# DOE Joint Solid-State Lighting Roundtables on Science Challenges

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## DISCLAIMER



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## COMMENTS

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# Contents

# 1. Introduction

Recognizing the benefits of coordinated research and development (R&D) efforts, the Department of Energy (DOE) Office of Basic Energy Sciences (BES) and the DOE Energy Efficiency and Renewable Energy (EERE) Solid-State Lighting (SSL) program convened a roundtable discussion among leading experts in LED technology to consider opportunities for further advancement of SSL technology through coordinated R&D actions. The meeting was held on September 14, 2016 at the offices of Navigant Consulting, Inc. in Washington D.C. This report is a summary of the findings from this meeting.

The BES program, on the one hand, supports fundamental research to understand, predict, and ultimately control matter and energy at the electronic, atomic, and molecular levels, and in order ultimately to provide the foundations for new energy technologies. Advances in the fundamental understanding of materials may ultimately result in revolutionary advances for many energy relevant technologies. The EERE SSL program, on the other hand, has a specific mission to support work that will advance the technology into useful, marketable general illumination products that can produce significant energy savings. EERE SSL funded R&D covers a broad range of activities from applied research in Core Technologies, through Product Development, to Manufacturing R&D. Generally, the R&D projects funded under EERE are on a shorter time scale than those in BES, with industry-relevant milestones and deliverables to ensure continuous progress.

The DOE BES and EERE SSL programs have a history of working together to explore the basic science needs for SSL with the objective of continuing to advance the scientific understanding that supports potential technology advances in terms of efficiency, cost, and lighting performance. The first collaborative meeting took place in May 2006, a second took place in October 2011, and a third was hosted in October 2014. Additionally, the SSL program in the Office of Building Technologies of EERE holds annual Roundtable meetings independent of BES to identify areas of critical SSL research needs and to advise DOE on Workshop content and future R&D priorities.

In addition to coordinating R&D efforts, the meeting served to promote discussion on critical applied research priorities for future EERE SSL funding and help identify discussion topics for the January DOE SSL R&D workshop. The roundtable format provided an opportunity for LED experts across the research spectrum to exchange ideas and explore collaborative research concepts. Participants included 14 invited experts in LED-relevant science and technology disciplines drawn from academia, National Laboratories, and industry. They included BES-funded researchers, EERE-SSL-funded researchers, and non-DOE-funded researchers.

## 1.1. Objectives and Process

The following three objectives for the roundtable meeting were outlined in the introduction:

1. Identify critical science and technology research needs for the continued advancement of SSL.
2. Maintain coordination between BES and EERE SSL activities and researchers.
3. Gather input and suggestions for the upcoming 2017 SSL R&D Workshop to be held January 31 – February 2, 2017 in California.

In order to gather the input required to meet these objectives each participant was invited to give a 10 minute "Soapbox" presentation describing what they believed to be the critical R&D challenges for SSL. A brief outline of each presentation is found in Appendix A: Participant Presentations. The presentations were followed by an open discussion of the key challenges. During the discussion, participants were also asked for suggestions on how to enhance collaboration and ideas for the upcoming SSL R&D Workshop.

## 1.2. Key Conclusions

The meeting format encouraged each of the attendees to participate and present his/her perspectives on critical R&D challenges. The discussions that followed the soapbox presentations offered a variety of valuable insights into a range of research topics that could advance SSL technology; however, there were some recurring themes that arose during these discussions regarding fundamental understanding of underlying processes that could lead to significant breakthroughs in SSL performance. These themes are as follows and are outlined in more detail in Section 2:

- Emitter materials research
- Improved down-converters (phosphors and quantum dots)
- Novel device architectures
- Improved materials discovery methods
- Improved characterization and analysis techniques

Additionally, participants expressed the need for DOE to support projects with the goal of understanding underlying mechanisms associated with the critical R&D challenges, the semiconductor physics behind droop, and degradation mechanisms for down converters. Focusing on these more fundamental issues could lead to a deeper understanding of the issues which could in turn ultimately lead to improved SSL performance. It was also recommended that DOE support more collaborative efforts between industry and academia so that the advantages of each group can expedite technological advancement in LEDs.

# 2. Critical R&D Topic Areas

## 2.1. Emitter Materials Research

Although blue emitters now have very high quantum efficiency (QE) and allow for high efficacy phosphor converted LEDs (pc-LEDs), current density droop was still acknowledged as a critical research area. To address droop, new epi structures that lead to improved carrier transport and more field screening and enable thick quantum wells (QWs) are still a challenge to achieve using metal-organic vapor phase deposition (MOCVD). The changes in the active region required to improve transport hurts other properties, such as radiative recombination rates, due to deteriorating materials quality. Thicker QWs reduce Auger recombination (widely accepted as the main cause of current density droop), but also lead 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 material constraints has limited progress so far.

Participants agreed that color-mixed LED (cm-LED) lighting systems have a greater theoretical potential of reaching much higher efficacies, as high as 400 lm/W. In order to reach these efficacies, emitters across the “green-yellow-amber” gap are needed, as well as red emitters. These direct emission LEDs need to improve peak QE as well as efficiency at higher temperatures (thermal droop) and current densities (current density droop). New active region designs and improved material quality are required to achieve these longer wavelength LEDs indium gallium nitride (InGaN) materials. New methods should also be considered for optimizing InGaN in order to reduce its decomposition and improve its quantum efficiency. Research focused on developing an efficient InGaN red LED could be especially fruitful, as it would have the likely side benefit of leading to an efficient InGaN green LED (which uses lower indium compositions). Also, continued research on preparing and growing GaN on different polarities (from nonpolar to semi-polar) could lead to new insights, and ultimately unique and desirable properties. However, more research is needed to understand nonpolar and semi-polar GaN.

In addition to InGaN based materials system, aluminum gallium indium phosphide (AlGaInP) is widely used for in amber to red LEDs. While this semiconductor system is relatively mature, further work can be done to improve performance, especially performance at higher operating temperatures. The development of unique structures that can improve the hot performance, the light extraction efficiency, and the carrier transport (e.g., mitigation of carrier overflow in amber) should be focus areas.

## 2.2. Improved Down-Converters (Phosphors and Quantum Dots)

Participants agreed that phosphors and other down-converters, such as quantum dots (QDs), continue to be a critical area of research for SSL. Down-converters for red and green emission are especially critical for further spectral efficiency improvements. For both phosphors and QDs, the focus should be on improving their reliability at high temperatures and flux densities, lowering their photo-thermal quenching, and narrowing their emission linewidth.

***Phosphors***

Narrowing the emission linewidth of red phosphors can reduce the amount of light emitted outside of the visible spectrum and enable higher efficacies for white LED packages, particularly packages with high color quality. Similarly, narrower emission linewidths of phosphors in other spectral regions (green and yellow) could enable higher overall white-light luminous efficacies due to improved spectral efficiency. Photo-thermal quenching (PTQ) in red phosphors leads to reduced efficiency at elevated temperatures and therefore to color shifts of the emitted white light from a blue-LED pumped source. Phosphors with reduced thermal quenching can improve color stability and simplify the design constraints for higher power LED, and possibly for laser-based lighting by allowing for higher operational temperatures. However, photo-quenching instability in phosphors is currently poorly understood, and more fundamental research is necessary.

***Quantum Dots***

Further work is required to understand stability issues associated with QDs such as PTQ, photo-bleaching, blinking, and surface passivation in order to allow for on-chip application in LED packages. Challenges to address include minimizing Auger recombination, understanding heterogeneity in luminescence dynamics, eliminating charge trapping and passivating surfaces. The QD structure must be better understood, including interactions between the shell and core of QDs, in order to address these short-comings. Current research on “giant” QDs, which are much larger than traditional quantum dots due to increased thickness of the shell, might provide some answers since they are non-blinking, non-bleaching, and suppress non-radiative processes such as Auger. New techniques for studying QDs optically and structurally at the single dot level can help the understanding of what causes some QDs to have high quantum yield (QY) and others to have low QY. The synthesis method also can have a big impact on the resulting QY and PTQ. New synthesis methods must be developed to better control the QD structure to improve its performance level.

## 2.3. Novel Device Architectures

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

***Tunnel Junctions***

Participants talked about the use of tunnel junctions (TJs) as an opportunity to improve LED performance by mitigating droop in a cascading LED heterostructure. Theoretically, TJs could produce the same amount of light as a conventional single junction device, but at a lower current density, and without requiring a current-spreading p-contact layer such as indium tin oxide (ITO). While research into TJs has increased in recent years, several obstacles remain. The increased voltage drop that results from the increased stack voltage can be an issue in TJs and needs to be reduced. Additionally, there are issues associated with activating the p-type dopant in buried active regions grown by MOCVD and absorption when using InGaN TJs. Moreover, developing growth processes for growing high-quality TJs is required to keep defect densities low and minimize negative impacts of subsequent LED junctions. Alternatively, growth processes such as molecular beam epitaxy (MBE) can be used to overcome some of the growth and activation challenges facing MOCVD (though the added cost of a second growth technique must be overcome).

***Nanostructures***

Researchers have demonstrated nanostructures can change the physical properties of the light emitters over conventional planar structures. The characteristics of these nanostructures allow for more degrees of freedom and control in the growth dynamics leading to improved performance of the resulting light emitters. For example, nanowires allow you to control the crystallographic planes and the resulting indium incorporation and strain levels to enable longer wavelength InGaN emitters (green to red), as well as having few or no defects in the active region. The architecture can also change the active region volume which can change the density of states, which can eliminate Auger recombination and result in higher QE.

Nanowire arrays on single chips were also discussed as a method to create efficient white light. Red, green and blue nanowire arrays offer suitable current and voltage characteristics, while producing full spectrum white light. Methods to control epitaxial growth in nanowire arrays would allow for control over white optical emission from a single chip, but research is needed to fully understand how. Research has also demonstrated forming quantum dots in the nanowires, which allows for wavelength tuning from red to blue by varying the nanowire diameter and hence resulting indium incorporation.
Currently, nanowire LED technology is being pursued for display-based applications, but the fundamentals could translate to SSL technology once they are better understood.

***Dielectric Metamaterials***

The introduction of dielectric metamaterials and metasurfaces for the development of embedded optics could allow for control of directionality and extraction efficiency through controlled, coherent light scattering with lower optical absorption losses than associated with more traditional metal-based metamaterials. Metalenses with variable focus or conformal lenses can lead to new dynamic beam steering capabilities with LED lighting. Assemblies of light emitters and metamaterials can provide monolithic devices with embedded optical control. In order to achieve this monolithic integration, more research is first needed to find materials which exhibit a high refractive index since the current optical metamaterial research is quite new and has been focused on applications outside of the visible spectrum.

## 2.4. Improved materials discovery methods

The concept of exploring and developing new materials for LED lighting systems including new phosphors and semiconductor materials for light emission through computational processes was discussed by the participants. In the case of phosphors, if the fundamental physical mechanisms of the light emission processes could be understood and computationally simulated with respect to the material properties, then it is conceivable that materials could be modeled and engineered to achieve the desired light emission properties. In the case of LED emitter materials, new semiconducting materials such as the II-IV-$V_2$ materials system could lead to more efficient light emitters in the longer wavelengths. Accelerated materials discovery requires high-throughput computation techniques coupled with high-throughput experiments (e.g. combinatorial deposition – vary composition, temperature, etc.) with spatially-resolved characterization, data analysis and data mining. This approach could be continually refined as our understanding of the relationships between different materials combinations and their light emission properties improves. In the case of other materials in the LED package, including thermal and optical materials, these could also, conceivably, be explored and designed through computational processes. Research into metamaterials could potentially decrease the optical losses in LEDs once the necessary materials are discovered. Methods to quickly and effectively predict material characteristics could expedite these processes, and lead to improved emitters and heterostructures.

### 2.5. Improved characterization and analysis techniques

Complementary to the improved materials discovery methods discussed above, the development and application of new and novel characterization and analysis techniques may also provide a path to solving many challenging materials issues. Advanced characterization techniques can help improve our understanding of degradation mechanisms in down-converters (phosphors and QDs). Atomic probe microscopy efforts are underway to better understand facet-dependent indium concentration. Efforts to rapidly assess and map out the phase space of new materials can also improve the characterization process. This improved understanding of materials characteristics should lead to the development of predictive modeling and verification of these models through testing on state-of-the-art materials.

Colloidal QDs is a technology area where greater characterization and analysis techniques to map the QD alloy structure and surface chemistry are critical to improving QD performance and lifetime. A better understanding of the how the synthesis processes control the resulting structure is critical. Photo-oxidation at the surface is one the problematic degradation mechanisms. Additional QD research is needed, both at the synthesis stage and the structural level to gain a more thorough understanding. More research using single dot characterization techniques could build correlations between different structural features of QDs.

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

The DOE SSL program 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) | |
|---|---|---|
| **1. Emitter Materials Research** | A.1.2 Emitter Materials Research[1] | B.3.6 Package Architecture |
| **2. Down-Converters** | A.1.3 Down-Converters | B.1.3 Phosphors |
| **3. Novel Devices** | A.2.2 Novel Emitter Architectures | B.2.0 Device Materials and Architectures |
| **4. Improved materials discovery methods** | A.1.2 Emitter materials research<br>A.2.2 Novel emitter materials and architectures | |
| **5. Improved characterization and analysis techniques** | A.2.2 Novel emitter materials and architectures[2] | |

[1] Applied Research ("Core R&D") task areas begin with an 'A' and Product Development task areas start with 'B'.
[2] New task descriptions may be considered where existing task description do not fully capture the nature and impact of the proposed R&D.

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.

## 4. Suggestions for the DOE SSL R&D Workshop

The 2017 SSL R&D Workshop, which is to be held January 31 – February 2, 2017, offers another opportunity to continue the discussion on critical R&D challenges. Another goal of the BES/EERE roundtable meeting was therefore to gather input and suggestions for suitable topics and speakers, and ideas for panel discussions. Participants suggested the following:

1. Set up discussion topics for the display industry on their experiences with down-converters (specifically QDs) and micro-pixels.
2. Include discussion topics around horticulture lighting and overall energy consumption, including discussions around where outdoor lighting color quality is going to go and what other features are needed.
3. Discuss better ways to foster and encourage collaboration between industry and academia.

## Appendix A: Participant Presentations

***1. Oleg Shchekin, Lumileds – Down conversion: Phosphor Challenges***

Oleg Shchekin, a senior director at Lumileds, presented his research on the challenges LED manufacturers face with phosphors. There is a significant opportunity to improve pc-LEDs through additional research into phosphors that exhibit high PTQ. Shchekin pointed out that phosphor QE is typically reported when the blue light irradiance is zero, but these efficiencies can drop drastically for the red nitride-based phosphors as blue irradiance increases. At high blue irradiance (1.25 W $mm^2$), the conversion efficiency (CE) of pc-LEDs using the $Eu^{2+}$ (divalent Europium) red nitrides can drop to around 80%, but cerium-doped aluminum garnets show little dependence of photo-quenching on temperature. However, while cerium-doped aluminum garnets show promise, they tend to exhibit considerable thermal quenching.

From Shchekin's research, thermal quenching accounts for 20-25% of the total efficiency droop in LEDs. It is responsible for bringing the QE of red nitride phosphors to as low as 80%, while thermal quenching in garnets (green phosphors) can drop the QE to below 95%; both phosphor QEs are below the DOE targets of 90% and 98% for red and green phosphors respectively. An overall white-light CE of 24% for 3000K 80 CRI light could be achieved with optimum peak narrow band red and green phosphors, but a phosphor with those capabilities has not yet been discovered. At a moderate drive, LEDs could improve as much as 30% with improved phosphors, and 10% of this would come from improvements in PTQ. Research focused on improving PTQ is becoming increasingly important as higher lumens per chip are required, particularly for chip-on-board (COB) architectures.

***2. Jonathan Melman, Lumenari – Red Phosphors for LED Lighting***

Jonathan Melman, the CTO of Lumenari Inc., talked about the large efficiency gains that can be realized with improved red downconverter materials. DOE goals target 95% quantum yield (QY) at room temperature, but using an extremely narrow well-positioned activator in certain red phosphors, it is not necessary to reach 95% in order to already begin to see efficiency benefits. According to Melman's research, $Eu^{3+}$, at 55% QE with a peak at 625 nm, leads to a 5% increase in overall white light efficacy over red oxynitride phosphors with broad peak emissions at higher QEs. Additionally, by eliminating the near infrared emissions, significant increases in LER (up to 40%) can be realized. Melman also spoke of research into decreasing parasitic absorption of nitrides as another area for large efficacy gains with red phosphors. Parasitic absorption reduces overall CE, reduces CRI, and increases package temperature.

Melman emphasized that efficacy gains in red phosphors can come from focusing on narrow emission phosphors and minimal parasitic excitation. Although the heating effect in packages due to lower QE should be considered, only moderate QE is required to reach higher theoretical efficacies if the peak width is narrow enough.

***3. Jon Owen, Columbia University – Designing Photochemically Stable Quantum Dots***

Jon Owen, an Associate Professor of Chemistry at Columbia University, focuses on the inorganic chemistry of semiconductors and metal nanocrystals. Owen presented his research into the design of QDs and highlighted the important of increasing knowledge of QD structure at the molecular level. He explained that QDs offer the ability to reduce losses associated with wider-band phosphors, but currently suffer from poor reliability. Once applied to an LED chip, QDs must survive high temperatures and high flux, but photo-brightening/darkening and Auger recombination due to charge trappings at high flux lead to decay, especially with increased heterogeneity.

In order to solve these issues, Owen stressed the need to better understand the QD molecular structure, particularly the surface structures and buried interfaces of the microstructure of alloys. Although QDs can be synthesized today, chemically defined QDs and controlled, scalable syntheses are lacking and require further research.

4. ***Noah Orfield, Los Alamos National Laboratories – Quantum Dot Phosphors: Meeting Quantum Yield, Stability and Scale-up Challenges***

Noah Orfield is working with his team at Los Alamos National Laboratories to produce QD with QY above 90% while achieving minimal to no thermal quenching and high reliability for integration with LED chips. His research focuses on thick-shelled nanocrystal QDs (i.e., giant DQs) which are characterized by superior photostability. These quantum dots are non-blinking, non-bleaching and are non-self-reabsorbing. However, achieving a low enough excitation level is a hurdle.

In order to advance giant QDs, Orfield's group is applying a new technique to understand the challenge of achieving a high QY. This technique finds correlations between optical and structural characterizations using single dot measurements to pinpoint structures that exhibit ideal properties for use in a device. Orfield explained that this method has led them to determine that there is no fundamental limit to giant QD QYs. They also conducted single dot flux, thermal, and humidity tests to find correlations between single dot structure and device level performance. These tests found that the stability of a QD depends on the synthetic method and resulting core-shell internal structure, and that thick-shelled nanocrystal QDs are more stable at higher temperatures than their thinner-shelled counterparts.

5. ***Isaac Wildeson, Lumileds – Efficiency Droop in c-plane AlInGaN LEDs → Focus Areas***

Isaac Wildeson, the Director of Nitride Epitaxy Technology at Lumileds, presented on the dominant mechanisms for high current efficiency droop and Lumileds' methods for improving the two elements attributing to Auger recombination; the carrier density in the QWs, and the Auger matrix element. Wildeson indicated that improving (decreasing) carrier density requires improving hole transport, which typically hurts the material quality. Improved hole transport active region designs and thicker QWs generally have higher efficiencies at high currents, but the material quality drops too quickly to negating these benefits from the heterostructure improvements. However, if the same structure is grown with better materials, then the benefits at higher currents can be realized. Lumileds is currently funded by the DOE to conduct fundamental epitaxial growth and characterization studies on low droop structures so that the defects can be analyzed.

Another approach to addressing the efficacy droop, described by Wildeson, is to use tunnel junction LEDs to reduce current density and allow near peak external quantum efficiency (EQE). For example, when stacking three junctions, each will run at one third of the current density, while the voltage drop across all increases three-fold. While EQE is increased with this method, issues with high voltage drop and activating the buried p-side GaN are introduced. Additionally, increased heat, photon absorption, and longer growth times are created, which can degrade the sensitive InGaN QWs. Increased heat can lead to wavelength shifts and as the number of TJs increases, and light from the bottom activators refracts and is absorbed by upper stacks more frequently.

Wildeson finished by stating that efficiency droop in III-Nitride LEDs and III-Phosphide LEDs are two key developmental areas for LED research. For nitrides, research is needed for distributing the carriers among the QWs and increasing the IQE in each well, as well as increasing the recombination rate. This requires efforts to understand the physics and the growth structure of the nitrides to avoid defects. For phosphides, Wildeson indicated that research is needed to develop unique structures that can improve performance under high heat conditions, improve extraction efficiency, and improve carrier transport.

### *6. Jim Speck, University of California Santa Barbara – High Luminous Efficacy Green LEDs with AlGaN Cap Layer and Hybrid MOCVD/MBE GaN Tunnel Junctions for III-Nitride LEDs and Laser Diodes*

Jim Speck of the University of California Santa Barbara presented research on developing highly efficient green LEDs and hybrid GaN tunnel junctions. Speck indicated that direct green emitters offer a massive opportunity for improvement by implementing and optimizing an AlGaN cap layer above the InGaN green emitting layer in the active region. Speck described how his team was able to improve the surface morphology of the green single quantum well (SQW) layer using a three-step barrier growth method. Using this method, Speck and his colleagues were able to achieve a peak external quantum efficiency (EQE) of 45% for the green emitters, slightly less efficient than the maximum achieved so far. Speck pointed out that there is a huge excess of voltage for green LEDs which is not understood commercially, but leads to a significant loss in wall plug efficiency. This, along with recombination and droop, are the major challenges that remain for green LEDs.

Next, Speck described his work with hybrid MOCVD/molecular beam epitaxy (MBE) GaN tunnel junctions and how they have the potential to increase light extraction for LEDs. Tunnel junctions pose an advantage as they negate the need to use a p-type spreading contact such as ITO, which result in a reduction of optical losses in LEDs. Speck's team was able to improve tunnel junction quality and decrease tunneling distance by oxygen delta-doping their regrowth interfaces. Their research also revealed that hydrofluoric acid is the most effective treatment for the regrowth interface and provides the lowest voltage for c-plane tunnel junctions. It also removes excess magnesium that was not incorporated into the crystal structure, which reduces the tailing effect. Speck's future research goals include reducing the fabrication steps to decrease cost, increasing light extraction efficiency, and enabling multiple active regions via tunnel junctions.

### *7. Sriram Krishnamoorthy, Ohio State University - Tunnel Junctions for Next-Generation SSL*

Sriram Krishnamoorthy of the Department of Electrical and Computer Engineering at Ohio State University presented his group's research into efficient tunnel junctions. Krishnamoorthy explained that tunnel junctions offer the ability to address the efficiency droop at high power and improve the "green gap" by operating at high voltage and low current density, along with allowing for regeneration. He also indicated that tunnel junctions have the potential to provide low resistance, transparent contacts that could enable high current density laser-based lighting. He was supportive of research into using p-down LED structures with reverse polarity emitters because they reduce the excess depletion due to carrier overflow.

Currently, Krishnamoorthy's research has focused on MBE tunnel junctions, however he plans to also investigate MOCVD tunnel junctions. His group has shown the improved high power output for tunnel junction LEDs without using flip chip designs or an ITO layer. They hope to achieve MOCVD compatible designs in the future and find solutions to absorption and activation issues, and develop a better method for defect control at tunnel junctions due to high doping and InGaN.

### *8. Jonathan Wierer, Lehigh University – Research Areas for Ultra-Efficient SSL*

Jonathan Wierer of the Center for Photonics and Nanoelectronics at Lehigh University presented research for developing ultra-efficiency (>70% QE) SSL devices. According to Wierer, very high QE, operating powers, and luminous efficacy white are the three challenges for achieving high efficiency SSL. There are a few methods currently being pursued that address such high QE at high operating powers. As an example, he presented data on how growing an InGaN capping layer followed by a barrier layer grown at very high temperature prevents out-diffusion, increases photoluminescence, and improves morphology. Additionally, while very high indium content typically increases the defect density, at very high temperatures, a polarity effect is created which behaves like a capping effect thereby reducing defects.

Another issue that Wierer discussed was how quantum wells suffer from Auger recombination. Theoretically, QD active layers can achieve lower transparent carrier density and lower thresholds for activation. This means that QD laser diodes can reach high peak power conversion efficiencies at lower current densities and lower Auger recombination rates while sustaining higher power conversion efficiencies at higher currents. Wierer also emphasized the opportunity to explore alternative materials, such as GaNAs, which has shown a lower Auger recombination rate.

In conclusion, Wierer supported the need for additional research into existing methods that increase QE as well as those that are more radical and represent new approaches. This includes increasing research and testing on InGaN capping methods already in play, continuing research and development into QDs for use in QWs, but also exploring alternative materials.

### *9. Jung Han, Yale University – Nonpolar and Semipolar GaN for LED Lighting: Will They Ever Become Manufacturable?*

Jung Han of the Department of Electrical Engineering at Yale University presented research on nonpolar and semipolar GaN for LED lighting. Han began by introducing the possibility of using nonpolar and semipolar orientations for producing GaN layers. Previous growth methods – growth on sapphire and epitaxial lateral overgrowth (ELO) – exhibit high density defects known as basal-plane stacking faults (BSFs) in these orientations. More recent efforts to grow on PSS have shown improvements, and could eventually lead to stacking-fault-free, semipolar GaN. At Yale, Han and his team used PSS with facet controlled growth to eliminate stacking faults and couple it into mainstream LEDs.

Han believes that semipolar and nonpolar GaN are strong options for high efficiency LEDs, but that there needs to be more collective research from the GaN community, citing the positive correlation between the number of academic papers published per year on traditional GaN and the increase in efficacy of LEDs. Additionally, access to large area semipolar and nonpolar materials is limited in academia, and this presents a barrier to new discovery. Projects on semipolar GaN have been funded by DOE in the past, and additional funding for research could be useful in finding the best possible orientation for semipolar GaN.

### *10. Adele Tamboli, National Renewable Energy Laboratory – Developing New Materials for Color-Mixed LEDs*

Adele Tamboli of the National Renewable Energy Laboratory presented her research on the benefits and challenges associated with investigating new materials to enable high efficiency cm-LEDs. There are very few materials in use in semiconductors today, but large improvements may be possible through better materials. Tamboli discussed how aluminum gallium indium phosphide (AlGaInP), the material system used for amber LEDs, has an EQE of 10%, but aluminum indium phosphide (AlInP), a less explored III-V phosphide material, has the potential to reach over 50% power conversion efficiency (PCE). She also discussed that many new II-IV-$V_2$ nitride materials have been discovered with similar bandgaps and lattice constants to the incumbent III-V materials. Zinc germanium nitride ($ZnGeN_2$) and zinc tin nitride ($ZnSnN_2$) have very similar lattice structures to GaN and InN, but with even less lattice mismatch. Her research shows that the atomic structure of these new materials can be undergo bandgap tuning using alloying or cation site disorder.

Tamboli and her colleagues use an accelerated materials discovery technique to quickly map out the phase space of new materials and are able to make predictions about which ones are worth testing. This accelerated method is able capable of analyzing large sample groups – up to 40 samples at once. The process is not currently in use for LEDs, but has the potential to yield ground-breaking results. Additionally, Tamboli discussed the potential benefits of applying alternative growth techniques, such as hydride vapor phase epitaxy (HVPE) rather than metalorganic vapor phase epitaxy (MOVPE). Migrating to HVPE could result in a 200x reduction in cost for SSL devices. More research is needed to identify if these novel materials and techniques could improve the quality and cost of LEDs.

### 11. *Rick Schneider, glō USA – Opportunities for Science and Technology Research of GaN-based Nanostructures for Display*

Rick Schneider, the CTO of glō USA, presented on R&D opportunities for nanowire LEDs in emerging high-brightness, low-power density displays. While "direct-view" displays use micro-LEDs for each sub-pixel, nanowire displays use less power and are brighter. They also can produce higher indium content required for green and red emission. Additionally, having a high concentration of nanowires per chip offers greater resilience to defects. Schneider suggested that these concepts are applicable to LEDs for illumination, and greater collaboration between SSL researchers and small business manufacturers is beneficial to both parties.

In his presentation, Schneider emphasized the importance of research and science to a start-up manufacturing companies. Research is unscheduled and can be random, whereas development is very scheduled and directed. Research can provide a fundamental understanding of the methods that are deployed by manufacturers, and in turn this leads to improved operational methods. Schneider explained that achieving a "high-quality cycle of learning" is essential to testing fundamental designs that researchers have developed. This cycling between researchers and manufacturers enables a higher level of control and leads to accelerated progress. For example, there has been less research on GaN-based nanowires to date, and as a result, the fundamental understanding of the technology has slowed. Schneider indicated that in order to accelerate progress research into fundamental understanding is needed. Funding in collaborative efforts would bolster understanding in nanowires, and improve the US technological position in the industry.

### 12. *Zetian Mi, University of Michigan – Full-Color and Deep Ultraviolet Light Emitters Using III-Nitride Nanowire Arrays*

Zetian Mi of the Department of Electrical Engineering and Computer Science at the University of Michigan presented his research into monolithic multi-color nanowire LEDs, and how similar technology can be used to reach highly efficient deep ultraviolet (UV) band light. In his experiments, different size nanowires were grown using selective area epitaxy with embedded QDs that formed on different crystallographic planes, depending on the nanowire diameters. Because indium incorporation increased with increasing size of the nanowires, larger diameter wires produced longer wavelengths. Therefore, Mi was able to tune the optical emissions from red to blue in a single epitaxy step. With this knowledge, Mi produced full spectrum white light by incorporated four nanowires of different spectra onto a single chip. While promising, these full-color nanowire LEDs still require research. In particular, there are challenges to achieving high efficiencies in the deep UV range since there is a negative correlation between QE and wavelength. This decrease is due to the aluminum in AlGaN, in which Mg acceptors have a much higher ionization energy than in GaN or InGaN.

With further research, efficient current conduction in AlGaN nanowires and selective area epitaxy could be used to make highly efficient UV LEDs and surface emitting lasers. Mi asserted that III-nitride nanostructures provide good opportunities to address the visible and deep UV wavelength range issues of conventional planar LEDs. However, many LED and nanowire array challenges must be addressed, before this technology is commercially viable.

### 13. *Igal Brener, Sandia National Labs – New Optical Functionality using All-Dielectric Metamaterials: Potential for SSL Devices*

Igal Brener of Sandia National Labs and the Center for Integrated Nanotechnologies presented research efforts into all-dielectric metamaterials. Dielectric materials allow for control over scattering by creating

Huygens’ sources. These are in the form of nanodisks that have very high transmittance and a 2π phase shift. While promising, Brener emphasized that new materials with a high refractive index and bandgap are needed to advance the performance and enable the application of metamaterials.

Brener explained that all-dielectric surfaces can be used to create metalenses with multiple functionalities, however, Brener’s research aims to discover the limit to spectral brightness per solid angle achievable with a monolithic and small (compared to wavelength) LED. His research could lead to monolithic devices with an optical layer that can control focusing, wavelength splitting, filtering, directionality, modulation, and other functions.

Brener proposed as interesting research topics: discovering how fast the radiative rate in the visible spectrum can be while maintaining close to 100% efficiency and high directionality; controlling electronic scattering processes via methods other than changing the semiconductor; and making use of new two-dimensional semiconductors as the basis for new device concepts.

### 14. *Mike Coltrin, Sandia National Laboratories – Syntheses of and Emission from Nanostructures: Understanding and Control*

Mike Coltrin of Sandia National Laboratories presented his research on nanostructure emitters. Nanostructures offer a greater amount of control and access to the crystal facets, which can result in different and desirable properties. The small size of the nanostructures also leads to a reduction in defects, greater indium incorporation, and the possibility of growth on foreign substrates. Coltrin explained that nanostructures also open the door to a variety of synthesis approaches including MBE, catalytic (VLS), MOCVD, HVPE, as well as several others. With nanostructures, the unique architecture allows the study of unique emission processes. Additionally, Coltrin indicated that etchings can be used to create nanowire displays and that self-limiting PEC etching allows for size-selective, monodispersed QD synthesis.

Sponsorships from BES and the Energy Frontier Research Centers (EFRC) have enabled Coltrin’s group to conduct research using a variety of tooling equipment which has led to a greater understanding of nanostructure evolution and emission. He emphasized that the use of tools and analysis rooted in basic science provides guidance and a basis for understanding in the technology-development environment. In addition, Coltrin indicated that keeping a rapid pace of development can provide rigorous testing of scientific understanding.

## Appendix B: R&D Task Descriptions

The R&D task descriptions, defined in the 2014 DOE SSL R&D MYPP, the 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 |
|---|---|
| **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 and advanced characterization approaches. 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. |
| **A.8.2** Physiological Impacts of Light | Develop an improved understanding of the underlying physiological responses to light for humans, livestock, plants, or nocturnal animals. Such understanding should enable development of SSL products that improve well-being or productivity in humans, increase well-being and productivity in livestock production, increase productivity and reduce cost of indoor crop production, or minimize ecological impacts of lights at night. Researchers in this area should define the current status of the underlying physiological responses to light and describe research targets as well as the impact of the proposed research in terms of energy savings, productivity, well-being, and ecological impacts. Work to develop novel, specialized LED research tools that enable specific R&D in this topic may also be considered. |
| **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. |

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| **B.1.3** Phosphors | Optimize phosphors for LED white light applications, including color uniformity, color maintenance, thermal sensitivity and stability. |
| **B.3.2** Encapsulation | Improve the LED package light extraction/light mixing/optical scattering/absorption system through development of new encapsulant-phosphor-LED chip materials and configurations. Develop new encapsulant formulations that provide a tuned 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, improve 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. Develop materials and approaches that enable low-cost wafer scale deposition of phosphor and encapsulant materials. |
| **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.<br>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 |

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| | 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. |