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

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DISCLAIMER

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COMMENTS

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Introduction

On September 15, 2016 thirteen experts on 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, January 31- February 2, 2017 in California.

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.

- Novel device architecture – laser diodes
- Down-converters & packaging materials
- LED drivers
- Lighting metrics
- Color stability
- Connected lighting and controls
- Engineered spectra - lighting for humans, plants and animals

1. Novel Device Architecture – Laser Diodes

Laser diodes (LDs) can provide a very small optical source size which allows for improved optical control in directional applications. This can lead to very narrow beam angle and improve the delivered efficacy to the applications with directional lighting. Another benefit of blue lasers is the elimination of current droop, which plagues LEDs at high current density operation. In LDs, 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 can enable high flux density and higher wall-plug efficiencies than LEDs at very high current density operation. Another benefit of lasers is a much higher modulation speed than LEDs allowing for faster data transmission in Li-Fi, or visual light communications (VLC). Further research and development work for lasers in lighting includes increasing the wall plug efficiency (WPE) of the LD from the current 30-40% range to 60% (LED level).

Another challenge with laser-based white lighting systems is the availability of down-converters that are efficient at the high photon fluxes in these systems. New phosphor and binder materials are required to handle the heat associated with extremely high optical flux densities from the coherent beams. Higher thermal conductivity binders for the phosphor, such as glass, is one area to explore. Single crystal phosphors are another potential area of development work. In addition, integration schemes for LDs, which require the ability to diffuse a coherent light beam to a diffuse source, must be developed for general lighting uses.

Participants agreed while LDs will not replace LEDs as the solid-state lighting source in many general illumination applications, they do enable improvements to directional lighting as well as unlock new performance potential for architectural lighting, dynamic illumination, and Li-Fi.

2. Down-Converters & Packaging Materials

Phosphors and other down-converters, such as quantum dots (QDs), were noted to still be a critical area of research for SSL. Narrow-band red and green down-converters can improve the luminous efficacy of radiation (LER) by 20-25%. Improved temperature and environmental stability should be a focus in addition to narrow spectral line widths.

Representatives from various SSL companies agreed that the main drawbacks for QDs as down-converters in SSL applications are lifetime and reliability issues. Further research on QD materials is needed to improve their performance at high temperatures and to improve optical flux densities to allow for the on-chip LED application that is necessary to be compatible with current LED industry manufacturing practices. Besides the materials and integration challenges, there are also significant manufacturing challenges for QDs. A more concentrated effort to address reproducibility and scale-up for QD manufacturing is needed.

In addition to improving the down-converter materials themselves, encapsulants must be improved to have higher thermal conductivities and refractive index for both LEDs and laser lighting. Co-development of QDs and matrix materials can to provide the optimum system of down-converter and matrix for on-chip performance and reliability.

3. LED Drivers

Participants from SSL manufacturers agreed that 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. This surge problem is causing field failures when the power quality is poor.

Further research is needed to improve driver temperature performance, surge rating, reliability and cost. Solid-state component integration into the driver should be explored as a more robust alternative since solid-state drivers can simplify the part count and reduce failures. It would also improve the surge rating and reduce the driver size. Moving to gallium nitride (GaN) or silicon carbide (SiC)-based power electronics has the potential to improve the efficiency and reliability, though today these solid-state components are still very costly and further research is required in the electronics industry to improve the defect count and reduce cost. Establishing the reliability for GaN and SiC components and the impact on driver reliability is an important opportunity and should be an area of focus for DOE.

There is a need for developing predictive driver reliability models to determine the lifetime of the LED luminaire. More research is needed to understand the impact of the growing amount of lighting controls and sensors in LED luminaire systems. Current models, such as mean time between failures (MBTF) for individual components, are insufficient for measuring reliability. Developing additional key metrics to define failure, and ways to predict them would be beneficial to the SSL industry.

4. Lighting Metrics

Participants expressed that existing lighting metrics are not sufficient for visual comfort, for example, when defining glare. The current design criteria being used was developed for traditional lighting and is not best for the user in terms of glare and uniformity with new LED light sources. Color rendering index (CRI) is another metric that does not adequately describe the way people perceive light and color quality. There are differences in visual perception that is not fully captured by the CRI metric. For example, when engineering spectrum for retail applications, peaks from the spectra are tuned specifically for the products that are being illuminated. Often these tailored have targeted wavelength peaks and gaps in other wavelengths of the spectrum, which result in lower CRI than 80 but provide the best color quality for the application. A high CRI requires that peaks in the visual spectrum sensitive to human receptors are filled, but this is not ideal for certain applications.

The participants expressed that the current CRI requirements and illuminance levels in different applications do not take into account the new understanding of lighting requirements for these various applications and the new options for spectral engineering, optical control, and lighting control available with LEDs. The feedback was to consider new standards for glare, uniformity, and CRI to account for LED lighting capabilities and the recent understanding of spectral tuning for humans, plants, and animals.

Other parameters, such as fidelity and gamut area, may better describe the quality of the light, as defined by TM-30-15 (a technical memorandum, published by the Illuminating Engineering Society of North America). However, TM-30-15 still does not indicate the preferred visual experience. Further R&D is necessary to identify a more appropriate metric of the visual experience.

5. Color Stability

Color shift in LED luminaires remains an issue that poses reliability and product warranty challenges. To improve color stability, more stable materials and LED designs are required. Red phosphor materials will have spectral shift at high humidity and temperatures; optical materials will discolor. Participants agreed further research developing new phosphor materials and matrix materials to withstand the higher temperatures and flux densities is needed.

Color tunable lighting systems have been growing in the marketplace to meet the various engineered spectra for humans, plant, and animals. The various colored LED sources (e.g. red, amber, green, blue), each with their own aging behavior, adds another degree of system complexity and makes color stability more challenging to predict and manage. Further work developing algorithms to manage color stability of systems consisting of direct emission LEDs of varying colors is needed.

6. Connected Lighting and Controls

Connected lighting and controls are ever growing in LED luminaires and the participants discussed the need for third-party case studies to validate the energy savings and return on investment with the use of LED lighting with controls. In addition, the participants expressed the need to compare the connected lighting system efficiency between conventional AC-powered lighting, power over Ethernet (PoE), and direct current (DC) micro-grids. It was suggested these types of case studies should be explored by the DOE Gateway program. Finally, a few participants suggested the need for applied R&D in developing algorithms and data analytics and proving them out in a demonstration project.

Connected lighting requires further work in interoperability and end-to-end security. The lighting fixtures need to have authentication and security certificates for each node. In addition, the sensor data needs to be "signed" to make sure it is coming from the correct sensor. More standards are required to discuss how the device manager communicates with the lights and sensors. While the interoperability and security challenge is of critical importance, technology development is not the key barrier. Therefore, these challenges are better handled throughout other DOE efforts than direct R&D funding.

7. Engineered Spectra – Lighting for Humans, Plants and Animals

Participants discussed the need for better understanding of how light interacts with humans, plants, and animals. All these areas have very different needs for optimal spectra for their health and productivity, but further research is required to quantify the physiological response and develop the right light for the subjects, while continuing to achieve energy savings. These studies should strive to develop the right lighting metrics for human, plant, and animal well-being. Research and case studies should develop the right engineered spectra and benefits for various applications.

Participants agreed that building strategic partnerships with other federal agencies such as the Department of Transportation (DOT), the US Department of Agriculture (USDA), and the National Institute of Health (NIH) will be imperative to perform the required research into human health, horticulture, and livestock to develop appropriate lighting metrics. The participants stressed the need for government research and case studies as a neutral third party instead of relying only on corporate research and case studies.

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	**Related SSL Program R&D Task(s)**	
	Product Development	Manufacturing R&D
1. Lighting for human health, horticulture and animal well-being	(Proposed New Task) Human Factors – Physiological Responses, and Light Quality Metrics	
2. Novel Devices	B.2.0 Device Materials and Architectures	
3. Advanced Packaging	B.3.6 Package Architecture	
4. LED Drivers	B.6.3 System Reliability and Lifetime (Proposed New Task) Solid-State Components Integration in LED Drivers	M.L.2 Driver Manufacturing
5. Color Stability and Reliability	B.5.2 Color Maintenance B.6.3 System Reliability and Lifetime B.7.1 Color Maintenance (Electronics/Drivers)	

These tasks will provide a starting point for further discussions at the 2017 DOE SSL R&D Workshop, January 31–February 2 in California. 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. Tal Margalith, University of California, Santa Barbara – Laser-Based Solid-State Lighting

Tal Margalith, the Executive Director of Technology at of the University of California, Santa Barbara, discussed the benefits of lasers for lighting over LED lighting including elimination of current droop and faster device modulation speeds for visible lighting communication (> 5 Gbit/sec, 4 GHz). Lasers have a very small light emitting spot size of 0.3 mm^2 which lends itself to applications such as direction lighting, long-throw spot lighting or fiber/waveguide lighting with remote light sources. Other applications include projection and automotive.

Margalith continued that research challenges for laser lighting include improving laser wall plug efficiency by focusing on reducing threshold voltage and minimizing optical losses. Phosphor materials need to be developed to withstand the higher temperature and flux density of the laser device – this includes red phosphors for warm white illumination. Another challenge involves the integration of coupling the blue laser and to the phosphor while providing thermal management for the laser device as well as the phosphor.

2. James Raring, Soraa Laser – Laser Diode Pumped Phosphors for Highly Directional Solid-State Lighting

James Raring, the Vice President of Engineering at Soraa Laser, presented on how lasers can provide better optical control for directional lighting applications due to the very small spot size of 0.3 mm. They have the potential to improve the luminance delivered to the task by 100 times that of an LED. At distances of 15 m from the light source to the task, lasers can surpass LEDs in terms of delivered lumens per watt. Laser can provide other features to lighting not available with LEDs including spatially patterned light and dynamic illumination. According to Raring, There are opportunities to leverage these capabilities in architectural lighting. Future research required for lasers in lighting includes improving the wall plug efficiency and the thermal management of the laser diode.

3. Berthold Hahn, OSRAM Opto Semiconductors – Laser for SSL Applications

Berthold Hahn, a Senior Director at OSRAM Opto Semiconductors, presented on the benefits and challenges in implementing lasers for lighting over LEDs. Lasers-based light sources are much smaller than LED based solutions. Their brightness (white phosphor converted light) delivers about 10x more light from same active area. These features have led to laser integration into applications such as car head lamps. Several applications can use these benefits including directional spot lighting, novel designs with fiber based lighting, and projection. Challenges with lasers include the lower efficiency compared to LEDs. The laser chip itself has about two-thirds of the efficiency of an LED chip. Benefit in optical system efficiency may compensate this gap some.

Challenges in phosphors for laser lighting need to be addressed. Hahn mentioned that improving the matrix material’s thermal conductivity is important in order to deal with the high temperatures of the phosphor particles under high flux densities. In addition, developing a red phosphor that can withstand the high flux densities of lasers would lead to the ability to provide a warm white source. Avenues for research include developing high thermal conductivity matrix materials (e.g. phosphor in glass) and improving the quality of the red phosphor.

4. Wouter Soer, Lumileds – Engineered Spectra for LED Applications

Wouter Soer, a Senior Manager for Illumination Systems and product Strategy R&D at Lumileds, explained how engineering the white light spectra can have benefits for the end lighting applications by providing light for visual effects and preferences in the retail markets to non-visual effects such as lighting for physiological effects in humans, plants and animals. In some applications, efficacy and CRI are not key metrics for lighting. For example, a high CRI requires you to fill wavelength peaks through

the visible spectrum, but in some retail applications where you are optimizing for specific products such as meat displays, the optimum spectrum has gaps in the green portion leading to a lower CRI. Lighting metrics should be reevaluated for requirements in engineered spectra LED lighting solutions.
The physiological impact on various spectral peaks should be studied further in humans, and also on ecological impacts in outdoor lighting for plants and animals (which have different numbers of photoreceptors than humans). Further R&D on direct emission LEDs in the ultraviolet (UV) and far red wavelengths are important for horticulture applications. Also, research on narrow band down-converters for tunable material systems in the central part of visible spectrum is needed for improved spectral engineering.

5. Paul Fini, Cree - SSL Energy Savings – Beyond lm/W

Paul Fini, a research scientist at Cree, presented on how luminaire efficacies are rapidly rising (130 lm/W), and that maximum energy savings will be achieved with widespread adoption, encouraged by user-friendly, intelligence-enabled controls. Controls must move beyond simple occupancy detection moving to more sophisticated scene sensing with improved occupant detection, counting, and traffic. Luminaires with positional awareness and spatially resolved illuminance are needed. Modular lighting mounted sensors with improved performance are needed for this scene sensing. Integrating these luminaires and sensors with building management systems that can control other systems such as HVAC will generate further value beyond just energy savings. This allows for features such as space utilization, asset tracking, safety, and security.

Applied R&D is needed in developing algorithms and analytics for these connected lighting systems. Supporting third party demonstration projects that can document the energy savings and other benefits of controls is needed to further support integrating these features into buildings.

6. Ramanujam Ramabhadran, GE Global Research – Challenges in Designing Power Electronics for Next Generation Fixtures

Ramanujam Ramabhadran of GE Lighting spoke on how improvements in LED drivers can lead to more efficient, lower cost luminaires that are more reliable in the field. Drivers need to be improved to withstand higher operating temperatures and to provide improved surge protection for the luminaire. Solid-state component integration into the driver should be explored as a more robust alternative since solid-state drivers can simplify the part count and reduce failures while improving the surge rating. Other benefits to wide bandgap devices includes more room for controls, fewer magnetics, and ease of manufacturing (magnetics have high labor content). It would also improve the surge rating and reduce the driver size. Moving to GaN or SiC-based power electronics has the potential to improve the efficiency and reliability. Today, these solid state components are still very costly and further research is required in the electronics industry to improve the defect count in order to reduce cost. Establishing the reliability for GaN and SiC components and the impact on driver reliability is an important opportunity and should be an area of focus for DOE.

Ramabhadran noted that other driver component development needs include novel manufacturing methods to reduce size and weight of magnetics, as well as developing critical components such as surge protection and fuses with appropriate voltage ratings, in a surface mount configuration.

7. Mark Hand, Acuity Brands – Winning the Battles……Let’s Win the War

Mark Hand, the Vice President of Indoor Engineering Solutions at Acuity Brands, presented on the issues with LED lighting that still remain. Glare continues to be an issue in today’s luminaire design. The focus on smaller and brighter point sources to reduce cost have led to more visual discomfort due to glare. Existing metrics for glare are not always accurate and are difficult to use in design practices. More R&D is required to develop better metrics that address glare, while focusing on lumens-on-task rather than lumens-per-watt.

Hand also spoke on how further R&D is needed for agriculture lighting in terms understanding the opportunity beyond energy savings. Europe is leading in the R&D of the impact of lighting on horticulture and livestock. The impact of lighting and spectral content for human circadian rhythm needs further quantification. Currently, there is a lack of standardization on reporting of the circadian impact quantitatively. Further research is needed to quantify the benefits of lighting on circadian rhythm and develop a matrix of understanding keeping all the factors in mind. The DOE should partner with other US agencies such as the USDA and NIH to develop this understanding.

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

Ashjaq Chowdhury, the Chief Engineer of LED Lighting Technology at GE Lighting, spoke on research areas that have the best chance of improving energy efficiency while being profitable. 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 an opportunity to make better controls. Interoperability is the main challenge preventing further deployment. Cost effective and easily commissioned residential and commercial systems are needed, but the key is developing smart and intelligent drivers that can communicate between different building systems. Third party case studies are needed to validate the full return of investment with controls and connected lighting 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.

9. Lynn Davis, RTI International – Opportunities in Chromaticity Management

Lynn Davis of RTI International presented on the color shift of LEDs and what is needed to deal with it. Color shift is a warranty challenge for luminaires when some customers request ten year warranties. There is a clear need for predictive modeling for LED color shift and reliable testing methods. Understanding of chromaticity shifts in LEDs is improving and has highlighted the need for further R&D on chromatically stable materials and LED designs. Better phosphor binder materials that can withstand higher operating temperatures and optical flux densities are needed, as well as red phosphors with better thermal stability and narrow linewidths.

Color tunable lighting systems are being developed in the market and DOE is currently funding activities in lighting systems for hospitals and schools. These systems are inherently more complicated than single-color LED devices and offer opportunities for new R&D to determine the energy efficiency and benefits of these dynamically controlled spectrum systems on humans, plants, and animals. Davis noted that other research is needed in the viability of the systems to understand long term chromaticity stability of the different color direct emitter LEDs and how to address color drifts in these color tunable systems. Lastly, development of more efficient multiple channel drivers and control technology will help increase the commercial viability of these systems.

10. Warren Weeks, Hubbell Lighting – R&D Initiatives to Advance SSL

Warren Weeks, the Director of Innovation and Technology in the Advanced Technology Group at Hubbell Lighting, discussed what R&D is needed to advance SSL. R&D is needed to develop higher operating temperature, longer lifetime, higher efficiency (greater that 90%) Class 2 LED drivers. There is also a need for developing predictive driver reliability models to determine the lifetime of the LED luminaire. In addition, more research is needed to understand the impact of the increasing amount of lighting controls and sensors in the lifetime model. Current models, such as mean time between failures

(MBTF) for individual components, are insufficient for measuring reliability. Developing additional key metrics to define failure, and ways to predict them would be beneficial to the SSL industry.

From an energy saving perspective, further R&D and case studies are needed to understand the incremental value of integrated lighting controls in the era of 140 lm/W and higher commercial luminaires, since energy saved by controls declines with luminaire efficiency. Research and case studies to quantify energy savings should also be extended to compare comprehensive, fully connected lighting system efficiencies between AC-to-DC solutions versus power over Ethernet (PoE) or DC micro-grids. Third party validation is critical.

11. Nadya Piskun, Philips Lighting -

Nadya Piskun, the Director of Engineering at Philips Lighting, spoke on how connectivity and controls can lead to even bigger energy savings than LED conversion alone. The amount of sensors and data that will be integrated with lighting in the future will be enormous. Algorithms need to be developed to handle the data and harness all the energy savings and other value added features.

There is a need for further R&D to create the right metric for humans and lighting. Piskun said that further research is needed to determine the best spectrum for humans in various applications from hospitals and education, to offices and the home. It is necessary to support further work in this area to determine how to better design lighting.

12. Wen-Lin Tsao, Cisco – POE Lighting Systems

Wen-Lin Tsao, a Principal Solutions Architect in the Internet of Things (IoT) Solutions Group at Cisco, talked about how PoE switches can provide power management and reporting capability to lighting systems using Ethernet cables. Lighting devices embedded with sensors and individually addressable with internet protocol (IP) addresses can respond to commands and report status/events. PoE can allow the convergence of two distinct infrastructures – traditional lighting (with high voltage cabling) and the digital infrastructure (powering end devices through Ethernet cables). Converting lighting to a digital infrastructure can lead to a lower total cost of ownership (TCO) through reduced material and labor cost, and greater energy savings, while enabling an intelligent IP platform providing software analytics for broader building automation initiatives. PoE can also provide broader network infrastructure to converge disparate networks (WiFi, HVAC, IP video, etc.) into one IP network

Challenges for PoE lighting infrastructure includes the need for interoperability, end-to-end security with authentication and security certificates in the lights, sensor data that is “signed” to ensure it comes from the correct sensor, and standards on how the device managers talks to the lights. Integration of lighting with PoE allows for the digital ceiling which can drive new user experiences and space optimization.

13. Ron Gibbons, Virginia Tech – Roadway Lighting

Ron Gibbons, the Director of the Center for Infrastructure Based Safety Systems (CIBSS) at Virginia Tech, presented on the need to improve the application standards to ensure the maximum benefit of LED technology and to minimize the potential for problems. There are lighting applications where the design criteria are being met by LEDs, but they may not be the best for the user. Issues like glare and uniformity require better metrics beyond the typical Innovative Engineering Systems (IES) roadway metrics. For example, roadway lighting designs never considered lighting sidewalks because they were already lit by the back light thrown in that direction with HID technology. Since LED lighting is more directional, light for the sidewalk must be part of the design.

Gibbons also talked mentioned that the impact of outdoor lighting on flora and fauna must also be considered for lighting designs as they are sensitive to specific spectral regions depending on the species.

CRI and CCT do not capture these spectral sensitivities. New metrics are required to capture these impacts.

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, 2015 SSL R&D Plan, and the 2016 SSL R&D Plan are provided in the following table. Tasks identified in 2016 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 Advanced Luminaire Systems	Develop novel luminaire system architectures and form factors that take advantage of the unique properties of LEDs to improve efficacy, save energy, and define a pathway toward greater market adoption. Novel form factors, advanced luminaire system integration, optimized performance for specific lighting applications, and improved utilization of light are topics that will be considered. Another important element of this task could be the integration of energy-saving controls and sensors to add value to the lighting application and save additional energy.
B.7.0 LED Power Supply	Develop power supplies for luminaires with improved efficiency, reliability, and functionality. Explore new materials, circuit, and system designs for improved power supply system reliability. Develop power supply systems with full dimmability, minimal flicker, and maximum efficiency across the LED lamp or luminaire operating range. Enhance luminaire functionality through low-cost modular control and communication systems integrated with the power supply, including multi-channel control for multiple strings of LEDs.
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 Flexible Luminaire Manufacturing	Develop flexible manufacturing technologies and approaches for state-of-the-art LED luminaires. Suitable development activities would likely include on or more of the following areas: • Advanced LED package and die integration enabling an array of lumen packages for a variety of lighting applications • Optimized designs for efficient and low-cost manufacturing • More efficient use of components and raw materials • Use of novel, low environmental impact materials • Reduction in part count through the use of multi-functional components • Product designs using common components to reduce inventory and part count across a range of products or applications • Reduced manufacturing cost through the development of advanced automated assembly approaches and/or improvements to manufacturing tools
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.