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

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Introduction

On September 10, 2015 sixteen experts light emitting diode (LED) based lighting gathered in Washington, DC at the invitation of the Department of Energy (DOE) Solid State Lighting (SSL) Program to help identify critical research and development (R&D) topic areas for both the product development and manufacturing 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 three to five years. This was followed by a general discussion of the most critical technology challenges facing the industry today. Following these discussions, the participants were asked to contribute ideas regarding program content for the upcoming R&D Workshop, February 2-4, 2016 in Raleigh, NC.

This report summarizes the outcome of the discussions on critical technology challenges and identifies corresponding R&D tasks within the existing task structure. 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.

- Advanced Packaging
- Power Supplies - LED Drivers
- Color Stability, Reliability, & Lifetime
- Value-Added Proposition

1. Advanced Packaging

Participants agreed that moving more capabilities into the package will make the production of LED luminaires more cost effective. Taking functionality out of the luminaire and embedding it into the chip or package should be a priority research area. Several participants noted that phosphor integration with the encapsulant at the wafer level to create a white LED chip, or chip scale package (CSP), provides cost savings over a conventional package. There are technical challenges associated with the CSP configuration including uniform side wall coating, handling a chip with a fragile converter layer, and on-wafer measurement accuracy (due to aberrations from light coupling through the substrate). In addition, within a luminaire, the CSP cannot extract as much light as a full high power package (due to etendue). There is an opportunity to redesign the CSP architecture to capture back some of the light lost when abandoning the conventional package dome lens. Wafer scale packaging is key research area to help bring package features down into the chip level.

2. Power Supplies - LED Drivers

Solid State Drivers

Participants agree that to improve driver reliability, there is a need to move away from fragile components like electrolytic capacitors. Solid-state component integration into the driver should be explored as a more robust alternative since solid-state drivers have the potential to be much smaller, cheaper, and more efficient. Research shows that significant energy savings are possible by going to GaN-based power electronics. This is an important opportunity and should be an area of focus for DOE.

Power Supply Reliability
Providing reliability test results for individual components in a luminaire and then developing predictive models to determine the lifetime of the LED luminaire would be valuable. Current models, such as mean time between failures (MBTF), are insufficient for measuring reliability. Developing additional key metrics to define failure, and ways to predict them would be beneficial to the SSL industry.

Power surges and other electrical events that cause abnormalities in power quality can damage LED lighting components. While this is not a problem unique to lighting, as more fragile components are introduced into the SSL system, protecting LED luminaires from poor power quality becomes more important. Participants also noted that current surge protection systems are built around larger events, meaning that several smaller events are able to get though surge protection systems and do more damage over time. In the industrial space, often LEDs and LED drivers are not as robust as incumbent high intensity discharge (HID) copper wound ballast systems.

3. Color Stability, Reliability, and Lifetime

Several participants raised concerns about color stability, reliability, and lifetime. Color shift remains a big issue that poses reliability and product warranty challenges. In addition, there is a general lack of understanding regarding what is an acceptable amount of color shift since it varies by application. Research is required to understand the various color shift mechanisms in LED packages and develop predictive modeling. An IES (Illuminating Engineering Society of North America) testing procedure committee is working on a new technical memorandum ™ to help predict color shift. This procedure will provide a method to extrapolate color shift from accelerated test data. Participants noted that the extrapolation curves will be different for different pump wavelengths and operating conditions, and the solution will not likely be “one curve fits all”.

Participants also expressed that color rendering index (CRI) alone is not enough to describe the color quality of light; there are differences with the way people perceive light that is not fully captured by the CRI metric. Other parameters, such as fidelity and gamut area, better describe the quality of the light. TM-30-15, recently published by the IES in an attempt to better describe color quality as it relates to preference, defines a new fidelity matrix to replace CRI that uses 99 color samples and new metric related to gamut area. However, TM-30-15 still does not indicate the preferred visual experience. Continued research is necessary to identify a more applicable preference metric of the visual experience.

4. Value-Added Proposition

Participants discussed the opportunities to create value-added features that enable SSL to go beyond general illumination. Added value options cover many different areas from communications to human physiology and each area has its own specific R&D challenges associated with enabling the technology. These various new features not only change the functionality of SSL, but they change the value proposition as well. The participants stressed the importance of quantifying the value proposition of these added features for the customer in order to encourage adoption and merit the higher first cost of SSL lamps and luminaires. Research is needed in order to better understand the value of new features and how it can impact the payback of purchasing SSL. Major value-added features and their challenges are described below:

Smart Lighting & Controls
Interoperability was acknowledged by the participants as one of the biggest challenges facing smart lighting and controls. Currently many differing protocols that exist for lighting connectivity and controls that cause interoperability challenges and slows adoption of these products. While the interoperability

challenge is of critical importance, technology development is not the key barrier. Therefore this topic is better handled throughout other DOE efforts than direct R&D funding.

Sensors are a critical aspect to harness the most potential from smart lighting and controls. The sensor industry, driven by mobile devices, has already made significant progress in sensor technology. Because of the strong drive from the mobile industry, participants anticipate that the sensor industry is already on the path of developing the required technology for smart lighting applications; therefore, targeted R&D support is not required.

An area for possible R&D investment is in Li-Fi, or visual light communications (VLC), using LEDs. VLC requires improvements to enable faster data transmission speeds to address one of the current challenges for data transfer with lighting. More research is required to improve the modulation speeds of the LEDs to increase the transmission speeds to make this added communication functionality valuable. This may require the exploration of laser diodes (LD) for lighting with their faster modulation speeds.

Human Factors

The spectral content in light has physiological and biological impacts, which can be both beneficial and detrimental to human health and productivity. LED lighting provides a flexible platform to take advantage of tailored spectral content that has the potential to improve our health and productivity, but more research is needed to quantify and verify these claims. There is a need for real world polychromatic testing data in order to understand the effect blue pump LEDs have on human physiology and biology. Currently, all action spectrum data is about 14 years old and was conducted with monochromatic light in highly controlled laboratory setting. Developing new lighting platforms and research tools for human factors experts to better carry out their experiments is another valuable area of R&D the DOE could support. Getting the right tools in the hands of the researchers can make the human factors studies more effective. More research is also needed to understand people's preference for color, start up time, dimming, etc. Studies need to be well designed as there are multiple factors to consider when looking at different applications and populations.

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

The R&D planning process described in the R&D Plan 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 funding opportunity announcement (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)**	
	Product Development	Manufacturing R&D
1. Added Value Proposition	(Proposed New Task) Connected Lighting (Proposed New Task) Human Factors – Preference, Physiological Responses, and Light Quality Metrics	

2. Power Supplies - LED Drivers	B.6.3 System Reliability and Lifetime (Proposed New Task) Power supply – Solid State Components	M.L.2 Driver Manufacturing
3. Advanced Packaging	B.3.6 Package Architecture	M.L.6 LED Packaging
4. Color Stability, 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 2016 DOE Solid-State Lighting R&D Workshop, February 2-4 in Raleigh, NC. The combined results of the Roundtable and Workshop discussions will guide the DOE in soliciting projects for the LED R&D Program.

Appendix A: Participant Presentations

1. George Papasouliotis, Veeco Instruments – CoO Reduction and MOCVD Reactor Scale-up

Aggressive reduction of LED cost will enable faster SSL adoption. The critical elements of cost of ownership (CoO) reduction include metal organic chemical vapor deposition (MOCVD) reactor scale up, MOCVD tool automation and performance/yield improvements. The Veeco roadmap has helped facilitate LED cost reduction; the K465i and MaxBright are amongst the best-selling MOCVD platforms between 2009 and 2014 and have improved market share from 29% to 60%.

Veeco's latest reactor, the EPIK700, was built with some modifications that help facilitate improvements in productivity, performance, and wavelength uniformity. These modifications include an improved injection system to distribute gases, improved susceptor design for more uniform temperature control, and improved cycle time. These features have led to a CoO advantage over its predecessor K465i of about 42%.

2. Wouter Soer, Lumileds – Wafer Scale Packaging

Wafer scale packaging is currently being employed for today's CSP architectures. Currently, CSPs can be made for a reduced cost due to minimal packaging around LED. There are opportunities to realize ultimate cost reduction by achieving a higher die density in back-end process and elimination of pick-and-place steps.

Phosphor integration is the main challenge at the wafer level for color control due to the strict requirements for blue wavelength control and phosphor material amount for that given wavelength to get a uniform white color point across the wafer. This requires MOCVD growth uniformity for the blue emitter and a uniform phosphor deposition process across the wafer full of blue die. Techniques to provide uniform white wafers require: reducing within-wafer pump wavelength variation and/or within-wafer converter variation, using phosphor materials with broader absorption spectrum to eliminate effects from the wavelength distribution, and new phosphor integration process allowing the adjustment of parameters or thickness as phosphor is applied to the wafer. In addition to the uniformity challenge, current wafer level processes are not compatible with the high packing density on a wafer. This high packing density of LED die requires a uniform phosphor coating in high aspect ratio trenches between die to assure good side wall coverage on the chip.

Wafer-level testing needs to be improved to provide an accurate measurement of the die without interference of light coupling through the substrate, and the testing needs to capture all the light from the die to be accurate. Intermediate tests are required to enable process control and phosphor targeting, and accurate calibrated optical measurements are required for color point targeting. The biggest challenge for intermediate testing is that light is coupled into the substrate and interacts with neighboring die. Final testing of the LED product to specification requires capturing all emitted light from the die for proper calibration. The biggest challenge is simultaneously accessing electrodes to perform proper photometric measurement since the wafer is typically on carrier at this stage (i.e., post-singulation).

3. Steve DenBaars, University of California Santa Barbra – Novel LED and LD devices for Next Generation High Quality SSL

Some of the major well known issues in SSL include current droop and thermal droop. Press releases in the industry show the efficacy of LEDs to be beyond 200 lm/W, but actual commercial LEDs are in the 70 to90 lm/W range. While there have been improvements, droop is still the most dominant complaint from manufacturers. Migrating to laser-based white light provides great benefits over traditional LED based white light. For LDs, current droop is eliminated when lasing occurs since all excess carriers are consumed by stimulated emission, thus reducing the availability of carriers for the non-radiative Auger recombination processes. This enables high flux density and higher wall-plug efficiencies than LEDs at very high current density operation.

In addition to the droop benefit, the required epitaxial area for a certain light level is dramatically reduced with LDs. For example, a 60W incandescent light bulb requires 28 mm^2 of LED epi, $3mm^2$ of bulk GaN LEDs or $0.3mm^2$ for a LD. This helps reduce the cost per lumen for a LD, because while the device itself is more expensive than an LED, the significantly improved epi utilization makes the overall cost more reasonable.

Currently, LDs combined with phosphors have poor CRI. This is not an issue for automobile headlights, but it is a significant drawback for general lighting applications and needs improvement. Further research on integration with phosphors would be beneficial.

4. Ashfaq Chowdhury, GE Lighting – Realizing Energy Savings Profitably

There are several different approaches to white LEDs, but the most prominent, cost-effective path is phosphor-converted (pc) integrated packages in low and medium power settings. There needs to be increased focus on developing new narrow-band green and red down-converting materials for pc-LEDs.

There is still the opportunity to make better controls. Interoperability is the main challenge preventing further deployment. Cost effective and easily commissioned residential and commercial systems are needed, and the key is developing smart and intelligent drivers that can communicate between different building systems.

Beyond energy efficiency, there are alternate value propositions attainable with spectral control such as health, worker productivity improvement, and horticulture. Further research is needed to determine the correct special-purpose spectrum for these applications.

5. Joel McDonald, Dow Corning - Materials Development for SSL

The approach of a holistic phosphor integration is critical to get the most out of the phosphor and encapsulant materials. The major challenge is that phosphor/binder interactions are poorly understood, even though they are critical for device function. The difficulty in this area of research is that the evaluation of phosphor/binder interactions requires cooperation between research entities and manufacturers, and usually involves an exchange of proprietary information. To enable future material development, the DOE can consider funding an expertise center focused on phosphor integration.

Novel lighting materials such as phosphors, quantum dots (QDs), high refractive index additives, and binders are under development. Unfortunately, LED devices and luminaires are complicated systems, and few have sufficient vertical integration to perform to comprehensive materials testing in device form factors to enable development. There is a need for third party materials evaluation to help drive understanding and innovation.

There is a need for in-situ diagnostics devices for monitoring/collection of environmental, photometric, and electronic diagnostics to better understand the variety of possible failure modes that occur in LED devices and luminaires. Developing ways to measure properties, such as temperature inside the luminaire, during this process would add great value.

Achieving efficacy targets requires improving efficiencies at all points in the luminaire; however, actual losses associated with optics is not widely understood. Developing better luminaire loss models would help prioritize the role of lenses and diffusers, and hence prioritize the required optical materials development activities.

6. Yoshi Ohno, National Institute of Standards and Technology (NIST) – Color Quality Issues
A vision experiment conducted by NIST in 2013 showed that the preferred D_{uv} level of white chromaticity fell below the black body curve. In 2015, the same experiment was repeated but light was modified so that at each point the gamut was the same, and there was the same saturation for red and green samples. The experiment was conducted for 21 subjects and results were similar to 2013. The findings show that the CRI, a color fidelity metric, cannot accurately measure perception of color rendering. The biggest problem is that the CRI score does not correlate well with perception when chroma is more saturated, so a new color preference metric is needed.

IES TM-30 has been recently published using a new fidelity metric to replace CRI and a second metric related to gamut area. While it is widely recognized that fidelity alone is insufficient and agree that something more is necessary, there is no preference metric yet. Only gamut area can be measured right now. Since there is not enough research yet, TM-30 does not claim an optimum gamut area. It is an area in need of further research by the industry. There will not be a perfect solution because gamut area is average for all colors but perception is different for each color. Studies suggest red and green are more important than blue and yellow. A new preference metric can help score things higher than 80 CRI for Energy Star, and make it possible to use fidelity and preference metrics. The hope is to come up with a metric so that good products are no longer penalized by CRI.

7. Steve Lester, Toshiba – Chip Scale Packaging and LED Drivers
In LED packaging, everything on-wafer is done in batch processes, but the package is assembled individually. Consequently, the major cost in LED packages is not the semiconductor, but the packaging. It is crucial to be able to scale-up the packaging technique to batch level processes. Currently, the efficacy for CSPs have performance is lower than traditionally packaged LEDs. The fundamental reason is an etendue problem – the surface area to junction area ratio is too small. Current state-of-the-art LEDs can get 20% more light output using a domed lens. Approaches to overcome the etendue limitation include building the phosphor very tall or limiting the junction area relative to the phosphor, which requires a creative device structure using a submount to create the rest of the wafer scale package around the epi chip. Parallel pick-and-place methods, where you can place and construct a package at the wafer level, is another approach that needs to be developed. This allows for surface area larger than the junction area.

GaN power transistors can improve the performance of LED drivers. Their advantages include: high temperature operation, high frequency, smaller sized passive components, and lower switching loss. More synergy between the government funded programs in power electronics and SSL should be explored.

8. Doug Hamilton, Hubbell Lighting – Driver Reliability
The bulk of luminaire warranty issues are driver related, and the majority of failures seen are caused by drivers wearing out not infant mortality. So what is the best way to test drivers? MTBF calculations assume a constant failure rate for each component, which may not be true. For example, a product with MTBF of 50,000 hours will exhibit about 15% failures in the first year (8000 hours). Data from the European Power Supply Manufacturers Association, an independent trade body, found that MTBF figures for the same product could vary by 10:1, depending on the methodology used in calculating them. This is further evidence that an over-emphasis on MTBF as a measure of real-world reliability is just marketing smoke and mirrors. SSL successfully uses IES standards LM-80 and TM-21 for LED and in-situ fixture lumen maintenance predictions, and a similar approach should be applied to drivers.

9. Mark Hand, Acuity Brands – SSL Challenges
Color shift of LEDs is a warranty challenge for luminaires, with some customers requesting 10 year warranties. There is a clear need for predictive modeling for LED color shift and reliable testing methods.

LED drivers are typically the weakest link in the luminaire system. Manufacturers want to get cheapest driver possible, as drivers are the most expensive singular component in the luminaire. Therefore, cost is important and quality is being further eroded. Research is needed to improve the quality of driver and then to build predictive models. Integrating solid-state capacitors may also improve the reliability of LED drivers.

Creating standards around LED package size and performance will bring the cost down and accelerate SSL adoption. It also alleviates the supply chain risk and the need to carry dual supply of LEDs. Standardization can also alleviate the testing burden on the luminaire manufacturer for different LED manufacturers.

10. Troy Trottier, CREE - Areas for Advancement in LED Lighting Products

Enabling color/intensity sensing in lighting opens the door to feedback and control as added features. Currently, getting data from a bulb is problematic because sensor technology is too costly and too big to fit in the bulb form factors. In luminaire applications, smart intensity/color control can be used for long term monitoring of luminaire health. System level applications include networked lighting, localized adjustment/effects relative to neighboring luminaires, and ambient balance/correction.

Small form factor devices (like bulbs) are heat constrained due to surface area limitations and of course, cost. It is fairly easy to move heat from one point to another within the operating bulb environment, but it is not easy to move heat out to the ambient surroundings. These systems are categorized as convection constrained systems, and the limitation is in the final step (i.e., emitting heat from the bulb surfaces to the air around it efficiently). There are a number of ways to improve thermal performance. Passive cooling has the advantage of no heat sink (one of the most expensive components in bulbs); however, they struggle with limited air movement capability, orientation sensitivity, and ingress protection. Active cooling at small sizes using fans or other active cooling technology has the challenges of reliability, cost, noise, and efficiency.

11. Ron Gibbons, Virginia Tech – Roadway Lighting

In roadway lighting, there is a significant need to improve the application standards to ensure the maximum benefit of the LED technology and to minimize the potential for problems. IES has developed standards based on the limitations of traditional lighting technology. With LEDs there are applications where the design criteria are being met but they may not be the best for the user. Night to day crash ratio is one issue. The more uniformly lit the road surface is, the higher the crash rate. People need a bit of non-uniformity to see because daylight is coming from a light source diffused through the atmosphere (sunlight) and not a light source directly above the surface. Another issue is that, previously, roadway lighting designs never considered lighting sidewalks because there was back light thrown that direction with HID technology. Since LED lighting is more directional, light for the sidewalk must be part of the design.

Electrical standards have been developed that can be exceeded by the existing technology. Magnetic ballasts and starters are relatively robust whereas electronic starters are not. This is important to consider in the event of accidents that knock down power lines. In addition, requirements for the physical performance of the luminaire should be evaluated for vibration, weather conditions, and impact. The luminaire performance in the field needs to be considered in the design stage.

12. Susanne Seitinger, Philips– Lighting Controls

We can draw inspiration from various industries that impact the way we think about interacting with light (i.e., adding value, going beyond the energy story and linking it to values people can get). For example, the delicate way in which light is integrated into vehicle environments exceeds the way it is experienced in other environments. There is only light where it is needed when using the car.

Interactions with robotics and large amounts of data are shifting rapidly with the advance of human-robot interactions, natural language processing, and better gesture/peripheral interaction techniques. Environments where humans and machines interact in the same space may provide a different way to think about lighting systems.

Our expectations for performance-based metrics and interaction with the buildings we inhabit are slowly changing, but not in the ways one might have expected. There is a disconnect somewhere between the construction and design phase, and there needs to be a way of thinking about the building post occupancy. The need to enhance light and make it a part of consumer experience has been established. Now people expect things to integrate with each other.

Research should focus on "controls for users" to better integrate how people engage with the lighting experience. More application focused work that takes into account different kinds of scenarios on how users engage with their environment is needed. Expand the language used around light, and get people educated and involved. Look at preferences and figure out a way to scale it massively.

13. Lori Brock, Osram – Smart Lighting Challenges

Smart lighting is an intelligent and connected ecosystem that extends beyond illumination. The features that are required of smart lighting include:

- Interoperability to work with other products
- System resiliency (i.e., no single point of failure)
- Reliability for critical applications
- Low latency
- Scalability to meet application needs
- Seamless connectivity to devices
- Easy and/or self- commissioning
- Security.

While all these features are clearly needed for the application, they are all areas needing research and innovation in order to deliver the promise of smart lighting. One major, but often forgotten, area listed above is cybersecurity. Every major communications protocol used in industry is being hacked. With the exponential internet of things (IoT) growth (i.e., 8 billion devices connected to the internet in 2015 vs. 500 million in 2005), this becomes an increasing liability in how to use smart lighting.

14. Brian Chemel, Digital Lumens - A Downstream Perspective

How much further will Haitz's law take us? The rate of change in technology is slowing down, so the fixture redesign rate is slowing too which is leading to longer design cycles. How will we match the historical rate of improvement going forward? The biggest challenge is the tradeoff between cost, efficiency, and reliability, since "you can only pick two". High power devices are efficient, reliable, and meaningfully more expensive. Mid power devices are cheap, efficient, and not very reliable.

Recommended areas for research include:

- Packaging: Producing more low cost stable material systems.
- Spectrum: Our customers look at things with same CRI but perceive differences.
- Optics: Making products with less glare and how to balance efficiency and aesthetics.
- Power: Better topologies, better components and new high frequency technologies.
- Controllability: Standardize digital dimming

Key application areas include:

- Responsive Lighting Controls: Automation, customization and optimization is important to meet demand.
- Human Biological Factors: how light affects sleep patterns or workplace productivity.
- Horticulture: spectral tuning tailored to specific crops, and active growth cycle management.

15. Evan Petridis, Enlighted - Sensing and Control Architecture for SSL

Corporate spending per square foot of office space per year shows lighting expenses as minimal. The impact of lighting influencing productivity, however, is huge. Essential features for the IoT include compute power, memory, bandwidth, sensing, and real estate (i.e., the light fixture).The light fixture is real estate, and that is what is valuable.

Today's lighting controls are relatively simple and incorporate ambient light, temperature, and ultrasonic functionalities. There is immense pressure to progress features to imaging, visible, local Bluetooth, and networking, but these drive up bandwidth requirements. Today, a few tens of bits per second (bit/s) per sensor is required, but this will increase to thousands of bit/s (kbit/s) per sensor next year. Getting the data out of the sensors requires standard protocols. There are some protocols that work well for small environments, but not for large scale applications like the lighting industry looking to implement. Luminaire external interface standards that define kbit/s per sensor, is both wired and wireless, and is scalable to the enterprise would help with these challenges. An intra-luminaire sensor interface, how the sensors communicate with the driver, is important as well. Standards around the mechanical envelope, electrical requirements (e.g., power, data, and local control), and protocols/data structures would be beneficial.

16. John Hanifin, Thomas Jefferson University – SSL and Human Health

Light has good and bad effects for humans. A five year study published in 2001 investigated the effect of light on the neuroendocrine system. Subjects walked through spectrum and were given different doses of light. The suppressive effect of light on pineal melatonin in blood was examined. Studies show that peak melatonin is in the blue range, which coincides with the peak of blue pump phosphor LEDs.

Light has an impact on a whole host of biological effects, including acute effects of light on melatonin secretion, body temperature, cortisol secretion, heart rate, alertness, and brain blood flow, to list a few. Light also has long term biological effects, including circadian phase-shift, circadian entrainment, and sleep physiology. Light can even be used as therapy to treat seasonal affective disorder. Light has beneficial effects, but also harmful ones that have been recognized worldwide, so it is a double-edged sword. As the future of lighting evolves, there is a gap between technology and what can be done with it. More research dollars are needed to have evidence based lighting and to end claims based on secondary and tertiary reasoning.

Appendix B: R&D Task Descriptions

The R&D task descriptions, defined in the 2014 DOE SSL R&D MYPP, 2014 DOE SSL Manufacturing R&D Roadmap, and the 2015 SSL R&D Plan are provided in the following table. Tasks identified in 2015 as priorities are shown in red.

R&D Task	Description
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 new encapsulant formulations that provide a higher refractive index to improve light extraction from the LED package. Explore new materials such as improved silicone composites or glass for higher temperature, more thermally stable encapsulants to improve light output, long term lumen maintenance, and reduce color shift. Develop matrix materials for phosphor or quantum dot down-converters with improved understanding of how the chemical interactions affected performance and reliability.
B.3.6 Package/Module Architecture Integration	Develop novel integrations schemes that focus combining the LED package and other luminaire subsystems or sensors into Level 2+ LED module products, which can be readily integrated into luminaires. Architectures should address the integration of driver, optics and package in a flexible integration platform to allow for easy manufacturing of customized performance specifications. Advanced features such as optical components that can shape the beam or mix the colored outputs from LED sources evenly across the beam pattern are encouraged, along with novel thermal handling and electrical integration while maintaining state of the art package efficiency. Integration of low cost sensors for added functionality of LED lighting systems is also encouraged.
B.4.2 Epitaxial Growth	Develop and demonstrate growth reactors and monitoring tools or other methods capable of growing state of the art LED materials at low cost and high reproducibility and uniformity with improved materials-use efficiency.
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 Mechanical Design	Integrate all aspects of LED luminaire design: thermal, mechanical, optical, 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.6.4 Novel LED Luminaire Systems	Develop novel luminaire system architectures and form factors that take advantage of the unique properties of LEDs to save energy and represent a pathway toward greater market adoption. Novel form factors, luminaire system integration, and optical beam steering that diffuse and or shape the light output into a desirable beam pattern, or optical components that mix the colored outputs from LED sources evenly across the beam pattern should be considered to improve the efficiency of the light source and provide efficient utilization of light. Another important element of this task could be the integration of energy-saving controls and sensors to enable utilization of the unique LED properties and save additional energy.
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.4 Tools for Epitaxial Growth	Tools, processes and precursors to lower cost of ownership and improve uniformity
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.