Solid State Lighting LED Manufacturing Roundtable Summary

Introduction

On March 13, 2013, fourteen LED experts gathered in Washington, D.C., at the invitation of the Department of Energy (DOE) to help identify high-impact task areas for the Manufacturing Research and Development (R&D) Initiative. Participants were asked to give brief presentations addressing one or more of the discussion questions distributed prior to the roundtable meeting. These discussion questions, listed below, relate to the barriers and opportunities associated with the current state of LED manufacturing, as well as how DOE can best facilitate progress within the industry.

1. To realize the full energy savings potential envisioned by the DOE SSL program, the supply of SSL products will need to expand by orders of magnitude. In terms of light output, they need to grow from providing a very small percentage in 2012 to 1500 Tlm-hrs by 2025, just for the residential sector. By that time, almost half the electric light in the US should be coming from SSL sources; globally it may be more. That suggests that fundamentally new manufacturing methods and processes will be needed very soon to get the ball rolling! What needs to be done? Who does what? How does DOE help? Can this need be met?
2. What innovation(s) could lead to a step change in SSL performance, cost and deployment?
3. Are existing test procedures and equipment suitable for high volume production? What changes are needed? How can we reduce the cost of testing? What can DOE do to facilitate it?
4. Where are the weaknesses in the manufacturing supply chain? How might we address them?
5. How can DOE best assist manufacturers of materials, components, and equipment?
6. Are there specific common problems where a collaborative approach might be most effective?
7. What will the LED manufacturing landscape look like 4 years from now? What actions can DOE take to have the most beneficial impact on the US SSL manufacturing industry?
8. Is there specific future-looking manufacturing R&D that DOE can support for the benefit of LED lighting manufacturers, such as automation, wafer level packaging, automated testing, etc.?
9. How can the DOE SSL Program best help to facilitate development of advanced manufacturing for SSL? Are solicitations and individual projects the right path? In what areas of manufacturing, generally, is DOE likely to have the biggest impact? Are there projects that could have a dramatic and rapid impact?

Participants were also asked to comment on the organization and content of the Manufacturing Roadmap.

This report summarizes the discussions of the roundtable meeting, including the tasks framed in the Manufacturing Roadmap, a summary of discussion points relevant to those tasks, and an outline of participant presentations and remarks.

Discussion of Questions

Participants of the roundtable provided short presentations as outlined below in response to the discussion questions.

Question 1
To realize the full energy savings potential envisioned by the DOE SSL program, the supply of SSL products will need to expand by orders of magnitude. In terms of light output, they need to grow from providing a very small percentage in 2012 to 1500 Tlm-hrs by 2025, just for the residential sector. By that time, almost half the electric light in the US should be coming from SSL sources; globally it may be more. That suggests that fundamentally new manufacturing methods and processes will be needed very soon to get the ball rolling! What needs to be done? Who does what? How does DOE help? Can this need be met?

Jay Montgomery, Veeco Instruments, Inc.

- Cost of ownership (COO) is the key to reaching the market inflection point and will continue to drive the demand curve for earlier adoption of LED lighting.
- DOE can help manufacturers meet future demand by funding "side" and "forward reaching" projects that would not necessarily be supported within the industry.
    - DOE funding, related to the development of MOCVD equipment for critical epitaxial device layers, helped accelerate Veeco's roadmap and resulted in the rapid release of the MaxBright multi-chamber platform which helped place Veeco in a market-leading position for MOCVD equipment.
- The LED lighting market is focused on a 4" wafer production path, especially China. The SSL market would benefit greatly from high-capacity, automated equipment with significant floor-space efficiency.
    - Projects focused on increasing automation are necessary to ensure that the industry can meet the potential future demand for LED lighting products.
- GaN-on-Si LED manufacturing is important for the future of LED manufacturing and one in which R&D investments are being made, especially in Korea.
    - DOE funding should not necessarily be directed to GaN-on-Si projects; however, DOE should be aware of the technology's progress and viability since it would lead to higher yields and hence greater adoption of LED products.
    - Projects the DOE could support that might accelerate viability testing include GaN-on-Si high yield reactors with significant automation.
        - Automation will drive adoption.
- SSL would benefit from a dedicated SEMATECH-like consortium this would:
    - Help build a common standard for device measurements,
    - And provide a more open arena for discussions to connect OEM's with critical manufacturing line performance.
        - OEMs need a connection with manufacturers to ensure performance metrics reflect realistic COO gains.

Paul Fini, Cree, Inc.

- Large improvements to the normalized price ($/klm or $/lm/watt) are still needed in the SSL manufacturing industry.
- LED replacement lamps are good for initial adoption by the risk-averse and help to result in more "immediate" energy savings with minimal initial investment but the industry needs to move beyond the replacement market towards new architectures, smart controls, and ultra-high efficacy.

    - Replacement lamps have no need for DOE funding because industry will drive this on its own.
- DOE should focus on LED luminaires and the development of new architectures that better utilize LED emission as new point sources. These luminaire designs should be integrated, use intelligent controls, and widely leveraged platform architectures making the fixture compatible with what is best for the LED properties.
    - Luminaires currently have a very broad selection of options (there's a large SKU); the designs and features need to be simplified.
    - Controls should be the initial focus of SSL intelligence; eventually these can be incorporated at a higher level.
- DOE also should push for standardization and encourage performance specifications for applications and luminaire types beyond just A-types and streetlights, similar to their efforts for the Streetlight Consortium.
    - Allows the industry to better educate consumers with realistic expectations.
    - Fosters a simplified more transparent supply chain.
    - Result in lower $/klm.

<u>Jerry Zheng, iWatt, Inc.</u>

- Drivers still represent one of the weakest links for LED lighting products.
- Currently the manufacturing cost of the driver comprises ~80% bill of materials, 5-10% assembly, 5% testing, and 5% mechanical.
- In order to get the driver costs down many driver manufacturers will sacrifice the driver quality and reliability.
    - Poor driver quality has led to product recall and safety issues due to flickering, dimmability issues, and health impacts (stroboscopic effect). Product recall is a big concern for manufacturing companies.
    - Most of the recall issues center around TRIAC dimmers, which make up the majority of currently installed dimmer systems. Currently no one has the perfect solution for how to make LEDs work with these dimmer systems and this has a big impact on price.
    - Research is needed to understand retro-fit dimming approaches and the impact of flicker on human health. Universities may be the best group for this task.
- Better driver reliability modeling and software is needed; currently the industry's model is based on MTBF.
- Currently there is no standard interface between the LED and driver module; standardization of manufacturing processes, component specifications, and test plans must be developed.
    - Furthermore, there needs to be more localization for LED manufacturing. The business model needs to change to local assembly thereby saving costs and reducing risks.

<u>General Discussion</u>

- The ability to achieve DOE's light output goals is not simply based on manufacturing capacity or capability. It is primarily based on market adoption of the technology regardless of the application.
- Market adoption of the product is hindered mainly by cost until a tipping point is reached when paybacks become more realistic.
- Quality and reliability also play a role in market adoption. A big issue with SSL product reliability is failure caused by driver issues. From a market adoption and manufacturing standpoint, driver quality is key.
    - Currently there is an unrealistic vision of the reliability of these products. The lifetime claims may be reliable for the LED packages themselves but they are not accurate for the luminaire's lifetime. The community needs to be educated on this issue.

- DOE could support the industry on developing driver standards.

Question 2
What innovation(s) could lead to a step change in SSL performance, cost and deployment?

<u>Devendra Sadana, IBM Corp.</u>

- The industry needs to develop a novel, low cost LED manufacturing technology.
- Key LED architectures will play a role in this development. Currently, most LED architectures are based on a lateral structure but employing a vertical structure would enable higher efficacies to be achieved.
- There is a great need for high quality low cost substrates as the cost of substrate reflects heavily on the resulting price of an LED.
    - IBM has developed a high quality substrate that can be reused, and therefore has great potential to reduce substrate costs. This technology also allows you to get a higher efficiency out of the LED device. The new process involves controlled spalling which has been demonstrated on GaN with success.
- DOE should help with the adoption of this technology and help facilitate collaboration for further research. IBM wants to bring this new technology to manufacturing but lacks proper funding.
    - This technology can produce thin flexible substrate layers and has the potential for high volume Roll-to-Roll (R2R) processing with some initial investment.
    - In collaboration with Veeco, a tool to help commercialize this technology could be developed.

<u>John Tremblay, Osram Sylvania, Inc.</u>

- Traditional lighting suppliers have achieved market expectations for performance, cost, and deployment, and have developed a strong supply chain. LED manufacturing needs a similarly strong supply chain in order to drive performance and cost improvements.
- Currently there are several weaknesses to the LED supply chain. These include:
    - The vast majority of components are produced overseas which impacts costs and inventories.
    - The lack of design stabilization creates a diverse bill of materials (BOM) and prevents volume leverage on prices.
- The LED supply chain could be strengthened by increasing manufacturing in the US. Manufacturing the volume needed locally cannot be done in a cost effective manner without some kind of automation. However, as long as BOM cost is high and the cost of automation is high, manufacturing will be done in other countries.
- Design for manufacturing and design stabilization is needed. Until the design is stabilized or standardized, US LED manufacturing cannot move forward. Design stabilization allows for more automation which combined with product differentiation would strengthen US manufacturing. There are several techniques to accomplish this:
    - Focus on new manufacturing techniques vs. processes.
        - Molding "in-place".
        - "On the fly" board printing.
    - Develop more intelligent equipment and leverage technology (virtual management).
        - Equipment for rapid design change such as flexible line and 3D printing.
        - Automation design testing.
        - "Smart" (virtually driven) factories.
    - Improve technical skill sets of workers – this can be more important than developing some manufacturing processes.
        - Problem solving, project management.

        - Design for manufacturability and better modeling.

<u>General Discussion</u>

- There needs to be a faster testing method over the current UL submission method. In electronics, a lot of ICC testing is performed so there are some test systems available but there is no automated circuit testing. There is not any focus currently on how to automate testing or acceptance.
- The industry would benefit from developing a more flexible approach to testing within the manufacturing line (e.g. testing on the fly) and from the use of predictive modeling to help minimize final product testing requirements.
- New modeling techniques are also needed. 21st century modeling is not the linear modeling of the past; design of material is now embedded in the process.

Question 3
Are existing test procedures and equipment suitable for high volume production? What changes are needed? How can we reduce the cost of testing? What can DOE do to facilitate it?

<u>Warren Weeks, Hubbell Lighting Inc.</u>

- Compliance and testing through UL is currently too lengthy a process. There are no UL listed SSL components. In particular, UL driver standards do not currently exist nor is there any push to create them.
    - Industry needs to develop driver standards in order to move towards driver interchangeability.
- Currently, the available SSL standards are all over the place. Both Energy Star and DLC specification are not necessary. There is little connection or common testing among certification bodies and they are smothering the industry with different testing standards.
    - For example, UL requires thermal behavior testing but Energy Star does not.
- Furthermore, CA Title 24 for 2014 will be implemented soon and it is unclear whether the SSL industry will be ready.
- Lighting manufacturers spend a lot of money on compliance testing as there are currently no "best practices" for measuring flux, CCT, and CRI for the final luminaire/fixture. This is especially true for large fixtures.
- Full testing on outdoor fixtures is a challenge for luminaire manufacturers. There is also no consensus on how burn-in testing is conducted or even whether it is required.
    - Should burn-in tests be conducted for the driver, deck assemblies and/or final fixture? There are no industry standards on what is enough or necessary.
- Reliability and driver performance is another big issue. . The current methods to predict driver reliability are not adequate. MTTF and MTBF are not good metrics for driver failure.
    - LM-80 is not sufficient to use on the fixture; it does not account for several important factors (i.e. the driver).
    - The industry needs better understanding of driver performance and independent testing.
- Required end-of-the-line testing for controls (e.g., photocell testing) also needs to be standardized.

<u>Dennis Bradley, GE Lighting Solutions, LLC</u>

- The industry still needs common standards and testing/regulatory requirements. Currently there are many competing testing requirements (i.e. Energy Star, DLC, UL) which makes any degree of standardization difficult.
- Lumen maintenance protocols for LEDs, lamps, and luminaires require many hours of testing, and accelerated lumen testing is very difficult.

- Life claim standards need to be developed because many manufacturers claim luminaire lifetimes equal to the LED lifetime. These standards should cover technology not warranties.
  - Warranty policies should be determined by the manufacturer.
- The top two drivers for consumer adoption of LED products are light output and cost; lumen output level cannot be too low and cost cannot be too high.
  - Lifetime and color quality are also important, but to a lesser extent.
  - In general, consumers do not trust claims for product lifetimes over 10,000 hours and cannot even fathom 25,000 hours.
- The contributing factors to LED replacement lamp costs are:
  - Power factor. LED power factors can range from .9 to as low as .1 as compared to CFL power factors of around .5.
  - Strict regulatory requirements.
    - Currently, GE's non-Energy Star products are selling better than their Energy Star rated products largely due to lower costs.
  - EMI, current ripple, life requirements in excess of 10 years and luminous distribution are other contributing factors to costs.
- The industry needs some level of standardization.
  - Physical interchangeability will be a benefit of standardization.
  - Establishing a standardized footprint or form factor can be done now with the LEDs on the market.

<u>General Discussion</u>

- The lighting industry has been around a long time so there are many regulatory bodies that require testing to meet certain requirements. There are legacy tests that have been slightly tailored to meet the needs of SSL but the DOE cannot control UL or Energy Star therefore the LED industry needs to take another approach to solving issues related to testing.
  - One method could be to learn from what other industries have done in similar situations. For example, SEMI has done a lot of work on manufacturing standards for photovoltaics and flat panel displays. Holding a meeting or panel session with SEMI to discuss all the different standards, their complexity conflicts and how to interpret or approach them could prove useful.
- Manufacturing overhead costs are much more burdensome then direct manufacturing costs. Manufacturing overhead costs and time to market is preventing manufacturers from being able to sell the products at the prices needed to spur adoption. In the past, focus has been on the BOM and while these costs are still important overhead and testing costs are the biggest issues.
  - If the testing and compliance costs are included in the consumer cost it will only serve to hinder further adoption. It is the additional costs that make it difficult to get the product into the consumers hand cheaply.
- Distribution channel costs are also an issue since there are so many channels involved, each of which increases costs. More fixture level testing will remove added distribution channel costs. Distribution channel costs can also be alleviated by consumer education.
- Driver manufacturing lags behind the rest of the manufacturing community and presents an opportunity for innovation and cost reduction.
- Simplifying the product design and thus the supply chain will also reduce costs.

Question 4
Where are the weaknesses in the manufacturing supply chain? How might we address them?

General Discussion

- Lack of standardization makes the supply chain harder to manage. Until SSL products are standardized (e.g., standard form factors) the industry is forced into a build-to-order model instead of a build-to-stock model.
- Proliferation of SKUs is a big issue.
- A few standard products would make managing inventory and supply chains easier and allow for construction of more efficient lines to market *however* this is not the nature of lighting.
    - There are a few applications where a relatively small pool of designs will work *however* SSL needs to stop trying to change the nature of lighting and begin thinking about flexible manufacturing methods and technologies for SSL.
    - Several participants disagree with this mindset believing that if SSL makes a few very specific products with very specific form factors this will satisfy consumers. If the focus is to be on driving down the costs of the products then simplification is necessary.
- The greatest weakness in the supply chain is the driver. The driver needs to be brought up to speed with LEDs.
    - Some LEDs are interchangeable but dual sourcing of drivers is challenging and UL poses issues as well.
    - Having the right driver in the right location at the right time is the big weakness for the industry right now.
- Another problem in the supply chain is that suppliers sometimes deviate from the specification.

Question 5
How can DOE best assist manufacturers of materials, components, and equipment?

This topic was addressed in combination with Question 6.

Question 6
Are there specific common problems where a collaborative approach might be most effective?

James Zahler, GT Advanced Technologies, Inc.

- There is no need for DOE to continue funding sapphire research. Currently, the touch screen/electronics industry is driving sapphire technology.
    - From a sapphire for LED standpoint, supplies can be ramped up very fast.
    - However, if smartphone displays move towards utilizing sapphire it is likely that short term supply shortages would occur.
- GTAT in partnership with Soitec has been working on developing high productivity HVPE equipment. The benefits of a hybrid HVPE/MOCVD process include:
    - Reduction of epitaxy stack costs by roughly 25 percent,
    - Increased LED quality (thicker/smoother n-GaN layer), and;
    - Significantly increased throughput and simultaneous reduction in capital expenditure (CAPEX) for MOCVD.
- GTAT has also developed an implantation system that enables the production of thin substrates with negligible kerf loss and lower consumable cost.
    - This process originally developed for silicon on insulator substrates for a bonded composite substrate has many potential applications such as solar, sapphire and SiC. It also could be used for very low density polar GaN.
- DOE funding should be focused on standards and opportunities that drive costs down.

    - One example is wafer standards, such as those being developed by SEMI, to clarify requirements.
- New materials technology is another area where DOE investment should be focused.
    - A big emphasis should be placed on fostering collaboration. to help defray some of the risk associated with developing new materials.
    - Facilitating opportunities for collaborative projects that enable material developers and device manufacturers to work together.
        - For example, GTAT can build the equipment but needs collaborative efforts to prove the value.

<u>Frank Burkeen, KLA Tencor, Corp.</u>

- KLA Tencor is exploring opportunities to reduce cost at the emitter level and have several DOE supported equipment manufacturing initiatives with active end-user involvement:
    - Candela 8620 (epitaxy yield improvement project) – completed in 2012
        - Helped to improve sapphire quality control and the ability to use defect maps.
    - Faster/more accurate hot testing – ongoing and initiated in 2012
- Significant cost savings can be realized with an LED epitaxy binning solution.
    - Off-specification dies are the single largest contributor to poor yield.
    - Average bin yields continue to be a challenge requiring innovative solutions throughout the manufacturing process.
- Cost savings would be recognized if the industry can understand yield earlier in process (i.e. on demand manufacturing).
    - To effectively execute this feed forward approach requires deriving the performance data at the un-patterned epitaxy level. This is a major hurdle to overcome for this process to work.
        - Comprehensive parametric measurements after LED epitaxy are needed but technically challenging.
- DOE's role should be to support projects that are 1) available industry wide; and 2) would not happen without a DOE-industry partnership.
    - Risk is a big factor for many companies and the availability of project funding support helps to lower the risk.
- Many manufacturers have good ideas but not significant IP. DOE could push for collaboration along these lines – taking the sensitivity out of IP and fostering collaboration.

<u>Gary Shuck, Intematix, Corp.</u>

- Standardizing characterization methods for phosphors is a challenge.
- LED package suppliers all have their own phosphor testing method for measuring brightness/QE and chromaticity. These disparate methods do not correlate well (correlation coefficients are as low as ~0.7).
    - Unlike phosphor manufacturers, LED manufacturers have their own bin distributions allowing them to average out the noise. Phosphor manufacturers need reduced variation.
- Precision of current measurement techniques are poor and thus require many samples. This is costly and time consuming.
- The industry needs a standardized phosphor characterization method to mitigate these issues.
    - Defining these characteristics will allow manufacturers to better supply the customer with a product that meets their requirements and may also lead to improved color control as well as yield.
    - This would best be done through a collaborative project.

- The benefit would be reduced variation in phosphor performance that would help the whole industry by improving color control and yield as well as reducing recipe tuning time leading to faster cycle times.

General Discussion

- The industry would not be where it is today without the support of the DOE.
- From a manufacturing standpoint, the industry needs to break away from the chip or component and move to the luminaire. There needs to be more input from driver manufacturers.
  - Developing a roadmap at the lighting fixture level might be needed.
- Luminaire manufacturing and integration is important to the manufacturing effort, so specifically how does the DOE support that? What does this support look like on the luminaire side?
  - Maybe a CALiPER type program at the manufacturing level.
    - It would need to be more accelerated than the current CALiPER program; cannot lag behind a couple years.
  - Perhaps the reliability consortium which has been moving forward.
- Testing is a suitable subject for collaboration. For example, DOE could assist in establishing round-robin exercises to establish testing equivalence within the industry.

Question 7
What will the LED manufacturing landscape look like 4 years from now? What actions can DOE take to have the most beneficial impact on the US SSL manufacturing industry?

This topic was addressed in combination with Question 8

Question 8
Is there specific future-looking manufacturing R&D that DOE can support for the benefit of LED lighting manufacturers, such as automation, wafer level packaging, automated testing, etc.?

Michael Bremser, Tempo Industries, Inc.

- There is a lack of confidence in overall products and technology, and although strides have been made to this end, there is still more work to be done.
- SSL industry support channels face various issues today:
  - Distributors face the challenge of an ever changing product line.
  - Established fixture manufacturers have had to spend money bringing products to market while their legacy business declines.
  - Startup groups are faced with the question of whether the new lighting technologies they are pushing will really provide value and provide what the lighting industry truly needs.
- Looking into the future, it is important to consider what other value can be added to LED products beyond efficacy improvements:
  - Move beyond performance/quality and reliability metrics towards enhanced value propositions like controls.
  - Consider lighting in terms of the illumination produced by the system not simply a collection of LED bulbs and lights.
  - Add features. All consumers want lower prices but at some point they are going to want more features producing a trade-off with price.
  - Need to ask ourselves as an industry what else can be done? What is the effect of illumination on people?
- Where does the industry go from here?
  - Industry should provide a holistic, value proposition for customers rather than a “fixture”.
  - Lighting equipment manufacturers and components suppliers will need separate, yet synergistic, roadmaps.

    - Off-the-shelf and readily available components are needed instead of having to rely on trans-Pacific supply chains, sole source suppliers, and long component lead times.

Iain Black, Philips LUMILEDS

- There has been a blurring of the lines between high power (HP) and medium power (MP) LEDs for lighting applications. HP LEDs have traditionally been used for lighting while MP LEDs have been used for display backlighting. Recently MP LEDs have started to match the efficacy performance of HP LEDs using smaller and cheaper packages, and have become suitable for lighting applications.
- GaN-on-Si or GaN-on-GaN are future-looking manufacturing R&D tracks.
    - GaN-on-Si enables wafer scaling on smaller scales but the level of performance achievable is unknown.
    - GaN-on-GaN is viable but no money will be invested in large scale volume production on GaN in the next few years.
- The opportunity for high volume manufacturing without high performance (i.e., lighting niches or vertical integration) is limited. Cannot simply sell commodity parts without generating revenue in another way. One approach might be to regard these commodity parts as a loss-leader within a broader product portfolio to entice the customer toward higher margin products.
- If OLEDs take over the market, LEDs will lose a big customer base but will become available for new lighting opportunities.
    - This could potentially help the industry focus on the uses of LED lighting beyond the traditional form factors and enable the industry to extract more value from the technology such as additional applications or integration.
- The future of multi-color emitting light bulbs is currently unclear. Could these products be a player in the consumer markets or will they only truly be viable in custom applications.
- The future is likewise unclear for narrow band red phosphors and quantum dot (QD) technology. Will this technology really be developed enough over the next few years?
    - Efficacy improvements with narrow band red phosphors could be astronomical.
- DOE should focus on projects like the development of narrow band red phosphors which have the potential for huge performance advances.
- The DOE can also assist with the introduction of automated factories to help bring manufacturing of systems and modules to the US.
    - Need to move towards the development of standardized components and materials so that automated factories are a possibility.

Jennifer Burns, Philips Electronics North America

- The major considerations for determining locations for products manufacturing are:
    - Labor cost
    - Delivery time (customers want/expect instant delivery)
    - Shipping cost (largest concern is with luminaires)
    - Flexibility (quick design changes, CCT, light output, etc.)
    - Tariffs (LED lamps)
- There is some U.S. based manufacturing in terms of LED, modules and luminaires but in order to promote regional manufacturing on a large scale in the future it is important that the cost of labor be addressed.
    - Increasing manufacturing automation would reduce the labor cost component while at the same time increasing manufacturing capacity.
    - This raises concerns regarding standardization. As volume and automation increases in the manufacturing arena moving straight to standardization might stifle innovation.

- Moving manufacturing to the U.S. also brings new timing challenges. Currently, LED manufacturing technology is growing so quickly (product cycles are about six months) which makes it difficult to determine at what point automation can and should be introduced.
    - Moving manufacturing to the U.S. will be heavily dependent on increasing automation.
    - The Philips L Prize lamp is a prime example. Manufacturing was extremely manual and required significant testing. This product would not have been cost-effective to produce in the U.S. the way it was originally specified.
    - However, there could be an opportunity for LED manufacturing to improve and become more local using automation. For example, there is fluorescent lamp manufacturing facility in Kansas which is nearly 100% automated.
- How can the DOE help?
    - Standardization efforts should be focused on testing protocols and data requirements, and efforts should be made to reduce testing requirements. Over-specification and standardization at the product level should be resisted. Manufacturers need to be able to retain flexibility to allow them to make rapid changes on short notice to cope with short product cycles and high SKUs
- DOE can work to help reverse the current over-specification of LED products and investigate automation best practices in other U.S. industries. These could be benchmarked and translated to the LED industry.

<u>General Discussion</u>

- On the topic of standards, it is important to discuss standards in the context of manufacturing and only focus on those that will affect the manufacturing landscape.
    - Focus on identifying area that can be standardized without stifling innovation.
- Reducing duplication of testing would be helpful; defining what needs testing and what does not.
    - We have too many embedded testing requirements; how do we reduce or eliminate those.
- On the topic of automation, “industrial engineering” can be thought of as an intermediate step between manual and full automation. Equipment can be built to allow for faster and easier production.
    - This could be an area for collaboration that does not tread into competitive issues.
    - This would require identification of areas that are important to multiple companies.
- Specific manufacturing practices that the DOE could support include:
    - Research into prototyping methods that could be used to accelerate the market.
        - 3D printing has been used extensively for prototyping; does it have a place in manufacturing?
    - Low cost glass optics could be another manufacturing-based research area.
    - Research to model systems more effectively would facilitate faster design cycles. This includes DFM and simulation approaches.

Question 9
How can the DOE SSL Program best help to facilitate development of advanced manufacturing for SSL? Are solicitations and individual projects the right path? In what areas of manufacturing, generally, is DOE likely to have the biggest impact? Are there projects that could have a dramatic and rapid impact?

<u>Paul Fini, Cree, Inc.</u>

- There is too much overlap between DOE’s R&D plan (MYPP) and Manufacturing R&D Roadmap. Consider either consolidating or further differentiating them.
- DOE should also encourage performance specs for more types of lamps than just A-types such as downlights or 2x4 foot troffers.

    - Including different lamp types in the roadmap helps manufacturers educate consumers on what they should be expecting and give them real expectations about what they are getting. This reduces variation in the market and will lead to a simplified supply chain. The end result is lower end user $/klm costs.

General Discussion

- Need outside the box projects not simply incremental improvements. These will have a bigger impact if successful.
- Educating the end-user could also be a support role for the DOE. The individuals representing LED manufacturing as an industry lack adequate knowledge.
    - There is a gap between the current state of the technology and where consumers think that it is.

Manufacturing Task Notes

The following tables provide descriptions, metrics and goals for the discussed tasks. The task tables shown do not reflect any modifications suggested by roundtable participants. All comments, including suggested changes to each task, are summarized below each of the respective task tables. These comments represent a summarized transcript of the general commentary at the roundtables and require further discussion at the 2013 DOE Solid-State Lighting Manufacturing R&D Workshop on June 5th and 6th in Boston, MA. The combined results of the Roundtable and Workshop discussions will guide the DOE in soliciting projects for the LED Manufacturing R&D Program.

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

M.L1 Roundtable Participant Comments

- The development of new manufacturing methods for LEDs is still an important pursuit.
- DOE support should focus on LED luminaires and the development of new architectures that better utilize LED emission. These luminaire designs should be integrated, use intelligent controls, and leverage platform architectures.
  - Currently, luminaires have a very broad selection of options (i.e., large SKU); the range of designs and features need to be simplified.
  - 3D printing for the flexible manufacturing of LED luminaire optical components was also mentioned as being a research area opportunity for the industry.
- The description needs significant editing to clarify the focus of the task making it apparent that this M.L1 is devoted to bringing package *or* chip and subsequent luminaire together (while M.L6 is focused on the package).
  - The first focal area point also needs clarification, explaining that the objective is removal of superfluous interfaces and overall product simplification with solutions like chip-on-board (COB), chip-on-flex (COF), or mounting the chip directly on the heat sink. This

focal area could also be expanded to include better integration of any sub-component into the luminaire

- The current task format does not easily facilitate the drafting of suitable proposals; the description should be narrowed down and/or divided into more specific sub-tasks. Multiple suggestions were offered on how to partition this task; they are as follows:
    - Split into separate sub-tasks related to luminaire materials, assembly, automation, and modeling.
    - Separate into LED luminaire and package-related sub-tasks.
    - Separate each focal area into two sub-tasks, one at the component level and one at the fixture level; or at least include one grouping that is beyond the chip level.
    - Remove the materials portion of the luminaire from this task and incorporate it with the newly proposed stand-alone materials task.
- This task has three key sub-groups: materials, assembly, and modeling. Design for manufacture (DFM) and automation is also an important area but it can be coupled with assembly.
    - Materials:
        - There was support for the creation of a separate materials task that would incorporate some of the relevant focal areas noted in the current M.L1 task description.
            - Specific areas identified for inclusion in the materials task were phosphors, silicones and plastics.
    - Assembly:
        - Driver failure occurs in LED lighting products largely due to poor product assembly (i.e. poor soldering, spacing issues and contact failure). Better epoxy and heat sink materials are needed.
        - DFM/Automation should be a focal area of this task; this should be reflected in the description rewrite.
        - Research projects targeted towards increasing automation will help ensure that the industry can meet future demands for LED lighting products.
        - Research into existing U.S. automated manufacturing technology could also help facilitate the domestic manufacture of LEDs in the future.
            - Identify effective and currently employed automation solutions in other industries and translate these techniques or concepts over to LED manufacturing.
    - Modeling:
        - The seventh focal area point could be extracted from this task to serve as a basis for a separate modeling task.
            - In its current form too many areas are targeted; it needs to be parsed out.
        - The industry lacks good modeling software. An improvement in predictive modeling capabilities could enable a significant reduction in final product testing costs.
        - Model platforms should focus on the manufacturing process and performance predictions for the final luminaire product.
            - In order to develop a good predictive model with broad acceptance in the industry, collaboration between manufacturers will be necessary.
            - Other research opportunity areas include modeling driver performance and lifetime as well as component and overall luminaire reliability.
    - Modeling efforts geared toward the analysis of product/material consistency throughout the LED supply chain would help the industry and the DOE to better determine the most essential areas for further manufacturing research.

M.L2 Driver Manufacturing		
Improve the consistency and reliability of driver performance, reduce costs, and allow for greater flexibility in system design. Approaches may include emphasis on design-for-manufacture, automation, and attention to materials and components in the supply chain.		
Metric(s)	**Current Status**	**2015 Target(s)**
Luminaire cost reduction through driver integration ($/klm)		15% reduction in luminaire cost over non-integrated driver approaches
Driver cost ($/klm)	22	4

M.L2 Roundtable Participant Comments

- Driver manufacturing is an important research area mainly because driver failures cause luminaire failures. The lifetime of luminaires far extend those of LED drivers.
- Automated testing, modeling and lifetime predictions are all necessities for improving LED driver systems.
    - Better lifetime predictions are especially necessary as the current method, mean time between failures (MTBF), is not a useful way to gauge the reliability of the driver or any other individual system component.

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 5 years
$/Units per hour		50% reduction every 2-3 years

M.L3 Roundtable Participant Comments

- Luminaire quality control is still an issue within the industry.
- Similar to M.L1, there was a lot of support for parsing out M.L3 into three segments: modeling, materials and assembly.
- It was suggested to focus this task on the luminaire as fixture testing, particularly cheap fixture testing, was a recurring theme in the roundtable discussions.
    - LED die or packages should be excluded or at least separated from luminaires.
- Testing costs represent a significant portion of the total SSL product manufacturing cost due to extensive product and compliance testing for Energy Star, DLC, UL and other certification bodies.
    - Identifying the real cost drivers for luminaires allows the industry to better determine the areas that need attention.
    - Testing cost are particularly significant for large outdoor door luminaires due to the considerable time needed to complete photometric testing (i.e. time to reach thermal stabilization is significant).
    - In addition to the actual testing costs, the number of tests required is also burdensome.
- Device testing and specification costs translate all the way up to the luminaire. A lot of resources can be spent simply trying to determine the specifications.
    - A consortium on important electrical properties would help reduce these costs.
    - It is advantageous for luminaire manufacturers to know tolerance windows earlier on in the line. While this can be done through modeling, good quality data is still needed to feed into these models.
- As a manufacturer, having a wide distribution of photometric performance can be an important cost driver. Reducing or eliminating binning operations can remove substantial costs from the overall manufacturing process.
    - The industry is working on reducing binning. DOE can assist in these efforts by supporting projects that focus on narrowing the process window or development of equipment with better process control.
- While the majority of participants acknowledged that the additional testing overhead associated with binning is an issue, there was disagreement on whether development efforts should be funded by industry or government.
    - Some believed that government needed to support the industry to develop improved manufacturing equipment with better process control in order to reduce the need for binning (M.L4 and M.L5).

    - Others were of the opinion that since LEDs have reached suitable performance levels for consumers, the solution will be driven from within the industry as manufacturers realize the economic benefit from process improvements.
- Die-level testing is becoming a more serious issue. Since testing cost is independent of component size, performing tests on these smaller parts effectively increases the percent cost of the total LED.
- Developing good predictive models would allow for some of the testing costs to be removed. Reliability modeling is also needed. There is currently no good way to measure reliability – it takes too long and is too complicated.

M.L4 Tools for Epitaxial Growth		
Support for the development of manufacturing tools, processes, and precursors for lower cost of ownership and more uniform epitaxy.		
Metric(s)	**Current Status**	**2015 Target(s)**
Throughput (wafers/hr)	5 (for 2” equivalent wafers)	10 (for 2” equivalent wafers)
Wafer uniformity [1σ] (nm)	1.7	0.5
Wafer-to-wafer reproducibility (nm)	1.5	0.6
Run-to-run reproducibility (nm)	2.0	0.9
Epitaxy growth cost ($\$/\mu m \cdot cm^2$)	0.3	0.1

M.L4 Roundtable Participant Comments

- The industry is gradually transitioning to larger diameter substrates (e.g. 6” or 8” wafers) in the interest of reducing manufacturing costs.
  - A big advantage to switching from 2” to 6” substrates is that the most recent generations of processing equipment offer narrower process control windows giving better control over lithography and other system processes.
  - Epitaxial growth equipment must be capable of handling these larger diameter substrates while achieving improved uniformity and reproducibility, and lower epitaxial growth costs.
- Improved wavelength uniformity at the epitaxial growth stage would have a positive impact on the need for binning and could potentially reduce the testing overhead.
- In the current context, some believed that epitaxial equipment advancements are not a crucial task.
  - Reducing other costs, like overhead, would have a greater impact.

M.L5 Wafer Processing Equipment		
Support is required for the development of improved manufacturing equipment for LED wafer level processing. This activity covers processing equipment used to create an individual LED from an epitaxial wafer. Equipment must offer significant improvements in the cost of ownership or throughput over existing equipment, resulting in lower cost LED packages.		
Metric(s)	**Current Status**	**2015 Target(s)**
Overall wafer throughput (wafers/hr)	50 (for 2" equivalent wafers)	100 (for 2" equivalent wafers)
Overall wafer yield (%)	60	90
Overall process productivity (%)	50	90

M.L5 Roundtable Participant Comments

- Wafer processing equipment was not deemed an urgent priority.
- The tool sets and platforms already exist and do not need to be customized for LEDs.

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

M.L6 Roundtable Participant Comments

- Some participants indicated that research is still needed for subsystem packaging and that DOE funding for projects related to driver integration would also be helpful.
- However others believed that since LED chip manufacturing methods are well-known this task should not be a priority area for DOE support.
  - As the industry shifts towards integration and fewer components there will be less focus on the LED package.
  - The strong industry push towards mid-power LEDs will also reduce the need for DOE support in reducing packaging costs.
- It was proposed to broaden this task to encompass wafer-level packaging and/or package integration. Package integration would incorporate additional components within the LED package such as the driver as well as optical, electrical and thermal components.
- This task should be more explicit with an emphasis on subsystem packaging and assembly so as not to be confused with system integration.
  - The description should be modified to reflect a move away from packages containing a single LED die.
- Currently, there is no standard interface between the LED and driver module which will be necessary for the industry to move towards driver interchangeability.
  - There are many issues with driver subsystems including assembly, contacts, spacing and thermal management.

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

M.L7 Roundtable Participant Comments

- It was proposed to reframe this task as material manufacturing with a focus on reducing process variation for existing materials (e.g., phosphors, substrates, silicone, solder, epoxy, acrylics, and poly-carbonates).
    - Material outgassing is still an issue within the LED manufacturing industry as one of the major causes of LED damage (corrosion), especially to optical components.
        - More stable/compatible materials must be developed.
- Another suggestion was to incorporate M.L7 under a general testing/modeling task with a specific focus on (phosphor) R&D modeling efforts.
    - Phosphor modeling could help manufacturers better understand and improve material consistency.
    - The current lack of consistency between phosphor batches is significant and requires that manufacturers test all incoming materials.
    - Research into cheaper and more consistent silicones and plastics for matrix materials could also help reduce process variations and manufacturing costs.
- This task would benefit greatly from collaboration to promote progress on the development of continuous or higher-level processing techniques.

General Roundtable Comments

Testing & Standards

- Several participants commented that current SSL standards are overlapping. Having specifications provided by Energy Star, UL, and DLC increase testing costs for the industry.
- The LED industry would benefit from a dedicated SEMATECH-like consortium.
- On the subject of task M.L2, a research study was proposed to assess the real impact of power factor and the reasonable trade-off or level to encourage standards bodies to target.
    - It was noted that PNNL is currently working on this but it could be a good research study idea although perhaps not relevant to a manufacturing project.
- In general participants agreed that there is a great need to move to standardization for manufacturing processes, component specifications, and test plans.
- More priority needs to be placed on consistency and other areas that have an effect further up the value chain. Local optimization is not the goal.
    - The DOE should help guide applicants towards proposed projects which hit multiple levels and are not just focused on dollar metrics.
        - The priority should be to improve consistency in higher level assemblies.

Task Structure

- Development of a separate materials task was advocated by several participants. The materials in the new materials task proposed should include phosphors, silicone, plastics, etc.
    - One area suggested for inclusion in this new task was addressing outgassing issues. The second major cause of field problems is outgassing of volatiles used in the construction of luminaires that damages the LEDs.
    - Development of more stable materials is needed with better thermal and mechanical specifications not simply optical improvements.
        - If the aim is to develop a whole new material this is an R&D task. If the goal is to narrow the manufacturing window or process for a specific material then this is an option for a manufacturing task.

Collaboration

- It was agreed that continued collaboration across the LED manufacturing supply chain is important and will benefit the entire industry.

Modeling

- Better lifetime and reliability modeling for LED products and components (e.g., the driver) is necessary. Many participants also agreed that driver standards would be beneficial to the industry.
- R&D is needed for modeling luminaire integration and various subsystems.
    - Uniformity of silicone materials and materials in general, is an issue as consistency from one batch to a next differs. Specifically, the refractive index or hardness of a material, a characteristic of curing, may differ from one batch to another.
- A new modeling task should specify three key elements:
    - Modeling of all systems individually providing a holistic system level view,
    - Modeling of the manufacturing process and modeling of the luminaire itself, and;
        - Do not want modeling efforts to be too broad; focus must be on critical items.
        - Predictive modeling is the goal.
    - Include a sensitivity analysis (not as strong a priority as the previous two).
- If a new stand-alone modeling task is not created then at least remove it from existing ones.

LED Roundtable Participants

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Gary Shuck	Intematix, Corp.
John Tremblay	Osram Sylvania, Inc.
Ralph Tuttle	Cree, Inc.
Warren Weeks	Hubbell Lighting, Inc.
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