Solid State Lighting LED Product Development and Manufacturing R&D Roundtable

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DISCLAIMER

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COMMENTS

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

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Introduction

On October 8, 2014 thirteen LED lighting experts gathered in Washington, DC at the invitation of the DOE to help identify critical R&D topic areas for both the product development and manufacturing research and development (R&D) initiatives. The meeting commenced with "soapbox" presentations where each participant was invited to give a short presentation describing what they believed to be the key technology challenges for SSL over the next 3 to 5 years. This was followed by a general discussion of the most critical technology challenges facing the industry today. Following these discussions the participant were asked to comment on the overall program milestones and were also invited to contribute ideas regarding program content for the upcoming R&D Workshop.

This report summarizes the outcome of the discussions on critical technology challenges, identifies corresponding R&D tasks within the existing task structure, and summarizes proposed changes to the program milestones. Outlines of the participants' soapbox presentations and related remarks are included in Appendix A of the report.

Critical R&D Topic Areas

Based on the presentations from the attendees and the subsequent discussion, the critical LED R&D challenges could be grouped into a few broad research themes. These are outlined in the following section. While all of the discussions offered insights on research that could advance SSL technology, there were a few recurring themes that participants felt could lead to significant breakthroughs in SSL product development and manufacturing. These critical R&D topic areas, listed below (in no particular order), are discussed in more detail in the following section.

- Substrate Development
- Down Converters
- New Materials
- Testing & Measurement
- LED Drivers & Passive Components
- Advanced Packaging
- Color Consistency, Reliability, & Lifetime

1. Substrate Development

- Participants identified a need for improved sapphire and GaN substrates in terms of manufacturing tolerances (sapphire) and cost (GaN).
- For sapphire substrates, minor variations in miscut angle can result in significant variations in emission wavelength, affecting the yield of LED die falling within a specific wavelength bin. Similarly, variations in bow and warp and in wafer thickness impact the emission wavelength and have a negative impact on yield. There is a need to develop improved manufacturing processes to achieve tighter tolerances.
- A step change in yield, and reduction in cost, can potentially occur in the MOCVD process by moving to a single wafer reactor if industry transitions to larger diameter substrates (8"-12"), so this may be another area of interest.
- Bulk GaN growth is currently limited in terms of wafer size, and substrates are very expensive. Work is required to improve manufacturing methods. Current manufacturing methods for GaN substrates using HVPE isn't very efficient (only 20% source utilization) and Japan dominates this manufacturing technology.
    - Bulk GaN substrate cost is $5000/4" wafer which is prohibitive but there is an important opportunity to get this cost down.
    - It was suggested that the manufacturing of bulk GaN substrates offers a good opportunity for U.S. manufacturers.

- It was argued that bulk GaN substrates possess electrical, thermal, and optical properties that can be advantageous in the manufacturing of LEDs for lighting.
- It was suggested that GaN-on-GaN approaches using bulk-GaN substrates should continue to be supported alongside GaN-on-sapphire, GaN-on-SiC, and GaN-on-Si

2. Down Converters

- We are approaching the theoretical limit for efficiency for many current phosphors like garnets, aluminates, silicates, and nitrides. However, other characteristics such as thermal quenching, color consistency, spectral linewidth, and lifetime could still be improved.
- New down-converters need to be developed in order to realize thermally stable, efficient, and narrow linewidth emission in the red, green, and cyan spectral regions.
- Developing down-converters with tunable emission wavelengths would provide a wider color gamut and improved control over CCT, CRI, and other color qualities.
- Desired properties include:
  - High quantum yield
  - Spectral linewidths of 30-50 nm or less.
  - Tunable emission wavelength
  - Good thermal stability
  - Good flux stability
  - Good long term reliability
  - Scalable manufacturing for low cost.
- Also, there was interest in the development of long persistence phosphors as a possible solution to flicker.
- The roundtable participants noted that the description of A.1.3 and/or B.1.3 (phosphor development tasks) should be updated to include work on down-converter and matrix material interactions.

3. New Materials

- New packaging and luminaire materials are necessary in order to continue to advance LED products in terms of efficiency, overall quality and cost.
- New multi-functional materials may enable the integration of optical, electrical, and mechanical components or other novel LED luminaire systems with improved functionality and lifetime.
- We need to understand how small changes in the materials over time affect the overall functionality and lifetime of LED luminaire systems.

Glass materials for optics

- Glass has number of useful properties, such as long term stability with light and heat (better than 40K hours), high transparency, and good dielectric strength, but it is difficult to manufacture complicated glass forms at low cost. It was suggested that the industry would benefit from cost-effective techniques to shape, cut, and form glass.
- Participants noted an opportunity to improve thermal conductivity of glass.
- Tough glass that was thin and break-proof would also be beneficial.

Silicone/Encapsulant

- Participants suggested that more research on silicones and other encapsulant materials could yield benefits in a number of areas including:
  - increased refractive index for improved light extraction
  - improved stability with respect to light flux and temperature

    - improved matrix materials for applying phosphors and down-converters with improved understanding of chemical interactions affecting performance and reliability
- Participants also noted that qualification of new products (with the long test cycles and high required testing costs) impacts the customer acceptance and time scale to introductions.

Solder

- It was suggested that conventional tin-silver-copper (SnAgCu or SAC) solders may begin to impact system reliability as operating temperatures are increased in order to lower system costs through reduced LED counts and removal of heat sink material, and that new lead-free thermal shock solders will likely be required.

4. Testing & Measurement

- Some participants felt that there are gaps in testing and measurement at the LED luminaire and package level and suggested that the industry would benefit from:
    - interoperability testing
    - a way to assure year to year reproducibility without expensive/redundant testing
    - improved equipment for in-line testing
    - a determination of where best to apply such testing (e.g. at the component level, the luminaire level, or both)
- Participants explained that customers need to be able to mix manufacturer products; however, there are still fundamental differences in the procedures manufacturers employ for measuring and testing their LEDs. Current tolerances and measurement variability require that the customer re-measure the LEDs they purchase. Standardization of testing procedures, improved equipment calibration standards, improving measurement accuracy, and more effective reporting of test results to luminaire manufacturers may improve customer confidence.
- It was also noted that the LED luminaire manufacturers are currently requesting a 2-step MacAdam ellipse bin tolerance although they would prefer a 1-step tolerance. This would require improved color point measurement accuracies, as well as process improvements and is therefore a potential opportunity for R&D. Current measurements are quoted to a 3-step tolerance.

5. LED Driver- Passive Components

Inductors

- Participants noted that the drive for more compact driver architectures would also benefit from 'inductor-free' designs, or designs that minimize the magnetic inductor component size or performance requirements.

Capacitors

- Participants discussed the need for improved electrolytic capacitors in terms of reliability, cost and physical dimensions.
    - Currently the reliability of electrolytic capacitors is very temperature dependent. For example, a +20˚C change in operating temperature can result in a >2.5x change in failure rate.
- Alternatively, new capacitors offering high capacitance values, compact form factors, low cost and high reliability need to be developed.
- Alongside these developments, participants suggested that driver manufacturers consider 'capacitor-free' designs, or designs that minimize capacitor requirements to alleviate these issues.

6. Advanced Packaging

- In conventional high power packages the packaging material and processes can comprise more than half the cost of the LED package and therefore significant cost savings could potentially be realized by minimizing the area of packaging material being employed.
    - Chip-scale packaging is being developed with the intention of reducing LED package manufacturing costs by reducing the package area to the size of the LED die.
    - These chip-scale packages are generally manufactured using a wafer-scale fabrication approach where interconnects, phosphors, and contacts are directly applied during wafer manufacturing.
    - Wafer-scale die fabrication lends itself to wafer-scale packaging where all the die are transferred from the original wafer to a "packaging" wafer/panel. This is best achieved using flip-chip (direct attach) LEDs. The remaining packaging actions are performed simultaneously on the array of LEDs before singulation to create individual chip-scale packages.
- Participants suggested embedding more functionality within the package, such as sensors and controls, and that this would need to go hand-in-hand with package cost reduction approaches or enable reduced system cost
- Moving to integrated multi-junction die could allow a single high voltage die to replace multiple series connected die, which would simplify the packaging requirements and reduce driver costs.
- Another innovation to help reduce costs could be to develop massively parallel pick and place methods for batch packaging of LED die for SSL applications.
- Participants discussed the importance of having flexible manufacturing processes that can react quickly to different product lines in order to meet customization desired from Level 2 integrated LED modules.
    - This would require simplified manufacturing approaches and, possibly, new multi-purpose, designed for manufacturing package architectures
    - This flexibility could enable reduction in supply chain complexity (through improved design for manufacturing),and reduced product development and manufacturing cycle times
    - Modular system approaches could also enable flexible manufacturing approaches

7. Color Stability, Reliability, and Lifetime

- A number of participants raised concerns over color stability, reliability and lifetime. Color shifts during luminaire operation are not well understood and are becoming recognized as a major issue for luminaire manufacturers with long term warranty liability consequences. Reliability in general, whether through catastrophic failure, long term lumen depreciation, or color shift, remains a significant issue requiring continuing research. Specific concerns were raised regarding phosphors, silicone (matrix materials, encapsulants), solders, and capacitors, but work was required on all components and systems that affect product lifetime and reliability.
- 'Time to use' is a barrier to innovation, and right now there is no way to get around the need to test products for 6,000 hours. We need proven acceleration factors that can shorten these times.

Relationship Between Critical R&D Topic Areas and Existing Task Structure

The R&D planning process described in the MYPP and Manufacturing roadmap is based around a list of R&D Tasks which are reviewed each year and the highest priority tasks identified. These priority tasks form the basis of the FOA. The overall task structure is updated periodically as the R&D requirements evolve. The roundtable discussions on critical R&D topic areas were undertaken without specific reference to the existing task structure but it will be important to reconcile these with a suitable set of priority tasks during subsequent discussions. To assist in the next steps, the table below shows the critical R&D topic areas discussed in the previous section and the closest corresponding R&D tasks. Descriptions of each R&D task may be found in Appendix B of the report.

Critical R&D Topic Area	**Corresponding R&D Task(s)**		
	Core Technology	Product Development	Manufacturing R&D
1. Substrate Development		B.1.1 Substrate Development	
2. Down Converters	A.1.3 Down-Converters	B.1.3 Phosphors Proposal to include matrix material interactions in existing task	M.L.7 Phosphor Manufacturing and Application
3. New Materials *New materials requirements appear in many tasks including the following:	A.5.1 Optical Component Materials A.6.2 Thermal Components Research	B.3.2 Encapsulation B.5.3 Diffusion and Beam Shaping B.6.1 Luminaire Mechanical Design B.6.2 Luminaire Thermal Design Proposal for new focused task	
4. Testing & Measurement			M.L.3Test and Inspection Equipment
5. LED Drivers & Passive Components	A.7.4 Driver Electronics	Proposal for new task	M.L.2 Driver Manufacturing
6. Advanced Packaging		B.3.6 Package Architecture Proposal for new task	M.L.1 Luminaire Manufacturing M.L.6 LED Packaging
7. Color Consistency, Reliability & Lifetime		B.5.2 Color Maintenance B.6.3 System Reliability and Lifetime B.7.1 Color Maintenance (Electronics)	

These tasks will provide a starting point for further discussions at the 2015 DOE Solid-State Lighting R&D Workshop on January 27th through the 29th in San Francisco, CA. The combined results of the Roundtable and Workshop discussions will guide the DOE in soliciting projects for the LED R&D Program.

LED Milestones

Roundtable attendees were also asked to give feedback on the SSL Program R&D Milestones outlined in Table 4.4 of the 2014 DOE SSL MYPP (copied below).

Year	2014 Milestones
FY10	Package: >140 lm/W (cool-white); >90 lm/W (warm-white); <$13/klm (cool-white)
FY12	Luminaire: 100 lm/W; ~1,000 lumens; 3500K; 80 CRI; 50,000 hours
FY15	Package: ~$2/klm (cool-white); ~$2.2/klm (warm-white)
FY17	Luminaire: >3,500 lumens (neutral-white); <$100; >150 lm/W
FY20	Luminaire: 200 lm/W Smart troffer with integrated controls: <$85
	Note: Packaged devices measured at 25°C and 35 A/cm^2.

Roundtable Participant Comments:

- The industry is currently exceeding the FY15 milestone of $2/klm so this needs to be more aggressive.
  - Mid power LED packages today are at about $0.66/klm (1500 lumens/$)
  - High power LED packages today are at about $0.9-1.1/klm (900-1100 lumens/$)
- The FY17 milestone remains a good target for luminaires.
- The typical price of a 3,500 lumen 2'x4' LED troffer at 100 lm/W is currently about $90-95 per unit, however work is still required to reach 150 lm/W
- The FY20 milestone remains a good, aggressive target.

Appendix A: Participant Presentations

1. Mike Krames, Soraa

- Bulk GaN in the 21st century – important for lighting (LEDs), projection displays (lasers) and the energy sector (electric vehicles, solar panels, etc.)
- Need to move from GaN-on-X to bulk GaN (GaN-on-GaN)
  - With bulk GaN you can utilize the electrical, thermal, and optical properties to improve LED lighting.
    - Operates at 5-10x the current density of current LEDs with (GaN-on-X)
- The industry is currently moving to larger and larger die areas in order to get to higher efficiencies, but this is not necessarily better for low cost.
  - For example, larger die areas need larger optics and this is a significant cost. We need to depart from this trajectory.
- GaN on GaN produces many more lumens per wafer than other substrates (GaN-on-SiC, etc.)
  - 6" GaN-on-sapphire and GaN-on-SiC produces 1.2 million lumens per wafer
  - 8" GaN-on-Si produces 1.9 million lumens per wafer
  - But 4" GaN-on-GaN produces 2.7 million lumens per wafer
- Bulk GaN also has significant potential for power electronics. Bulk GaN comes the closest to technology limits – in addition to lighting you can design power conversion systems to make them more efficient
  - Has lower on-resistance, higher breakdown voltage, higher conversion efficiencies, and smaller (faster) systems
- Bulk GaN growth – current manufacturing based on HVPE isn't very efficient (only 20% source utilization) and Japan dominates this manufacturing technology
  - Cost is around $5000 for a 4" substrate which is too high (cost prohibitive), and it doesn't have to be this high.
  - Alternative substrate manufacturing processes based on the bulk growth approach used for quartz could produce uniform material with good source utilization and offer prices as low as $500 for a 4" substrate (this was the target in the 2013 MYPP)
  - $500 may still seem expensive but with 10x the current density this is a good deal
- Manufacturing in the US is important and bulk GaN manufacturing is a good opportunity.

2. Eric Armour, Veeco Instruments, Inc.

- Veeco has an internal Roadmap and has tried to align its goals for normalized epitaxy costs ($\$/\mu m.cm^2$) to the projections provided in DOE's Roadmap.
  - Veeco just introduced a new reactor that is helping to lower the cost of epitaxy – and it plans to further lower costs using advanced, next generation technology.
  - The recently released EPIK700 platform has a throughput increase of 30% and a 20% reduction in cost of ownership (CoO).
  - The EPIK700 is a cluster tool and is mostly automated.
- Veeco sees a path to a further 30-40% CoO reduction through incremental improvements over the next 3 years – but the headroom is limited based on this style of reactor design.
- However a step change in yield could potentially occur through transition to a single wafer reactor design as the industry transitions to larger diameter substrates.
  - A single wafer reactor design could offer higher wafer yield through uniformity improvements and therefore become feasible from a CoO perspective.
- If the industry sticks with sapphire substrates, it will be important for the substrate manufacturers to improve control of the miscut angle & bow/warp/TTV. Miscut angle has been found to

influence emission wavelength hence tighter substrate tolerances will assist the industry in moving to smaller bins with higher yields.
    - Most sapphire vendors are not located in the US and are not ready for tighter controls. Right now rather than asking for improvements to sapphire control, people are just dealing with the low quality.
    - Veeco has tried varying flow conditions, but the miscut issues still hold.
- Veeco highlighted that it needs to be aware of the direction industry is moving so that it can align its equipment development roadmap and have suitable equipment available at the right time. For example, would there be a shift to other approaches such as RGB? These alternative approaches often require different equipment capabilities to be developed.
    - Veeco indicated that it had some ideas for improving green/red InGaN materials which they could pursue if there were sufficient industry interest.
    - It needs to stay in-sync so it can optimize its products for what LED manufacturers need.
    - Veeco operates on about a 1.5 year cycle (used to be about 3 years), meaning it takes 1.5 years to get from initial concept to introduction of a new reactor. This is because a lot of research is needed to make the best possible reactor.
- There is a general trend to reduced cycle times, which can be achieved using a split process with the cluster tool, but currently most people do the whole stack at once. Reducing cycle times may reduce costs.
- The GaN material system is also interesting for power electronics and as wafer diameters increase there may be an advantage in moving to a single wafer system. These advantages include improved uniformity and a lower CoO due to the machine requiring fewer sources per chamber.

3. Xiongfei Shen, Intematix

- There are limited prospects for quantum efficiency improvements in current phosphors
    - In phosphor systems we are approaching the theoretical efficiency limits for many current phosphors like Garnet, Aluminate, Silicate, and Red Nitride (IQE of 0.98, 0.99, 0.94, and 0.95 respectively).
    - We are working hard to make further improvements, but we only get a 1% or 2% improvement on quantum efficiency so we need a new strategy.
    - Note: These are room temperature yields, and it would be lower for operating temperature. We need to be looking for higher yield materials at higher temperature.
- Prospects for cost reduction is another concern.
    - Garnet, aluminate, and silicate are already in mass production in places, so costs won't come down much further.
    - The major challenge for low cost is the red nitride phosphor since this requires furnaces operating at high pressures and high temperatures. Furnace costs for the red nitrides are significantly less in China than in the U.S. (~10% the cost) and this offers a route to lower cost manufacturing.
- One key approach for white LED brightness and color gamut improvement is to develop a narrow band red emission phosphor
    - A fluoride based narrow band red phosphor is possible but is not tunable (630 nm peak) plus there are reliability and manufacturing scale-up challenges. This phosphor is more appropriate for backlighting applications.
    - There is also concern about possible chemical reactions in the LED component resulting in the release of hydrogen fluoride.
- Narrow band phosphors for LED applications need to satisfy the following requirements:
    - Wavelength tunability for each color phosphor from green to red
    - Good thermal stability
    - Good reliability

    - Manufacturing feasibility (scalable)
- In the past 6 months we have found a candidate system covering the 610 to 630 nm wavelength range which has high efficiency (+14% brightness compared to current CASN red phosphors), and narrow linewidth (50 nm compared to 80 nm for CASN red phosphors).
    - We have already scaled up to pilot scale (1kg), and it is promising.
    - We are currently working on thermal stability, reliability and manufacturability.

4. Joel McDonald, Dow Corning Corporation

- Material performance and reliability impacts the entire SSL value chain, and not all silicone is created equally. Dow is looking for preferred materials for each application.
    - Key research needs to include understanding the fundamentals of phosphor integration with matrix material.
        - We need to understand how silicone interacts with phosphor materials to help improve performance at higher temperatures, and compare phenyl and methyl based silicones.
- Input is required on applications and materials demands in order to support the SSL industry.
    - A lot of current applications are indoor accent, industrial and sport, indoor diffuse, and outdoor.
    - All segments must maintain CCT and lumen output over the lifetime of the luminaire, and light quality and system reliability and lifetime are important issues.
    - Silicone impacts color stability, and it is a big problem. The unpredictability is in the degradation of the materials used for the packaging and the lens. Silicone is used because of its relative stability over long periods of time but we need to understand the degradation mechanisms in this particular application and develop the ability to predict color shift over time.
    - Current the Illuminating Engineering Society (IES) LM and TM and Commission on Illumination (CIE) standards focus on light engine and luminaire, but we also need to understand the optics and materials that go into the integrated final product.
    - Materials suppliers need to develop test methods and models to predict product performance in SSL applications.
        - Tests would include photo-thermal stability for 85˚C and 85% humidity, UV exposure, and dry heat aging.
        - There are many different test methodologies being employed and the lack of standardization is a problem.
    - Key Questions that need to be addressed include:
        - Which standards are structured to resolve failure modes at the LED or luminaire level?
        - Can material suppliers provide better information to LED/SSL manufacturers relative to these tests?
        - How can year to year reproducibility be assured without expensive/redundant testing?
- Opportunities:
    - Material suppliers have a role to play in enabling novel LED luminaire systems with improved functionality and lifetime.
        - We should investigate integration of optical, electrical, and mechanical components. There could be a L-prize type competition for this.
    - We should work with LED manufacturers to establish how reproducibility can be assured without expensive/redundant testing, e.g. certification of materials based on sustained performance vs. IES standards/methods.
    - Can something like Zhaga be developed for materials?

    - Develop phosphor integration and standard procedures which are relevant to each SSL application and certification.
- Questions and discussion:
    - Another area of interest is developing higher refractive index materials for better light extraction
        - Phenyl materials have a refractive index of about 1.5 but increasing the refractive index for silicones to around 2.0 could potentially impact the color stability of the product.

5. Steve Lester

- It is important to figure out what do we do about the packaging cost since this is a major cost component of the LED.
- Toshiba is looking at getting rid of the package altogether by introducing wafer-level packaging methods on silicon substrates.
    - Phosphor is applied at the wafer level before cutting the wafer up and producing multiple small chip-scale packages
    - This approach builds on the trend from single emitters to chip-on-board and offers the prospect of more highly integrated solutions.
    - There are products like this now, but they are integrating many diodes into one package.
        - For example, the original Cree bulb has 80 junctions in series in 20 separate packages (4 LED/package) to achieve a high operating voltage, which facilitates the use of efficient, compact, and low cost drivers.
    - Moving to integrated multi-junction chips would enable package level innovation and drive down costs at the system level.
        - For example, a 32 junction chip would deliver an operating voltage of 100-110 volts and would avoid some of the costs associated with the packaging and assembly of 32 individual die.
- Some institutions are working on massively parallel pick and place batch packaging methods for LED displays.
    - All die are transferred from the original wafer to a “packaging” wafer/panel, typically using flip-chip (direct attach) LEDs.
    - This approach provides the possibility to package all die on a wafer simultaneously, and could be applied to LED lighting

6. Jim Neff, Philips LUMILEDS

- Lumileds is seeing a market demand for rapid customization at the board/module level such as integrated light engines comprising of LEDs and the driver.
    - LEDs are placed on ceramic or composite materials for active cooling and optics.
    - Customers do not want to hire someone do each piece, they want someone that can do all the integration.
    - Lumileds refers to this as “Level 2” (L2) integration, while “Level 1” (L1) is just the package or just the driver.
- There are good examples in the electronics industry of the move to higher levels of integration
    - The first cellphones were Si transistor, then GaAs with single IC – then multi-bands.
    - We will see the same thing with LED lamps and luminaires, and this will move the industry to smart modules.
- The marriage of hardware and software will also drive the market:
    - The Philips HUE has been very successful partly due to the software being made open source.

    - This led to the development of all kinds of apps. It's not just about the light bulb hardware, but it will be about the software that goes with it.
    - Markets will move toward providing a software solution.
- The current market trend is towards L2 integration since it simplifies the manufacturing process.
    - L2 integration may be most efficiently handled by the LED manufacturer since he knows how to best apply them.
    - Careful system optimization at L2 allows you to tailor the LED operating conditions, optimize the number of packages employed, and simplify the L2 configuration for lower manufacturing cost while retaining quality and reliability.
    - This translates to reduced system size and cost, which is valued by customers.
    - In order to implement rapid customization at L2 and provide customer solutions, manufacturing systems must be able to react quickly, e.g. flexible lines (maybe located near customers) and operation systems that allow you to switch from one customer need to another.
- Questions and Discussion
    - ISO standards require that you know where all of the LED chips used in a lamp/luminaire product came from, and participants asked if this would be a problem for integrated L2 modules.
        - Neff did not believe so, because those conditions were known in the factory, some LED suppliers choose to trace that, others do not, but they will be motivated to do it for the customer. Additionally, data is cheap so it is mainly about the software used to access this information
    - Participants asked if moving to system level integration will better enable us to develop a solution for compatibility issues with existing dimmers in a residential setting
        - Neff acknowledged that dimmer compatibility is a problem, and while he was sure there was an electronic solution out the, he suggested that backwards compatibility may not be the answer.
        - He suggested that driving down the cost for a 60 W equivalent A19 to $3 and achieving mass adoption would not be possible if we have flicker. It was possible to manufacture drivers that can drive a 60W equivalent for 50 cents but the quality is poor. This might be an idea for an R&D project.

7. Troy Trottier, CREE

- Solders
    - We are pushing to higher operating temperatures to drive down the lumens per dollar and SAC solders will become one of the warranty limiting materials in the system.
    - Using the Norris Lanszberg Model, we calculate that SAC solders can operate for about 13 years at an operating temperature of 110˚C, but this drops to only 2 years at an operating temperature of 160˚C.
- Drivers
    - The drivers for bulbs in general are a big issue.
    - The limiting factor is cost.
    - Need improved reliability and large value compatible capacitors (typically electrolytic)
    - At rated operating voltage (80˚C) a +20˚C change in operating temperature of an electrolytic capacitor will result in a >2.5x change in failure rate.
    - Most LED bulbs use non-isolated power supplies for cost and efficiency reasons, but ideally we need isolated power supplies with the same efficiency and cost of non-isolated supplies for safety reasons (so people cannot potentially be exposed to 240V if glass were to break).
- Glass

- Glass has number of useful properties. It offers long term stability with light and heat (better at 40K hours), high transparency, and good dielectric strength, but it is difficult to form complex glass shapes.
- We need to develop techniques to shape, cut, and form glass. You need absolute control, and it would be interesting to have better tools and capabilities in the glass world.
- We need to develop glasses with improved thermal conductivity.
- Tough glass that is thin and break-proof would be beneficial.
- Glass has applications beyond the residential light bulb, and with improvements, glass would be nice to have on commercial side as well. Currently plastic is used because of shaping requirements.

- Alternative materials systems to GaN
  - Can we solve droop in the 3 to 5 year time frame? This could help us reduce operating temperatures at high drive currents.
  - Are there other materials that we can utilize?
  - If we could get rid of the heat sink that would be great, but junction temperatures are creeping up to reduce cost and at some point we will hit the limit.

8. Dave Bartine, Maxik Labs

- Where are we going? LED efficiency is continuing to rise and likely will beat the DOE goal.
  - 100 lm/W is common now and most manufacturers are targeting 150 lm/W.
- In terms of power supply developments:
  - Efficiencies are getting better, and are at about 90% now and are expected to get to 95%
  - Magnetics transformers are getting smaller
  - Capacitors remain a problem. We need electrolytic replacements, and we need to move to a design that uses no magnetics.
  - There is an opportunity to develop new capacitors.
  - We are moving to higher levels of integration with the power supply and LEDs on the same substrate.
  - Reliability is currently limited and temperature dependent; at 105˚C the 5000 hour failure rate isn't good enough, so you need to pay more to get longer life.
  - The bottom line is that power supplies have been shrinking and getting cheaper, but to continue, we need an economical approach to improving or replacing the electrolytic capacitor.
- Questions and Discussion:
  - What about electromagnetic interference (EMI) problems if you use smaller capacitors and operate at higher switching frequencies?
    - With capacitors you trade EMI for high frequency, this is a challenge.
  - The EMI testing burden is getting worse, can something be done in the long term from a standards perceptive?
    - The FCC has done a pretty good job, but as the luminaire gets more complex, e.g. including battery back-up and motion sensor with the LED and driver, and we move to networked LEDs and wireless communications, this will become more involved. We need to make sure we can pass reliability tests and perform out in the field.
  - Is NEMA looking at this?
    - NEMA is seeing increasing complaints in USA from wireless companies since the airways are getting more crowded. They are starting to question whether or not we are testing the right way.
  - What can the DOE do for innovation?

        - Industry is often blind-sided by new standards and testing requirements, however, this is probably not something that the DOE SSL Program can assist on.
    - Is it practical to think of a single IC for one power supply?
        - That is the direction we are going, but there is no way to know if we will get there.
    - The capacitor remains a limiting factor. Is this an opportunity for a capacitor contest?
        - Sure, if you have a research topic you might get multiple approaches, but it is hard to get components that work with the system. You must give the right parameters.
    - Can the DOE help with this? Can we look at developments for electric cars supported elsewhere?
        - Ideas from the field battery technology area might be appropriate. There is a lot of work being supported in this field and maybe there is something there of relevance.

9. Yan Rodriguez, Acuity Brands

- In the past, only 5-10% dimming was required for fluorescent technology, however since incandescent was 100% dimming that is now the expectation for SSL regardless of application.
- Today 95% of SSL is dimmable and is replacing compact and linear fluorescents.
- There are two main types of dimming for SSL – you can either do 0-10V dimming or phase voltage dimming.
- There are other “controls”-based dimming methods which are gaining acceptance in commercial and architectural spaces such as Dali, Nlight, and DMX, however this discussion will focus on 0-10V dimming.
- There are a multitude of differences found in 0-10V dimming:
    - Turn on time
    - Turn off time
    - Dim curve
    - Low dim point (0.1% - 3%)
- These inconsistencies have become a frustrating issue in the marketplace.
    - In some spaces you can have 4 or 5 different kinds of lighting, and when you try to dim them all together, none of them dim in the same way.
    - This problem is made worse by the fact that even if the specifications match, the actual dimming appearance may not. The meaning of 0.1% dimming is specified differently from manufacturer to manufacturer.
- SSL can dim to 0.1%, but there is still a big difference compared to incandescent which can get to 0%.
- How do we specify what 0.1%, 1% or black really means? These specifications need to be defined and consistent from manufacturer to manufacturer.
- What are the expectations for marketplace? We need a better definition for what the marketplace wants, e.g. turn-on time. What do they want, and what is achievable?
- As we develop curves or dimming, what is the definition for each one? We need published curve definitions for dimming of SSL products.
- Another issue with LED dimming is from product to product where you can end up at different brightness when you dim. How do we want to measure this?
    - We had this same problem with fluorescent lighting, but the market for dimmable fluorescent was a small market. If dimming was really important you would use a different technology.

    - But SSL has to dim and because of cost pressure, we would rather have poor dimming than none at all. However, this becomes a source of frustration in the field and gives SSL a bad name.
- We need to determine the consumer expectation with color dimming.
    - Many expect the dim-to-warm to be become standard, but is this truly a requirement or is it something we just think customers want?
        - Hospitality and restaurants claim to want it, but the Lighting Research Center did experiments and found that zero participants cited color as an issue during LED dimming so maybe it is not needed for general service lighting.
- Possible R&D Work includes:
    - Dimming technologies and issues with drivers: dimming to near black and understanding where the challenges are.
    - Understanding the market expectation from a visual side, and determining what the specification should be. Determining what we really want or need (i.e. human factors research).
    - Determining industry standard terminology and acceptance, and the research needed to back up the definitions. We should consider if this is for IES or ANSI.
        - Such research is difficult to do cheaply and requires support

10. Dennis Bradley, GE Lighting

- Consumer education is a big issue, the consumer is confused.
    - They do not understand benefits.
    - Energy savings are not a priority.
    - They kind of understand lumens, but CCT and CRI are mysteries.
    - We need better retail staff training and education on lighting products.
    - We need better labeling or education programs.
        - Consumer will not pay for warm dimming
- Application efficiency vs. appliance efficiency
    - We should focus on application efficiency. We need to consider where the light needs to be because it is important for developing truly energy efficient products.
    - We need to consider the <u>useful</u> lumens per watt.
    - How do we get to utilization efficiency? We need to pursue the concept of lighting the space and only putting light where you need it. This is a key advantage of SSL.
- Color and outdoor lighting
    - ANSI c78.377 does not apply to outdoor lighting but the customer will still request it.
    - Do we have to have 80 CRI? For roadway and area lighting this may not be necessary.
    - These over constraints add cost.
- Controls
    - Controls are demanded more and more, e.g. the California standard requires all lamps to be controllable.
        - Do controls really need to be a requirement for every application?
        - Are they all being used and are they saving energy? Need some monitoring.
        - There have been many studies that have shown that controls do reduce energy consumption, but are people installing controls effectively and appropriately?
    - Dimming of outdoor roadway lighting could save energy, but this could be a safety issue.
        - In the US we have concerns about getting sued. What are the safety standards for roadway lighting?
    - Inter-operability standards are need for controls to ensure all controls and lighting products work together.

11. **Steve Paolini, NEXT Lighting**

- There are those that want to save energy and there are those that want to make money. The key to both is deployment.
    - We can add value or reduce price.
    - However, the main focus cannot be reducing price, since that would drive us to cheaper and lower quality products. Reducing prices should be secondary to adding value.
    - The smart phone is a successful example of this logic where price is secondary.
- How to go about adding value:
    - Control the spectrum.
        - Encourage all colors other than white, in all packages.
            - Developing other colors will still need R&D work.
        - Encourage daylight replication. Enabling customers to supplement natural light or create specific daylight conditions is valuable.
        - Both fire and incandescent dim to warm, and daylighting also dims to black.
            - Replicating this would add value.
        - Add data. The RF spectrum is getting crowded but there are other spectral regions.
        - Need to measure and control the spectrum at every color, and we need to know what every LED is doing.
    - Control the beam distribution.
        - We have LEDs and laser diodes, and controlling the beam distribution can be used to add value.
    - Controls
        - We are moving beyond dimmers, and we have gotten to the color wheel, but this isn't the end point.
            - Need to get to automated and predictive color tuning.
            - Need to be human and machine capable (need to collect data).
            - HUE is open source and this has led to innovation and creativity. If we want to get consumers to adapt to SSL, we need this kind of approach.
            - Need two way data flow. The lighting needs to understand what is going on in the room.
                - Lighting can know how many people are in the room, and lights are really good software platforms.
            - But different luminaires will need to communicate with each other to effectively light a room. This may mean having standards.
- U.S. production and consumption of SSL
    - Rebates are nice but value demand is better.
    - We need more outreach (teaching the value beyond energy) education programs.
    - We need permanent demo rooms to show off value (and save energy).
    - Taxes are beyond our pay grade, but are a big deal.

12. **Jeff Tsao, Sandia National Laboratories**

- Lasers offer certain benefits as sources for SSL.
    - The etendue case: They generate a narrower beam, use a much smaller phosphor area, and have much higher etendue.
    - The valley of droop case: Lasers offer the potential for high efficiency at high power densities compared with LEDs that suffer from droop.
        - It is possible that lasers can extend the useful region of high efficiency operation and minimize the impact of droop

    - Cost case: The rule of thumb for conventional lighting is $CoL_{capital} < CoL_{operating}/6$ where CoL = cost of laser.
        - If we take strict cost criteria, then lasers can be cheap photon sources.
- Is getting power density at low cost possible?
    - Photonic crystal surface emitting lasers (PCSEL) based on an InGaAs quantum well are 25% efficient.
        - Currently this is only for IR wavelengths but the results are exciting.
    - The surface emitting geometry is compatible with batch processing since everything can be done on wafer. This should reduce costs.
- Lasers applications for theater lighting
    - Software can only act on hardware. We can conceive micro systems that can steer and guide beams in every office and room, but we will need an engine that enables it.
- Defect densities for GaN on sapphire substrates do not support lasers, so GaN substrates would be important for technology.
- A red emitter is more difficult. Maybe it will be possible to use a blue laser in conjunction with a phosphor. Longer term it would be great to have a mixed color laser. However guiding the beam is valuable regardless.
    - If you use a pulsed laser, this might give phosphor time to cool down and maintain efficiency.
    - Lowering threshold current densities is important for lasers.
    - One vision is to have a few powerful sources but another vision is to have hundreds of low power tunable light sources. Now you have much more control and as you distribute the power the thermals become easier to handle although things would have to be cheap
- It is well established that lasers make sense for directional applications but what about other applications?
    - In most cases people will want a mix of ambient and focused lighting.

Appendix B: R&D Task Descriptions

The R&D task descriptions, defined in the 2014 DOE SSL R&D MYPP and the 2014 DOE SSL Manufacturing R&D Roadmap[1], are provided in the following table. Tasks identified in 2014 as priorities are shown in red.

R&D Task	Description
Core Technology:	
A.1.3 Down-Converters	Explore new, high-efficiency wavelength conversion materials for the purposes of creating warm-white LEDs, with a particular emphasis on improving spectral efficiency with high color quality and improved thermal stability and longevity. Non-rare earth metal and nontoxic down-converters are encouraged.
A.5.1 Optical Component Materials	Develop optical component materials that last at least as long as the LED source (50,000 hours) under lighting conditions that would include: elevated ambient and operating temperatures, UV- and blue-light exposure, and wet or moist environments.
A.6.2 Thermal Components Research	Research and develop novel thermal materials and devices that can be applied to solid-state LED products.
A.7.4 Driver Electronics	Develop advanced solid-state electronic materials and components that enable higher efficiency and longer lifetime for control and driving of LED light sources.
Product Development:	
B.1.1 Substrate Development	Develop alternative substrate solutions that are compatible with the demonstration of low cost high efficacy LED packages. Suitable substrate solutions might include native GaN, GaN-on-Si, GaN templates, etc. Demonstrate state-of-the-art LEDs on these substrates and establish a pathway to target performance and cost.
B.1.3 Phosphors	Optimize phosphors for LED white light applications, including color uniformity, color maintenance, thermal sensitivity and stability.
B.3.2 Encapsulation	Develop a thermal-/photo-resistant encapsulant that exhibits long life and has a high refractive index.
B.3.6 Package Architecture	Develop novel LED package and module architectures that can be readily integrated into luminaires. Architectures should address some of the following issues: thermal management, cost, color-efficiency, optical distribution, electrical integration, sensing, reliability, and ease of integration into the luminaire or replacement lamp while maintaining state-of-the-art efficiency. The novel packages should address technology and performance gaps within the current state-of-the-art. Proposed approaches could employ novel phosphor conversion approaches, RGB+ architectures, system-in-package, hybrid color, chip-on-heat-sink, or other approaches to address these issues.
B.5.2 Color Maintenance	Ensure luminaire maintains the initial color point and color quality over the life of the luminaire. Product: Luminaire/replacement lamp
B.5.3 Diffusion and Beam Shaping	Develop optical components that diffuse and/or shape the light output from the LED source(s) into a desirable beam pattern and develop optical components that mix the colored outputs from the LED sources evenly across the beam pattern.
B.6.1 Luminaire	Integrate all aspects of LED luminaire design: thermal, mechanical, optical,

[1] http://energy.gov/eere/ssl/technology-roadmaps

Mechanical Design	and electrical. Design must be cost-effective, energy-efficient, and reliable.
B.6.2 Luminaire Thermal Design	Design low-cost integrated thermal management techniques to protect the LED source, maintain the luminaire efficiency and color quality.
B.6.3 System Reliability and Lifetime	Collection and analysis of system reliability data for SSL luminaires and components to determine failure mechanisms and improve luminaire reliability and lifetime (including color stability). Develop and validate accelerated test methods, taking into consideration component interactions. Develop an openly available and widely usable software tool to model SSL reliability and lifetime verified by experimental data and a reliability database for components, materials, and subsystems. This task includes projects that focus on specific subsystems such as LED package, driver, and optical and mechanical components.
B.7.1 Color Maintenance (Electronics)	Develop LED driver electronics that maintain a color set point over the life of the luminaire by compensating for changes in LED output over time and temperature, and degradation of luminaire components.
Manufacturing R&D:	
M.L.1 Luminaire Manufacturing	Support for the development of flexible manufacturing of state-of-the-art LED modules, light engines, and luminaires.
M.L.3 Test and Inspection Equipment	Support for the development of high-throughput, high-resolution, non-destructive test equipment with standardized test procedures and appropriate metrics. Such equipment might enhance test and inspection capabilities at various stages within the manufacturing line, such as 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 activities will develop and demonstrate effective integration of test and inspection equipment in high-throughput manufacturing tools or in high-throughput process lines, and will identify and quantify cost of ownership improvements.
M.L.2 Driver Manufacturing	Improved design for manufacture for flexibility, reduced parts count and cost, while maintaining performance.
M.L.3 Test and Inspection Equipment	Support for the development of high-speed, high resolution, non-destructive test equipment with standardized test procedures and appropriate metrics.
M.L.6 LED Packaging	Identify critical issues with back-end processes for packaged LEDs and develop improved processes and/or equipment to optimize quality and consistency and reduce costs.
M.L.7 Phosphor Manufacturing and Application	Support for the development of efficient manufacturing and improved application of phosphors (including alternative down converters) used in solid-state lighting.