Solid State Lighting LED Manufacturing R&D Roundtable Summary

Introduction

On February 11, 2014 nine LED experts gathered in Washington, DC at the invitation of the DOE to help identify high-impact task areas for the Manufacturing Research and Development (R&D) Initiative. Two additional experts were unable to attend the meeting, but submitted written inputs to the DOE for consideration. The meeting commenced with "soapbox" presentations from each of the participants, followed by a general discussion to define specific work needing attention. Participants were also invited to comment on the organization and content of the Manufacturing Roadmap, and offer suggestions of program content for the Manufacturing R&D Workshop. This report summarizes the discussions of the Roundtable meeting, including the proposed manufacturing priority tasks, discussion relevant to those tasks, and a short summary of each participant's soapbox presentation.

Proposed Priority Tasks

The following tables provide the original descriptions, metrics and goals for the discussed tasks. 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 provide a starting point for further discussions at the 2013 DOE Solid-State Lighting Manufacturing R&D Workshop on May 7th and 8th in San Diego, CA. 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**	**2016 Target(s)**
Retail Lamp Price		50% reduction
Assembly Cost ($)		50% reduction
Color Control (SDCM)	7	2-3

M.L1 Roundtable Participant Comments

Proposed changes to description:

- Luminaire color consistency over product lifetime is important. Text should be added to this task description, or a new task created to reflect this concept.
- In order to drive adoption, and hence energy savings, luminaire manufacturers must pursue added value features such as integrating sensor and control technologies as well as color tunability. It was suggested that these refinements be added to the list of integrated components in the sixth area listed in the description.

Proposed changes to metrics:

- It was proposed to add a metric for color shift:
    - Maximum allowable color shift throughout LED luminaire lifetime, $\Delta u'v'$
        - Current Status: 3 steps
        - 2016 Target: 2 steps

Other comments:

- The emphasis must be on technologies that drive lower first cost, such as simple cost-effective systems, subsystem integration, standardized components, and standardized interface between subsystems.
- LED lighting products are highly complex. Integrating and reducing the number of components should be a priority.
- 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. In order to further reduce costs, there is a need for integration of components at the system level.
- The electrolytic capacitor is the main cause of driver failure. Simple and integrated driver designs that remove this component are possible and should be further developed.
- Color stability over time presents a large risk to the LED adoption. There is a need to develop predictive models for color shift to help manufacturers understand, control, and confidently predict performance.
    - Plastics have significant impact on color shift over time due to unpredictable yellowing/browning.
    - The phosphor coatings and package can crack or peel away after prolonged exposure to heat, which allows blue light to emit from the LED. This is the biggest color shift contributor.
    - Additional research is needed to determine consumer tolerance for variations in color and output with respect to different lighting applications.

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**	**2016 Target(s)**
Throughput (single bin units per hour)		2x increase
Cost of Ownership		50% reduction
$/Units per hour		

M.L3 Roundtable Participant Comments

Proposed changes to description:

- The task description should be modified to emphasize the need for improved phosphor measurement tools, as well as standardized testing procedures.

Other comments:

- Product consistency is recognized as one of the primary technological barriers to the adoption of LED lighting products.
- Luminaire manufacturers cited the difficulty in meeting tight color specifications, as well as maintaining color consistency both within product families and from product to product. Luminaire manufacturers purchase LEDs from a variety of chip manufacturers and the color variations from manufacturer to manufacturer are significant.
- The current binning system presents challenges because LED color points are not evenly distributed within a bin – and are typically skewed. In contrast to receiving average bin performance, luminaire manufacturers conceded that exact color point data for each LED would be more valuable although they would not currently be able to cope with the added complexity or stocking requirements.
- For color consistency, standardized measurement processes and procedures are needed.
    - If standard testing procedures are developed, then color measurements will become more consistent, both within a product family and from manufacturer to manufacturer.
    - In addition, the industry should standardize the presentation of color data.
- Hot binning and testing at 85°C is an improvement, however, LEDs typically operate at higher temperatures. There is a need for testing equipment that produces meaningful results at real operating conditions.
- There is a need for improved in-situ temperature control and measurements during wafer processing to improve yield.
- There is a need for tighter inspection and control on sapphire wafer polishing and surface variability.
- Participants cited that better testing and characterization of phosphors is needed. It was suggested that standardization of testing equipment and methods would help to achieve better consistency between phosphors.
- Testing costs are becoming a major contributor to overall LED manufacturing cost. Solutions are needed to help alleviate this burden.

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**	**2016 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 ($/μm·cm^2)	0.3	0.1

M.L4 Roundtable Participant Comments

Proposed changes to description:

- The description should be expanded to include the importance of sapphire wafer control; miscut, bow, and surface finish, since these significantly affect yield.
- The description should convey the importance of communication and collaboration between equipment and wafer manufacturers.

Proposed changes to metrics:

- The 2016 target for wafer to wafer reproducibility, 0.6 nm, might be too low.

Other comments:

- The variation of sapphire quality is a problem. Manufacturers have to make significant investments to assure the quality of sapphire. See also comments for Task M.L3.
- Growth equipment with reliable in-situ process control is needed to minimize yield losses from wafer bow and miscut.
- It was proposed that combining HVPE and metalorganic vapor phase epitaxy (MOCVD) could reduce epi stack cost by approximately 25% and significantly increase throughput.

M.L7 Phosphor Manufacturing and Application		
This task supports the development of improved manufacturing and application of down-converter materials, used in solid state lighting. This could include projects focused on phosphors to increase production volume and manufacturing techniques to improve quality and reduce performance variation. This task also supports the developments of down-converter materials, application materials, and techniques which improve color consistency of the packaged LEDs and reduce the cost without degrading LED efficacy or reliability.		
Metric(s)	**Current Status**	**2016 Target(s)**
Material Usage Efficiency	50%	90%
(D90-D10)/D50 (Conventional Phosphor)	30	10
Δu'v' Control	0.012[1]	<0.004[2]
Material Cost ($/klm)		15% reduction per year
FWHM (Quantum Dots)	40nm	<30nm

M.L7 Roundtable Participant Comments

Proposed changes to description:

- The description should reflect the interest in manufacturing quantum dots and near UV excited phosphors as alternatives to blue-pump phosphors.
- Toxic heavy metals, like cadmium, are used to stabilize quantum dot phosphors and this is currently limiting manufacturing feasibility. Text should be added to emphasize the need for a non-toxic alternative that does not sacrifice stability.

Proposed changes to metrics:

- The 2016 target for Δu'v' control should be changed to 0.003.

Other comments:

- The development of stable phosphors is critical to color consistency.
- There are some phosphor chemistries, especially narrow band phosphors, which are difficult to manufacture, it was suggested that this is an area where the U.S. can have a lead.
- In general there is a need for narrow band green and red phosphors.
- There is a need to reduce the cost of remote phosphors; standard forms and optics were suggested as possible solutions.
- Near UV excited phosphors can produce higher power lighting and enhanced color quality compared to blue pump LEDs; however, their availability is lower and at a higher cost. R&D efforts are needed to increase availability and to bring down cost.
    - Research is also needed to explore whether utilizing near UV excited phosphors could allow the escape of harmful near UV light.
- Further development of wafer scale phosphor deposition could enable package-less LED design, however, it was indicated that some non-U.S. manufacturers are already pursuing this solution.
- The interactions between phosphors and silicone matrix materials present issues with stability, cost, and integration.
- The phosphor coatings and package can crack or peel away after prolonged exposure to heat, which

[1] Applies to full distribution of LEDs (not at luminaire level)
[2] At fixed blue wavelength

allows blue light to emit from the LED, contributing to color shift.

- Phosphor performance evaluation is highly affected by the testing instrument and package type; there is a need for the standardization of materials and testing. Furthermore, phosphors must be tested within the matrix (e.g. silicone) in order to produce more accurate performance testing results.
- Long persistence phosphors could enable simpler driver designs and improve reliability by eliminating the need for electrolytic capacitors. However, this work would be better suited as a Core Technology Research task.

Discussion: Accelerated LED Testing

Roundtable Participant Comments

- There is a need for accelerated LED testing. Manufacturers commented that by the time end-of-life data becomes available, the product has often evolved significantly from its original design. LM-80 testing is conducted over a minimum of 6,000 hours and by the time that data is available LED manufacturers often already have newer products on the market.
- There is a need to agree on accelerated aging protocols and collaborate for the creation of predictive models.
- The ability to tie tested lumen maintenance of the LEDs to how the luminaire will perform would help to accelerate testing and avoid redundancy.
- There is a need for testing and failure mode analysis by an impartial third party and promote broad dissemination of findings. DOE's existing reliability effort through the LED Systems Reliability Consortium (LSRC) is working on this with RTI International. It was suggested that the LSRC also focus on developing methods for accelerated LED lifetime testing.
- Color stability over time is an unknown for LED luminaires, and presents a large risk to LED adoption. There is a need to develop testing standards and predictive models for color shift to help manufacturers understand, control, and confidently predict performance.
- Testing is expensive. Continued support for the development of standard test methods for accelerating aging of SSL luminaires and critical components is needed without imposing excessive testing burden on manufacturers.

Participant Presentations

1. **Richard Solarz, KLA Tencor, Corp.**
   - The linear fluorescent troffer represents the largest application by lumen production, and also the hardest to displace with SSL.
     - In 2011, a study performed by Pacific Northwest National Laboratory showed that LEDs had no advantage for troffers.
     - Linear fluorescent efficacy is quite good, and only recently have LED options surpassed this efficacy.
     - High end linear fluorescent products are cheap, and at $4 a piece they have efficacies of 100 lm/W (not taking into account the approximately 70% efficiency of the luminaire).
     - Because of high first cost of LEDs and no previous advantage in efficacy, LED troffers have a long payback.
       - In order to reduce payback LED troffers need to have a much higher system efficacy. Currently industry is around 90 lm/W, but this needs to improve to greater than 120 lm/W.
     - Linear fluorescent fixtures have a very good lifetime if you turn it on and leave it on, 7,000 to 25,000 hours; however, cycling the fixture on and off drastically reduces the lifetime.
       - This creates a distinct advantage for LEDs over linear fluorescent lamps, once you introduce occupancy controls.
     - The standard for color uniformity in linear fluorescents is 2 MacAdam ellipses, current LEDs are only at 4 MacAdam ellipses. To compete with incumbent technology, LEDs must show 2 MacAdam ellipse color uniformity.
     - People order the center 4 quads in the bins grouped around the CCT they want, but distributions within a bin are not uniform so quad mixing schemes only do 3 to 3.5 MacAdam ellipses.
     - In addition, only half of what LED manufacturers make are high color quality center bins, the rest are too far from the CCT point and harder to sell.
     - As a result, LED manufacturers may have trouble meeting demands.
     - Need to characterize medium brightness LEDs better.
       - Color coordinate varies greatly with medium angle.
       - They are never hot tested.
       - Color coordinates shift with applied current and operating temperature, so resulting color binning cannot be done well.

2. **P.S. Raghavan, GT Advanced Technologies, Inc.**
   - The cost of LEDs must come down for them to survive in the lighting industry.
   - LED industry priorities have changed since 2008. Then the focus was on margin erosion and production volume. In 2013, the focus shifted to cost and consolidation so that going forward the focus can be on profitability.
   - From 2012 to 2013, the chip cost as a proportion of the LED package cost has reduced from 55% to 47%.
     - There has been a relative reduction in substrate and wafer processing costs due to high volume manufacturing but a relative increase in packaging costs resulting from additional testing and binning requirements.
   - The path to cost ($/klm) reduction follows improving manufacturing efficiency or LED performance.
     - If sapphire cost decreases due to higher equipment throughput and yield

improvements, the LED cost decreases.
    - Increasing the efficacy of LED packages reduces costs by creating more light per chip (and drive current).
- GTAT has a diversified product portfolio that contributes to the end market of low cost LEDs.
    - Sapphire production equipment includes:
        - ASF, KY, and EFG systems, which are sapphire crystal growth technologies which allow the growth method to be tailored for the end application.
        - Automated sapphire inspection tools, which improve yields and quality of material entering downstream production.
        - Sapphire annealing furnace, which is a key technology for production of sapphire material for a variety of consumer and industrial applications (outside of LEDs).
    - GaN HVPE and Hyperion Ion Implant systems are currently in development.
        - Hyperion Ion Implant system enables the production of thin substrates with negligible kerf loss and lower consumable cost.
            - Enables the use of engineered substrates that are 1 nm of sapphire, GaN etc. on a layer of silicon, effectively lowering cost.
- Sapphire growth strategy needs to focus on downstream LED operations such as cutting, polishing, and epitaxial fabrication.
- GaN can be grown on a substrate using:
    - Molecular beam epitaxy (MBE), but it requires high vacuum and is prone to nitrogen deficiency.
    - HVPE which has high growth rates and is carbon free, but it is susceptible to reverse reactions.
    - MOCVD which is the most common process today, and has a slow growth rate, minimal reverse reactions, and adduct formation.
- GTAT is proposing a hybrid HVPE + MOCVD process:
    - Benefits claimed include a ~25% reduction in Epi stack cost, an improvement in LED material quality (thicker and less defective n-GaN layer).
    - GT is currently developing a high-volume production tool HVPE process.
    - Each HVPE tool feeds up to two MOCVD tools and lowers CAPEX by up to 25%.
    - GTAT HVPE differentiates itself from traditional processes that use molten liquid Galium at temperatures of 800-900°C. GTAT uses solid $GaCl_3$ which results in an 80% reduction in precursor cost and a 10x faster growth rate.
- Regarding alternatives to sapphire substrates, a lot of companies are working on bulk GaN growth, but it will take time because the process occurs at high pressure and is very time consuming. The use of silicon substrates is not thought to be cost effective because it increases the complexity of the epitaxial layers.

3. Ashfaqul Chowdhury, GE Lighting

- Three things have cost implications and lead to market adoption: system considerations, efficiency considerations, and adoption considerations.
- There are currently three white LED technologies:
    - Phosphor-converted: the most cost effective solution in the near term, and most of adoption will come from phosphor-converted LEDs.
    - Discrete RGBA: the furthest from realization due to complex multi-channel drivers and optics and issues with red and green direct emitters
    - BSY-R/A (hybrid LEDs): efficiency gain from using narrow emission down converters (for red and green) is compromised by the same complex multichannel

driver/optics issues. GE believes that this technology will be limited to high-end and niche applications.

- How do we foster adoption?
  - At the luminaire level:
    - Offer warranties to encourage customer confidence.
      - Need the ability to tie LED maintenance results to how the luminaire will perform over the lifespan of the warranty.
      - Requires accelerated testing at luminaire level.
      - 6,000 hour onward prediction is too slow.
    - Emphasize technologies that help achieve a lower first cost.
      - Simple cost effective systems, subsystem integration, standardized components, standardized interface between subsystems.
  - At the lamp level:
    - Reduce prices further since first cost is still the main hurdle.
      - The sensitive price points for customers are $9.99 and $4.99.
        - $9.99 is very quickly within reach, but $4.99 is when adoption will really start to happen.
    - Temper customer expectations.
      - Lifetime requirements of more than 10 years are excessive and do not make sense from a business standpoint.
        - There should not be a push for very long life because it will hurt the cost structure by lowering the replacement volume.
      - Regulatory requirements are even more stringent than with CFLs.
        - Beam shaping causes a loss of efficiency and value.

4. Yan Rodriguez, Acuity Brands

- There is a lot of talk about the color consistency initially, how you bin it, purchase them etc., but we do a lot of work in developing our luminaires to meet customers demand for color consistency, not just unit to unit, but across different types of fixtures.
- No manufacturers use the same LED manufacturer for all of their products; they want to pick and choose the vendor based on the latest and greatest chips.
- In mid power LEDs, plastics have significant impact on color shift over time due to yellowing/browning of the plastics which is unpredictable.
- Heat can degrade the performance of phosphors, and phosphor coatings may lift off the package allowing blue light to escape.
  - In a downlight the center packages are hotter than outer packages so degradation is not consistent
- This color instability presents a huge problem for the luminaire reliability, and is the biggest risk to adoption.
- Manufacturers pay a premium for center bins, test dies, test the final luminaire, and then ship a product that consistently hits a certain target. They know to expect small color shifts within 100 hours, but there is no data or methodology to allow them to predict color shifts after 10,000 hours.
  - Because of LM-80 the LED package manufacturer provides 6,000 hour data for color shift, but none beyond that. For hospitals and museums especially, there is a high concern. Warrantees need to be 5 to 10 years for some applications.

5. **John Tremblay, Osram Sylvania, Inc.**
   - Light engines (LEDs), power supply (components), and assembly (metal, plastic, etc.) come together to create an SSL fixture.
     - Osram touches all pieces of this, manufacturing LEDs, power supplies, and fixtures, and focuses on a system approach.
   - Within the bill of materials (BOM), LEDs, power supply and controls used to make up the majority of the costs, but material instability, evolving designs, test and certification, and standard materials have become significant cost drivers.
     - Lamp/luminaire design is evolving, and "form factors" are closing in on standards.
     - BOM costs are within reach, some troffers are less than $100 and some of the form factors are narrowed in. The material instability and testing and certification are the two major issues that are left.
       - The instability of LEDs makes it difficult to deal with different chips and different projects. There is a need for a focus on binning and life testing.
       - There is a need for better testing and certification, and color tuning and controls added.
   - Other remaining hurdles:
     - The electrolytic capacitor is the weak link and, if possible, should be removed from driver design.
     - Thermal design puts constraints on manufacturing, and issues still need to be resolved.
     - Testing costs.

6. **Jim Neff, Philips LUMILEDS**
   - To get the next leap in system performance and cost, we need to integrate.
   - In the cost distribution for luminaires, the LEDs themselves used to be the largest component, but that has been reduced to a third of what it used to be. Thermal, mechanical, electrical and optical costs have not changed much at all because they are mature industries. They reach an asymptote, and LEDs will do the same thing. In order to further reduce costs, there is a need to optimize the luminaire at the system level.
   - Integrated Color-Control Electronics:
     - Current example: A hybrid light engine with white LEDs on the same board as red or amber. Challenge is controlling color and lumen output because InGaN and AlInGaP LEDs have different behavior as a function of current and temperature.
     - Cost of testing is becoming a major portion of the cost of making LEDs.
       - Solutions include avoiding excessively tight specifications and using available test data to eliminate test redundancy.
   - Driver Integration:
     - Currently available products include AC-LEDs with integrated diode rectifiers and arrays with integrated drivers.
     - Benefits include saving on BOM costs, but they are limited by tight forward voltage specifications and have no integrated surge protection.
   - Future challenges require LEDs to build complexity into product lines. Functionality can be put right into the light engine.
   - Software for manufacturing would help. Manufacturing Execution Systems (MES) are not tooled to handle binning and do not directly address the typical SSL assembly floor.

7. **Fred Maxik, Lighting Science**
   - There is a need to dematerialize the industry, morphing it into something that is transportable.
   - There is a need for an understanding of where we can create value for the manufacturing industry.

- Integration of electronics is a highly valuable activity, but there is also value in integrating and developing new features with light and color that has not been done before.
- If there is a new value metric to be created, the DOE can make an impact there.
- There are novel ways to integrate sensors, and we are starting to merge all of the control systems into LEDs.
  - It might be that SSL is given away or sold at material costs because they offer value as sensors in collecting data sets (traffic patterns, biometrics, safety etc.).
  - There is a need to look at forward integration and controls integration so that we can manufacture here in the U.S.
- Delivering additional value will help accomplish adoption and energy savings more quickly.

8. Xiongfei Shen, Intematix, Corp.

- The key challenges for phosphor manufacturing can be broken down into the following categories:
  - Remote Phosphor:
    - Different techniques are needed to standardize form and optics shapes of remote phosphors.
    - U.S. infrastructure has a low ability to create phosphors; manufacturing in the U.S. is much higher cost than in parts of Asia.
    - Costs must be reduced by over 50%.
  - Narrow Band Phosphor:
    - Many customers request nano-emission phosphors due to high efficiency.
    - There is currently a lack of narrow band green, and reliability challenges associated with current narrow band reds.
    - Sensitivity to moisture and temperature must be reduced for lighting applications especially in mid or high power.
  - Quantum Dot (QD):
    - Has the advantage of narrow band emissions tunable from green to red.
    - Relatively low stability and reliability make volume production challenging and limits applications.
    - Toxic heavy metals, including cadmium, limit manufacturing feasibility. The US has limitations on that material entirely. Some QDs are available without Cd, but they are not as stable.
  - UV Excited Phosphor (defined as 360-420 nm):
    - UV LEDs can produce higher power lighting than blue LEDs, but the major challenge is higher cost and lower availability than blue.
    - Much more R&D is needed in this area to increase availability and bring down cost. This is a potential area for U.S. R&D funding.
    - Several companies are requesting UV LEDs. Detail retailers with high end products like the violet content because it acts on optical brightening agents in fabrics to enhance the quality of color reproduction.
  - Testing Standardization:
    - Phosphor performance evaluation (quantum efficiency, brightness, color etc.) is highly affected by the instrument and package type.
    - There is a need for standardization of materials and testing, so that there is a reference point.
      - Phosphors must be tested within their matrix (e.g. silicone) to give meaningful results.
    - Standardization of testing equipment/method can help to improve testing

correlation between phosphor manufacturers and LED lighting product manufacturers and thus improve quality control and improve yield of both sides.

9. **Eric Armour, Veeco Instruments, Inc.**
   - Veeco is driving down the cost of epi growth.
   - The current focus for cost reduction is on yield.
     - Need to get down to a 2.5 nm bin, and are currently at least 5nm.
     - Veeco has processes they are currently working on, which they believe will enable higher yields soon.
   - Veeco has taken their technology and looked at adjacent markets including power electronics.
     - There is a big effort for GaN-on-silicon in power electronics, which could spill over into LEDs and help realize some cost reductions.
   - Some of Veeco's customers are looking at GaN substrate technologies, but that seems to be niche oriented.
   - In order to establish an equipment development roadmap, various questions were raised about future directions:
     - Do we go near UV or stay at the blue phosphor pump? From an OEM perspective UV makes sense.
     - If we are moving towards active control applications, does it make sense to go to RGB discrete LEDs?
     - Will the market move to an all nitride solution (including the reds) or a mixed GaN and AlGaInP system?
     - Will laser based lighting solutions start occurring or not?
     - How does OLED factor into lighting market?
   -

10. **Terry Clark, Finelite, Inc. (written submission)**
    - The DOE recognizes the need to address the primary technological barriers to the adoption of SSL products – manufacturing cost and product consistency.
      - The area of "product consistency" rather than lower costs is where DOE research funds will have the most impact and deliver the best value to our emerging industry.
    - Finelite supports the goal to improve color point consistency in the final product.
      - This could be done via process improvements during epitaxial growth, improved testing, and better encapsulation materials.
      - Should also focus on developing consistent, efficient, and stable emitters across the visible spectrum.
      - Additional research is needed to determine "what is the tolerance for variations in color and output with respect to the lighting application."
    - Improved color point consistency was also highlighted as a key area in the recently published DOE document "Solid-State Lighting; Early Lessons Learned on the Way to Market".
      - Lesson 4: The range of color quality available with LED-based products and the limitations of existing color metrics may confuse users.
      - Lesson 5: The color delivered by some LEDs shifts over time, enough to negatively impact adoption in some applications.
    - There are unique challenges with respect to indoor architectural lighting. These include:
      - Interior designers almost always object to luminaires that are adjacent to each other that demonstrate a color difference of (3) MacAdam Ellipse.
      - However, the distance of a MacAdam Ellipse is from the center of the ellipse to the outer edge of the ellipse. That means within a (3) MacAdam Ellipse one could have a

color shift approaching (6) MacAdam Ellipse. This happens if one point is on one of the far edges of the circle and the other point is on the other far edge.
    - That means a 3-McAdam Ellipse cannot be a target for the architectural segment.
    - The architectural segment needs to have a 1 to 1.2 MacAdam Ellipse target.
    - The DOE is the right party to bring this issue to the table and to indicate that research needs to begin now to meet this important application requirement.
- Since the indoor "architectural" space encompasses many office buildings, educational facilities, retail stores, and health care facilities, there is about 20-billion square feet of space that needs better color consistency. That represents a tremendous energy savings potential that could be delayed due to false starts of inferior products.
- Accordingly, "improved product consistency" should be ranked immediately below "improved efficacy". Other items are important; however, they need to be further down in rank.

11. Eric Haugaard, (written submission)

- There is a need for SSL luminaire reliability models and understanding of physics of failure.
- The model must take into account:
    - Components: LEDs have received most of the focus so far, and there is general agreement on excellent performance. Drivers appear to be an issue, but which part? Is it the electrolytic capacitors? Lenses, reflectors, and other components must also be considered.
    - Luminaire: There are thousands of different luminaire designs, so it is difficult to work that into the model. The first question is "where to start?" Lack of public information on luminaire reliability will also create complications.
    - Accelerated testing: What are the appropriate stressors and the appropriate stress level? Testing is expensive, and there is issue with the burden being placed on manufacturers. There is a need for information sharing, maybe through the LSRC.
- Next steps:
    - Luminaire models are beginning to emerge from core technology research. The issue of luminaire lifetime is complex and funding for this important work should continue.
    - Focus for the research should align with industry's needs:
        - Continued support for the development of standard test methods for accelerating aging of SSL luminaires and critical components without imposing excessive testing burden on manufacturers.
        - Continue support for testing and failure mode analysis by an impartial third party, RTI International, and promote broad dissemination of findings.
        - Include an examination of color shift in testing and modeling efforts.
    - Promote discussion and information sharing on SSL luminaire lifetime via the LSRC.

DOE LED Roundtable Participants

Eric Armour	Veeco Instruments, Inc.
Ashfaqul Chowdhury	GE Lighting
Fred Maxik	Lighting Science
Jim Neff	Philips LUMILEDS
P.S. Raghavan	GT Advanced Technologies, Inc.
Yan Rodriguez	Acuity Brands
Xiongfei Shen	Intematix, Corp.
Richard Solarz	KLA Tencor, Corp.
John Tremblay	Osram Sylvania, Inc.

Provided written inputs to the DOE for consideration:

Terry Clark	Finelite, Inc.
Eric Haugaard	Cree