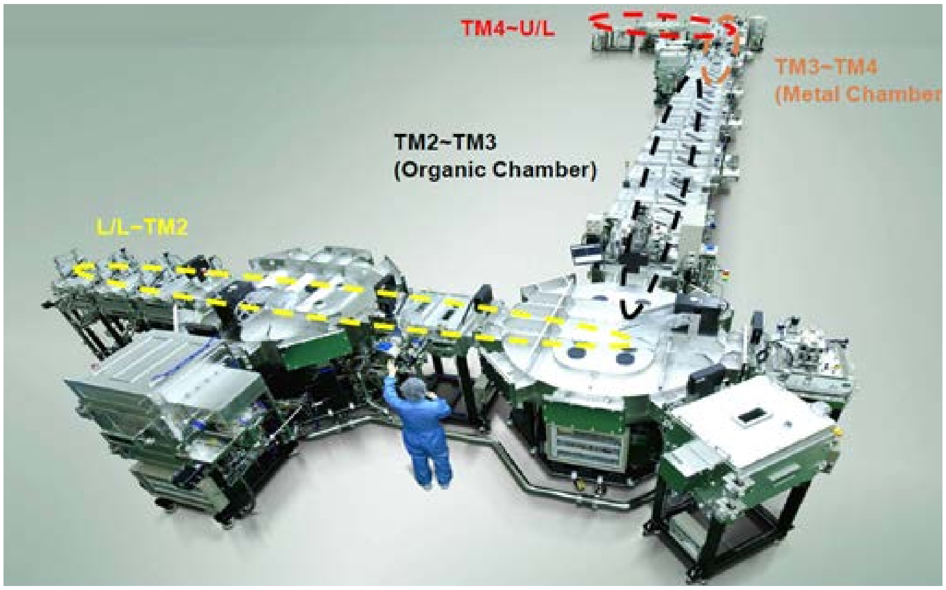


Figure 3-4. Gen 2 production line with cluster and in-line stages
Source: LG Chem

This section is concerned with the deposition of the organic materials and cathode, which represent steps that are almost unique to OLEDs. There is some overlap with organic solar panel formation, but the fabrication of these core layers deserves the most detailed description. Issues concerning integrated substrates and encapsulation will be addressed in Section 3.3.

3.2.1 Vapor Deposition of Organic Layers

The active layers of almost all OLEDs for display applications are formed by vapor deposition. The organic materials are delivered to the workpiece either in high vacuum (10^{-6} mBar) or through the mediation of an inert carrier gas at pressures around 1 mBar. Significant progress has been reported in the development of vapor deposition tools for lighting applications during the past two years. The material utilization has been increased through the introduction of linear sources or closely-coupled shower heads and the use of heated walls and supply lines.

In the Light In Line (LILi) project, funded by Germany's Federal Ministry of Education and Research (BMBF), Applied Materials (AMAT) has demonstrated that a Gen 4 evaporator can be run continuously for more than 600 hours with rate stability better than ± 3.5%. Control over the deposition rate was achieved through the use of optical absorption techniques and improved quartz oscillators in which anomalies due to the accumulation of material on the detector have been eliminated. Hole transport materials (HTM) from Merck were deposited at rates of between 2 and 60 nm per minute by varying the crucible temperature between 280°C and 315°C. This enabled a 40 nm layer to be deposited well within the target cycle time of 90 seconds. Tests were performed to make sure that these temperatures did not result in decomposition of the organic materials. On the basis of these results and work carried out at COMEDD in Dresden, Applied Materials has completed their design of a Gen 4 linear deposition system with an annual throughput of 240,000 m^2 and material utilization of 60%. Figure 3-5 illustrates how this might be incorporated in a fabrication facility.

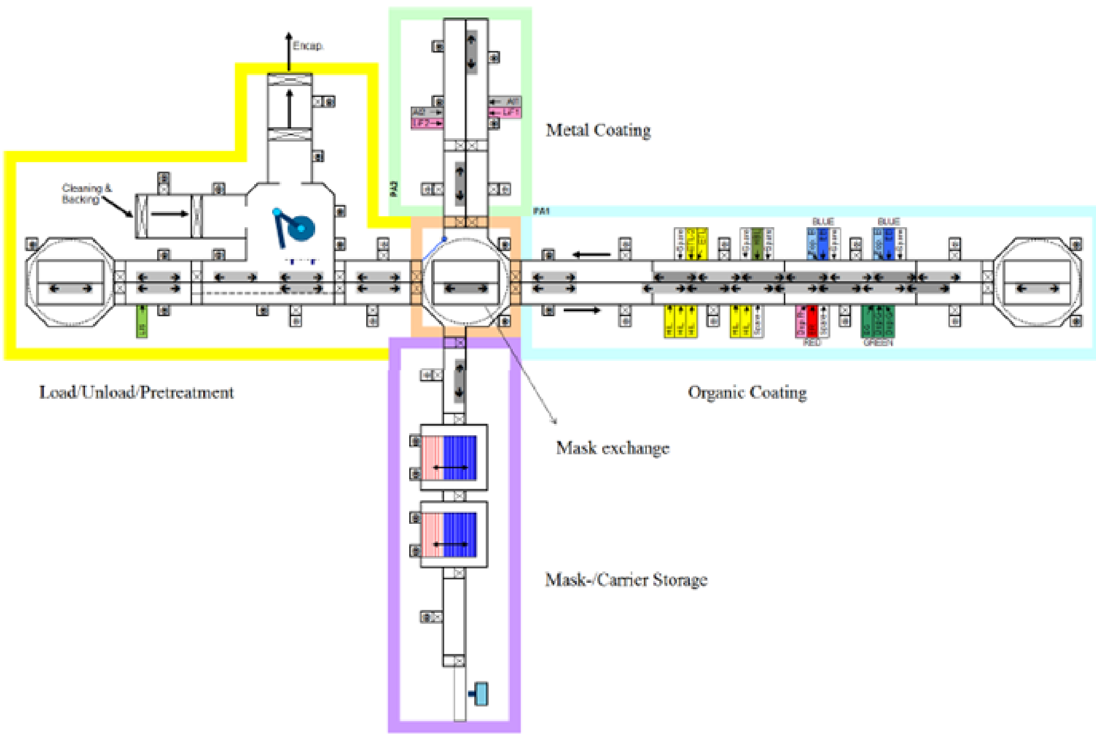


Figure 3-5. 4th Gen manufacturing line using in-line vapor deposition tools
Source: AMAT 2012

Panasonic has also implemented an in-line deposition system, with the substrate passing steadily over multiple linear sources. They also used heated chamber walls, along with a high-speed evaporation process and have achieved 70% material utilization with thickness control of ± 3% over 200 mm wide sources

Aixtron has continued to develop its Organic Vapor Phase Deposition tools, based on IP licensed through Universal Display Corporation. This work has also received financial support from BMBF, through the project Topas 2012, in which Aixtron, BASF, Osram and Philips are committed to the production of OLED panels producing 1000 lumens. The use of a closely coupled shower head means that neither the source nor the substrate need move during deposition and materials from multiple sources can be deposited simultaneously. This enables the creation of graded layers and interface regions with controlled inter-penetration. Multiple tools are arranged in the traditional cluster formation rather than in a linear array. Aixtron has devised several techniques to reduce the thermal stress on the organic materials. The introduction of flash evaporation reduces the time that the material need be stored at high temperature. HTM's can be deposited at a rate of 240 nm per minute at temperatures of only 200°C. The volume of the deposition tool is reduced and a system for 650mm x 780mm substrates has been qualified by a customer. Aixtron's goal for material utilization is 70%.

The Korean Government instituted a two-year pilot project for OLED lighting of tools for substrate areas in excess of 1 m^2 in June 2010. Gen 5 vacuum evaporators from both Sunic Systems and SNU Precision are being evaluated and system integration is being undertaken by DMS. This project was due to be completed by August 2012, but no results have yet been publicly announced.

3.2.2 Solution Processing of Organic Layers

Manufacturers such as GE, Konica Minolta and Sumitomo Chemical believe that the best strategy to achieve the manufacturing cost targets for OLED lighting is to replace vapor deposition with solution processing. Previous attempts to deposit all of the layers in solution have led to significant reductions in performance, both in efficacy and lifetime. Thus the first introduction of solution processing is expected to be within hybrid systems in which a thick hole injection layer is deposited to planarize the anode and prevent shorting. This would be particularly appropriate for anodes composed of nanowires or carbon nanotubes, which can also be deposited in solution, as described in section 3.2.4. The SSL Product Development project by Cambrios and Plextronics has shown that the rough surfaces can be effectively planarized by the hole-injection layer (HIL). Although this approach leads to larger leakage currents, the operating voltages and lifetime appear to be similar to those obtained with indium tin oxide (ITO) anodes.

DuPont and Plextronics have pioneered the development of solution-processable HIL materials. Although the original Plextronics materials were designed for use with aqueous solvents, new formulations have been introduced that are compatible with non-aqueous solvents. This reduces the risk of collateral damage to phosphorescent emitter layers.

The hole transport layer is crucial for a high efficiency and long lifetime OLED. The HTL not only helps to lower the injection barrier from HIL to the emissive layer (EML) but may also serve to block any exciton/electron leakage from the EML into the HIL and minimize losses such as any quenching from HIL/anode. Combination of HIL and hole transport layer (HTL) can be effectively used to tune the charge balance and the recombination zone in the device thus determining the overall efficiency and lifetime. Plextronics has developed a solution processed HTL which meets the criteria specified above. One of the key features these HTLs is that they show no film loss when exposed to common EML solvents such as toluene and o-xylene.

Slot-die coating provides a relatively inexpensive way to deposit uniform films over large areas. Work by Panasonic Electric Works and Tazmo Co. has demonstrated that the thickness of 30 nm layers can be controlled to within ±3% with the linear coater (or substrate) moving at 0.2 m/s. This approach has been used in flat-panel display manufacturing with slot lengths in excess of two meters. Smaller tools have been validated for the deposition of thin layers of high-performance organic materials. For example, Plextronics has successfully coated HIL layers with thickness between 25 nm and 225 nm, with uniformity of ±3nm.

Unwanted materials between multiple panels on a single substrate have traditionally been removed after deposition, using low-resolution lithographic techniques. However, nTact has demonstrated that the required patterning can be accomplished during slot-die coating. Gravure printing offers an alternative way to define individual panels.

Emitting layers can also be deposited by slot-die or gravure coating. However, there is greater interest in the use of nozzle printing to deposit stripes of red, green and blue emitters. This reduces the number of required layers and enables dynamic color control. DuPont has designed and tested a system to produce 5,000 m^2 of panel area each month. The printer uses 15 nozzles with a head speed of two to five meters per second leading to a cycle time less than three minutes for a 730mm x 920mm substrate. Thickness variation is typically 2 nm. This approach has been used to create white OLED panels with color temperatures that can be controlled by the user to between 2700K and 6500K.The drive electronics uses a simple constant current, pulse-width-modulation scheme, combined with a small microprocessor containing a ‘look-up’ table of the color-mix ratios for the various whites.

Although DuPont has developed a compatible electron transport layer, most proponents of solution processing simplify their structures by avoiding the use of separate ETL and EIL layers and design the EML for direct electron injection from the cathode. Merck and others have demonstrated that the efficacy and lifetime can be improved through the use of hybrid systems with vapor deposited ETL and EIL layers. This need not introduce extra complications in the manufacturing line for high-performance panels, since vacuum deposition is needed for the cathode.

Many OLED designs are more complex, with several additional layers. For example, charge balance can be improved by adding blocking layers, to prevent electrons or holes passing through the recombination layer and reaching the far electrode. The operational lifetime can be extended substantially through the use of tandem structures, in which two or three sets of the standard emission and transport layers are separated by charge-generation layers. In almost all implementations of these more complex structures, the additional layers are deposited in vapor phase.

3.2.3 Cathode Deposition

Cathode deposition is one of the most difficult steps, both for batch and web processing, due to the fragility of the underlying organic layers. Evaporation is the preferred technique in research environments, but may not be fast enough to meet the aggressive industry targets for processing time using a single chamber. It may be necessary to operate several evaporators in parallel to achieve cycle times under 60 seconds. Magnetron sputtering can be accomplished more quickly, but the work piece is exposed to plasma damage. DuPont has demonstrated that ion-beam sputtering inflicts less damage, since the plasma is remote from the OLED. An alternative approach is to form a composite cathode in which a very thin layer is formed slowly by evaporation or sputtering at low power. This provides protection for the organic material from high-power sputter deposition of the remaining metal.

The use of scattering layers to enhance light extraction increases the importance of minimizing the reflectance of the cathode. This may lead to the replacement of the favorite Al material by Ag or other metals.

3.3 Substrates and Encapsulation

In AMOLED displays, the fabrication of the TFT backplane is by far the most difficult part of the manufacturing process. The structures that underlie the organic materials in OLED lighting panels are simpler, but still constitute a major portion of the material and processing costs and present unsolved manufacturing challenges. For example, high performance panels with standard bottom emitting architectures may include the following components:

- Transparent substrate;
- Light extraction structures;
- Transparent conducting layer (anode); and
- Current spreading approach.

These composite structures are often referred to as integrated substrates. Most of the materials here are inorganic and the processing challenges are very different from those of the active layers. Thus, it is possible that panel manufacturers could purchase integrated substrates from an external vendor. Discussions at previous Workshops have raised the possibility of manufacturing these structures during the formation of the glass. However, it was emphasized by glass manufacturers at the 2012 Manufacturing Workshop that due to the high speeds and large widths at which their glass production lines operate, a very large production volume would be necessary to make such an approach economic. Alignment of capacity and plans for growth throughout the supply chain would facilitate low-cost manufacture, but customization would be difficult.

The SSL manufacturing project at GE Research Laboratories has demonstrated that it is extremely expensive to carry out early stages of manufacturing development by R2R processing. This, together with the demonstration by PPG Industries that soda-lime glass can be used for OLED lighting panels, has helped to focus short-term attention on the use of rigid glass substrates. Work by Alcoa and others has shown that thin metal foils are an acceptable alternative for use in R2R processing with top-emission architectures. Corning and other glass companies have developed ultra-thin glass that is conformable and can be used in R2R mode. If made available at affordable costs, this could combine the benefits of R2R processing with the benefits of glass which include stability, transparency, and impermeability and could also allow for a low weight, impermeable encapsulation scheme.

3.3.1 Light Extraction Enhancement Structures

Intensive research into ways to enhance the extraction of light from OLED panels has provided many potential solutions. However, almost all have proved to be difficult or expensive to manufacture over large areas. Various approaches to extraction enhancement include the development of external, internal, or cathode technologies.

External light extraction approaches generally help to extract light trapped in substrate wave-guided modes. One method is to roughen the external surface of the transparent substrate. The surface of the glass can be modified during glass formation or after cooling by chemical or mechanical etching. Alternatively a patterned layer of index-matched material can be laminated to the outside, for example using micro-lens arrays. Similar films have been developed for several other applications. Very good results have been reported for OLED light extraction by 3M[24], but the commercial availability of their films is not yet assured.

The value of external light enhancement films can be enhanced significantly through the use of substrate materials with refractive index that matches that of the emitting layers. Such materials are available, but the cost is high at the moment. If these high-index materials cannot be obtained at affordable prices, internal structures may be needed to increase the amount of light that reaches the substrate.

Internal light extraction approaches can be developed to extract light from wave-guided ITO/organic modes. One approach is the use of low-index grids on top of the ITO layer or a grid-patterned ITO layer used in combination with a conductive polymer. Such techniques have demonstrated extraction enhancement of 1.7 – 2.3x but have not proven to be amenable to high volume manufacturing due to the additional deposition and patterning steps required. Another internal light extraction approach is the incorporation of a scattering layer between the glass and ITO. This layer may comprise nanoparticles distributed in a polymer matrix with a substantially different refractive index, or may involve other scattering nanoparticles, such as Ag spheres or wires. Alternatively, the scattering layer may also serve as a replacement for the ITO layer in the case of the use of Ag nanowire anodes. Such layers could be deposited inexpensively by slot-die coating or jet printing. Such techniques show promise and could be scalable, but have not been adequately developed for use in manufacture. Challenges include issues with roughness, appropriate particle distribution within the matrix, and compatibility with subsequent processing steps. Others have demonstrated the use of “buckle” structures to scatter light trapped in wave-guided modes. The non-planar topography of such structures may translate through the device to the cathode and thus further enhance the light extraction effect by reducing losses due to surface plasmon polaritons. Though effective in demonstrating extraction enhancement of great than 2x, such non-planar structures introduce manufacturing challenges in terms of yield and control of uniformity due to the thin layer thicknesses and complex stacks often required in OLED structures and the process of buckle formation may not be scalable. A different approach to reduce surface plasmon polaritons while extracting light from the ITO/organic layers is the use

[24] Light Extraction Films for OLED Displays on Rigid and Flexible Substrates - Fred McCormick, 3M, Flextech Alliance Conference, February 2012

of ETL scattering layers adjacent the cathode such as was demonstrated by Novaled to achieve an extraction enhancement of 1.7x.

Cathode light extraction technologies are being developed in the laboratory making use of microstructures on the metal cathode, with reported gains of 100%. These approaches are not yet well developed in manufacture. An alternative approach would be to attach a thin plastic film to the inside of the substrate. For example Panasonic[25] uses a thin layer of high-index plastic, such as PEN, with microstructures imprinted on one surface and the transparent electrode deposited on the other, as shown Figure 3-6. This film is laminated onto a normal glass substrate, with the structured surface facing towards the substrate, forming an “air gap” between the two to act as a low-index layer. Using this technique, Panasonic has been able to achieve an extraction efficiency of over 44%, giving an efficacy of 101 lm/W in a 1 cm^2 device.

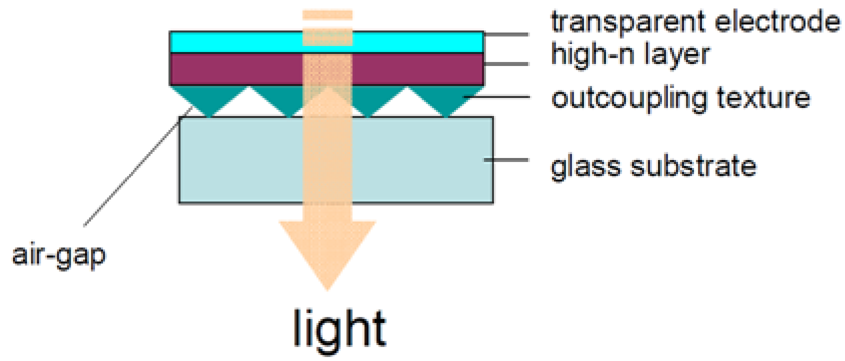


Figure 3-6. Internal extraction structure with laminated plastic film
Source: Panasonic

3.3.2 Transparent Anodes

The formation of the anode structure is critical to achieving reliable, cost-effective OLED manufacturing. There has been much publicity about the high cost of obtaining patterned ITO in small quantities from external vendors and about the potential shortage of indium if demand for ITO continues to increase. Estimates of the cost for polished ITO vary from $6/$m^2$ to over $100/$m^2$, but manufacturers who install their own sputtering equipment are able to form the ITO layer for around $15/$m^2$. This cost estimate should provide a comparison for consideration of the many alternative transparent conductors, such as the doped ZnO films favored by Arkema and the silver nanowire structures developed by Cambrios and others.

Nano-particle-based alternatives to ITO as transparent conductors can be deposited from solution. For example, Cambrios has developed silver nanowire-based anodes planarized with a thick HTL achieving sheet resistance of less than 10 ohms/square. These anodes have been successfully implemented in OLED devices showing 43 lm/W efficacy at 3,000 lm/m^2. In 5cm x 5cm devices, 10% variation in luminance across the device is observed and angular dependence

[25] High-Efficiency White OLEDs with Built-up Outcoupling Substrate - Kazuyuki Yamae, Panasonic, SID Symposium 2012, paper 51.4

of color is greatly reduced as compared to reference devices on ITO. In parallel work on the manufacture of touch screens and organic photovoltaic cells, Cambrios has also demonstrated that their Clear-Ohm coatings can be deposited over large areas by slot-die coating and gravure printing. This work on other applications should help to reduce the cost of applying the approach to OLEDs and will facilitate the extension to large OLED substrates.

With typical sheet resistance of transparent conductors, the use of a homogeneous sheet across a large panel (>10cm linear dimension) would result in intolerable voltage drops, leading to non-uniform emission of light and significant energy loss. One approach is to split the panel into strips and to connect the cathode of one strip to the anode of its neighbor. This approach has been used in solar panels but little experience has been gained in the production of such structures for OLED applications. The major challenge is in patterning the metal vias and surrounding insulation to prevent shorting between the strips. A second approach is to construct a metallic grid, either using parallel bus lines, or a 2D structure. Although a single set of parallel metal lines minimizes the blockage of light, the use of a 2D grid provides extra protection against the occurrence of breaks in the individual lines.

The height of the metal lines is typically about1µm, which is larger than the total thickness of the organic layers. The lines must be covered by an insulating layer, which is usually tapered around the metal, to prevent shorting across the OLED. The metal can be deposited either below or on top of the transparent conductor.

The best choice of deposition technique for the metal grids has not yet been established. The highest conductivity can be obtained by depositing bulk metal, for example by sputtering, and removing the unwanted metal by lithography. This leads to large amounts of waste, which must be recycled to minimize costs. Since the lines widths are relatively large, the grids can be formed directly by several printing techniques. However, there is usually a substantial penalty in conductivity in the use of inks or pastes rather bulk metal.

The choice of material involves a trade-off between cost and conductivity. The preferred metal is Ag, which has been used for many years for the bus lines in plasma displays. However, even if waste is minimized in the patterning process, silver may be too expensive to comply with the OLED cost constraints. Less expensive materials, such as Al and Cu, must be protected against oxidation, but these problems have been overcome in the semiconductor industry and elsewhere.

3.3.3 Encapsulation

Once the OLED layers have been deposited, the panels need to be protected against the atmosphere and connected to an external power supply and control system. When multiple panels are formed on a single substrate, the panels need to be separated, either before or after encapsulation. The methods used for OLED displays, such as scribe and break or laser cutting, should also be applicable to lighting applications. The OLED materials deposited near the edge of the substrates are usually removed to facilitate edge sealing. Two or more conducting paths must be provided through the seal to allow the flow of current.

The conventional encapsulation materials used in OLED displays are very expensive, and breakthroughs in performance and cost are needed as the technology is adapted to lighting applications. It is generally accepted that an encapsulation system for OLED lighting should limit the permeation of water vapor to less than 10^{-6} g/m^2·day and oxygen to less than 10^{-4} cc/m^2·day·atm. If glass sheets or metal foil substrates and covers are used, there should be no problem with ingress through the substrate or cover and the problem is confined to the edge seals. However, the porosity of all known plastics is much higher than these limits. Thus, when plastic substrates or covers are used the addition of a barrier coating is essential. In the short term, the use of at least one sheet of glass seems to be required. The opposite surface could be another sheet of glass or a metal foil, unless the luminaire needs to be transparent,

Traditional edge seal technology has proved to be inadequate for OLED panels. In early OLED displays, large amounts of dessicant were required and the cover glass was formed with a cavity to accommodate it. In recent years Corning has developed a laser-cured frit sealing process that is specifically designed for use with their borosilicate glass. This is still expensive, but at least in small displays, it eliminates the need for cavity glass and dessicant. Despite the success of this approach for small OLED displays, the technology must be adapted to the less expensive soda-lime glass and needs to be extended to larger areas. In scaling the size of the encapsulation cover, less edge sealant is needed due to the reduced perimeter per area as compared to smaller panels, but the weight of the glass can lead to degradation of the edge seal. The R&D that is needed for large area encapsulation may be leveraged from the display industry, but the adaptation to soda-lime glass may present a substantial challenge for large panels used in lighting applications.

For plastic covers with barrier coatings, the absence of pin-holes is essential, as well as the use of a material with very low bulk permeability. Unfortunately, measurement of permeation rates below approximately10^{-4} g/m^2·day requires highly specialized equipment that is not available to most manufacturers. Even where available, such testing only permits spot checking and is expensive and time-consuming, making it difficult to confirm manufacturing permeation rates across large volumes of barrier layers. Furthermore, direct lifetime tests can only be performed on a reasonable time scale using accelerated degradation techniques. Therefore, until real experience is obtained with working panels, 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, defect-free production is a formidable challenge. High levels of particulate control will be needed during manufacturing and handling errors could easily lead to damage, either during the production of the film or during the manufacturing of the OLED luminaire. The cost of manufacturing these barrier films can be very high, with estimates ranging upwards from \$50/m^2. Some savings can be made by reducing the number of layers in the barrier film, but whether a single layer will ever suffice is a matter of intense debate. The favored way to improve the quality of the inorganic layers is through the use of atomic layer deposition (ALD), but this is usually a very slow process. Work is underway at the Flexible Display Center in Arizona to accelerate the ALD process, but others believe that high-quality films can be obtained at lower cost by variations of PECVD or sputtering.

If an adequate moisture barrier is developed for plastic covers, one could also deposit the same films directly onto the OLED. This would reduce the thickness and weight of the resultant panel. Although it may be very difficult to provide life-time protection in this way, the deposition of a thin-film barrier would provide temporary protection to the panel while fabrication is completed by edge-sealing two non-porous surfaces. Single layer barrier films should be adequate for this limited task.

3.4 OLED Panel Cost Targets

Because of the delays in the transition of OLED lighting technology from the laboratory into production, the short term cost projections for OLED panels and luminaires were raised significantly in the previous 2011 edition of this Roadmap. However, future cost targets need to take into consideration market expectations as well as projections of current manufacturing costs.

3.4.1 Market Price Constraints

During the past year, many manufacturers of LED luminaires have realized the advantages of spreading the light sources over large area to produce “soft” lighting with minimal glare. Thermal management problems have been ameliorated by using many low or medium power chips in one-dimensional (1-D) or two-dimensional (2-D) arrays. In the past, this approach increased the total cost of the LEDs, but the experience gained in fabricating chips for flat panel displays has led to rapid reduction in the cost of low and mid-power sources.

High quality 2 feet x 4 feet LED troffers are now available from several U.S. manufacturers with high efficacy (over 90 lm/W) and high CRI (90) at retail prices around \$60/klm and wholesale prices around \$45/klm. The majority of these luminaires are designed with similar form factors to fluorescent troffers, using diffusers or reflectors to spread the light more uniformly over the surface of the fixture. Technology transfer from the display industry has also led to the development of thin planar light guides that can be illuminated from the edge by one or more strips of LEDs. Although very thin light guides are used in hand-held devices, the typical thickness of large area panels is 4 to 15mm.

The edge-lit light guides provide some of the same benefits as OLEDs and have already been introduced into the general lighting market, either as suspended or surface-mounted fixtures. Innovative form factors enabled by conformable panels are also emerging onto the market, but these commercial light guides are not yet fully flexible.

3.4.2 Corporate Price Projections

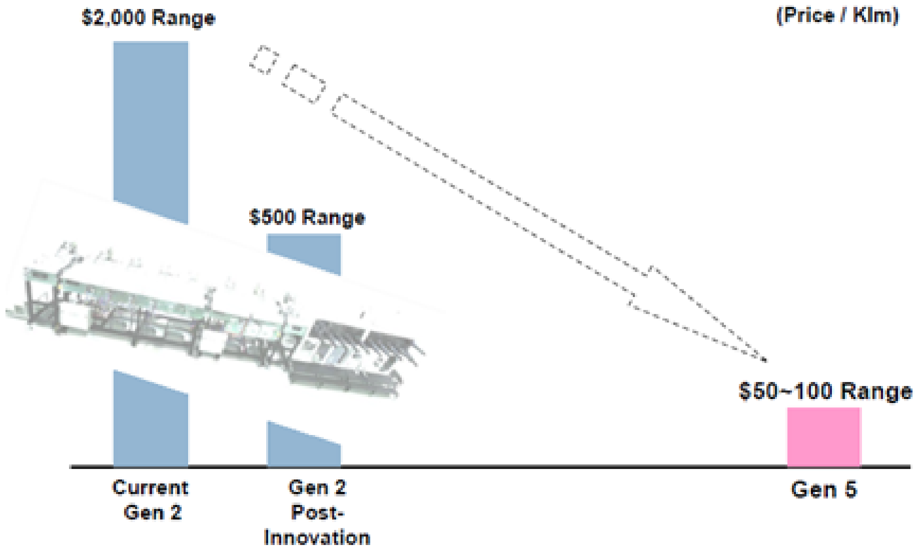


Figure 3-7. Cost reduction anticipated by process optimization and volume scaling
Source: LG Chem

As shown in Figure 3-7, LG Chem has estimated that costs can be reduced from $2,000/klm in early 2012 to $500/klm in 2013 by optimization of their current line. The savings are expected to come mainly from the front end process, through reduction in the use of photolithography and in encapsulation through introduction of frit glass sealing. Significant reduction in the per unit cost of organic materials is not anticipated until high volume is reached in the future. Yield improvement will be critical in the early stages of production. Although LG Chem predicts that the cost can be reduced an additional five to ten–fold through the transition to Gen 5 substrates, the range is still well above the projections described in Figure 1-4. This confirms that high priority should be given to the development of alternative materials and processing techniques.

Philips has a more aggressive cost reduction target, forecasting prices of $1,250/m^2 by the end of 2013. Assuming that the luminous emittance is 10 klm/m^2, this would be equivalent to about $125/klm. One critical factor in their cost savings is the reduction of cycle time from 30 minutes to two minutes. Moser Baer believes that it has a strategy to reach lower costs while using smaller substrates, by leveraging their experience as a leading manufacturer of optical disks. Their short-term goal is to reduce the cycle time to one minute, while processing four 150mm x 150mm panels separately positioned on a “Gen 1” substrate. Their cost target for 2015 is $50/klm. As a result of their SSL Product Development Project, DuPont has projected that significant savings can be made by introducing solution processing in the early deposition steps. The cost of such a hybrid approach was estimated to be $67/klm for Gen 4 equipment and $27/klm for Gen 5. When targets are scaled against light output, the gap that still exists in the performance of solution-processed emitter layers can be allowed for by increasing the panel area and reducing the luminous emittance.

3.4.3 Material Costs

The demonstration that soda-lime float glass can be used instead of boro-silicate glass produced by the fusion process, should reduce the cost of the two glass sheets to between $10 and $15. This will probably mean that the thickness of each sheet needs to be at least 2 mm. The provision of thinner glass is likely to lead to increased cost. The current cost of organic materials is estimated to be $300/m^2, equivalent to $2 for a 4.8 inch smart phone display. Three developments should lead to rapid reduction in these costs:

- Increase in material utilization;
- Improve the efficiency of material manufacturing; and
- Amortize the fixed costs of the manufacturers over higher volumes.

Provided that the material utilization can be increased to over 70% and the production yields to over 80%, the total cost of organic materials should be less than $50/m^2 by the time the total OLED production reaches 10 million m^2/yr.

A similar situation may be faced in the purchase of external films for light extraction enhancement. In the display industry, simple micro-lens array films can be obtained for approximately $5/m^2, whereas complex multifunction films can cost around $20/m^2, even though they are produced in very large quantities. Thus films that provide extraction enhancement factors of 1.3 to 1.5 may cost less than $10/m^2, whereas those that provide factor of two improvement with some light focusing could cost greater than $20/m^2, especially in low volume.

3.4.4 Processing Costs

As discussed in Section 3.4.2, Moser Baer Technologies (MBT) intends to reduce the depreciation cost to $50/m^2 though the use of rapid processing on small substrates. AMAT and Veeco have also suggested that this target can be reached through vapor deposition with an in-line configuration using larger equipment. Veeco has estimated that the cost of Gen 4 deposition equipment that would enable the fabrication of tandem structures with10 to 14 layers should be about $30 million, so that the total capital investment in equipment should be less than $50 million enabling annual production of 180,000 m^2.

Proponents of solution processing estimate that the cost of coating machines with the associated curing equipment will be less than $3 million per layer. This means that a complete Gen 4 line for single stack structures could be constructed for less than $30 million. As suggested above, a hybrid line with solution processing used to deposit the internal scattering layer, anode structures, HIL and perhaps HTL may offer the best compromise between low cost and high performance.

Thus although further experience will be needed before one can judge the relative merits of each approach, there seem to be several routes to attain the cost projections summarized in Figure 1-4 and in the following tables.

3.4.5 Cost Model

The cost breakdown shown in Table 3-3 is based on a detailed cost model for 2015 developed within the SSL Manufacturing Project conducted by UDC and MBT. Their estimates have been modified to take into account input from other participants in Round Tables and Workshop

Table 3-3. Direct cost projections for panel production by vapor processing ($\$/m^2$)

Cost Component	**2015**	**2017**	**2020**
Substrate	10	9	8
Extraction enhancement layers	25	20	10
Anode structures	25	15	10
Organic materials	40	25	15
Cover	10	9	7
Sealant and dessicant	25	15	10
Other materials	15	12	10
Total Bill of Materials	**150**	**105**	**70**
Depreciation	110	40	20
Labor	40	25	10
Total Direct Costs	**300**	**170**	**100**

Assuming a luminous emittance of 10,000 lm/m^2, these targets scale to $30/klm in 2015, $17/klm in 2017 and $10/klm in 2020. The introduction of solution processing should lead to lower equipment costs and to simpler structures. However, the efficacy of devices with solution-processed emitters is still substantially less than that of conventional structures, at ~5 lm/W without extraction enhancement and 35 lm/w with enhancement. The operating lifetime is also shorter. This deficiency can be offset by increasing the area of the panel and decreasing the brightness. The lower brightness leads to substantial increases in lifetime and smaller gains in efficacy. Table 3-4 displays the solution processing cost breakdown.

Table 3-4. Direct cost projections for panel production by solution processing ($/m^2)

Cost Component	2015	2017	2020
Substrate	10	9	8
Extraction enhancement layers	25	20	10
Anode structures	20	15	10
Organic materials	25	15	10
Cover	10	9	7
Sealant and dessicant	25	15	10
Other materials	15	12	10
Total Bill of Materials	**130**	**95**	**65**
Depreciation	80	30	15
Labor	30	20	10
Total Direct Costs	**240**	**145**	**90**

The two approaches would lead to the same costs per klm if the luminance emittance for the solution processed panels were 8,000 lm/m^2 in both 2015 and 2017, and were increased to 9,000 lm/m^2 in 2020. Little experience has been gained to support quantitative projections of the cost of OLED luminaires. Thus the cost breakdown presented in Table 3-5 is based on analogy with LED luminaires. Assembly costs must allow for transportation from the panel maker to the luminaire manufacturer, which may be higher than for LED packages, because of the larger size and possible fragility of OLED panels. Automation may be more difficult than for LEDs, especially if there is a high degree of customization.

Table 3-5. Projected OLED luminaire costs ($/klm)

Cost Component	2015	2017	2020
Panel	30	17	10
Driver	10	6	4
Mechanical & Optics	5	4	3
Assembly	5	3	3
Total Direct Costs	**50**	**30**	**20**

Note that these costs do not include any indirect costs or profit margins added by the panel manufacturer. Thus they do not reflect the price for a luminaire manufacturer who buys panels from another supplier.

3.5 OLED Luminaires

Most of the attention of the OLED lighting community has focused on the development of planar panels. Many panel products are being offered and over the past year, improvements in panel performance – efficacy, color, output, and lifetime – have also been realized. Though performance improvements are desired, the technology is at the point where low-cost manufacturability needs to be realized to enable competitive luminaire products.

In the past year, the number of OLED manufacturers has risen and those who have been involved are becoming further committed to OLED technology. Major lighting companies, such as Philips and Osram have devoted significant resources to the development of OLED technology and have demonstrated their interest in incorporating this technology in their future lighting offerings through lighting displays at trade shows. Further, OLED materials manufacturers, such as Novaled, are positioning themselves as luminaire manufacturers as well as materials suppliers. Though the luminaires offered at this point are still high-end, high-cost, artistic luminaires, manufacturers are looking to incorporate OLEDs cost-effectively into general illumination applications.

Although many luminaire concepts have been exhibited, the interplay between design innovation, functionality, manufacturability and cost needs further analysis. This section identifies some of the critical issues, including sizing and brightness, variability and binning, light shaping, standardization of luminaire components, and reliability issues.

3.5.1 Sizing Issues and Brightness

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

Though higher brightness means more light output per area, large areas are still required for general illumination. For example, even at a brightness of 10,000 lm/m^2, in order to get 3,000 to 5,000 lumens to light a space with an overhead luminaire, a total panel area of 0.3 to 0.5 m^2 is needed. If, for example, 6 inch square panels are used, this means 15 to 25 panels are necessary to produce adequate light output for this general illumination application. These panels may be grouped in one large overhead luminaire or separated into smaller modules to potentially improve application efficiency.

In the long term, to meet cost targets for panel manufacture and luminaire assembly, substrate sizes are likely to increase. In the near term, smaller substrate size could be more economical considering the present demand for OLED lighting and the high cost of manufacturing equipment. Smaller panel size may require tiling, but could be advantageous to luminaire designers by offering high flexibility in design and not limiting design to large area, planar designs such as troffer replacements.

3.5.2 Variability/Binning

Whether luminaires are built around single or multiple tiles, issues will arise from the variability in the performance of manufactured panels. Manufacturing reliability is critical, and unless yields are very high, it will be economically unacceptable to discard all panels with observable deviations in brightness or color from the intended values. The permissible range of deviation depends on the specific luminaire and application. Depending upon the design of the panel and luminaire, it is possible that issues such as variations in brightness, color, and ageing can be corrected through drive electronics, color tuning techniques, or optics. Ultimately, variability tolerances need to be established and specified by luminaire manufacturers. Also, production schemes need to be developed to ensure uniform, repeatable color and luminance. In the 2012 MYPP, DOE performance targets for 2020 include achieving color control within a two SDCM bin and brightness uniformity of 10% across a 200 cm^2 panel.

In order to achieve these high yields, very tight control of manufacturing processes is necessary. The high deposition rates needed for low costs combined with the thinness of the OLED layers makes it difficult to achieve the high uniformity required and repeatability of the manufacturing processes. Manufacturing tools and equipment, such as thickness monitors and novel deposition approaches are being developed for this. Most developers of OLED technology have assumed that greater control can be achieved over OLED processing than in traditional LED fabrication, so that binning can be avoided. However, initial experience with OLED panel prototypes suggests that some binning for color and efficacy may be necessary. Further research is needed to determine the effects of process tolerance at each of the manufacturing processes on the performance of the resulting panels, particularly with respect to efficacy, color, and lifetime.

3.5.3 Light Shaping

Most OLED panels emit light with a Lambertian angular distribution. Lambertian emission can work well in certain applications, such as in lighting a space with a large number of appropriately positioned, lower light output luminaires. However, in some applications, Lambertian emission may lead to glare and over-lighting of the region directly beneath the luminaire. Other light distributions may be preferred which can provide even illumination on the work surface and minimize glare. Considerations are being given to tailoring the angular distribution of the light emerging from the OLED stack by using micro-cavity effects, though this often results in variations of color with angle. Another approach being looked at is shaping the light through the use of patterned substrates or secondary optics. As with conventional light sources, reflectors or other optical components might also be used to shape the light. Diffusing films or components might be incorporated within the luminaire to improve the spatial uniformity of light or to mask the appearance of thick grid-lines or tile boundaries. With respect to manufacturing, in choosing a light distribution technique, cost and scalability, added weight and thickness to the luminaire design, and integration with light extraction techniques must be considered.

3.5.4 Standardization of Luminaire Components

At the OLED Manufacturing Roundtable, several participants expressed that it would be useful for there to be some standardization of OLED luminaire components. In particular, standard panel sizes, shapes, light output, color, drive requirements, and connectors – electrical and mechanical for connecting panels within the luminaire – could assist luminaire manufacturers in design efforts. While making firm recommendations may be premature, preparing draft specifications would be useful.

3.5.5 Reliability Issues

Much R&D effort has been focused on identifying the basic degradation issues that limit the operational lifetime of OLED devices and on the effectiveness of the various encapsulation procedures. Developing stable, robust and high performance stack and encapsulation materials are essential. Additionally, the demand for increased brightness will lead to accelerated degradation and increase the importance of thermal management. As brightness is increased, temperature increases. It has been observed that a 10°C rise in temperature corresponds to a reduction in lifetime of around a factor of two. Though lumen maintenance (L70) is improving to between 10,000 and 15,000 hours from initial levels of up to 10,000 lm/m^2, substantial uncertainties remain. Materials and architectures are rapidly evolving and almost all lifetime predictions are based on accelerated testing methods that may not give accurate results.

3.6 OLED Manufacturing Priority Tasks for 2012

As discussed in Section 5 of the 2012 SSL MYPP, DOE supports research and development of promising SSL technologies.[26] In order to achieve the OLED projections presented in Section 3, progress must be achieved in several research areas. Last year, DOE issued a Manufacturing Support competitive solicitation. In response to the proposals received, DOE engaged in two cooperative agreement awards related to OLED manufacturing. The awarded projects are briefly described in Appendix B.

Because of the continuing progress in the technology and better understanding of critical issues, DOE engaged members of the lighting field, from industry representatives to academic researchers, to revise the manufacturing priority tasks for the 2012 Manufacturing Roadmap. To develop the 2012 Roadmap, DOE first held SSL Roundtable sessions in Washington, D.C. in April 2012, where initial tasks were developed. The tasks were further discussed and refined in June 2012 at the Manufacturing Workshop in San Jose, CA. Using recommendations and further review, DOE further distilled the recommended tasks to a short list of two, defining the task priorities as described in below. Where possible, the task metrics and targets are listed for each of the priority research areas.

3.6.1 OLED Manufacturing Priority Tasks for 2012

The following priorities for OLED manufacturing R&D were identified by DOE based upon discussions at the 2012 Manufacturing Roundtable and Workshop.

[26] http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mypp2012_web.pdf

M.O1. OLED Deposition Equipment: Support for the development of manufacturing equipment enabling high speed, low cost, and uniform deposition of state of the art OLED structures and layers. This includes the development of new tool platforms or the adaptation of existing equipment to better address the requirements of OLED lighting products. Tools under this task should be used to manufacture integrated substrates or the OLED stack and must demonstrate the ability to maintain state of the art performance. Proposals must include a cost-of-ownership analysis and a comparison with existing tools available from foreign sources.	
Metric(s)	**2015 Target(s)**
Initial capital cost/line capacity	$100/m^2
Minimum Substrate Size	10x10cm (may be batch-processed)
Area Utilization	>80%
Uptime of Machine	>80%
Thin Film Layer Yield	>95% per layer (80% overall)
Materials Utilization	>70%

There is a large opportunity for cost reduction in the deposition and patterning steps of OLED manufacturing. Focus is also needed on equipment with lower capital cost and high volume production. Deposition equipment is needed for integrated substrates, encapsulation and the OLED stack, but deposition of the organic layers in the device stack tends to be the most expensive unit operation and thus could have a greater impact. There are many process flow options available (all solution, hybrid, etc.), therefore the development of unit operations, potentially on a per layer basis, could be an effective strategy to accommodate changing designs and flexibility in process flow.

Various approaches to manufacturing equipment development can be taken such as modifying an existing tool or process, developing a novel tool compatible with the overall process for better yield/lower cost, or research into the equipment improvements necessary for a complete OLED deposition process. It is felt by equipment manufacturers that though some tools and processes may have crossover functionality, most display process approaches are not likely to be applicable to SSL.

All research projects for Task M.O1 need to focus on the overriding metric of cost per area of good product and total cost-of-ownership. In high-volume production, the total capital cost of all deposition and patterning tools should be less than $100 for each square meter of good product produced each year. Thus, if a proposed project is focusing on equipment to deposit a specific layer, then the expectation is that the cost of this layer will be significantly lower than $100/m^2 and an explanation will be provided describing how the remainder will be used to complete all the layers. Other critical factors in processing cost include throughput, yield and materials utilization. However, the cost reduction targets must be met without sacrificing performance metrics identified in the 2012 MYPP, such as uniformity of luminous emittance and color, efficacy and lifetime. The value of the proposed work will be greatly enhanced if tool developers work with potential OLED manufacturers to demonstrate the relationship between the characteristics of the deposited layers and the performance of the resultant devices.

M.O3. OLED Materials Manufacturing: Support for the development of advanced manufacturing of low cost integrated substrates and encapsulation materials. Performers or partners should demonstrate a state of the art OLED lighting device using the materials contemplated under this task.		
Metric(s)		**2015 Target(s)**
Substrate	Total cost – dressed substrate	$60/m^2$
	Extraction efficiency	50%
	Effective Sheet Resistance	<1 ohms/square
Encapsulation	Permeability of H_2O	10^{-6} g/m^2/day
	Permeability of O_2	10^{-4}cc/m^2/day/atm
	Cost	$35/m^2

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

For projects focusing on the integrated substrate, DOE includes metrics that address cost while maintaining other attributes (defined in the 2012 MYPP) relating to light absorption, surface roughness, sheet resistance, and permeability to water and oxygen. Substrate proposals should focus upon the integration of the several elements in the composite structure; those concerning tools to deposit a single layer should be submitted under Task M.O1.

In the production of transparent substrates, such as glass or plastic, high efficiency of light extraction is the most critical performance issue. Low optical absorption is essential, but the metric for transmittance should be based upon passage from the high index organic layers into air, rather from air to air, as is usually measured. Effective transmission of current across the panel is also important to ensure uniform emission of light. The resistance of the electrode structure should be low enough that voltage differences across the panel can be kept within 0.1 volts. Since the target for the conductivity of the transparent electrode material can be relaxed due to the presence of a grid, the critical parameter is the effective sheet resistance of the whole anode structure.

The 2015 target cost of the integrated substrate has been raised to recognize the difficulty of meeting the desired light extraction goal.

For encapsulation, cost and the lifetime of the resulting OLED (measured through accelerated testing) are the major factors determining success. The extreme sensitivity of OLED materials to contaminants such as O_2 and H_2O means that porosity of the encapsulant material, the absence of pin-holes and edge-seal integrity are critical. Substantial progress has been made in the encapsulation of OLEDs for small displays through the introduction of hermetic seals, which eliminate the need for dessicants. However, it is unclear whether the frit glass solution used in those applications can be adapted for lighting panels with soda-lime glass. This development has reduced the anticipated growth of the market for dessicants, so that their price remains high. Thus the 2015 target cost for encapsulation has been raised to \$35/m^2, including the cover.

4. Standards

This section summarizes the different types of standards that are of interest to the SSL industry as well as the progress towards developing them. These sections focus on LED standards. OLED technology has not progressed to the point where standards are available although a parallel effort will eventually be needed. This section is not intended to be a complete exposition on the subject, but provides a useful reference point in ongoing conversations about SSL standards. As noted in the previous Roadmap editions, there are several uses of the term "standards" that have come up during discussions:

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

These are generally considered to be *industry* standards, but, any of these general types may eventually become a *regulatory or statutory requirement* having the force of law. They are then variously called "rules", "regulations", or "codes". While not always popular, they do provide a useful framework to keep unsafe or substandard products off the market. Examples might be a safety requirement such as Underwriters Laboratories Inc. (UL) type labeling that is generally required for electrical products, or a minimum efficiency requirement as may be required by Federal Appliance Efficiency legislation. Usually, such legal standards only appear after some period of maturity in the industry; to enforce them too early may mean stifling beneficial further innovation of the technology.

DOE works with a number of Standards Development Organizations (SDO) to accelerate the development and implementation of needed SSL standards. DOE provides standards development support to the process, which includes hosting ongoing Workshops to foster coordination and collaboration on related efforts. These Workshops are attended by representatives and committee members from the major standards groups: American National Standards Lighting Group (ANSLG), Illuminating Engineering Society of North America (IES), National Electrical Manufacturers Association (NEMA), National Institute of Standards and Technology (NIST), Underwriters Laboratories Inc. (UL), Commission Internationale de l'Eclairage (CIE), CSA International, and International Electrotechnical Commission (IEC). DOE will continue to provide updates on standards progress in this section because of the strong interest on the part of those involved with manufacturing. Standards directly related to manufacturing can be numerous and quite detailed, and often fall into the last two categories of processes/best practice and interoperability.

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

4.1 Definitions

4.1.1 SSL Product Definitions

The IES has done considerable work and service to the industry by promulgating RP-16-2010, *Nomenclature and Definitions for Illuminating Engineering*, which defines the components and products relating to LEDs for lighting. While this Roadmap may appropriately offer up suggestions for additional needs definitions, this work is best handled within existing standards groups.

4.1.2 Reliability Characterization and Lifetime Definitions

The lack of an agreed definition of LED package or luminaire lifetime has been a continuing problem because of unsubstantiated claims of very long life for LED-based luminaire products. Often these are simply taken from the best-case performance of LED packages operating under moderate drive conditions at room temperature. DOE has attempted to address this lack of clarity (and understanding) with the June 2011 release of a guide, *LED Luminaire Lifetime: Recommendations for Testing and Reporting*,[27] developed jointly with a Next Generation Lighting Industry Alliance (NGLIA) working group. An important message from this work is that more attention should be paid to more fully understand and account for the variety of failure mechanisms that can affect product lifetime. The effort will lead to more realistic claims for luminaire performance, with consequences for market acceptance and the economics of SSL. There is also an excellent discussion of the nuances of reliability and lifetime characterization for LED packages and LED-based luminaires in two DOE SSL factsheets, *LED Luminaire Reliability*[28] and *Lifetime of White LEDs.*[29](Updates to these factsheets are forthcoming; visit www.ssl.energy.gov/factsheets.html for current information.)

4.2 Minimum Performance Specifications

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

The implementation of minimum performance specifications has also been mentioned under the umbrella of standards. These may be either mandatory or voluntary, as noted above, and some may morph from one classification to the other. The most notable are Energy Star (voluntary) and UL (mandatory for many applications). In addition, recently NEMA published the standard SSL 4-2012 which provides suggested minimum performance levels for SSL retrofit products.

[27] http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/led_luminaire-lifetime-guide_june2011.pdf
[28] http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/luminaire_reliability.pdf
[29] http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/lifetime_white_leds.pdf

SSL 4-2012 applies to integral LED lamps, as well as retro-fit replacements for standard general service incandescent, decorative, and reflector lamps. The performance criteria include color, light output, operating voltage, lumen maintenance, size, and electrical characteristics.

Recently there has been some resistance to minimum performance standards coming from several quarters. Manufacturers have expressed concern over the number of different tests and measurements they are required to provide, partly through mandatory standards and partly through what is effectively a marketing requirement to participate in the voluntary standards. Some in the SSL domain question if the standards are sufficiently strong to provide direction towards the most energy-efficient products. And, finally, there has been some public resistance to performance standards in general, leading to uncertainty as to whether they will be enforced.

4.3 Characterization and Test Methods

In recent years, there has been increasing industry awareness of recommended standard measurement methods such as IES LM-79-2008 (LM-79), *Approved Method for the Electrical and Photometric Testing of Solid-State Lighting Devices* and IES LM-80-2008 (LM-80), *Approved Method for Measuring Lumen Depreciation of LED Light Sources,* for measurement of initial performance and lumen depreciation in LEDs, respectively. An ongoing issue has been how to extrapolate limited LM-80 lumen depreciation measurements to predict LED package lifetime, a very difficult proposition because of widely varying performance of different designs. An IES subcommittee, with DOE support, completed IES TM-21-2011 (TM-21), *Projecting Long Term Lumen Maintenance of LED Light Sources* in July 2011.[30] This document specifies a recommended method for projecting the lumen maintenance of LED light sources based on LM-80 data. While TM-21 does provide a means to estimate the luminaire lumen depreciation from multiple temperature data from LM-80 tests, DOE cautions, however, that this does not directly translate into a complete measurement of lifetime for a luminaire or lamp which may depend on other failure mechanisms.

Issues associated with chromaticity variations in SSL products have been discussed in previous sections. ANSI C78.377-2008, *Specifications for the Chromaticity of Solid-State Lighting Products,* was introduced as a standard for specifying LED binning ranges. In 2010 NEMA published SSL 3-2010, to improve understanding on color specifications between chip manufacturers and luminaire makers. While there have not been any recent releases regarding color, it remains a difficult issue for many applications and work continues in many quarters to find better ways to characterize the color and color shifts over time.

The Environmental Protection Agency's (EPA) Energy Star Program has defined test procedures for determining which LED products are to receive the Energy Star certification. DOE (Regulatory Group) provides ongoing technical support to the Energy Star Program which has been recently undergoing several procedural modifications. In order for an LED product to receive Energy Star certification, it must be tested at a laboratory holding appropriate accreditation. Qualification criteria for luminous efficacy of non-directional LED luminaires is a

[30] http://www.ies.org/store/product/projecting-long-term-lumen-maintenance-of-led-light-sources-1253.cfm

minimum of 65 lm/W (prior to 9/1/2013) and greater than or equal to 70 lm/W (after 9/1/2013) in accordance with the IES LM-82-2012 (LM-82) report published in March 2012.[31] Lumen maintenance measurements must comply with LM-80 and are to be provided by the LED manufacturer. For LED luminaires, the LM-79 approved methods and procedures are used for performing measurements of chromacity and power consumption.

In addition, on April 9th 2012 DOE published its Notice of Proposed Rulemaking (NOPR) detailing a test procedure for integrated LED lamps. The purpose of this procedure is to support the implementation of the Lighting Facts label set by the Federal Trade Commission (FTC) (see section 4.4 below for discussion on the FTC Lighting Facts label). The NOPR references LM-79 for measuring the lumen output, input power, and CCT of LED lamps providing some suggested modifications. Further, the NOPR references industry standards LM-80 for measuring lumen maintenance of the LED source, and then references TM-21 for projecting this value to L70 (the time required for the LED source component of the lamp to reach 70% of initial light output). The NOPR suggests that L70 of the LED source should be used as a proxy for estimating the rated lifetime of the complete LED lamp product.[32] A public meeting to discuss and provide comment on the LED test procedure NOPR was held May 3rd, 2012 and final comment submissions on the document were due June 25th, 2012.

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

4.4 Standardized Reporting Formats

This section discusses two types of standardized reporting formats: standardized reporting of luminaire component performance and standardized reporting of end product lighting performance. Buyers of lighting components continue to ask for a standard reporting format to facilitate the comparison of alternative choices. For example, they have also asserted a need for better reporting standards for drivers. This latter issue was discussed during the November 2010 Roundtable meetings where it was agreed that standardization in the reporting of driver performance would alleviate the burden of driver testing that currently falls to the luminaire manufacturer. Additional discussions were held at the CALiPER Roundtable meeting but at present no defined format or characterization method has been developed.

A standardized reporting format would also be useful for the end-product. Lighting designers, retailers and specifiers have for some time been calling for just such a standard data format for LED-based luminaires. However, with the rapidly evolving landscape for SSL products, it may be some time before this type of standardization will be possible.

[31] ENERGY STAR® Program Requirements Product Specification for Luminaires, Version 1.1 - http://www.energystar.gov/ia/partners/product_specs/program_reqs/Final_Luminaires_Program_Requirements.pdf

[32] Energy Conservation Program: Test Procedures for Light-Emitting Diode Lamps; Notice of Proposed Rulemaking. http://www.regulations.gov/#!documentDetail;D=EERE-2011-BT-TP-0071-0001

Simple labeling standards, however, offer a short-term alternative to help the buyer. DOE recognized the importance of introducing standardized reporting of LED-based lighting product performance for the consumer. In December 2008, LED Lighting Facts®, a voluntary pledge program, was created to assure that LED-based lighting products are represented accurately in the market. The LED Lighting Facts label provides a summary of verified product performance data. The label guards against exaggerated claims, and helps ensure a satisfactory experience for lighting buyers. Lamp and luminaire manufacturers who pledge to use the label are required to disclose performance data in five areas – light output (lumen), power consumption (Watts), Efficacy (lumens per Watt), correlated color temperature (CCT), and color rendering index (CRI) – as measured by the industry standard for testing photometric performance, LM-79. Additional metrics related to reliability including lumen maintenance and warranty have been added as optional label metrics. Figure 4-1 shows an example of what the LED Lighting Facts label looks like.

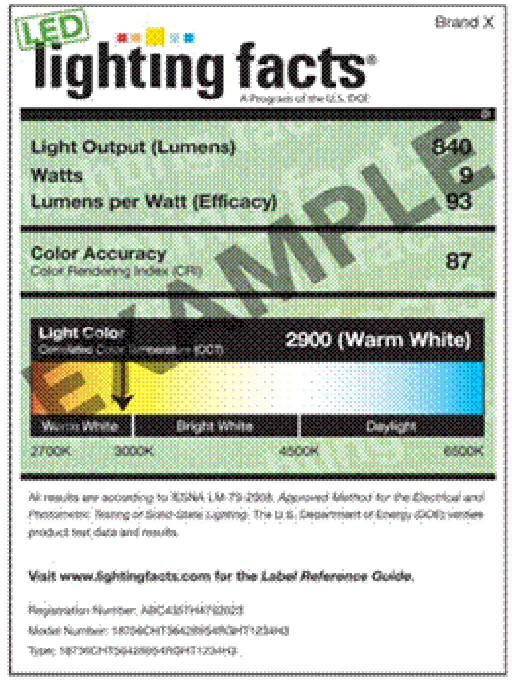


Figure 4-1. Example of DOE LED Lighting Facts Label
Source: DOE, LED Lighting Facts

Since January 1, 2012, FTC has mandated that all lighting manufacturers incorporate labeling on their medium screw base bulb packaging. The packaging labels emphasize brightness, energy cost, life expectancy, light appearance, wattage and whether the bulb contains mercury.

The FTC label is primarily a consumer label, while the DOE label is a valuable tool for buyers. In fact, the FTC encourages stakeholders to reference the LED Lighting Facts label, especially as DOE works to improve bulb life testing methodologies for LED lamps.[33]

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

4.5 Interoperability/Physical Standards

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

[33] http://www.lightingfacts.com/downloads/FTC_Guidelines_Consumer_April11.pdf

The other type includes the interfacing standards that enable complete products or component parts to be interchanged in a seamless fashion. NEMA is currently addressing this issue in part, with its issuance of NEMA LSD 45-2009, *Recommendations for Solid-State Lighting Sub-Assembly Interfaces for Luminaires.* Interconnects within an SSL luminaire have an added challenge to manage the thermal aspects of the system in order to keep the LED and electrical components cool enough such that light output and lifetime remains acceptable. The NEMA LSD 45-2009 provides the best industry information available for electrical, mechanical, and thermal SSL luminaire interconnects, and is intended to document existing and up to date industry best practices.[34]

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

Furthermore, in early 2010, an international group of companies from the lighting industry initiated the formation of the Zhaga Consortium, an industry-wide cooperation aimed at the development of standard specifications for LED light engines. Zhaga aims to provide specifications that cover the physical dimensions, as well as the photometric, electrical and thermal behavior of LED light engines.[35]

In February 2011, the Zhaga Consortium approved the first light engine specification for socketable LED light engines with integrated control gear. This specification describes the interfaces of a downlight engine. In the subsequent months, Zhaga has approved several additional specifications. These include:

- In June 2011, the second light engine specification for the interfaces of a spotlight engine was approved;
- In September 2011, Zhaga approved the third light engine specification which describes the interface of a socketable light engine;
- In December 2011, they approved a specification that defines aspects that are common in multiple Zhaga interface specifications, such as:
    - Common definitions;
    - The mechanical interface of separated electronic control gear; and
    - The generic aspects of the thermal interface.

[34] LSD 45 is available as free downloads from NEMA at: http://www.nema.org/stds/lsd45.cfm
[35] Zhaga Consortium, "Consortium for the Standardization of LED Light Engines", http://www.zhagastandard.org/about-us/our-vision/, (Accessed July 27, 2012).

These specifications are currently only available for Zhaga Consortium members. Also, LED light engine specifications are currently being developed by Zhaga for a spotlight, streetlight, indoor lighting and compact engine.[36]

4.6 Process Standards and Best Practices

When the DOE Manufacturing Initiative first began in 2009, there was a great deal of hesitation regarding the development of manufacturing or process standards for LED technology. But gradually as the industry has matured, this perspective has changed, due in large part to the efforts of Semiconductor Equipment and Materials International (SEMI) and its members who formed a HB-LED Standards Committee in November of 2010 with strong industry support among device makers, equipment manufacturers and material suppliers. Tom Morrow, EVP of the Emerging Markets Group at SEMI, summarized this activity at the Boston Manufacturing Workshop in 2011 and updated the work at this year's 2012 Manufacturing Workshop in San Jose.[37]

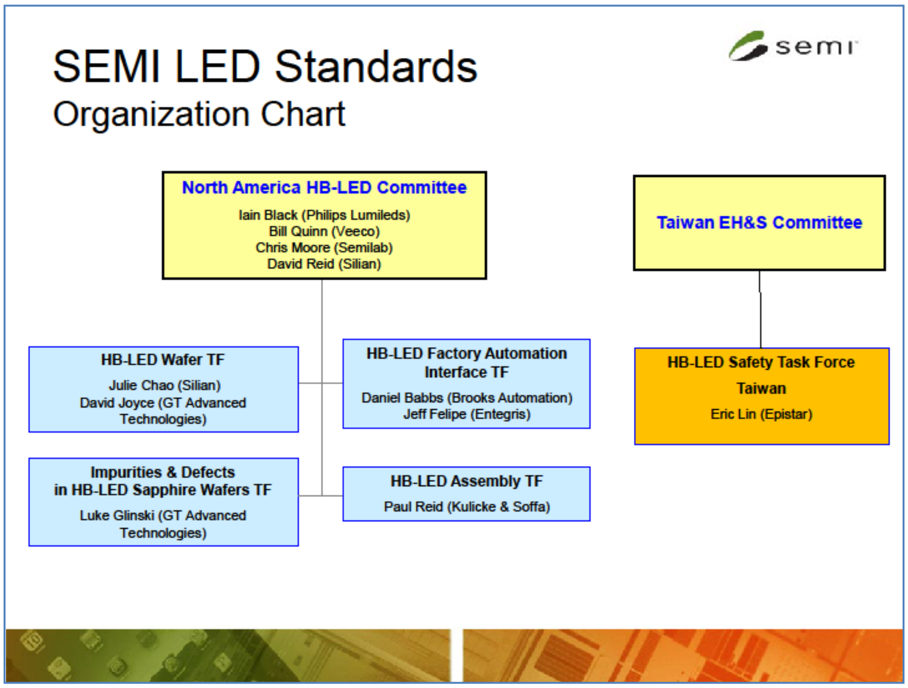


Figure 4-2. SEMI task forces directed at SSL manufacturing standards

Standards for materials and equipment used in manufacturing SSL products allow manufacturers to purchase equipment and materials from multiple vendors at lower cost, improved quality, and with minimum need for modification or adaptation to a particular line. For suppliers to the industry, standards also can reduce the need for excess inventories of many similar yet slightly different materials and parts. Reduced inventory means lower costs and faster deliveries. The SEMI HB-LED Standards Committee has now increased its effort to five task forces as indicated in Figure 4-2 adding Impurities and Defects and Safety to the focus areas for SSL. The new Impurities group is working on defining important types of defects and means for their detection, while the Safety effort is presently evaluating areas of LED manufacture not covered by prior

[36] Zhaga Consortium, "Approved Zhaga Specifications", http://www.zhagastandard.org/method/progress.html (Accessed June 3, 2011).
[37] Copy of the presentation is available on the DOE SSL website: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/morrow_standards_sanjose2012.pdf

SEMI standards. The Wafers Task Force is continuing its work to define the physical geometry for HB-LED 150 mm diameter sapphire substrates. The Factory Automation Interfaces Task Force has made good progress on handling standards for 150 mm wafers and is working on software standards. Many companies are now contributing to these efforts and SEMI welcomes their participation as well as that of others.

Appendix A Standards Development for SSL

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

Since 2006, DOE has hosted a series of Workshops to bring together the key standards organizations and foster greater coordination and collaboration among related efforts. These Workshops have been attended by representatives and committee members from the major standards groups: American National Standards Lighting Group (ANSLG), Illuminating Engineering Society of North America (IES), National Electrical Manufacturers Association (NEMA), National Institute of Standards and Technology (NIST), Underwriters Laboratories Inc. (UL), Commission Internationale de l'Eclairage (CIE), CSA International, and International Electrotechnical Commission (IEC).

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

Current SSL Standards and White Papers

The documents listed below are for information and reference only. Several are not directly related to DOE support work, or may not be applied by the industry at this time.

- **ANSI C78.377-2008, Specifications for the Chromaticity of Solid-State Lighting Products,** specifies recommended color ranges for white LEDs with various correlated color temperatures. Color range and color temperature are metrics of critical importance to lighting designers.[38]
- **ANSI C136.37-2011, Solid State Light Sources Used in Roadway and Area Lighting,** defines requirements for SSL fixtures used in roadway and off roadway luminaires including interchangeability, operating temperature range, chromacity, mounting provisions, and wiring.[39]
- **CIE 127-2007, Measurements of LEDs,** describes the measurement conditions of spectrum, luminous flux, and intensity distribution for individual low-power LED packages.[40]

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

[39]http://webstore.ansi.org/RecordDetail.aspx?sku=ANSI+C136.37-2011

[40]http://www.cie.co.at/index.php?i_ca_id=402

- **CIE 177-2007, Colour Rendering of White LED Light Sources,** describes the application of existing color rendition metrics to LEDs and recommends the development of improved metrics.[41]
- **IEC/TR 61341:2010, Method of Measurement of Centre Beam Intensity and Beam Angle(s) of Reflector Lamps,** describes the method of measuring and specifying the beam angle and intensity of reflector lamps. This measurement standard applies to LED-based reflector lamps for general lighting purposes.[42]
- **IEC 62031, LED Modules for General Lighting – Safety Specifications,** describes general and safety requirements for LED modules.[43]
- **IES G-2, Guideline for the Application of General Illumination ("White") Light-Emitting Diode (LED) Technologies,** presents technical information and application guidance for LED products.
- **IES LM-79-2008, Approved Method for the Electrical and Photometric Testing of Solid-State Lighting Devices,** enables the calculation of LED luminaire efficacy (net light output from the luminaire divided by the input power and measured in lumens per watt). Luminaire efficacy is the most reliable way to measure LED product performance, measuring luminaire performance as a whole instead of relying on traditional methods that separate lamp ratings and fixture efficiency. LM-79 helps establish a foundation for accurate comparisons of luminaire performance, not only for solid-state lighting, but for all sources.[44]
- **IES LM-80-2008, Approved Method for Measuring Lumen Depreciation of LED Light Sources,** defines a method of testing lamp depreciation. LED packages, like most light sources, fade over time, which is referred to as lumen depreciation. However, because LED packages have a long lifetime in the conventional sense, they may become unusable long before they actually fail, so it is important to have a sense of this mode of failure. LM-80 establishes a standard method for testing LED lumen depreciation. Note that LED source depreciation to a particular level of light, should not be construed as a measure of lifetime for luminaires, however, as other failure modes also exist which can, and in most cases will, shorten that lifetime.
- **IES LM-82-2012, Approved Method for the Characterization of LED Light Engines and LED Lamps for Electrical and Photometric Properties as a Function of Temperature,** provides a method for measuring the lumen degradation of light engine products at various temperatures in support of establishing consistent methods of testing to assist luminaire manufacturers in determining LED luminaire reliability and lifetime characteristics and thus aiding manufacturers in selecting LED light engines and lamps for their luminaires.
- **IES RP-16 Addenda a and b, Nomenclature and Definitions for Illuminating Engineering,** provides industry-standard definitions for terminology related to solid-state lighting.

---

[41] http://div1.cie.co.at/?i_ca_id=551&pubid=50
[42] http://webstore.iec.ch/webstore/webstore.nsf/Artnum_PK/43777
[43] http://webstore.iec.ch/webstore/webstore.nsf/Artnum_PK/38891
[44] Electronic copies of LM-79, LM-80, and RP-16may be purchased online through IES at www.ies.org/store.

- **IES TM-21-2011, Projecting Long Term Lumen Maintenance of LED Light Sources,** specifies a recommended method for projecting the lumen maintenance of LED light sources based on LM-80-2008 collected data.
- **NEMA LSD 45-2009, Recommendations for Solid-State Lighting Sub-Assembly Interfaces for Luminaires,** provides guidance on the design and construction of interconnects (sockets) for solid-state lighting applications.[45]
- **NEMA LSD 49-2010, Solid-State Lighting for Incandescent Replacement—Best Practices for Dimming,** provides recommendations for the application of dimming for screw-based incandescent replacement solid-state lighting products.
- **NEMA SSL-1-2010, Electronic Drivers for LED Devices, Arrays, or Systems**, provides specifications for and operating characteristics of non-integral electronic drivers (power supplies) for LED devices, arrays, or systems intended for general lighting applications.
- **NEMA SSL 3-2010, High-Power White LED Binning for General Illumination,** provides a consistent format for categorizing (binning) color varieties of LEDs during their production and integration into lighting products.
- **NEMA SSL 4-2012, SSL Retrofit Lamps: Minimum Performance Requirements,** supplies performance standards for integral LED lamps, including color, light output, operating voltage, lumen maintenance, size, and electrical characteristics.
- **NEMA SSL-6-2010, Solid State Lighting for Incandescent Replacement – Dimming,** provides guidance for those seeking to design and build or work with solid-state lighting products intended for retrofit into systems that previously used incandescent screw base lamps. Addresses the dimming of these products and the interaction between the dimmer (control) and the bulb (lamp).
- **UL 8750, Safety Standard for Light Emitting Diode (LED) Equipment for Use in Lighting Products,** specifies the minimum safety requirements for SSL components, including LEDs and LED arrays, power supplies, and control circuitry.[46]
- **UL 1598C, Safety Standard for Light Emitting Diode (LED) Retrofit Luminaire Conversion Kits,** specifies safety requirements for LED products that are meant to replace existing luminaire light sources.

Standards in Development

- **ANSI C82.XX, LED Driver Testing Method**
- **CIE TC1-69, Color Quality Scale,** provides a more effective method for relating the color characteristics of lighting products including LEDs.
- **CIE TC2-50, Measurement of the Optical Properties of LED Clusters and Arrays**

---

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

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

- **CIE TC2-63, Optical Measurement of High-Power LEDs**
- **CIE TC2-64, High Speed Testing Methods for LEDs**
- **IEEE P1789,** Recommended Practices of Modulating Current in High Brightness LEDs for Mitigating Health Risks to Viewers
- **LM-XX1, Approved Method for the Measurements of High Power LEDs**
- **LM-XX4, Approved Method for the Electrical and Photometric Measurements of Organic LED (OLED) Light Sources**
- **LM-XX5, Reliability Performance Tests for LED packages**
- **NEMA SSL-7, Dimming SSL Luminaires with Phase Cut Dimmers**
- **TM-26, Estimating the Rated Life of an LED Product** (incorporates lumen degradation and other failure modes)
- **TM-XX1, Approved Method for Measuring Lumen Maintenance of LED Light Engines and LED Integrated and Non-Integrated Lamps**

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

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

Appendix B Manufacturing R&D Projects

Currently Funded Projects

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

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

Recipient: Veeco Instruments
Title: Development of Production PVD-AlN Buffer Layer System and Processes to Reduce Epitaxy Costs and Increase LED Efficiency
Team Members: Veeco MOCVD Systems
Summary: ***This project seeks to realize a*** *60% reduction in epitaxy manufacturing costs through the development of a high productivity reactive sputtering system to achieve an effective sputtered aluminum-nitride (AlN) buffer/nucleation layer process. The AlN buffer deposition process will replace the current complex MOCVD buffer layer process and provide for a >80% reduction in cost of ownership and 3X increase in throughput. In addition, the project anticipates up to a 25% improvement in brightness through reductions in defect density. The focus will be on developing an AlN buffer layer for GaN-on-silicon (GaN/Si) epitaxial technology on 150mm silicon substrates which offers the prospect of an 80% reduction in substrate cost through the replacement of sapphire with silicon, and a 50% reduction in non-ESD yield loss through reductions in wafer bow and temperature variation.*

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

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

Recipient: Universal Display Corporation (UDC)
Title: Creation of a U.S. Phosphorescent OLED Lighting Panel Manufacturing Facility
Team Members: Moser Baer Technologies
Summary: *This project seeks to design and set up two pilot phosphorescent OLED (PHOLED) manufacturing lines. The team will implement UDC's PHOLED technology and provide prototype lighting panels to U.S. luminaire manufacturers for incorporation into products in order to facilitate testing of design and to gauge customer acceptance. The goal of this project is to establish the first U.S. manufacturing line for phosphorescent OLED lighting panels within a two year time frame, using known and proven procedures. The aim is to produce panels of size 150mm x 150mm that meet the MYPP performance targets, with luminance >76 lm/W, and to demonstrate a path towards meeting cost targets of $27/klm by 2013. The team will deliver panels to enable luminaire manufacturers to produce lighting products that will test design concepts and gauge consumer acceptance. The pilot line manufacturing technology will be implemented as an integrated process using up to three separate equipment clusters with intermediate substrate transfer capability:*

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

Recipient: Moser Baer Technologies
Title: Process and Product Yield Management for Low Cost Integrated Manufacturing and Quality Control of OLEDs
Team Members: Universal Display Corporation
Summary: *The objective of this project is to reduce the manufacturing cost of OLED lighting panels through the implementation of robust quality control methods in both production equipment and processes, resulting in consistently high product yield. The team will investigate the sensitivity of the panel performance and yield to variations in the substrate and OLED manufacturing processes, in order to determine which process parameters to monitor and control, as well as to develop and implement solutions having maximum tolerance to process variations. The overall outcome will be a solid understanding, given the chosen manufacturing technologies, of what yields can be achieved and where further yield improvement activities would be beneficial. The understanding of process tolerance and process control requirements will enable specification of the correct equipment for high volume OLED production lines, with strong confidence in the ability to obtain the desired yield and cost targets*

Newly Selected Projects (subject to negotiation as of July 2012)

Recipient: Cree, Inc. (Durham, NC)
Title: Low-Cost LED Luminaire for General Illumination
Summary: *This project plans to develop an optimized LED fixture design for efficient manufacture that can be readily integrated into buildings and outdoor applications and uses fewer raw materials—all without compromising the performance of the light source. The project builds upon Cree's existing LED platform and has the potential to quickly reduce the cost of producing an already highly efficient LED fixture and allowing it to compete with existing fluorescent systems. The goal is to efficiently provide warm-white light over a minimum lifetime of 50,000 hours, while reducing the cost of manufacturing the major components and assembled products.*

Recipient: KLA-Tencor (Milpitas, CA)
Title: High Throughput, High Precision Hot Testing Tool for HBLED Wafer Level Testing
Summary: *This project plans to remove one of the major barriers to the adoption of high-efficiency LED lighting—namely, the difficulty of providing low-cost white light that has consistent color quality and brightness. Current practice is to separate LEDs according to color during the manufacturing process in order to maximize product yield. Unfortunately, this creates variation in light output and color quality of the product, leading to reduced performance and increased costs. KLA-Tencor seeks to improve the color consistency of LEDs by utilizing a measurement tool during manufacturing that reduces the variation in LED quality, improving performance and reducing cost.*

Recipient: k-Space Associates (Dexter, MI)
Title: Optical Metrology for Volume OLED Manufacturing
Summary: *Most monitoring of the OLED layers during the manufacturing process currently takes place after the fact, so that if problems are detected there's little or no chance to change the production inputs. This project plans to create a more efficient manufacturing process by building on KSA's existing optical monitoring technology to enable high-precision measurements of OLED layers during mass production. The tool will measure layer thickness and composition to ultimately control the efficiency, color, and lifetime of OLEDs. This development, a first for the industry, will serve as a platform for future large-scale OLED production facilities, paving the way for a strong U.S. presence in OLED manufacturing.*

Appendix C DOE SSL Manufacturing R&D Tasks

The complete list of SSL Manufacturing R&D Tasks developed in 2010 and refined in 2012 is below. Priority tasks for 2012 are indicated with an asterisk. Some descriptions of non-prioritized tasks have been updated from previous versions.

LED Tasks

***M.L1.**	**Luminaire/Module Manufacturing** Support for the development of flexible manufacturing of state of the art LED modules, light engines, and luminaires.
M.L2.	**Driver Manufacturing** Improved design for manufacture for flexibility, reduced parts count and cost, while maintaining performance.
***M.L3.**	**Test and Inspection Equipment** Support for the development of high-speed, high-resolution, non-destructive test equipment with standardized test procedures and appropriate metrics.
M.L4.	**Tools for Epitaxial Growth** Tools, processes and precursors to lower cost of ownership and improve uniformity.
M.L5.	**Wafer Processing Equipment** Tailored tools for improvements in LED wafer processing.
***M.L6.**	**LED Packaging** Identify critical issues with back-end processes for packaged LEDs and develop improved processes and/or equipment to optimize quality and consistency and reduce costs.
***M.L7.**	**Phosphor Manufacturing and Application** Development of efficient manufacturing and improved application of phosphors (including alternative down converters) used in solid state lighting.

OLED Tasks

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