Solid State Lighting LED Manufacturing Roundtable Summary

Introduction

On April 18, 2012 nine LED experts gathered in Washington, DC at the invitation of the DOE to develop proposed priority tasks for the Manufacturing R&D initiative. The meeting commenced with "soapbox" presentations from each of the participants, followed by a general discussion to define specific work needing attention. On May 2, 2012, the DOE also held an LED Roundtable Teleconference to accommodate six additional LED experts who were unable to attend the April 18th roundtable meetings. This report summarizes the conclusions of those meetings, including the proposed priority tasks, a summary of discussion points relevant to those selections, and a short summary of the soapbox presentations.

General Roundtable Attendee Comments

- The main themes of the LED roundtable discussions were as follows:
- Substrates
  - There is a need for larger substrates which would drive the need for larger scale equipment and reduced raw materials costs.
  - Improved quality and consistency of products is required along with standard specifications.
  - Bulk growth processes need to be better understood and controlled.
  - There is a need for improved substrate fabrication processes.
  - There are opportunities for wafer standards to drive efficiency and consistency within the industry. Such standards would greatly clarify raw material requirements and help determine which substrate manufacturing processes are best, leading to cost reductions.
  - Substrate manufacturing could become a new priority task, however, improvement to substrate manufacturing will have a small impact on overall cost reductions for LED manufacturing.
- Epitaxy
  - There remains a need to continue reducing epitaxial wafer costs. Issues such as wavelength uniformity and reproducibility have an impact on cost, but it is important to consider end-to-end optimization of yields to improve overall costs rather than focus on any one step in the process. Hence further improvements in the epitaxial growth equipment should occur in conjunction with the development of other process equipment and process methodologies. Specific areas to address are improving in-situ and ex-situ monitoring/control, as well as platform stability.
  - It is important to continue the development of MOCVD equipment (i.e. Task M.L4); however, it is not a priority research area. Cost predictions indicate that future cost improvements (epitaxy cost per wafer area) will become more and more difficult to achieve. Therefore, future MOCVD equipment improvements will come in the form of increased process control, customization and fabrication integration.
  - There is also a need for more flexible MOCVD production equipment. Since it is predicted that manufacturers will continue to operate using a variety of wafer sizes (i.e. 2”, 4” and 6”).
- Wafer Processing
  - The main issue for wafer processing equipment suppliers is the need for flexibility to handle the wide range of substrate types and diameters currently used in production. Many customers place a high premium on low acquisition cost and still tend to modify their own equipment. Better partnering and standards would help the industry develop relevant equipment. Nevertheless the availability of such equipment is not regarded as a current roadblock.

    - The title of task M.L5 should be changed to 'Wafer Manufacturing and Processing Equipment'.
- Phosphor Application
    - Phosphor and matrix materials comprise a significant cost for various package designs. 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.
    - The focus should be on improving phosphor application with emphasis on reducing overall system cost and improving performance.
- Test and Measurement
    - There is a need for a closer interaction between the end-user and the equipment manufacturer.
    - Improved detection of killer defects as early as possible in the wafer processing is an important requirement in order to reduce manufacturing costs. Developing equipment to enable cost effective hot testing of LEDs is also important. High speed equipment must replicate as closely as possible the actual 'hot' environment for optimum accuracy.
    - There is a need for increased speed, accuracy, and repeatability of testing and metrology equipment.
- Die Packaging
    - More efficient use of materials (either using less material or finding more affordable alternatives) will enable lower cost LED packages without forsaking performance.
- Luminaire Manufacturing
    - There is a need to improve the implementation of formal design for manufacturing.
    - LED lighting needs to venture away from existing form factors – the industry needs to move away from retrofit designs, since these are less capable of using all of the inherent benefits of LED lighting technology.
    - Next generation luminaires will incorporate a broader range of technologies to achieve specific form factors and enhanced performance attributes that make use of the advantages offered by LED-based sources. Large area surface emitters and flexible PCB designs with direct die attach are possible directions. Tunable systems will provide new functionality and drive the need for high speed test equipment capable of accurately capturing color point information to meet tightening specifications.
    - A modular approach to luminaire assembly/integration will help reduce costs through reduced SKU counts. The introduction of control solutions and field adaptable/configurable systems would add further value. Optics design for luminaires currently lack beam pattern standardization for LED light sources resulting in re-engineering and increased costs. Solutions might include the use of direct chip-on-board where no primary optics would be involved.
    - Standardization, particularly regarding the LED footprint could lead to lower costs and more efficient luminaire manufacture. Such a standard would limit the operating conditions as well as the type and number of LED components and would simplify the manufacturing process. However, premature standardization could be detrimental to the industry, limiting innovation. A possibility would be to develop some standards (e.g., Zhaga) for "workhorse" products while keeping other options open for new designs and top-end performance.
    - A closer linkage is required between the luminaire manufacturing process and product reliability such that all interactions are understood, the impact of manufacturing changes could be anticipated, and improved predictions of product reliability could be achieved during the design phase.
    - Novel approaches to reducing parts counts and complexity in luminaires should be encouraged. One example might be die bonding direct to the heat sink with printed dielectrics and connection circuitry in order to remove a number of thermal interface layers,

improving performance and reducing costs.
    - A system level roadmap should be developed for luminaires and this should be mapped onto a technology level roadmap.
    - Luminaire cost projections in the roadmap should clearly reference the type of luminaire and should be supported by relevant price information.
- Other Comments
    - There is a need for improvements to yield and throughput across the whole manufacturing process. A definition for yield needs to be developed, however this is very difficult as LEDs are analog devices, and are binned by specific attributes, increasing the overall yield, but not addressing yield to tightly defined parameters.
    - More collaboration is needed in order to better advance LED manufacturing methods. A SEMATECH-like organization would potentially benefit the industry by providing a nexus for increased collaboration.

Proposed Priority Tasks

The following tables provide descriptions and metrics for the proposed priority tasks. The task tables shown do not reflect any modifications suggested by roundtable attendees. All comments, including suggested changes to each task description and metrics, are provided below each of the relevant task tables. These comments represent a summarized transcript of the general commentary and require further discussion at the Manufacturing R&D Workshop. The results of these discussions will guide the DOE in soliciting projects in the LED Manufacturing R&D Program during the coming year.

M.L1 Luminaire/Module Manufacturing		
Support for the development of flexible manufacturing of state-of-the-art LED modules, light engines, and luminaires. Suitable development activities will focus on advanced LED packaging and die integration (e.g. COB, COF, etc.), more efficient use of raw materials, simplified thermal designs, weight reduction, optimized designs for efficient manufacturing (such as ease of assembly), increased integration of mechanical, electrical and optical functions, and reduced manufacturing costs. The work should demonstrate higher quality products with improved color consistency, lower system costs, and improved time-to-market through successful implementation of integrated systems design, supply chain management, and quality control.		
Metric(s)	**Current Status**	**2015 Target(s)**
Downtime		50% reduction
Manufacturing Throughput		x2 increase
OEM Lamp Price	$50/klm	$10/klm
Assembly Cost ($)		50% reduction every 2-3 years
Color Control (SDCM)	7	4

Roundtable Attendee Comments (M.L1)

Proposed changes to description

- Designing LED products for manufacturing is important. This needs to be thought of as a manufacturing issue, not confined to product development. Text should be added to this task or a new task should be created to reflect this concept.
- The description should convey the need for cooperative efforts to help advance manufacturing process technology. Also, the description should emphasize that it is not so much the need for

advanced LED packaging, but processes for incorporating LEDs into luminaires.

- This task should be modified to include emphasis on processes that would lead to reducing complexity by integrating and reducing the number of LED components. This will help lead to significant cost reductions. Examples of these process-level changes could include wafer-scale packaging and/or eliminating layers in order to get closer to a simple chip on heat sink.

Other comments

- Attendees discussed the need for a domestic manufacturing base for robust quality optics.
- Consumers are expecting the cost of LED luminaires to reflect the same price decreases they have seen for LED packages. This expectation may be misplaced. The additional components and subsystems in an LED luminaire are not likely to fall in cost as rapidly as the LED sources, and manufacturers will not necessarily pass on all cost reductions to buyers except as competition demands.

M.L3 Test and inspection equipment		
Support for the development of high-speed, high-resolution, non-destructive test equipment with standardized test procedures and appropriate metrics for each stage of the value chain for semiconductor wafers, epitaxial layers, LED die, packaged LEDs, modules, luminaires, and optical components. Equipment might be used for incoming product quality assurance, in-situ process monitoring, in-line process control, or final product testing/binning. Suitable projects will develop and demonstrate effective integration of test and inspection equipment in high volume manufacturing tools or in high volume process lines, and will identify and quantify yield improvements.		
Metric	**2011 Status**	**2015 Target**
Throughput (units per hour)		x2 increase
Cost of ownership		2-3x reduction every 5 years
$/units per hour		
Attendee Suggested Metrics		
Yield of tool		
Reliability		

Roundtable Attendee Comments (M.L3)

Proposed changes to description

- A clause on testing accuracy should be included in the task description. In addition, test gauge capabilities need to be specified and measured with respect to current industry standards. Specific areas requiring improved testing accuracy include the measurement of color coordinates and the unambiguous identification of killer defects.
- Methods for characterizing and improving reliability are an important priority. Customers are beginning to understand and increasingly focus on system reliability; therefore it is important that the industry develop methods for monitoring the impact of each manufacturing step on product reliability in order to facilitate better quality assurance and cost control of products. The description should be modified to express this need.
- ’High-capability’ should take the place of ‘high-resolution’ in the task description because resolution is only one aspect of the testing capability.

Proposed changes to metrics

- A metric to measure the success of the reliability monitoring methods should be defined.
- A metric quantifying the yield or yield enhancements offered by the test and inspection tool needs to be added. This improvement could be quantified by specifying yield improvement or return on investment (ROI) within a certain time frame.
- 'Yield of tool' metric should require that yield improvements pay for the tool within 3 months of use.

Other comments

- The need for yield increases through improved test and inspection equipment was discussed by the attendees.
- Rapid feedback of test results is important as this can significantly affect throughput of good product and overall product quality and cost.
- The ability to target a specific bin with high yield should be a priority within this task. Specifically kill ratio improvement, that is, the ability of an inspection tool to identify fatal defects, should be emphasized. Current kill ratios are around 50%, i.e. only 50% of the observed defects result in a failure.
- Hot testing speed and accuracy at the wafer level was identified as an important requirement.
- Metrology, reliability testing and predictive modeling are needed to enable "mapping" of lab scale reliability testing to final product lifetime.
- TM-21 provides a defined method to project lumen maintenance at the LED package level; however that standard is missing at the luminaire level (this is currently being worked on). In addition, there are no procedures for predicting future color quality or color shift.
- Manufacturing environment testing for optics will become more important as customer demand for verification of optical claims increases.

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	**2011 Status**	**2015 Target**
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

Roundtable Attendee Comments (M.L6)

Proposed changes to description

- The emphasis of this task should be on enabling lower costs of LED packages without forsaking performance aspects. Emphasis should be placed on more efficient use of materials and better (or fewer) interfaces. These points should be incorporated into the task description. For example, AlN submount tiles are expensive (i.e. $15 per bare 4" square tile) and can add a significant cost per die. Suitable silicone materials are expensive.

Other comments

- Many different package designs exist along with many different packaging technologies. The key is to choose the right package design approach for a specific application. Both high power and low power package designs can find applications in solid state lighting. System design aspects at the luminaire level will primarily drive packaging requirements.
- There is a drive for high voltage packages (multi-junction or multi-die) to improve driver efficiency.
- Materials constitute a large part of reducible costs. The system should be designed for reduction of raw materials. Either using less material or finding more affordable alternatives.
- Defining standard package architectures would provide more clarity and consistency to manufacturers as well as help enable the design of better process equipment.
- Packaging decisions are very important and cost varies significantly depending on package choices and methods. To a large extent the epitaxy, wafer processing, and die fabrication process steps are relatively constant and differentiation for different applications occurs at the packaging stage, hence there is a need for flexible packaging equipment and packaging lines. Consequently more flexible package designs are needed and any proposed standardization should not overly constrain manufacturers.

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	**2011 Status**	**2015 Target**
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
Attendee Suggested Metrics		
Cost of ownership		
Conversion Efficiency		60 – 70%
Color Control		
Chromaticity		

Roundtable Attendee Comments (M.L7)

Proposed changes to description

- The title of this task should be changed to 'Phosphor Application' and any reference to the manufacturing of phosphor materials should be removed.
- The task description should include a statement regarding the relative cost of the phosphor and matrix materials which can vary significantly depending on the application, as well as the need for maintaining high conversion efficiency.
- The task description should include a statement regarding the need for efficient incorporation of the phosphor into the package.

Proposed changes to metrics

- It was proposed to add the following new metrics:
    - The cost of ownership (COO) of the phosphor system.
    - Conversion efficiency, with a proposed target of 60-70% for 2015
    - Color control/chromacity.
- There currently is no standard or method to measure color reproducibility to within 2 SDCM and it is needed.

Other comments

- This task should be focused on phosphor application which will include work on the entire phosphor system including the matrix/encapsulant, with the emphasis on reducing overall system cost and improving performance.
- Wafer level phosphor application should be considered, focusing on developing a broad range phosphor capable of correcting for any epitaxy wavelength non-uniformities. A goal for phosphor cost could be a 2-3x cost reduction by 2015.
- Currently the cost of the phosphor material can range from 30% of the matrix cost up to around twice the cost of the matrix depending on the package design/specification.
- The phosphor application cost can range from 20-40% of the overall package cost.

Presentations

1. **Building a US-based Native GaN "Ecosystem" for Solid State Lighting**
   Mark D'Evelyn, SORAA
   - The current LED ecosystem is dominated by sapphire substrates and production of this substrate is extremely material and process intensive. Native GaN ecosystems may be a better alternative. Some of the potential benefits are:
     - Higher performance and reliability.
     - Simpler architectures and processing.
     - Better MOCVD utilization.
       - Resources go further since layers can be thinner.
     - Reduces stress (e.g. bowing).
     - Compatibility with next-generation power electronics
   - There are three major challenges associated with developing low cost GaN based systems:
     - Raw materials
       - Most native GaN crystal approaches require a poly-GaN nutrient, the purity level of which is critical as it drives transparency.
     - Crystal growth equipment and processes
       - Sapphire crystal furnaces are widely available, but bulk GaN furnaces are nonstandard.
       - Bulk GaN furnaces are required which can be easily scaled to achieve increased wafer sizes (4" to 6" to 8") and increased numbers of boules/run (>100)
     - Chemical mechanical polishing
       - Requires different slurries compared to sapphire and the process will depend on the growth plane.
   - Moving to native GaN systems will enable the development of revolutionary integrated power electronics with the potential for significant energy savings, as well as the 10x LED cost reductions per the 2020 DOE target ($1/klm).
     - Potential for 10-88% higher motor efficiencies and 50% lower inverter losses.
   - In the U.S., infrastructure for the native GaN ecosystem is immature and expensive, but it does exist. Further development of these systems presents an opportunity for U.S. leadership in emerging manufacturing supply chains.

2. **DOE SSL Roundtable Topic**
   James Zahler, GT Advanced Technologies
   - GT Advanced Technologies is primarily an equipment supplier and in 2010, with the acquisition of Crystal Systems, began developing sapphire production equipment and substrate materials.
   - Maximizing performance and the minimizing cost impacts of crystalline materials should be a priority.
   - Improved substrate fabrication efficiency via increased throughput and material usage is also important. Should look to measure substrate fabrication efficiency in terms of $/kg of useful material.
   - Believes there are opportunities to improve substrate manufacturing and opportunities for wafer standards to drive efficiency and consistency within the industry. Such standards would greatly clarify raw materials requirements and lead to cost reductions.

3. **Productivity Improvements in MOCVD Technology**
   Rainer Beccard, Aixtron AG
   - MOCVD improvements are still a top priority for reducing LED manufacturing costs. Short term solutions have been to increase the size of the machines and wafer area (2" to 4" to 6") to reduce

operating costs. The throughput (or capacity) gains are greater than the cost increments associated with the machine upgrades.
- The AIXTRON LED epitaxy cost roadmap predicts that future cost improvements (epitaxy cost per wafer area) will become more and more difficult to achieve (assuming constant wafer yield).
- Future MOCVD equipment improvements will come in the form of increased process control, customization and fab integration.
- Customers are increasingly looking for the quality of machines now that relatively high volume has been achieved. Moving from quantity to quality.
  - Quality in the sense of improving yield, automation, capacity, metrology process flexibility and fabrication integration.

4. Local Optimization
Bill Quinn, Veeco

- It is important that the industry consider the entire manufacturing process and the resulting end-to-end yield and not just the yield of each individual process.
  - End-to-end yield is the most important factor in determining epitaxy cost.
- If downstream process costs are not known, localized yield optimization does not give lowest cost. There needs to be more communication across the LED supply chain, since knowledge of the entire manufacturing process is necessary to minimize cost.
- Within the LED industry there is a lack of communication which has led to local optimization. A SEMATECH-like organization would greatly benefit the industry by providing a medium for collaboration.

5. Flexible yet Low COO Production Equipment
Abdul Lateef, Plasma-Therm

- In the past the focus has been on improving MOCVD equipment, now funding needs to focus on methods for lowering the cost of ownership for all wafer processing equipment.
- There is still a need for more flexible production equipment since it is predicted that manufacturers will continue to operate using a variety of wafer sizes (i.e. 2", 4" and 6"). Therefore flexible equipment needs to be developed while still minimizing cost.
- High throughput/low COO equipment specifically designed for the LED market is needed.
- Equipment manufacturers need to receive better feedback from the end-users in order to develop improved tools for this industry.

6. Solid State Lighting Manufacturing Roundtable 2012
Rich Solarz, KLA Tencor

- Based on DOE models and projections, costs can be reduced by improving binning, yield and efficacy. Costs reductions can also be realized by faster and more accurate hot tests, cheaper phosphors and cheaper lens/binders. Unfortunately, most of the low hanging fruit has already been addressed
- The boundary between R&D and manufacturing needs to be clearly defined; die efficacy improvements are not a manufacturing issue.
- The ability to target a specific bin with high yield is a manufacturing issue and should be focused on. Specifically kill ratio improvement should be emphasized. Current kill ratios are around 50%.
- Adding non-morphological defect visualization capabilities to conventional optical inspection tools will help identify a greater range of potential killer defects and provide higher kill ratios, resulting in yield improvements.
- Development and acceptance of a fast and accurate hot testing tool will lower costs, establish

better color consistency, and help identify factors affecting bin distributions. Action is needed to help industry meet the new NEMA standard for very small bins for white light LEDs (NEMA SSL 3-20111 Binning Standards for White Light LEDs).

7. **LED System Solutions**
   Iain Black, Philips
   - LEDs are a much more complicated lamp product compared to traditional incandescents and CFLs; therefore there are significantly different cost drivers.
   - Currently high and medium power LED solutions are competing for LED lighting applications.
   - Medium power LEDs offer:
     - Better uniformity and dispersion
     - Lower cost and simplicity, but less reliable
     - Can provide string voltage and better driver compatibility
     - Can do chip-on-board (COB)
   - High power LEDs offer:
     - Smaller footprint
     - Can get high lumen output more easily
     - High reliability
     - Better directionality/punch (light where you want it)
     - Higher lumen maintenance
   - In the non-directional battleground for high volume illumination, very low cost medium power LEDs offer an excellent solution in particular where a very distributed light source is desired
   - In applications which are space constrained then high power LEDs offer a form factor, particularly for higher lumen packages, which is difficult to match with medium power LEDs even if using COB.
   - Therefore, the industry needs to match the design of LED lamps/luminaires to the capability of the different LED solutions that are available.
     - Need to move away from retrofit designs, since these are less capable of using all of the inherent benefits of LED lighting technology.
   - The SSL industry needs to look for synergy with products produced for other LED-based industries and evaluate what can be applied to the LED lighting market.

8. **Materials and Processes for Enabling Lower Cost, High Volume SSL Systems**
   Ravi Bhatkal, Cookson Electric
   - The hierarchy of the LED lighting system is:
     - Substrate/wafer – package – light engine – luminaire – power supply – control systems
   - When considering this hierarchy, there are several mechanisms that have the potential to enable lower cost, high volume LED lighting systems:
     - Materials and processes to enable integration and fewer “levels” in the system.
     - Materials and processes for wafer level processing and integration.
       - Need good materials and better control equipment sets.
     - Novel thermal and electronic interconnect materials and processes.
     - Reliable and HVM capable materials and manufacturing processes.
     - Metrology reliability testing and predictive modeling to enable “mapping” of lab scale reliability testing to lifetime, and appropriate material stack selection for lifetime.
       - What is the link between lifetime in the field versus lab?

9. **2012 DOE Manufacturing Roundtable**
   Steve Paolini, Lunera Lighting

- The next generation of LED lighting needs to utilize the unique capabilities of SSL technology:
  - Tunable spectrums will allow LED to adapt to the natural light available (i.e. during the day illumination through windows, at night through acrylic surfaces). Tunable spectrums will enable fewer SKU's, less binning and less inventory (all of which enable lower cost).
    - This creates a need for fast testers to characterize and program luminaires.
  - Large surfaces using large acrylic sheets (8' x 12') will allow for more flexible daughter sizes, flexible extraction as well as reduced glare and increased energy savings.
    - Need programmable machines to handle, extract, cut and polish light guides.
  - Long PCB/MCPCB
    - Need machines to fabricate, stuff, reflow and test large PCBs.

DOE LED Roundtable Participants

Dave Bartine*	Lighting Science Group Corp
Rainer Beccard	AIXTRON
Ravi Bhatkal	Cookson Electric
Iain Black	Philips Lumileds
Dennis Bradley*	GE Lighting Solutions, LLC
Mark D'Evelyn	SORAA, Inc
Craig Fenske*	Philips Lighting
Mark Hand*	Acuity Brand Lighting
Eric Haugaard*	Cree, Inc
Abdul Lateef	Plasma-Therm, LLC
Bill Quinn	Veeco Instruments
Steve Paolini	Lunera Lighting
Rich Solarz	KLA Tencor
Nikhil Taskar*	WAC Lighting
James Zahler	GT Advanced Technologies

* Participated in the separate LED Roundtable Teleconference