Solid State Lighting LED Core Technology R&D Roundtable

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Introduction

On September 9, 2015, sixteen experts in light emitting diode (LED) based lighting and related technology 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 Core Technology R&D. 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, participants were asked to contribute ideas regarding program content for the upcoming DOE SSL 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. Summaries 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 performance. These critical R&D topic areas, listed below (in no particular order), are discussed in more detail in the following section.

- Emitter Material Research
- Novel Devices
- Down-Converters
- Encapsulation
- Added Value Proposition

1. Emitter Material Research

Understanding and mitigating droop is still considered to be one of the most critical areas for the advancement of SSL. Droop impacts efficiency, which limits the total light output from a given LED area, hence driving up the number of LEDs required to reach the proper lumen level for lighting applications. Participants discussed some approaches and considerations for reducing current density droop. A key factor is improving the distribution and balance of charge carriers in the quantum wells (QWs) across the active region. The challenge is that changes in the active region required to improve transport hurts other properties, such as radiative recombination rates, due to materials quality suffering. Using thicker QWs reduces Auger recombination (widely accepted as the main cause of current density droop), but also leads to a smaller electron-hole wave function overlap due to the stronger polarization effects in the QWs. Managing these various trade-offs in heterostructure design and materials constraints has limited progress so far. Green LEDs are even more transport limited than blue resulting in the lower efficiency "green gap".

New active region designs and improved materials quality are required to advance state-of-the-art towards droop-free LEDs as well as LEDs with improved IQE at green emission wavelengths. Advanced characterization techniques will help with the materials optimization. For example, better understanding of the indium gallium nitride (InGaN) random alloy through atom probe microscopy can lead to better modeling agreement with experimental results. The use of unique characterization equipment is an area where strong industry and academia collaboration can help find viable solutions. Additionally, early studies have shown that increasing group-V partial pressures during high pressure metal-organic chemical

vapor deposition (MOCVD) growth can increase efficiency by reducing nitrogen vacancies. This area for InGaN growth R&D has not been exhaustively explored. Currently, the barrier for this approach is that most commercial MOCVD systems are not able to provide increased pressure.

2. Novel Devices

New device architectures can be explored to improve the LED efficiency over that achieved by more conventional LED architectures.

Lasers and Superluminescent Diodes

Blue laser diodes (LDs) and superluminescent diodes (SLDs) could have an efficiency advantage over blue LEDs at very high current densities. 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. An SLD is essentially an edge-emitting stripe laser below threshold (feedback suppressed), where the spontaneous emission is amplified by stimulated emission within a single pass in the waveguide. The light output shows a broader, smooth continuous spectrum, more like an LED, instead of the peaky multimode emission from a LD. The participants indicated further research is required in several areas including device design and integration schemes into lighting fixtures. Increasing the wall plug efficiency (WPE) of LDs and SLDs closer to LED levels is needed for high system efficiency.

Laser-based white lighting systems operating at high photon fluxes have already been demonstrated for commercial automotive applications, but these are expensive and complicated systems. New phosphor materials are required to handle the heat associated with extremely high optical flux densities from the coherent beams. Single crystal phosphors are one 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.

Tunnel Junctions

The use of tunnel junctions (TJs) provides an opportunity to improve LED performance by mitigating droop in a cascading LED heterostructure. The multi-junction LED structure operates in a high-voltage/low-current regime and can produce the same light output as a conventional single junction device but at a lower current density, thus minimizing the effects of current density droop. Another benefit of the lower operating current is reducing joule heating, which could simplify thermal management issues.

While successful demonstrations using TJs in LEDs have been published, participants agreed that significant opportunities exist for improvements, and that remaining challenges include addressing the growth of high quality TJs by MOCVD, the absorption associated with InGaN TJs and defect generation in layers grown above heavily doped TJ. Participants suggested modeling of TJs using properties that can practically be achieved with MOCVD growth would help properly design LED heterostructures. In addition to LEDs, TJs can be used in LD cladding layers to improve the doping profiles (switching p-type cladding to n-type).

Nanostructures

Participants suggested nanowires as a possible research area for DOE because they could provide significant efficiency improvements by reducing droop. The core shell architecture using high active region volume is currently the most popular approach for blue nanowire LEDs. Since there are no fundamental scientific limitations for this approach, sufficient investments in research may help overcome the technical issues including precise and uniform indium incorporation at the distal end of the nanowire to provide the proper active region volume to minimize droop.

Nanostructures have the benefit of strain accommodation, which allows heterostructures with high indium content to be created. Proper growth planes must be identified to allow for high indium incorporation or novel structures such as embedding InGaN quantum disks or dots within the nanowire structure. One practical challenge in nanostructure LED development involves materials characterization of such small structures. Non-standard characterization techniques must be developed to probe the small material volumes of the nanostructures.

Quantum Dot LEDs

Electrically-pumped quantum dot (QD) LEDs or QLEDs are another possible device solution for SSL due to the large area and potential for low cost manufacturing techniques (e.g., roll-to-roll processing). Red, green and blue QLEDs have been demonstrated with peak external quantum efficiencies (EQE) of 20%, 21% and 11%, respectively. While the initial demonstrations are promising, there remains fundamental science challenges that require further research. New material systems are needed to improve hole injection. Blue QLEDs have shorter lifetimes than red and green. There is a lack of understanding on failure modes for QLEDs, and research to investigate degradation mechanisms is needed. Additionally, manufacturing research is needed to developing printing processes for QLEDs.

3. Down-Converters

Participants agreed that phosphors and other down-converters, such as QDs, are still a critical area of research for SSL. For example, narrow-band down-converters can improve the luminous efficacy of radiation (LER) by 20-25%. For both phosphors and QDs, there should be a focus on understanding the impact of materials choices and designs on efficiency, spectral characteristics, wavelength tunability, and line width control.

Participants agreed that there needs to be more research on the process of making transparent downconverters and a more aggressive approach to creating down-converters in nanoparticle forms that can be cast into a transparent matrix. One area for research that could potentially provide significant efficiency improvements is producing down-converting phosphors in a gel form which has the potential to eliminate issues related to surfaces associated with phosphor particles (e.g., scattering).

Representatives from various SSL companies agreed that the main drawbacks for QDs as downconverters in SSL applications are lifetime and reliability issues. Further research on QD materials is needed to improve their performance at high temperatures and optical flux densities to allow for on-chip LED application 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 QD down-converter materials themselves, encapsulants must be co-developed to provide the optimum system of down-converter and matrix. These issues need to be addressed with significant research efforts to speed up adoption in SSL.

4. Encapsulation

Participants noted that key challenges regarding encapsulation remain in developing materials with improved thermal stability and higher refractive index. High thermal resistance is a significant challenge because high thermal boundary interface resistance determines the minimum particle size that can be used to increase thermal conductivity. Thermal transport of hybrid materials (e.g., high thermal conductivity additives in a silicone resin) presents an opportunity for improvement through engineering the thermal conductance of the polymer/particle matrix. Reducing the scattering cross-section of particle fillers can enable higher optical transparency at higher inorganic loading. Moving this concept to the extreme by

using inorganic encapsulants, such as low melting point glasses, is another potential path towards improving refractive index and thermal stability.

It was also noted during discussions that a greater focus on glass material and polymer containing emitters would be beneficial. More research that focuses on down-converter (i.e., phosphors or QDs) and encapsulant interactions as a system and potential areas for cost and performance improvements is needed.

5. Added Value Proposition

Added functionality in luminaires should be considered as a way to increase energy savings, product value, and luminaire adoption. Value-added features can take many different forms, from human factors benefits such as health improvements or productivity gains, new features such as indoor positioning for retail or Li-Fi capabilities for communication, to new energy saving controls. It is important to develop methods to quantify the impact of value-added features in lighting products including, but not limited to, color quality, dynamic lighting control, and communications.

The participants strongly supported the need for human factors studies to better quantify the physiological response to LED technology improvements, so they may ensure the benefits of LED lighting are appropriately communicated to the end customer. In order to quantify the value of the added features, participants noted the need for appropriate equipment and infrastructure to evaluate the impact of lighting on productivity and health. This could require the development of specific lighting fixtures to aid human factors researchers in better control of the studies. Participants noted that a collaborative effort between academia and industry will be invaluable for companies pursuing specific studies to develop new metrics to quantify physiological impacts.

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)	
	Core Technology	Product Development
1. Encapsulation		B.3.2 Encapsulation
2. Novel Devices	A.2.2 Novel Emitter Architectures	B.2.0 Device Materials and Architectures
3. Down-Converters	A.1.3 Down-Converters	B.3.6 Package Architecture B.1.3 Phosphors
4. Added Value Proposition	A.8.1 Light Quality Research	B.6.4 Novel LED Luminaire Systems
5. Emitter Materials Research	A.1.2 Emitter Materials Research	B.3.6 Package Architecture

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. Mike Krames, Arkesso - Basic Science & Core R&D

There has been significant progress in the blue and violet emitters as shown by the classic "s-curve" growth characteristic in the last decade. This leaves us with minimal opportunities for huge efficiency gains. In green, amber and red emitters, efficiencies have stalled. Red is most promising, but it seems unlikely that efficiencies are likely to improve significantly in the future because of the fundamental limits for aluminum gallium indium phosphide (AlGaInP) materials. Is green improvement viable? EQE values north of 50% should be the target. The best devices are in the range of 60-65% EQE for blue and 35-38% EQE for green.

With increased efficiencies, motivation for changing out light bulbs decreases. How do you convince people to further save energy if you only get a few dollars over five years for a fixture that costs \$100? From DOE perspective, how do we continue reduction in energy consumption as we are nearing asymptote in efficacy (250 lm/W)? There are opportunities to look in other areas for significant lighting related savings such as improved lighting for health. For example, how much benefit will LED lighting provide if health claims can be reduced by 1% or improved workplace lighting can result in 0.1% increased productivity?

2. Ed Stokes, University of North Carolina, Charlotte – HP-MOCVD Epitaxy

Higher pressure (HP)-MOCVD epitaxy has the potential for quantum efficiency improvements in InGaN based on results seen in other group III-V systems. For indium gallium arsenide (InGaAs) and indium gallium phosphide (InGaP), higher group-V partial pressure results in higher efficiency due to reduction of group-V vacancies. InGaN requires even higher pressure as bonds in ammonia (NH₃) are stronger than those in arsine (AsH₃) and phosphine (PH₃). Some benefits to HP-MOCVD are higher internal quantum efficiency (IQE), enhanced growth rate and lower cost of ownership. The challenges include flow instability, which increases particles and the difficulty of maintaining laminar flow.

A new HP-MOCVD reactor was designed and built through a National Science Foundation Major Research Instrumentation grant. The development of HP-MOCVD process is underway with the growth of multiple quantum well test structures. The effects of wafer rotation on boundary layer height are being performed (increased rotations per minute could mean higher boundary layer and more indium incorporation). The next step is moving to growth at 2.5 atm pressure and possibly going as high as 10 atm.

3. George Wang, Sandia National Laboratory – Nanostructures for Solid State Lighting

Nanowire LEDs have an advantage of high active region area compared to planar LED devices, which can lead to lower droop and cost. Nanoscale architecture also allows for flexibility in substrates used (e.g., silicon), which can be lower cost than conventional LED substrates. Blue micro-wire LEDs have been demonstrated with IQEs of 65%. Strain accommodation in nanowires allows the growth of heterostructures with high indium content (e.g., green-yellow-red gap). Proper growth planes must be identified to allow for high indium incorporation, such as semi-polar facets. Axial *c*-plane InGaN disc/dot-in-wire grown by molecular beam epitaxy (MBE) have shown 52% IQE at red wavelengths. There have been demonstrations integrating red-green-blue (RGB) nanowire arrays on the same monolithic chip. The major challenge is replicating axial heterostructures with MOCVD and the issue of uniform injection of nanowire arrays. Optically pumped nanowire lasers and QD lasers have potential benefits for LED lighting including long wavelengths, low thresholds, higher efficiencies, wavelength tuning, and improved nanophotonics.

4. Parijat Deb, Lumileds – Efficiency Droop in c-plane AlInGaN LEDs

It is important to improve or eliminate droop to bring down overall cost of LED luminaires. Lumileds and recent work from University of California Santa Barbara (UCSB) supports Auger as the dominant mechanism of high current efficiency droop. (Electron overflow is also cited as possible cause of efficiency droop). Auger matrix elements and the carrier density in the QWs are the main processes affecting Auger recombination rates. The Auger recombination increases with increasing carrier density and decreasing QW width. Engineering around the Auger matrix element formula is needed to improve and eliminate the current density droop.

Active regions can be designed to improve hole-transport resulting in emission from more QWs, but the changes made often result in poorer radiative recombination rates – a trade-off. Increasing the QW thickness will reduce Auger but also reduces electron-hole wave function overlap due to larger polarization fields – another trade-off. Solving material issues is crucial, as most LED structure changes that reduce Auger recombination rates hurt material quality. Understanding the defects is the first step to tackling the challenging materials issues.

5. Jim Speck, University of California Santa Barbra – Challenges for LEDs for SSL

A number of factors affect the resulting WPE of LEDs. IQE is impacted mainly by droop and natural alloy disorder. The escape efficiency for photons is well understood, and the major issue is limiting extraction efficiency in losses in the metal. Ohmic losses and electrical efficiencies are well understood except for the higher voltage issues present in longer wavelength InGaN LEDs (e.g., green). Is the higher voltage in green LEDs fundamental to barrier transport in the active region or due to lack of previous R&D effort in green? Also, the use of high performance TJs to dramatically reduce indium tin oxide loss represents a big opportunity to improve LED efficiencies.

For RGB architectures to be successful, LEDs with greater than 50% WPE are required, and green is the limiting factor. Currently, the main market for green LEDs is traffic lights, so the research efforts to improve on green is limited without a larger market driver. Toshiba's long wavelength LED results are exciting; the yellow and red LED efficiencies are far above the green gap in the EQE curve. USCB is following the Toshiba method to grow high indium content with high growth temperature and trimethlyindium flow and then capping the QW with 1-2nm of aluminum gallium nitride (AlGaN) to seal in indium to reduce the green gap. Peak EQEs of 26% have been realized in initial experiments.

DOE has an opportunity to look at research that can better characterize the InGaN random alloy using techniques such as atom probe microscopy. Better characterization of the material can lead to better modeling agreement with experimental results. In addition, Shockley-Read-Hall point defects are not yet identified and detailed mechanisms are not well understood. Other than heat and absence of light, there are no experimental signatures. Finding unique experimental signatures is a huge area for research.

6. Jon Wierer, Lehigh University – Breakthrough Research Leading to Ultra-efficient SSL

The current SSL challenges, such as droop, present the need for major research breakthroughs to further advance technology. Phosphor-converted white LEDs will not achieve ultra-high efficiency as Auger recombination in the blue pump and Stokes losses in the phosphor conversion present significant challenges. Funding these efforts is not likely to bring about extremely high white LED efficiencies. The U.S. is at risk of becoming less competitive in SSL as LEDs have become a margin business, and the U.S. government is being outspent by other countries. There is the need for breakthrough paradigm-shifting and disruptive ideas for SSL. It has become difficult to get funding for risky programs due to the success of existing SSL. There is a need for funding development programs that are target driven and industry led, but the DOE should also invest in university/lab work and radical, yet physically solid technologies, with a path for SSL industry adoption. This can produce a SSL workforce that could be used by industry and

academia to keep the U.S. competitive with other countries. DOE should change the SSL success metrics from efficiency targets to publications, patents, and quality PhDs produced.

Alternative emitting materials may be a way to overcome Auger losses. Dilute-arsenic gallium nitride alloy (GaNAs) is very different from InGaN. The higher level states are harder to get to, so Auger rates are much lower. Improved wave function overlap will improve efficiency. Alternative emission physics can lead to improvement in efficiencies. At high current densities, LDs are more efficient than LEDs. Recombination processes determine efficiency. Moving from spontaneous emission in LEDs to stimulated emission in LDs can circumvent current efficiency droop since Auger rates are fixed while stimulated emission rates grow after threshold. Power conversion efficiency of conventional gallium nitride (GaN)-based violet-blue lasers will hit a maximum at approximately 60% and the only way to surpass this is to find ways to lower threshold currents and reduce other parasitic losses.

7. Jung Han, Yale University – Laser Diode for SSL: A New Design to Bridge the Gap

A better design for LD lighting is needed; however, fundamental limitations exist. Typically, there is a weak index contrast in GaN LDs, which leads to poor optical mode confinement in the cladding layers. Higher AlGaN compositions are required for larger index contrast in the cladding, but it is hard to grow thick, high composition AlGaN layers by MOCVD due to lattice mismatch with the substrate. For increased power conversion efficiency, a lower laser threshold is required. To achieve this lower threshold, reduced optical losses and lower resistive losses (on *p*-side) are needed. This necessitates finding a material with stronger index variation to provide optical confinement and hopefully have lower resistance.

Engineering the optical index with mesoporous GaN can improve confinement by adding "air" into GaN to drastically reduce/tune the index of refraction. A new LD design with enhanced optical confinement and reduced electrical resistance can be realized by replacing the cladding layers with mesoporous GaN for the n-cladding and a transparent conductive oxide for the p-cladding. This design allows for an aluminum-free laser structure with enhanced confinement factor (based on optical modeling). The improved gain and reduced electrical resistance by removing the AlGaN claddings can lead to a higher modal gain and reduced threshold, and hence improve the power conversion efficiency of the laser.

8. Dan Feezel, University of New Mexico – Superluminescent Diodes: an Alternative to Lasers for Advanced Lighting Systems?

Lasers are well suited for the demands of new smart lighting systems such as dynamic color tunability, customizable spatial light distribution, and integrated visible light communications (VLC). In LDs, non-radiative (Auger) processes clamp at threshold, thus eliminating current density droop since all the excess carriers participate in the stimulated radiative recombination. In addition to droop improvements, LDs provide directional light output, which is ideal for illumination-projection applications. The stimulated emission also provides large modulation bandwidth for VLC. Potential issues with LDs for lighting include concern with eye safety and speckle.

SLDs are another potential light source with many of the key features that lasers have, including no droop, spatially coherent beam, and fast modulation for VLC. SLDs have a few key differences from lasers including a relatively broad spectral width (approximately 3-5 nm full width at half maximum) and temporal incoherency (speckle-free projection, more eye safe). There has been limited work in the area of InGaN/GaN SLDs (less than20 publications). Current state-of-the-art SLDs have a WPE of 20%, whereas blue LDs have WPEs at approximately 30%. Questions about the viability of SLDs include:

- Can SLDs provide a better solution to lighting than LDs or LEDs?
- Is the WPE performance deficit as compared to lasers due to a lack of research effort in SLDs or is there something more fundamental?
- Are SLDs easier (or cheaper) to fabricate than LDs?

9. Siddharth Rajan, Ohio State University – Tunneling-based Cascaded LEDs for Efficient SSL Tunnel junctions can be used to create new device architectures, such as LEDs with cascading active regions. This multi-junction LED structure operates in a high-voltage/low-current regime and can produce the same light output as a conventional single junction device at a lower current density, thus minimizing the effects of current density droop. Another benefit of the lower operating current with cascaded LEDs is less joule heating, which could simplify thermal management issues. Additionally, cascaded LED structures allow more optical power out of the same footprint.

To date, low resistance tunnel junctions have been demonstrated by MOCVD and MBE. Also, cascading of LEDs has been demonstrated with low resistance (MBE and MOCVD). Future research should include developing low absorption InGaN-based tunnel junctions. Defect generation at tunnel junctions (due to doping and InGaN) must be eliminated.

10. Berthold Hahn, OSRAM Opto Semiconductors– Long Wavelength Emitters for General Lighting Increasing the LER of LEDs, which is essentially the spectral efficiency, and decreasing current density droop are the two possible ways to increase the efficacy of white LEDs. Droop is the main efficiency loss mechanism in LEDs at operating currents, and eliminating droop provides a 26% potential for improvement in LED WPE. White LEDs can benefit from spectral tuning, with a potential LER improvement of 24% available by developing the right phosphors and tailoring the spectra.

The green gap is hardly existent if peak quantum efficiency is considered; it is mostly a result of current efficiency droop. The challenge is, how do you get high efficacy at operating conditions in green? There is more droop in green than blue which is currently affecting green development. With slower recombination rates, green is more transport limited than blue LEDs which leads to more droop. The key is solving the carrier transport issues in the active region. Recommended research areas include nanowire LEDs to achieve the highest IQE at the operating current. Additionally, increasing LER requires narrow bandwidth converters (green and red) or efficient long wavelength direct emitters (green and red).

11. Paul Fini, CREE – Spectral Efficiency and Color Quality in Lighting Systems

Opportunities exist to develop narrow-band spectra for ultra-high efficacy LEDs. Research includes the use of hybrid direct emission and phosphor-converted LED systems or to develop narrow-band converters (phosphors or QDs) in red and green wavelengths. Challenges in both types of solutions still exist. Thermal droop is still a real issue for red and yellow LEDs, and operating conditions are important. Other issues exist for narrow-band down-converters such as improving reliability at optical flux densities, temperatures, and humidity in real application conditions.

Combining multiple color emitters under one package takes care of color mixing but will have efficacy implications due to absorption, such as red absorbing blue and green. New efficient and "smart" optical color-mixing schemes are needed when brute force mixing (e.g., diffusion) is not sufficient. There is a need to look to newer optical designs without that tradeoff and still give us efficient beam shaping optics.

Color rendering index (CRI) is not enough of a color quality indicator to accurately reflect the visual experience. It is important to consider fidelity and gamut area when evaluating color rendering, as CRI is not based solely on fidelity. The new technical memorandum, TM-30-2015, and color quality scale need to be visually validated through human factor testing; however, getting preference correlation can be a challenge.

12. May Nyman, Oregon State University – Universal Transparency of Down-converters

The DOE SSL goals are narrow; bigger global goals that will apply to any phosphor or down-converter being examined are necessary. Transparent down-converters may be a good investment to deal with the problems of current phosphor powders including:

- Poor absorption of LED emission
- Particle surface defects
- Inconsistent characteristics between particles of different sizes and shapes
- Different morphology, size, and absorption behavior depending on presentation of crystallographic axes
- Ability to make monoliths

Developing transparent analogs to powder material can provide performance benefits. Transparent luminescent gel forms (i.e., coordination polymers, glasses, inorganic or organic polymers, rare-earth or transition-metal dopants, stoichiometric compounds) can be coated in a thin or thick film, incorporate multiple luminescent centers, have high refractive index, and be amorphous and robust (i.e., does not change form or degrade with heating).

Encapsulation chemistries should be optimized in combination with the luminescent material it hosts. Interfacial chemistries for QDs and phosphors for enhanced luminescence and improved stabilization should be further explored. Inorganic encapsulants also offer the opportunity for improved stability.

13. Jennifer Hollingsworth, Los Alamos National Laboratory – Quantum Dot Phosphors: Meeting Ultimate Stability and Scale-up Challenges

Giant quantum dots (g-QDs) are core/thick-shell QDs with novel functionality targeting SSL applications. Some of their unique properties include extreme photo-stability (i.e., non-blinking, non-bleaching), suppression of non-radiative processes, and large effective Stokes shift and minimal self-reabsorption. Current applied research focuses on addressing thermal quenching in order to move to higher power, understanding and addressing long-term photo-stability, and developing reliability for on-chip/high-flux operation. To date, red emitters have been the focus since they can have the quickest impact in SSL, but green thick-shell QD with suppressed blinking and photo-bleaching have also been recently demonstrated. To continue to improve g-QD performance, unique approaches are needed to afford new insight. Correlating single-QD optical properties (efficiency, radiative rates, and stability) with temperature/photon flux are needed to help address current challenges such as achieving high quantum yield, and improving thermal and photo-stability.

An opportunity exists to develop high throughput combinatorial chemistry and characterization techniques for manufacturing reproducibility and scale up. New manufacturing tools, such as an automated parallel reactor system with computer-controlled precursor addition, automated sampling, and in-situ characterization are required to improve QD manufacturing and scale-up. Materials manufacturing must also be supported by high-throughput structural/optical characterization.

14. Jesse Manders, Nanophotonica – Quantum Dot LEDs for Next Generation SSL and Displays

Electrically-pumped QLEDs are another possible device solution for SSL due to their large area and, low cost manufacturing techniques (e.g., roll-to-roll processing). Red, green, and blue QLEDs have all been demonstrated with peak EQEs of 20%, 21%, and 11% respectively. White LEDs have also been achieved using blue CIS₂/ZnS (copper indium sulfide/zinc selenide) QDs with a down-converting yellow broadband phosphor. In addition, a bi-layer blue and yellow QLED has also been demonstrated.

While the initial demonstrations are promising, there remains fundamental science challenges that require further research. Lifetimes are limited, with green QLEDs currently having the best lifetime with T_{95} of 1000 cd/m² at 230 hours. Blue QLEDs have shorter lifetimes than red and green. There is a lack of understanding on failure modes for QLEDs, and more research to investigate degradation mechanisms is needed. Manufacturing research is also needed to develop improved printing processes for roll-to-roll and small pixel fabrication.

Currently, QLEDs are very undermanned, and organic light emitting diodes (OLEDs) have received a lot more attention. More investment is needed for QLED R&D to achieve higher efficiency and long lifetime. In addition, more QLED outreach is needed (e.g., comparable visibility to OLEDs).

15. Michael Bockstaller, Carnegie Mellon University – Enhancing LED Performance – a Case for Research on Encapsulant Materials

Encapsulants are an important element in the LED package for various reasons including protection, light extraction, electrical insulation, reinforcement, stress mitigation, concealment, and improved heat dissipation. Since encapsulants make up a large part of the LED package, poor material properties impact the performance of the whole system by increasing cost and decreasing design flexibility. Low thermal conductivity of current siloxane encapsulants results in heating of phosphor particles and rapid degradation of conversion efficiency. Quantum efficiency associated with phosphors under operation of LED significantly decreases because loss mechanisms lead to formation of heat. With poor thermal conductivity, there is no way to conduct heat away from phosphor particles which leads to a cascade of problems.

A project to develop encapsulants to increase thermal conductivity is ongoing at Carnegie Mellon University. The thermal conductivity of polymers can be increased by manipulating chemical structure with the aim to introduce strong directional bonds to reduce phonon scattering. The introduction of particles to create hybrid polysiloxanes will ensure that encapsulants exhibit thermal conductivities of 1 W/mK and higher. Efficient heat transfer will increase the efficiency of phosphor in LEDs operating consistently at 35A/cm² up to 95% of the 25°C values. More specifically, the concept uses controlled radical polymerization process to engineer the surface of particle fillers to increase the thermal conductance of particle/matrix interface. Reducing the scattering cross section of particle fillers while maintaining a uniform dispersion of particles within matrix is critical.

16. David Bishop, Boston University – Painting with Light and Data

Where are the factor of two improvements available to SSL? Opportunities to double efficiency are elusive. There is need to not only create photons, but to utilize them more efficiently. Research is focused on creating low cost technologies to sculpt the light and data profiles in a room. The use of micro-electro-mechanical systems (MEMS) technology can help achieve this goal. A MEMS mirror can be steered in multiple directions when current is applied to each of the nodes. Complexity is free, as there is no additional cost beyond silicon processing for MEMS technology. The tip-tilt features allows beam steering over large angular range and the radius of curvature of the mirror can be modified to adjust light focus. The MEMS mirror can easily fit into a light bulb and mass production will be significantly cheaper than the current \$1 cost for research quantities.

Real time dynamic effects are next frontier for SSL. Li-Fi provides for very high speed data connectivity that is not constrained by electromagnetic spectrum availability issues. Sculpting the light in a room allows for a much more efficient use of the photons, and improves the user experience with SSL. Chromatic effects can have a profound impact on both health and productivity. MEMS can be a high performance, low cost solution to this challenge, but there are other viable technologies, which are also being explored.

Appendix B: R&D Task Descriptions The R&D task descriptions, defined in the 2014 DOE SSL R&D MYPP 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			
Core Technology:				
A.1.2 Emitter Materials Research	Identify fundamental physical mechanisms of efficiency droop for blue LEDs through experimentation using state-of-the-art epitaxial material and device structures in combination with theoretical analysis. Identify and demonstrate means to reduce current droop and thermal sensitivity for all colors through both experimental and theoretical work. Develop efficient red, green, or amber LEDs, which allow for optimization of spectral efficiency with high color quality over a range of CCT, and which also exhibit color and efficiency stability with respect to operating temperature.			
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.2.2 Novel Emitter Architectures	Devise novel emitter device architectures that show a clear pathway to lighting system efficiency improvement. Demonstrate a pathway to increased chip-level functionality offering luminaire or system efficiency improvements over existing approaches. Explore novel architectures for improved efficiency, color stability, and emission directionality. Examples include laser diodes for lighting, nanowire LEDs, superluminescent structures, and electroluminescent quantum dots.			
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.			
A.7.5 Electronics Reliability Research	Develop designs that improve and methods to predict the lifetime of electronic components in the SSL luminaire.			
A.8.1 Light Quality Research	Develop improved metrics for brightness perception, color discrimination, and color preference. Employ human factors visual response or vision science studies to evaluate the impact of various spectral power distributions on the above, including line-based vs. broadband sources, violet- vs. blue- based pc-white LEDs, etc.			
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 in	ıdex
to improve light extraction from the LED package. Explore new material	S
such as improved silicone composites or glass for higher temperature, me	ore
thermally stable encapsulants to improve light output, long term lumen	
maintenance, and reduce color shift. Develop matrix materials for phosp	lor
or quantum dot down-converters with improved understanding of how the	e
chemical interactions affected performance and reliability.	
B.3.6 Package/Module Develop novel integrations schemes that focus combining the LED package/	age
Architecture and other luminaire subsystems or sensors into Level 2+ LED module	
Integration 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 component	its
that can shape the beam or mix the colored outputs from LED sources ev	enly
across the beam pattern are encouraged, along with novel thermal handli	ng
and electrical integration while maintaining state of the art package	-
efficiency. Integration of low cost sensors for added functionality of LEI)
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 an	d
high reproducibility and uniformity with improved materials-use efficien	cy.
B.5.2 Color Ensure luminaire maintains the initial color point and color quality over t	he
Maintenance life of the luminaire.	
Product: Luminaire/replacement lamp	
B.5.3 Diffusion and Develop optical components that diffuse and/or shape the light output from	m
Beam Shaping 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, optic	al,
Mechanical Design and electrical. Design must be cost-effective, energy-efficient, and reliab	le.
B62 Juminaira Design low cost integrated thermal management techniques to protect th	0
Thermal Design LED source maintain the luminaire efficiency and color quality	5
B63 System Collection and analysis of system reliability data for SSL luminaires and	
Reliability and Lifetime components to determine failure mechanisms and improve luminaire	
reliability and lifetime (including color stability) Develop and validate	
accelerated test methods, taking into consideration component interaction	ne
Develop an openly available and widely usable software tool to model S	15. CI
reliability and lifetime verified by experimental data and a reliability	SL
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	anu
B 6 4 Novel L FD Develop novel luminaire system architectures and form factors that take	
Luminaire System are adventage of the unique properties of LEDs to save energy and represent	
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pathway toward greater market adoption. Novel form factors luminaire	a
pathway toward greater market adoption. Novel form factors, luminaire system integration, and optical beam steering that diffuse and or shape the	e e
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	a e the
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 colored outputs from LED sources evenly across the beam pattern should	a e the l be

	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	Develop LED driver electronics that maintain a color set point over the life
Maintenance	of the luminaire by compensating for changes in LED output over time and
(Electronics)	temperature, and degradation of luminaire components.