Solid State Lighting LED Manufacturing Roundtable Summary

Introduction

On March 16, 2010, 13 LED experts gathered at the invitation of the DOE to develop proposed priority tasks for the Manufacturing R&D initiative. The meeting commenced with a number of "soapbox" presentations from some of the participants, followed by a general discussion to define specific work needing attention. This report summarizes the conclusions of that meeting, including the proposed tasks, a summary of discussion points relevant to those selections (not all necessarily in support), and a short summary of the soapbox presentations. The next step is to discuss these suggestions at the SSL Manufacturing Workshop. This work will guide the DOE in selecting funded projects in the LED Manufacturing R&D Program during the coming year.

Tasks

The table below summarizes the tasks discussed with their associated metrics. Cost and product consistency, the Manufacturing R&D programmatic metrics, and product performance should be considered in all tasks. Below the following tables is a more detailed description including points made during the discussions.

	Task	Metric
M.L1.	**Luminaire/Module Manufacturing**	Product Design Cycle Time Product Quality Consistency Manufacturing Throughput Cost Inventory Reduction
M.L2.	**Phosphor Manufacturing**	Batch Size Uniformity Cost per kg
M.L3.	**Phosphor Application**	Thickness Uniformity Reproducibility Materials Usage Efficiency Duv Control
M.L4.	**Test and Inspection Equipment**	Cost of Ownership Process Yield
M.L5.	**Tools for Epitaxial Growth**	Precursor Efficiency Throughput Cost of Ownership Yield Wafer Uniformity Reproducibility
M.L6.	**LED Packaging**	Incremental Cost per LED Equipment Cost of Ownership
M.L7.	**Driver Integration and Manufacturing**	Lifetime Thermal Stability

M.L1. Luminaire/Module Manufacturing

Support the development of flexible manufacturing of state of the art LED modules, light engines luminaires, and luminaire components. This work could include re-tooling and automating of existing luminaire manufacturing sites in the U.S. for the lower cost manufacturing of energy-saving LED-based luminaires. The automation work could also include the development of integrated LED based luminaire components more amenable to low cost, automated manufacturing. The work should demonstrate successful implementation of integrated systems design, supply chain management and quality control processes.

DISCUSSION POINTS

- Perform study on how to retool luminaire manufacturing for SSL technologies
    - The assembly of LED luminaires needs to be standardized.
    - Maybe we can automate the process of building a light engine.
    - We are in a Just-In-Time manufacturing environment. Even commodity fixtures are build-to-order rather than build-to-stock. There needs to be a better connection throughout the supply chain.
    - Identify the internal manufacturing processes, and determine where the disparity is between LED luminaire manufacturing and traditional luminaire manufacturing.
    - Improve manufacturing equipment to reduce cost of ownership
- The supply chain needs to be shortened and integrated to eliminate the inefficiencies of multiple players. The development of a total solutions provider would improve the industry.
- Identify standardized building blocks for LED luminaires and drivers.
    - What we need is innovation in luminaire design and a more efficient supply chain.
    - LED Device standardization will lead to competitive LED prices and improved LED availability
    - A large scale manufacturing approach to SSL products does not address small design runs. The trend is turning to JIT manufacturing and short term manufacturing. The most efficient way to do lighting design is to design specifically for each space.
    - Standardization of some parts is needed to help reduce inventory costs, allow for substitutions, and simplify design efforts, e.g. power supplies.
- Reduce cost, increase flexibility of applying SSL in finished luminaire product
    - There is a need for modules for people who do not know how to design the boards. You will begin to see them this year. Philips and GE and several other companies are working on this.
- Small-scale manufacturing equipment to accelerate innovation
    - Need to introduce techniques such as 3D printing and local small scale manufacturing to speed up cycle times. For example, small scale and flexible pick and place equipment would enable innovative designs. The use of 'chip-on-flex' could further simplify custom manufacturing.
    - There is a need for machines of consistent design in order to avoid support problems..
    - You also need to look at the implications of scaling up all the manufacturing, such as environmental issues.

M.L2. Phosphor Manufacturing

Support for the development of improved manufacturing of phosphors. Development of high volume (kg-scale) phosphor manufacturing methods to reduce cost and improve consistency of phosphor materials used in high efficiency solid state lighting products.

Discussion Points

- The phosphor costs in the roadmap can be roughly split into phosphor application technology (1/3), phosphor materials (1/3) and IP licensing application fees (1/3). If you can reduce the IP costs, then the manufacturing and application costs will dominate. Developing or exploiting domestic IP would address the need for cost reduction.
- We need to establish high volume manufacturing of phosphors in the US.
- Phosphor production is currently a long moving furnace – with many small crucibles.

M.L3. Phosphor Application

Support for the development of tools and processes for the rapid and accurate phosphor deposition onto LED chips and remote phosphor components. This includes support for optical monitoring tools, deposition tools, and the development of manufacturing processes with improved binning yields and reduced materials usage for lower costs, and consistent color quality components.

Discussion Points

- Improve phosphor application techniques
  - Smart phosphors are being used where the phosphor can be altered to reduce the distribution of color.
  - Phosphor application costs are likely to decrease since they are still in the early, trial and error stages.
  - Currently the matching of LED and phosphor to achieve a specific color point is a manual process and would benefit from automation.
  - There is an inherent efficacy advantage to moving the phosphor off the device. However, if you have to use more phosphor on a disk it puts remote phosphors at a cost disadvantage.

M.L4. Test and Inspection Equipment

Develop high speed non-destructive optical test equipment and standardized test procedures for semiconductor wafers, epitaxial layers, LED die, packaged LEDs, modules, luminaires, and optical components. Equipment might be used for incoming product quality assurance, in-line process control, or final product testing/binning.

Discussion Points

- Testing
  - High speed monitoring of color quality and color consistency needs to be implemented in order to improve back end quality and lower costs.
  - Test equipment would facilitate the automation of LED and phosphor matching, and speed up final device binning.
  - Need to test things in a module
- Improve measurement of low defect density ($<10^8$) substrate materials
- Improve measurement of LED performance at use temperatures.
  - One of the roadblocks is the uncertainty of LED performance at actual use conditions (85°C steady-state versus 25°C pulsed). If luminaire manufacturers had this data, they could use the information to get better products out to the market.

M.L5. Tools for Epitaxial Growth

Support for the development of manufacturing tools for lower cost of ownership and more uniform epitaxy. This could include crystal growth tools with improved yield, throughput, materials efficiency, growth uniformity, and overall cost of ownership while maintaining the LED performance at state of the art levels. This task could also support in-situ metrology equipment which can improve growth uniformity, yield, and/or materials usage efficiency.

Discussion Points

- Develop scalable equipment for HVPE
  - In order to sustain an industry that can produce high volumes, you need to develop suitable manufacturing equipment.
  - Demonstrate the case for using HVPE templates in the LED production process. Partner with LED manufacturer to demonstrate LEDs with equivalent performance and reduced cost.
- Develop multiwafer reactor for activated MOCVD growth
  - MOCVD is a thermally activated process leading to difficult trade-offs and inefficient precursor utilization, especially during the growth of InGaN layers. High temperature is required for efficient dissociation of ammonia whereas low temperature is required to avoid indium desorption. Need to develop a non-thermally activated process (e.g. plasma or light) for better utilization of expensive precursors (currently the most expensive component of the epitaxial wafer cost).
  - The ammonia process is extremely inefficient and is a significant cost component of the epitaxial layer.
  - Maybe better quality control on the front end would lead to improving the downstream manufacturing. Someone who controls the process from epitaxial growth to the light engine would know best how to do this.
  - Improved COO

M.L6. LED Packaging:

Identify critical issues associated with back-end processes for packaged LEDs and develop improved processes and/or equipment to optimize quality and consistency, and reduce costs. Improvements might involve the development of automated assembly equipment and wafer-level assembly methods.

Discussion Points

- Back end processing accounts for 60% of LED cost which translates to 25% of the luminaire cost
  - Automation may reduce the cost and allow for U.S. manufacturing of packages
  - Packages designed for manufacturing may substantially reduce costs
  - Appropriately designed packages could also reduce luminaire manufacturing costs
  - High speed inspection equipment may increase throughput
- Identify specific back-end processes that are amenable for cost reduction and ways to improve them.
- The package and optimization of the packaging is each company's IP.
- Conduct materials characterization to assure quality of LED materials
  - One of the first steps would be to characterize all existing materials being used in the industry. This would provide the basic information (types, costs, locations, behavior, etc) of where we are at.
  - A second part of this characterization would be to determine how all the additive features (flame retardants, lens plastics, etc) affect the LED.

    - This could include an LM-80 characterization of materials, where you take an LED and see what happens to the materials.
    - Lenses have a big effect on the color quality and lumen output of an LED. However this effect is not quantified in a model. It would be fairly easy to collect the data to produce a model outlining the impact of lenses.

M.L7.Driver Integration and Manufacturing:

Solution might involve disaggregating/separating driver functions in order to integrate them more flexibly within the luminaire assembly while maintaining thermal performance and high reliability.

Discussion Points

- Identify standardized building blocks for drivers.
- The power supply is a place where we have the capability to drive costs down. Scale gets some cost reduction, however there are other cost reduction opportunities.
- Drivers have not advanced in reliability or life while the rest of the LED components have.
- The electrolytic capacitor is the weakest link. It degrades over time.
- The power supply needs to be researched so that the driver can be run at a higher temperature.

Recommendations for Core/Product Development

- Driver/Power supply products
    - Identify standardized building blocks for drivers.
    - Develop drivers with better reliability and higher life.
    - Develop more robust capacitor with longer lifetimes
    - The power supply needs to be researched so that the driver can be run at a higher temperature.
    - Develop drivers with demonstrated reliability compatible with LED lifetimes and readily integrated into LED luminaire products. Could include power supply/driver products with modular sub-components.
- Substrates
    - GaN substrates
    - Engineered substrates to improve growth uniformity and reduce LED cost
- Luminaire design software
    - Software can input data files from incoming components and model optical, thermal, electrical, and reliability performance
    - Support of standardized data files will improve product reliability and customer confidence
        - Driver performance
        - Optical performance of lens materials
        - Thermal performance of interface materials
        - Standardized reporting of LED electrical, thermal, and optical performance
- Improve integrated system approach to design
    - Identify product opportunities in the value chain where additional integration of components can reduce costs, improve performance, and simplify luminaire integration.
        - Thermal interfaces can be removed
        - Components can be integrated for a reduced part count
        - Integrated components can offer reduced product variability

        - Components with common electrical, thermal, and/or optical interfaces can be developed to simplify luminaire manufacturing
    - Reducing number of parts, simplifying assembly requirements and tolerances.
    - There are a lot of buried costs associated with distributing the heat that is generated. If this problem is approached in the standard way, there are extra materials that are embedded in the design which add costs. Alternative design approaches can reduce these costs.
        - Currently for every Watt that goes into an LED, around 0.5 W (50%) is extracted as heat. This number is expected to be 30% in 5 years.
    - Integrating all of the design, using accurate modeling software, will help. If the software industry is provided appropriate funding, they will be able to handle such a design easily.

General Recommendations for SSL Program

- DOE should continue to fund working groups for outreach and market coordination. DOE should also incentivize adoption of LEDs for consumers
- Develop U.S. portions of supply chain for materials and tools
    - Asian LED manufacturing tools are designed for an Asian market—Asian companies sell to Asian market first. Thus, it is difficult for US manufacturers to get a hold of certain foreign-developed tools.
- Support LED test data standardization
- Support global standards for SSL products – multiple standards/requirements add to luminaire cost
- The SBIR process is burdensome. A cleaner process would make this much easier for small scale manufacturers
- The DOE is encouraged to introduce ‘Micro Grants’ to stimulate innovation among smaller luminaire manufacturers, encouraging them to look at using LEDs, and help them get over the initial tooling cost. This approach would bring more products to market.

Presentations

1. **Addressable LED Concerns**
   Dennis Bradley, GE Lumination
    - LED availability- the supply of packaged LEDs does not meet demand and will not meet traditional availability lead time. Thus, DOE must support increasing output capacity.
    - US manufacturing- current manufacturing structure will be difficult to keep domestic because of high costs associated with supply chain, product, and inventory. Thus, work to convert US manufacturing by adding equipment and processes to populate LED boards and light engines.
    - Product performance exaggeration- heightened marketing and claims leads to customer dissatisfaction, hurts product adoption, and realistic companies. Thus, create standards for what and how data is collected, reported, and enforced.
    - LED device standardization- market differentiation has led to difficulty in interchangeability. Thus, work with ANSI/ NEMA to drive standard to using competitive bid process to get best price for LEDs, increasing overall SSL adoption.

2. **An Integrated Approach to SSL Manufacturing**
   Paul Pickard, CREE
    - There are 5 main contributors to the current LED cost structure:

    - LEDs, Mechanical, Driver, Optics, and Assembly
- By solely focusing on the cost reduction of the LED, the overall price will still be high. Thus, must use an integrated manufacturing approach to optimize each sub-system. This can be done by simplifying the SSL luminaire and getting rid of the unneeded "stuff".
- While focusing on cost, the performance, quality, consistency, and holistic system must be effective and marketable.
    - The semiconductor industry was successful because they all got on board one technology and the entire market focused on it. It was not important which technology was the best, it mattered that everyone supported it.
    - It is expected that the industry should turn to standards when everyone can achieve 200 lm/W and do so cheaply, which will probably occur in the 2016-2020 time range. This is because standards are good at eliminating little inefficiencies in developed technologies.
- ANSI standards take around 5 years to develop, so if we start now, the first standards may be completed around 2015.

3. Testing and Standards
Paul Kennedy, Philips

- LED test data standardization- although there is a standard at 25C, it does not reflect real-world situations. Thus, more realistic measurement standards should be established to reflect accurate LED performance.
- Reliability testing- current reliability LED reliability tests are not as robust as those for Lamps and Lighting Fixtures. Thus, reliability measurement standards need to be created for Lamps and Lighting Fixtures for LEDs to better and correctly inform consumers.
- Global standards- multiple regulatory bodies may or may not be coordinating standards for LEDs. It would be advantageous to push DOE Energy Star as global standard to avoid local regulatory complexities.

4. Bulk GaN Wafers for SSL
Edward Preble, Kyma Technologies

- Hydride Vapor Phase Epitaxy (HVPE) process is excellent for growing boules but not good for making seeds.
- Ammonothermal growth process is bad for growing boules but good for making seeds with high structural quality.
- Using HVPE to grow boules on ammonothermal-grown GaN seeds is the optimal approach, rapidly replicating with the desired electrical conductivity.

5. Advancing Technologies to Improve Product Application and Luminaire Manufacturing
Kevin Willmorth, Lumenique, LLC

- Since the core LED technology is established, it is time to expand product offerings to grow market presence and market demand.
    - Done by supporting innovation and entrepreneurship in product and manufacturing processes.
- Need help with the costs for new technique integration, establishing standard LED packaging, developing modular driver/power supply components, and automation of UL processes.
- Must develop technology to facilitate flexible designs and support low inventories of finished goods.

- One solution is to make $200,000 grants to companies for integrating SSL into luminaire manufacturing processes.

6. **Back end process presentation**
   Bill Quinn, Veeco Instruments, Inc.
   - "Back end" processes need a more detailed cost model to evaluate cost improvement. This is because these currently account for >60% of LED cost and ~25% of luminaire cost.
   - Light creation and extraction have large cost multipliers
     - The epitaxial structure and process determine light creation/extraction efficiency.
     - InGaN growth conditions fail at high temperatures (but are required for NH4 decomp).
   - Some methodologies exist in the lab but need production sized equipment to realize the activated growth potential.

7. **Phosphor Manufacturing presentation**
   Yongchi Tian, Lightscape Materials, Inc.
   - Nitride and oxynitride phosphors are almost ideal color converters for pcLEDs. However, the demand will not be able to be met in the next 5-10 years.
     - Deliver warm white (CCT<4000K, CRI>85, CQS>90), High power package (>5W package), High efficiency at high operation power (QE>90% for red), long lifetime (>>50,000 hr)
     - Demand ~3,000-5,000 kg by 2012 (based on Osram estimate)
   - Need IP-backed, commercially viable products in the US to compete with Japan and the EU.
     - LED lamp makers currently have no access to necessary and quality phosophors
     - Lightscape is developing IP-backed products under DOE SSL
     - Few US universities train phosphor engineers/scientists while the field continues to rely on hands-on experience and know-how.
   - Create a manufacturing technology base in the US to help scale processes up and ensure batch-to-batch consistency. Also, develop a cost effective and robust manufacturing process with quality control.
     - Reduce product cost <$5k/kg.

DOE LED Roundtable Participants

David I. Lackner	Applied Materials
Paul Pickard	Cree
Dennis S. Bradley	GE Lumination
Jeff Lagaly	Intematix Corporation
Richard Solarz	KLA-Tencor Corporation
Edward Preble	Kyma Technologies, Inc.
Yongchi Tian	Lightscape Materials, Inc.
Kevin L. Willmorth	Lumenique LLC
Geoffrey P. Hunt	Osram Sylvania
Frazer Anderson	Oxford Instruments
Paul Kennedy	Philips
Andrew M. Hawryluk	Ultratech
William E. Quinn	Veeco Instruments, Inc.

Appendix: Cross-References Between Manufacturing Tasks and the 2009 Roadmap and 2010 MYPP

If you are interested in participating in the discussion for an individual task listed below in bold, you may wish to read more by referring to the Roadmap and MYPP sections listed below each task. Unless otherwise noted, cross-references are to the 2009 Manufacturing Roadmap.

M.L1. Luminaire/Module Manufacturing
Section 1.2 (Figure 1)
Section 2.1 (Figure 5, Table 1†)
Section 2.2 (Figure 7)
Section 2.4

M.L2. Phosphor Manufacturing
Section 1.2 (Figure 2)
Section 2.1 (Figure 6, Table 1†)
Section 2.3.3/2.3.4

M.L3. Phosphor Application
Section 1.2 (Figure 2)
Section 2.1 (Figure 6, Table 1†)
Section 2.3.3/2.3.4

M.L4. Test and Inspection Equipment
Section 1.2 (Figure 2)
Section 2.1 (Table 1†)
Section 2.2 (Figure 7)
Section 2.3.3
Section 2.3.4 (Figure 12 and 13, Table 3)

M.L5. Tools for Epitaxial Growth
Section 1.2 (Figure 2)
Section 2.1 (Figure 6, Table 1†)
Section 2.3,1 (Figure 9, Table 2)
Section 2.3.2 (Figure 11)

M.L6. LED Packaging
Section 1.2 (Figure 2)
Section 2.1 (Figure 6, Table 1†)
Section 2.3.2 (Figure 11)
Section 2.3.3/2.3.4

M.L7. Driver Integration and Manufacturing
Section 1.2 (Figure 1)
Section 2.1 (Figure 5, Table 1†)
Section 2.2 (Figure 7)
Section 2.4

† See Table 4.4 of 2010 MYPP for updated LED projections.