DOE Joint Solid State Lighting Roundtables on Science Challenges

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DISCLAIMER

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Table of Contents

1. Introduction

As part of ongoing coordination activities, the U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE) invited the Office of Basic Energy Sciences (BES) to jointly conduct roundtable discussions to bring together the leading experts in solid state lighting (SSL) research, who are supported by each of the programs. The focus was consideration of opportunities for further advancement of the science and technology of solid state lighting. Two separate meetings were held on October 5 and 6, 2011 at the Bethesda Marriott Hotel in Bethesda, MD, one for LED technology, and one for OLED technology.

This report is a summary of the findings from those meetings. Participants included 17 invited experts in LED technology, and 14 invited experts in OLED technology. Current and past researchers supported by BES and EERE were invited to this joint event. In addition, a few non-DOE-funded experts were invited to participate.

The BES program supports fundamental research to understand, predict, and ultimately control matter and energy at the electronic, atomic, and molecular levels. Discoveries from the research provide the foundations for new energy technologies to support DOE's missions in energy, environment, and national security. In 2009, BES instituted and funded 46 Energy Frontier Research Centers (EFRCs). An EFRC was required to be focused on grand challenges in science (aligned with the BES mission) and "use-inspired" research, which address specific research areas relevant to the DOE mission. Several of the EFRCs have, as a use-inspired component, science that is relevant to advancing solid state lighting.

The SSL program in the Office of Building Technologies of EERE, on the other hand, has a specific mission to fund work that will advance the technology into useful, marketable products that can produce significant energy savings for application in general illumination. Work spans applied research in Core technologies, through Product Development, and into Manufacturing R&D for SSL products. Related efforts in the program provide Market Support to promote market acceptance of high quality, energy saving, solid state lighting products. Generally, the R&D projects funded under EERE[1] are on a shorter time scale than those in BES, and there are specific milestones and deliverables to ensure continuous progress.

It is noted that in May 2006, as part of the "Basic Research Needs" strategic planning activities, BES convened a workshop to explore the basic energy science needs for solid state lighting (SSL) with the objective of identifying the priority research directions to tackle the most demanding challenges to advance state-of-the-art technology towards practical, high-performing market products for general illumination. This workshop

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[1] A complete list of prioritized research and development tasks, as well as a listing of funded projects, can be found in the 2011 SSL Multi Year Program Plan (MYPP) and SSL Manufacturing Roadmap. Links to these documents can be found at: http://www1.eere.energy.gov/buildings/ssl/techroadmaps.html

included the DOE technology offices, academia, and industrial participants. That report concluded at the time, "Today, we cannot produce white SSL that is *simultaneously* high in efficiency, low in cost, and high in color-rendering quality. In fact, we cannot get within a factor of ten in either efficiency or cost."

However, much has changed for this technology in the past five years. Today, thousands of viable LED lighting products are available on the market. While many still do not meet the performance goals and cost targets envisioned in 2006, many do achieve the energy savings and lighting quality at a low enough cost to be acceptable to consumers. The technology is steadily working its way into the market. However, there remain gaps in understanding the science underlying the performance of LED and OLED emitters used in solid state lighting. The following discussion focuses on these areas of research.

1.1 Objectives and Process

Three key objectives were put forth for the roundtable meetings:

- Identify critical basic research needs for ongoing development of SSL;
- Foster collaboration among basic science, applied science, and industry researchers; and
- Maintain collaboration between EERE-BES SSL Programs.

These meetings provided an opportunity to share understandings of the state-of-the-art in LED and OLED based SSL technology as well as identifying gaps in that understanding. To accomplish this in a short time, the format of each meeting was to have a series of short, ten-minute, presentations by each attendee outlining what he or she considered to be an important challenge needing research attention. A brief abstract of each of these presentations is in the appendix of this report.

An open discussion followed the presentations, in which participants offered suggestions as to the essential research opportunities as well as perceived opportunities for collaboration. The attendees at the meeting represented a wide spectrum of research interests, from basic science researchers to industry scientists. Through selection of attendees with a range of research interests, and with these open discussions, we hope to have enhanced communication channels among the researchers focused on SSL.

1.2 Key Conclusions

The roundtable meeting was broken up into two, one-day sessions — one for the LED discussion and one for the OLED discussion. Based on the presentations from the attendees and the subsequent discussion, the critical basic science research challenges could be grouped into a few broad research themes for each LEDs and OLEDs. These are outlined in the next two sections.

While all of the discussions offered insights on research that could advance SSL technology, there were a few recurring themes that participants felt might provide some fundamental understanding of underlying processes that could lead to significant breakthroughs in SSL performance:

- *LED carrier dynamics and droop.* If current droop could be reduced or eliminated, a significant improvement in efficacy for practical devices would be realized and the cost of LED based lighting could be reduced as well.
- *LED Nanostructures.* Although there is much to learn, the eventual use of nanostructures in LEDs offers several potential benefits, including higher efficiency arising from reduced droop and fewer defects; and efficient longer wavelength emission into the green gap.
- *OLED device architecture.* The best-performing OLED devices today are very complex structures. Improving our understanding of OLED material combinations, interfaces, and composition could be the basis of simpler, more robust devices, which could be produced at a lower cost.

Beyond the imminent research needs of solid state lighting, LEDs and OLEDs offer a research window into broad areas of fundamental science. LED and OLED platforms enable fundamental research in the areas of materials properties, semiconductor physics, degradation processes, thin film optics, light emission processes, and more. Fundamental research using LEDs and OLEDs will not only advance the energy savings prospects of solid state lighting but will enhance the fundamental understanding of relatively new classes of electronic materials and devices leading to additional unforeseen technology breakthroughs.

2. LED Critical Basic Science Research Areas

In the LED discussion, the research discussions could be categorized into the broader themes of the science of nitride LEDs, novel materials for solid state lighting, LED nanostructures, and supporting technologies. A brief synopsis of each attendee's presentation is provided in the appendix. The following sections discuss each of these themes.

2.1 Science of Nitride LEDs

Under the theme of the science of nitride LEDs, there was considerable discussion on the need for a better understanding of 'current droop' — efficiency roll-off at higher operating current densities, the 'green gap' — lower internal quantum efficiency (IQE) at longer wavelengths (> ~480 nm), and the metal-organic chemical vapor deposition (MOCVD) growth of high quality LED structures. These topics have been considered thoroughly by industry researchers through experimental studies and observation and by academic researchers through theoretical and experimental studies. However, the roundtable attendees noted that considerably more work can be done to advance the fundamental understanding of these topics.

2.1.1 Fundamental Science of LED Carrier Dynamics and Droop

In the presentations and the following discussion, fundamental research of current droop was clearly identified as a basic science research topic that can not only advance the understanding of nitride LEDs and semiconductor physics but could also impact the technology of solid state lighting. Reducing current droop would enable higher light output per LED area, reducing the cost of LED sources while also improving their efficiency. However, the roundtable participants from industry research organizations did offer a warning – droop needs to be investigated on high IQE LED structures and high quality materials, otherwise the research findings might not be applicable to state of the art LEDs.

Current droop in nitride LEDs is likely caused by some combination of Auger recombination, uneven charge carrier transport, and non-radiative recombination, all of which are related to strain and polarization effects in the LED structure. These fundamental research topics need ongoing research so that the root causes of droop can be clearly identified, isolated, and mitigated. The roundtable participants suggested performing experimental studies to identify Auger carriers and experimentally verify theoretical Auger research. Some specific experiments were suggested such as looking for evidence of Auger recombination in other material systems like aluminum indium gallium phosphide (AlInGaP) LEDs and in alternative devices like nanoscale test structures- i.e. quantum dots or nanowires, and lasers. Theoretical-experimental studies could also be performed to better understand LED carrier recombination dynamics and determine dependencies of the various rates of recombination (non-radiative, radiative, Auger) on carrier density or other dynamic phenomena.

Advances are needed in the understanding of carrier transport and polarization effects in nitride LEDs. This would also aid in the understanding of droop and could generally enhance the understanding of the physics of these high efficiency LEDs. Research was recommended in the magnesium doping of nitride LEDs and the impact of the dopant on carrier transport which can create uneven charge carrier distribution in the quantum wells and possibly contribute to Auger recombination losses. In addition, novel active regions consisting of graded alloy compositions, engineered polarization fields, and alternative quantum well configurations were suggested areas for investigation. Hot carriers at higher voltage operation could also be contributing to droop and further study in this topic was recommended. To understand the effect of polarization on LED operation and droop in particular, study of LEDs and test structures in alternative crystal orientations with different levels of polarization fields could lead to a more refined understanding of the impact of polarization on LED operation and droop.

2.1.2 Understanding the Green Gap

The ‘Green Gap’ refers to the decrease in IQE of nitride and AlInGaP based LEDs as the emission wavelength of the LED approaches 550nm (green). Solving the green gap has been an active area of research for the last decade or more. It is well understood that white light generated by a mix of direct emitting LEDs (RGBA) could have the highest theoretical efficacy of any light source and this has driven research into solving the green gap. However, some LED manufacturers have indicated that simpler, phosphor converted approaches are more desirable for their currently higher efficacy and their simple device structure and integration. While research on the origins of the green gap has improved the IQE of green emitting LEDs they are still not to the level where an RGBA direct emitter approach would be more efficient than the phosphor converted architecture, which currently dominates the LED lighting market.

Even with the uncertainty as to the necessity of green LEDs for the broad application of lighting, ongoing research into the green gap could lead not only to more efficient green LEDs but also to valuable insight into the materials science and semiconductor physics of blue nitride LEDs and LEDs in general. Further research into the green gap and beyond for nitride LEDs could eventually unlock the possibility of using InGaN alloys for emission across the visible spectrum. Blue LED performance could improve with understanding of the impact of strain at higher indium concentrations and with understanding the role of indium itself in the emission process and how this role changes with concentration. Investigating droop in green LEDs and how droop responds with additional indium and strain in the LED structure could provide insights into droop in blue LEDs. Finally, the control of polarization through the use of selected crystal growth orientations to improve green IQE could also advance the understanding of nitride LEDs.

The green gap could also be addressed through the use of nanostructures, novel crystal growth techniques, or by pushing to shorter emission wavelengths with LEDs in the AlInGaP material system. These possibilities will be discussed in subsequent sections.

2.1.3 Fundamental understanding of the nitride crystal growth process

2.1.3.1 Epitaxy

Metal-Organic Chemical Vapor Deposition (MOCVD aka MOVPE or OMVPE) is by far the most prevalent growth technique of blue LEDs structures used in solid state lighting. Manufactures have identified the MOCVD growth parameters and reactor geometries that yield the best LEDs. However, the full dynamics of the growth process are not fully understood. *In-situ* growth studies coupled with theoretical analysis are needed for a better understanding of the growth process. Atomic scale mechanisms and intermediate chemical processes are still poorly understood in MOCVD growth. Similar to droop, research needs to be done in MOCVD growth situations that are as close as possible to conditions used to deposit materials for state-of-the-art LEDs in order for the results to be relevant to current growth processes. This could be difficult due to the complexity of making *in-situ* measurements in high performance MOCVD reactors as well as the difficulty of working with LED manufacturers who keep tight control of their crystal growth information. These studies could lead to: better control of the crystal growth process, improved LED yield and reduced performance variations of the LEDs; lower cost and higher throughput MOCVD tools; LED device architectures and growth techniques that could minimize droop; and growth processes that could improve the efficiency of green LEDs.

An improved understanding of the MOCVD growth of materials used for nitride LEDs could identify fundamental limitations in the growth process and point the way to new growth techniques for nitride LEDs that emit a green wavelengths and beyond. Higher pressure growth of InGaN LEDs was mentioned as a possible means of growing higher quality materials for green emitting LEDs since the InGaN layer growth temperature can be raised while also maintaining In concentration. Developing a better understanding of the underlying physical mechanisms of MOCVD growth will lead to a better understanding of the performance trade-offs in new growth regimes, allowing for more rapid exploration of the entire range of MOCVD growth parameters for LEDs.

2.1.3.2 Bulk GaN

The use of GaN substrates for GaN based LED growth may have inherent advantages in terms of LED performance. However, GaN substrates are not available in large enough diameters (> 2”) for large scale LED manufacturing and they are too expensive to justify their use for typical LED applications. Improved understanding of GaN bulk crystal growth processes could lead to more cost effective growth processes that could enhance the availability of bulk GaN substrates for LED applications. Improved bulk GaN growth processes could also provide substrates with alternative crystal orientations for the study of non-polar and semi-polar GaN LEDs, which may have reduced droop and improved efficiency as a result of reduced polarization fields in the LED structure. One method of bulk GaN growth that was mentioned as a particularly promising growth process for study was ammonothermal growth, where GaN would be grown in a supercritical solvent. Bulk quartz is grown by this technique at very low cost and large diameters demonstrating its potential to meet LED cost and size requirements.

2.2 Novel Materials for LEDs

Research on three categories of novel materials was discussed at the roundtable meeting — down converters, LED materials, transparent conductors. These are topics of ongoing basic research and could also have considerable impact on the technology of solid state lighting.

2.2.1 Down Converters

Down converting materials — phosphors and quantum dots — are ubiquitous in solid state lighting. They are used for converting a portion of the blue light from the underlying blue LED to green, yellow, and/or red in order to create white light. Most down converters are phosphors, but quantum dot technology has emerged as an additional option for down conversion.

While existing down conversion materials work well for SSL there are some performance and materials issues that need additional research. Many phosphors contain rare earth metals, which have recently experienced supply issues.[2] Developing alternative phosphor materials that do not contain rare earths could insulate the supply chain from disruptions. The development of new phosphor materials that can efficiently down convert light from blue to a broad range of visible light wavelengths is a considerable challenge and could be aided by a better fundamental understanding of luminescent materials. Conceivably, the development of novel luminescent materials could even be performed by rational design of materials. Performance aspects of phosphors that could be improved are related to the emission spectrum and the temperature instability. Narrowing the emission spectrum of phosphors can reduce the amount of light emitted outside of the visible spectrum and enable a greater range of color control (CRI, CCT) and efficiency in LED package architectures. The temperature instability (thermal quenching) in phosphors leads to reduced efficiency and color shifts in the light emitted by the LED package as the package heats up.

Quantum dots also have aspects that could be improved for use in solid state lighting. Currently, the highest conversion efficiency quantum dots contain cadmium, which could create compliance issues. This may inhibit their use in solid state lighting. There is ongoing research into high efficiency quantum dots that do not contain cadmium (Cd) or other regulated materials but these quantum dots down converters do not reach the same level of conversion efficiency as those based on Cd. Further research into novel materials for down converting quantum dots could benefit SSL by offering high efficiency, alternative down converters. In addition research was suggested that could narrow the emission spectrum of quantum dots for the same benefits as stated above. Quantum dots also need to become more thermally and environmentally stable to enhance their opportunities for use in solid state lighting.

2.2.2 LED Materials

The roundtable experts suggested that the further study of new and existing LED materials systems could yield insight into LED physics, nitride LED operation, and possible new emitter materials. The AlInGaP material system and II-VI LED material systems were mentioned as candidates for renewed study. Different material systems will have different strain states, polarization fields, active region structures, and growth techniques, which could be used to isolate and study possible performance limiting effects, such as Auger recombination or defects. In addition, the rapid growth in the use of LEDs has brought a new understanding of LED structure growth, design, and performance requirements that could enable the development of new LED materials for solid state lighting.

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[2] For further information on this issue, see DOE’s “Critical Materials Strategy” at the following link: http://energy.gov/sites/prod/files/edg/news/documents/criticalmaterialsstrategy.pdf

2.3 Nanostructures

Nanostructures offer several potential benefits as high efficiency light emitters and test structures to better understand LED physics. Nanorods, quantum dots (QDs), nanosheets, and photonic crystals were all discussed as areas of research for improved LED efficiency and understanding. In addition, the concept of improving LED efficiency through nanoscale architectures that couple the LED emission region with surface plasmons was also discussed. The general benefits of using nanostructured LEDs are the mitigation of defects, strain, and polarization fields leading to improved IQE, reduced droop, and longer wavelength emission. Nanostructures also have the possibility of achieving stimulated emission or taking advantage of the Purcell Effect to increase the rate of exciton decay. Nanostructures can also be used as experimental devices to isolate the effects of defects, strain, and polarization fields to better understand the physics of planar LEDs.

2.4 Supporting Technologies

In addition to the research themes discussed above, characterization and modeling techniques for LEDs are critical. Advanced characterization and modeling of LEDs, LED structure growth, LED materials, down converters, and nanostructures could lead to improved fundamental understanding of the materials science and physics of solid state lighting. In-situ chemical and atomic characterization within the epitaxial and bulk crystal growth processes could advance the understanding of very fine scale crystal growth processes. Improved and novel characterization techniques of electron transport could also offer insight into the charge carrier dynamics of LEDs and the operation of nanostructure devices.

Improved modeling of LED and nanostructure synthesis and operation is also a potential area of fundamental research that could benefit the technology of solid state lighting. The theory and modeling of recombination mechanisms could be a useful area of research including: microscopic interactions in k-space, many-body effects, and electron-electron interactions. Other device modeling topics that were discussed were modeling of disorder and defects in LEDs and modeling of quantum dots and other nanostructures since the more discrete nature of the nanostructures may lend them to more accurate modeling of their materials and operation.

3. OLED Critical Basic Science Research Areas

In the OLED meeting, the research discussions were categorized into the broader themes of: OLED device architecture, OLED materials, and modeling and characterization of OLED devices and materials. All of the presentation topics by the attendees could fit into at least one of these themes. A brief synopsis of each attendee's presentation is provided in the appendix.

Beyond the immediate research needs of solid state lighting, OLEDs offer a research window into organic electronic materials properties, degradation of organic materials, thin film optical systems, organic semiconductor physics and organic device physics. Fundamental research using OLEDs will not only advance the energy savings prospects of OLED solid state lighting but will enhance the fundamental understanding of a relatively new class of electronic materials and devices leading to additional unforeseen technology breakthroughs.

3.1 OLED System Architecture

In order to achieve higher efficiency (approaching 100 lumens per watt), OLED device structures have become increasingly complex. However, simplified OLED architectures may be desirable to reduce manufacturing costs and improve the reliability of OLEDs. Several of the presentations covered this topic. There were also several presentations discussing the need for new approaches for light extraction. Improved light extraction increases the efficiency of the OLED and increases the light output, reducing the per lumen cost without increasing the current density or otherwise adversely affecting the OLED.

3.1.1 Light Extraction

Light extraction is a challenge for OLEDs due to the thin structure of the OLED device and the index contrast between the OLED materials and the substrate. Light generated in the OLED emissive region is lost within the OLED materials/ITO stack and within the substrate. To extract the substrate modes, well known approaches exist for texturing of the output surface. However, the challenge for OLEDs is to develop a light extraction approach for the substrate surface that can be done effectively over a large area at very low cost, so that the OLEDs can be cost competitive as a general purpose light source. New approaches for fine texturing of large optical surfaces need to be developed, which are compatible with OLED fabrication and operation and work together with any light extraction approach used within the organic materials stack.

Optical modes within the organic/ITO materials stack suffer from a combination of plasmon losses, emission quenching, metallic cathode losses, and wave-guiding and re-absorption. Some research groups have had success employing a scattering layer within the organic stack to direct light out of the organic layers and into the substrate. However, plasmon losses, emission quenching, and metallic cathode losses need to be better understood and addressed. One of the roundtable participants claimed that if plasmon losses could be removed there would be a 50% improvement in OLED efficiency. Several approaches were offered for the mitigation of plasmon losses within the OLED device but they all require further study. The simplest approach is to increase the distance between the emissive layer and the metal cathode. However, due to the extra material, this approach may increase the OLED operating voltage and, possibly, increase light absorption. Solutions for this trade-off need to be developed, such as increased conductivity in the charge injection layers which would allow for thicker layers with less of a voltage increase. Other proposed research aimed at reducing plasmon losses was the use of periodic nanostructures within the OLED cathode, which could serve to redirect plasmon modes back into optical modes within the organic layers.

Much time was spent discussing the critical need for improved light extraction from both the internal organic layers and the substrate. The cost constraints and sensitive nature of the OLED require novel approaches and insight into light extraction. Approaches must be low cost, scalable to large area devices, engineered to optimize both the internal and external light extraction together, compatible with OLED device architectures, and robust with respect to lifetime and environmental degradation. These requirements suggest that fundamental research is necessary to better understand and mitigate the optical losses within the OLED stack and to develop entirely novel approaches for large area light extraction from the substrate.

3.1.2 OLED Device Architecture

Research on OLED architectures was discussed at the roundtable meeting. It is important to better understand the influence of interfaces within the OLED and the effects of nanoscale spatial composition variations of the organic materials on the performance and stability of OLED devices. With this understanding, new architectures using mixed materials, graded material compositions, or hybrid material combinations (phosphorescent-fluorescent) could be developed with fewer or better engineered material interfaces. For example, OLEDs with double host cells are very efficient compared to single OLED cells, but perhaps these could be simplified by understanding and controlling the nanoscale spatial composition of the material to achieve the benefits of the double cell within a single layer of material. Another approach discussed was the use of a graded emissive layer with broad mixing of the hole and electron transport materials to control the recombination zone of the device and improve charge balance within the device. Fundamental research of aspects of OLED device architectures, such as charge transport across interfaces, nanoscale composition, and material mixing and grading approaches may lead to new device architectures beyond the typical multi-layer approach.

The deposition of materials for OLEDs has become increasingly complex which has resulted in an increase in manufacturing complexity and costs. With a better understanding of the influence of material interfaces and nanoscale compositional variations, new architectures could be implemented that would simplify the OLED structure and reduce the number of layers within the device without sacrificing functionality or performance. These newer architectures might require fewer materials, fewer layers, and fewer deposition steps, increasing the stability of the device and the manufacturing process. Ultimately, a better understanding of the material composition, interface charge dynamics, and material mixing behavior could lead to materials and device architectures with increased luminescent yield, stability, and ease of manufacturing.

3.2 OLED Materials

As stated in the previous section, mixing materials may lead to simplified device structures, enhanced stability, and improved performance. Similarly, single materials with multiple functions such as light emission/charge transport/charge blocking could also simplify OLED device architecture and OLED materials deposition.

The efficiency, lifetime, and stability of blue emissive materials are still issues for OLED devices. Research is needed to advance our understanding of existing materials and the development of new materials could have a large impact on OLED performance. The participants suggested theoretical modeling as a pathway to the discovery of new organic materials for blue light emission as well as a way to improve other functions within the OLED device. Theoretical studies need to be coupled with experimental research to identify new OLED materials and new OLED materials need to be compatible with OLED device architectures, materials, and manufacturing methods.

3.3 Modeling and Characterization of OLEDs

As mentioned above, the possibility exists to theoretically model new materials for use in OLEDs based on the chemical structure and the desired electrical properties. However, at the present time, theoretical modeling cannot fully predict the performance for organic electronic materials used in OLEDs. This is an area of fundamental science research where advancements could enable better predictions of structure-property relationships, enabling the design of new, organic electronic materials. For all of the research topics discussed at the roundtable meeting, improved modeling was seen as an area that could have a significant impact on the field.

Likewise, the development of new characterization techniques for organic devices and materials could also advance all aspects of OLED understanding and performance. At the roundtable meeting, a TEM technique for characterizing the degradation of OLED material and interfaces over operating life was presented. Additional characterization techniques are needed for organic electronic materials. These new techniques could provide insight into the nanoscale composition of the organic materials within the OLED structure as well as other aspects of OLED material and device properties.

4. Collaboration and Coordination

One of the goals of the BES/EERE roundtable sessions was to foster collaboration between basic and applied scientists. Accordingly, a portion of each of the two roundtables was set aside to discuss the coordination of BES and EERE efforts. Several opportunities were identified, as discussed further below.

4.1 Coordination Opportunities

Several participants felt that the roundtable discussions offered an excellent opportunity to enhance communication and coordination between BES and EERE funded principal investigators. Closer interaction would accelerate the transition of basic science research discoveries to practical applications. Participants noted that it is common for academic and industrial researchers to partner on existing EERE projects. Several participants hoped these roundtables would continue on a more frequent basis just for this reason.

4.2 Internships

Several participants proposed internships for academic researchers to work in industry labs or vice versa as a mechanism to integrate academic and industrial research activities. A “fellowship” program was proposed to defray the costs of such a program. Concerns about intellectual property surfaced during this discussion. One industrial participant flatly stated that companies will not bring students into their labs for fear of losing control of their IP, and several others concurred. Another issue is that some companies felt their resources were insufficient to allow their staff to go for an extended time into an academic internship. So, while most participants could see the advantages of internships, more thought is needed to address key concerns.

4.3 A Cooperative Development Project

This discussion went along several paths. One thought was to create a centrally-funded lab for some cooperative projects that are not particularly proprietary. For example, standard packaging technology development and reliability studies were suggested. Taking this idea one step further, this organization could also provide a centralized testing capability for devices, thus reducing the need for duplicative capital investments in advanced testing. This facility could also provide a near-state-of-the-art fabrication facility so that universities could do their work on better, more industry relevant devices. Such an approach was used in Sematech facility in Texas for integrated circuit development and manufacturing. IP concerns again came up in this context, and some thought that the community does not really need such a central organization. Many in the group were not very familiar with Sematech, but a few noted that they had worked through similar concerns, identified projects that were relatively non-proprietary but of common concern, and had had considerable success in the semiconductor industry.

4.4 “Science” versus “Development”

Also included in the above discussions were questions regarding the different roles of “basic science” and “applied research” relative to SSL. The question, “What can a university/national laboratory do that is relevant to industry?” or some variant of that, came up in both roundtables. Without being very specific, there was consensus that there were many technological challenges that need to be overcome for industry to succeed. Contributions from the basic science community are needed to bridge major gaps in our understanding of phenomena that limit the efficiency, performance and lifetime of the SSL materials and devices. Some noted that the time horizon for BES is about 10 – 20 years while that for applied research supported by EERE and for industry “core” work is 5 or less. (A few commented that 5 years was a rather generous estimate for industrial work.) The groups also identified the well-known “funding gap” between topics that are too fundamental (not within EERE’s mission) and too applied (not within BES’ mission) and encouraged DOE look for ways to reduce the gap.

4.5 The Role of Equipment Companies

For silicon, the tool manufacturers are the “repository of industry knowledge.” For SSL, however, the development of standardized tools is more nascent than in the semiconductor community. LED companies don’t want to share their epitaxial growth trade secrets with the tool makers. This will probably change over time, and most seemed to feel that ultimately it is the design architecture, not processing technology, that will define both the key IP and the differences among manufacturers. For now, however, much of the group seemed to believe it is not a particularly fertile ground for cooperation down to the basic research level. They seemed to feel that this type of cooperation would be at the manufacturing R&D level which is not suitable for universities. We note that this last thought begs the question as to why university people do not feel they can or should do manufacturing R&D — that might be something worth thinking about.

4.6 Final Thoughts

Industry researchers are interested in collaboration with university and National Laboratory scientists, but programs to enable this, and not jeopardize IP, need to be developed. Legal agreements, although difficult, might avoid some of the difficulties in getting useful devices to cooperating partners. IP can be protected to some degree, while universities get to investigate state of the art materials and devices. Several felt the “Exceptional Circumstances Determination”[3] within the DOE EERE SSL Program discourages some scientists from proposing applied research to that program. This may impede the kind of transition from science to market that is needed to accelerate the

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[3] For more information regarding the “Exceptional Circumstances Determination” see Appendix F of the 2011 DOE SSL MYPP at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mypp2011_web.pdf

commercial field. They urged DOE to consider how this arrangement might be changed to remove this barrier.

Material transfer agreements, although difficult to implement, might provide one avenue of cooperation that avoids some of these difficulties. The IP can be protected and will give university researchers access to state-of-the-art devices.

The OLED participants seemed to have particular difficulty with this topic, primarily because state-of-the-art OLED devices are less accessible to universities than are LED devices, although the issue affects both communities. Of the options noted above, internships and material transfer agreements appeared to be the most promising.

Appendix: Attendee Presentation Summaries

LED Section

Mike Krames

GaN-related materials challenges for SSL

New material systems or structures are needed to revolutionize the InGaN LED industry and reach the theoretical limits of performance. Currently, commercial LED package products are approaching 100 lumens per watt (lm/W) but the more typical efficacy is 50 lm/W. Counteracting the effects of droop is a key challenge to improving the efficacy of LED sources. Indium Gallium Nitride (InGaN) has three sources of droop: wavelength, temperature and current density. Currently, the highest achievable external quantum efficiency (EQE) is 65% for blue light, dropping down to 5% for green light. Wavelength droop is the biggest challenge to raising these numbers. The fundamental cause of droop is not known. There are multiple theories, Auger recombination and carrier leakage being the most accepted, but there is no experimental proof. An additional challenge for InGaN materials is the lack of a native substrate. As one becomes available, potential benefits will be low dislocations, simplified chip architecture and reliability at high current density. Another area that needs to be addressed is developing large-area, low-cost, scalable GaN manufacturing processes.

Chris Van de Walle

Understanding and overcoming loss mechanisms in nitride light emitters

Efficiency droop needs to be addressed; the mechanisms to address this are multi-fold. Three of the potential origins of the droop phenomenon are quantum wells carrier leakage, non-radiative recombination at defects, and Auger recombination. Carrier leakage can be controlled by engineering the barrier heights to prevent carrier overshoot at high temperatures. Non-radiative recombination due to defects is unlikely to dominate as a source of efficiency droop at high current densities due to its linear relationship with carrier density. Rather, Auger recombination should be investigated further as a primary source of efficiency droop. Because it is difficult identify the experimental signature of Auger recombination, droop should be investigated through state of the art first principles calculations. Based on the theory, to reduce Auger effects, the carrier density must be reduced through increasing the active volume. However, this introduces hole transport issues which must be mitigated through avenues such as optimization of the electron blocking layer and Mg doping of the barriers.

Jerry Simmons

Foundational InGaN materials physics: microscopic processes associated with macroscopic light emission

Filling in the amber-yellow-green gap and ultra-high internal quantum efficiency (IQE) at high and low current densities are two longstanding solid state lighting (SSL) technology goals. In recent years, efficiency droop has been addressed using the ABC approximation model. However, this equation is too simple to address the complexity of the phenomenon. One problem is that the carrier density is treated identically for all three terms. Rather, there should be different definitions for current density for each of the A, B, and C terms. In addition, the ABC coefficients themselves vary with carrier density. More sophisticated theoretical models are necessary. In addition, single quantum well devices should be investigated to further our understanding of the basic underlying mechanism of droop.

Christian Wetzel

Rare earth-free full spectrum direct emitters and what it takes to grow them

As the Chinese control on rare-earths increases the price of these materials, we need to look for rare-earth free full spectrum direct emitters, rather than phosphors. Green wavelengths are currently characterized by numerous structural defects or threading dislocations. There are many areas where research is still needed. Bulk GaN growth at various crystal orientations is one such area. Nano-patterned substrate template growth is promising but defects must be reduced and strain relaxed. High-pressure growth of InGaN is another place to direct focus because high temperature crystal growth processes lend high-purity materials.

Jim Speck

Combination of bulk GaN for LEDs and nonpolar and semipolar LEDs

Structurally the best bulk GaN is through ammonobasic growth under monothermal methods where GaN grows in a supercritical solvent. There are many advantages to growing bulk GaN. Non-polar bulk GaN has lower threading dislocations and similar growth rates to c-plane densities. Bulk semi-polar GaN orientations render significant plastic relaxation. In m-plane photonic crystal LEDs, non-polar orientations change the sequence of valence bands which produces a significant separation of the x,y,z planes and changes polarized light emission. With polarized light emission and an embedded photonic crystal structure it is possible to achieve polarization preserving light extraction of blue light. When this is used to pump phosphors the result is polarized luminescence which could potentially reduce glare. Bulk GaN will also help optimize p-n junction location and the dynamics of carriers in InGaN/GaN multiple quantum wells (QWs).

Mike Craven

Key Challenges for Illumination-Grade LED Technology

Lumens per dollar (lm/$) is the LED valuation of most concern. The goal is a tenfold lm/$ reduction achieved in two parts: a fourfold increase in performance and a 60% decrease in cost. Costs reductions will be realized through manufacturing advancements. Performance enhancement will stem from improvements in wall plug efficiency, conversion efficiency and power density. Emphasis on high temperature performance is essential. Hot wall plug efficiency and hot/cold factor are two key performance indicators. Currently the set temperature is 80 – 85°C. To maximize lm/$, LEDs should be driven to the thermal limit of the system, reaching temperatures of at least 100°C. Phosphor conversion efficiency is another area for improvements. Warm white LEDs require a breakthrough in narrow red phosphors. Current red phosphors have broad emission around 90 – 100nm. Ideally, it should be under 40nm. A reduction in the width of red phosphor emission could increase efficacy by 20% but a narrow red phosphor solution should be low cost, stable up to 200°C and maintain quantum efficiency at high excitation densities. To maximize lm/$ LEDs need to be driven to the thermal limit of the system. SSL technology must boost LED efficiency at high temperature, boost phosphor efficiency at high temperature and support research with breakthrough potential for high temperature LED performance and durability

Paul Fuoss

In Situ X-Ray Studies of the Reactive Synthesis of SSL Materials

Atomic scale mechanisms and intermediate chemical processes are poorly understood in many practical synthesis and patterning processes for advanced materials. To better understand the detailed chemical reactions researchers have been using high energy x-ray scatter to examine the processes and composition of the materials during MOVCD growth. The challenge of employing this synchrotron x-ray process is going from a lot of data to what is a microscopic model and interpreting the results. Discrete Fourier transform predictions of decomposition pathways is a technique that has been used for analysis but there are many reactions and configurations which lead to complex phase diagrams. There are a lot of opportunities with x-ray synchrotron radiation techniques to advance materials science and technology and understanding of MOCVD, atomic layer deposition (ALD) and other crystal growth chemical processes. In-situ x-ray scattering can be an important tool for measuring and understanding catalytic processes in MOCVD growth. These in-situ measurements combined with computational simulation and modeling will allow for a better understanding of the science of synthesis and a wider range of materials.

James Ibbetson

Current SSL Technology and Future Goals to Increase Market Adoption

From an industry point of view, spectral tuning for high efficacy and high CRI is crucial. CREE is leading the industry in warm white LED performance. The goal is to achieve a luminaire efficacy of radiation of 360 lm/W and a CRI above 90. Using a narrow red spectrum will reduce wasted light. Mixing yellow shifted blue LEDs with the red LEDs affords a reasonably efficient narrow red, no Stokes loss and a 20% advantage towards the luminaire efficacy of radiation goal. However red LEDs are not particularly efficient. 150 lumens per watt is achievable today using a low current density but lower current densities mean higher costs. BES should be targeting an efficacy of 150 or higher. Novel spectral materials are needed to obtain 360 lm/W and a CRI over 90 for blue pumped warm white led packages. Other needs are ease of product integration, 50,000 hour reliability under operation and low cost LEDs compared to other products on market. Cost and economics of SSL are critical.

Pallab Bhattacharya

Quantum Dot and Nanowire Green LEDs and Lasers

Quantum dots (QDs) have many advantages. They can provide better e-h overlap and reduced radiative lifetimes compared to InGaN quantum wells. They also have lower density of structural defects due to a built-in strain field. The localization of carriers in quantum dots inhibits non-radiative recombination with surrounding dislocations. QDs are formed from strain relaxation of the InGaN layer, thus the piezoelectric polarization effects are weakened and quantum-confined Stark effects are reduced. Carrier density is higher due to smaller wells and higher time for recombination. Auger recombination and carrier leakage are the most important contributors to droop. When low energy holes were injected into each dot layer the results were holes and electrons inhabiting every layer and a narrowing of the photoluminescence linewidth. Catalyst free MBE GaN/InGaN nanowire LEDs grown with the c-axis parallel to the direction of growth featured very low defect densities and reduced Auger coefficients. LEDs based on these nanowires showed minimal blue shift with excitation, were absent of defects and had no hard efficiency roll-off.

Dan Dapkus

GaN Nanostructure LED Research

For GaN LEDs, efficiency decreases with increasing injection current and efficiency droop is a significant problem especially with green LEDs. The GaN bond contains a strong polar component. Since the lattice constant of InGaN is strongly dependent on Indium content, quantum wells are inevitably strained leading to strong piezoelectric fields. The strong polarization and piezoelectric fields in InGaN quantum wells distort the well shape and reduce efficiency for wide wells. Narrow wells inefficiently capture electrons and lead to inhomogeneous filling of the wells and carrier leakage. High carrier density in wells leads to enhanced non-radiative recombination at high currents, which leads to efficiency droop. A possible solution is to grow nanorods with non-polar facets to create strain relaxation. InGaN/GaN quantum wells can be grown on these non-polar GaN planes to reduce or eliminate the piezoelectric field inside the quantum well active region. Strain relaxation in nanostructures may allow for wider wells to more efficiently capture electrons. These nanorods can be assembled vertically to create nanosheets. The InGaN active regions on vertical planes increase the effective junction area. They have wide quantum wells and lower carrier densities at a fixed current. These devices can be operated at a lower carrier density, which could potentially lower droop effects. Nanosheets show strong luminescence, and grow relatively defect free. Since these nanosheets are formed by selective area growth and grow near defect free, silicon substrate can be used. Low cost fill and printing techniques can also be employed giving these nanostructure based LED devices the potential to have a low overall cost.

Jeff Tsao

Novel emitter architectures: aiming for near-100% efficiency

Exploring novel emitter architectures that might enable ultra-high efficiency is important. Increasing efficiency is essential because in the long term the cost of light is ultimately determined by the energy put into light. Therefore higher efficiency means lower cost. There are several potential types of emitter architectures that could facilitate near 100% efficiencies. The use of lasers and stimulated emission is one possibility. Above the lasing threshold, stimulated emission dominates over spontaneous emission and carrier densities get clamped. This indicates that a non-radiative carrier recombination mechanism, like Auger recombination which kicks in at high carrier densities, might be circumvented in a laser device. Potential drawbacks of these lasers are the high cost and narrow linewidths. However, Sandia has demonstrated that narrow linewidths can have high LER without sacrificing color quality. A second option is to control spontaneous emission rates by texturing space using dielectrics or metals. The idea is to utilize the intense and localized electric fields of surface plasmon polaritons to excite electron-hole pairs and diffract the phonon excitations out into free-space radiation. Metal losses in the blue or green pose a challenge but it might be possible to do in the red. The third option is exploring non-planar non-2D structures like nanowires. Currently the only efficient GaN-based light emitter is in the blue, and is based on very low Indium content InGaN. To get to the green, yellow and, especially, the red, higher Indium content InGaN is needed at which point strain becomes a problem. With nanowires, the aspect ratios are large enough that strain can be accommodated more easily.

Jung Han

Frontiers of III-Nitride Research for Lighting

Three areas of III-Nitride research are recommended. The use of micro-cavities and VCSELs to elicit radiative transitions through a novel GaN/air DBR structure should be explored. Second, by creating InGaN nanostructures through confined and selective area growth (SAG) for long-wavelength nano-LEDs, there is the potential to reduce defects and attain further control over the amber and green wavelength range of light emission. Third, epitaxial techniques that produce device-quality semi- & non-polar GaN on sapphire should be developed.

Roberto Paiella

Plasmonic Nanostructures for Light-Emission-Efficiency Enhancement in Nitride Quantum Wells

Plasmonic nanostructures can be used to enhance the efficiency of light emission in Nitride quantum wells. When exposed to metallic nanostructures, electron-hole pairs can recombine through the electromagnetic field resonant excitation of surface plasmon polaritons and the excited SPPs can be scattered into radiation instead of being absorbed into the metal. Without plasmonic nanostructures, if the surface plasmon polaritons scattering efficiency is larger than the active layer IQE the luminescence intensity can be greater. For this method to be effective it is necessary that there be a close match between the emission wavelength and the plasmonic resonance, a close proximity between the active layer and the metallic surface and efficient surface plasmon polariton scattering. In plasmon enhanced light emission the quantum well region has stronger photoluminescence (PL) intensity which is indicative of efficient scattering. The observed variations in PL-intensity enhancement with nanoparticle diameter are the result of two competing requirements: close spectral match between the light-emitting excitons and the nanoparticle plasmonic resonances, favoring small nanoparticles and large scattering efficiency of the excited plasmonic resonances, favoring large nanoparticles. Increasing diameter means increase in photoluminescence intensity but also means resonance coupling becomes weaker (trade-off). Using lattice surface modes instead of localized resonance of particles can help resolve the tradeoff. Large plasmonic oscillations are excited in each nanoparticle by the in-phase addition of the incident light and the first-order diffracted light by the other nanoparticles (propagating in the plane of the array). The resulting resonances have two important advantages: relatively delocalized fields in the plane of the quantum wells which means more quantum well excitons they can interact with the nanoparticles can be obtained with larger nanoparticles compared to Localized Surface Plasmon Resonances(LSPRs) at similar wavelengths which means larger scattering efficiency.

Angelo Mascarenhas

Lattice mismatched phosphide alloys for color mixing white light LEDs

Currently, the most common method for color mixing white light is mixing a blue LED with green and red phosphors. In this method maximum efficiency is limited by Stokes losses and CRIs are under 92. An alternative is a four color LED approach adding amber/yellow to the mix using GaN based III-V alloys tiled together. With this method tunnel injections are not needed so each color can be independently controlled. One issue with this approach is that dislocations at each interface can develop and too many dislocations could kill the device. To control dislocation graded buffer layers can be used. With large step graded buffers, the large separation of the interfaces can reduce dislocation interactions. A quasi-continuous step graded buffer provides the same benefit as the large step buffer in addition to decreasing the number of dislocations at each interface. A second problem is the development of cladding layers. A partial solution is to change the atomic structure and symmetry of an alloy by spontaneous ordering it. The third issue is inter-valley transfer of electrons or valence transfer. To optimize the trade-off in highest achievable emission energy and emission efficiency, the composition and energy at which the direct-indirect crossover occurs should be known.

Makarand Chipalkatti

High Priority Research Challenges for LEDs in Solid State Lighting

The key challenge is to get the cost of LED light sources down so that real energy savings are accrued while simultaneously increasing functionality. Rare earth elements are in very short supply and thus very costly. Non-rare earth options for color conversion are needed. A good alternative is Cadmium-free Quantum Dots (QDs). Their advantages include tunable emission, low toxicity, narrow line width, small Stokes shift and high quantum efficiency (QE) in solution. Their problems are low external quantum efficiency (EQE) in solid composites, poor temperature dependence, degradation in air/humidity and the costs of this technology are not fully known. In addition to researching new material alternatives, technologies to improve LED manufacturing processes should also be investigated. Increasing functionality of LEDs could reduce the dollars per lumen value. Consider the concept of flexible led multi chip modules. Their integrated circuitry and material structure could increase function and add value. Their design could facilitate low-cost, high speed roll-to-roll processing and self assembly with no wire bonding. Lumen output is the big challenge for this type of LED concept. Improving efficiency should be a priority, not produce more light but to produce less heat. Heat management is a major cost element and reducing the cost per lumen is the key to accelerating LED adoption.

Jennifer Hollingsworth

"Giant" Nanocrystal Quantum Dots: A New Class of Optical Nanomaterials for Light Emission Applications

Giant quantum dots are a novel nanocrystal created at Los Alamos National Lab (LANL) by applying an ultra-thick-shell to a quantum dot core. The thick-shell facilitates manipulation of both charging and Auger recombination, in addition to impact on blinking behavior which can improve light emission. Potential issues associated with giant quantum dots include charge injection impedance by the thick outer shells and reduced quantum yields. Similar to standard quantum dots they have a tunable bandgap, narrow emission and broadband and efficient absorption. The quantum heterostructure facilitates control over exciton conversion pathways forcing charge carriers into quantum confinement. The quantum confinement effect leads to the formation of well separated energy levels with sharper density of states. The suppression of blinking in giant quantum dots is independent of surface ligands. Their thick shells also afford minimal self-absorption. The electron-hole exchange interaction that define the splitting between the bright and dark exciton states can be tuned by the growth of thick shell which lead to reduction of electron-hole spatial overlap. Using giant quantum dots as a red phosphor material you get a large Stokes shift which minimizes self re-absorption and green absorption and the thick shell affords temporal stability. Significant strides have been made toward understanding and controlling exciton which leads to photon conversion pathways at the single-quantum dot level.

Vladimir Bulovic

Colloidal quantum dot-based LEDs

Colloidal quantum dots are spectrally tunable, have stable operation and are solution processable. Current lighting technology performance is characterized by a trade-off between CRI and efficacy. This is not the case with quantum dots. In addition, they have good stability and do not darken much over time. Finally, ink-jet printing cadmium selenide (CdSe) quantum dots with metal-oxide active films minimize concern for solvent effect on LED operation. The four main mechanisms for quantum dot-LED operation are radiative energy transfer, Forster energy transfer, direct charge injection and quantum dot ionization. Using direct charge injection, voltage and brightness may fluctuate but the same voltage will produce the same luminance each time. In field-driven quantum dot ionization, voltage drop per quantum dot corresponds to the band gap energy of the quantum dot. More understanding is still needed about AC operation for quantum dot ionization and the mechanism behind direct charge injection and interfacing with quantum dots.

OLED Section

Sebastian Reineke

High brightness OLEDs for SSL

OLEDs will be viable when higher brightness (>1000cd/m^2) and high efficiency can be maintained. In phosphorescent systems, efficiency roll-off occurs at high brightness. Increasing OLED panel size can increase light output, but will simultaneously increase cost. In contrast, increasing the light output per unit area(in other words, increase efficiency) reduces the cost of the OLED per lumen output. High photoluminescent (PL) efficiency is maintained by high evenly dispersing emitting molecules. There are two main problems with aggregated emitter molecules: One is a reduction of IQE. Holes cannot reach emitting states so the concentration of holes is increased to compensate which lowers PL efficiency. The second is the creation of additional pathways for triplet-triplet annihilation (TTA). If TTA diffusion effects can be eliminated, theoretically OLEDs could be operated at 10,000 cd/m^2 without significant IQE roll-off. Investigation is needed into the nano-composition of the emission layers of fluorescent and phosphorescent OLED systems to improve luminescent yield and to gain better control of the nanostructure. Long term stability and degradation also needs to be better understood.

Franky So

Challenges in OLED Light Extraction

Light extraction is one of the greatest challenges for OLEDs. OLEDs are thin and light extraction is difficult from a film/source without a high index. A large fraction of emitted light can get trapped and lost in the ITO/organic layer and glass substrate. The ITO/organic mode is characterized by low EQE because of the low out-coupling efficiency due to the refractive index mismatch in OLEDs. There are two approaches to light extraction in general. The first, which addresses substrate modes, is simply to use a lens array or a diffuser which is relatively easy and inexpensive. Thin film guided modes within the ITO/organic layers present more of a challenge. OLED material has high resistivity so thickness is an issue. Corrugated structures can be used but light extraction highly sensitive to wavelength and angle. A Japanese company created a bubble in the high index film and was able to increase light extraction. Very efficient light operation is possible but the problem is the cost. High cost structures for OLED lighting panels and exotic approaches are not going to lead to greater commercialization. Novel, low cost approaches to the substrate issue and light extraction are required.

Gao Liu

Probe Material and Interface Changes of an OLED Device

TEM techniques have been developed to observe degradation of OLED thin films. This technique can clearly distinguish the sharp interfaces and distinct layers of a high quality OLED. Interfaces become rougher when the OLED operated to 50% of its original light output. Oxides start to develop at broken grain boundaries. Adding a fluoride layer at the interface stabilizes the device helping to improve lifetime and light emission. Improved chemistry for long life operation is the key to improving commercial devices. Further TEM characterization studies on advanced OLED structures can yield insight into stability and degradation mechanisms.

Joe Shinar

Recent Ames Laboratory Achievements & Outstanding Challenges in OLED Science & Technology

At Ames spin-coated small molecule OLEDs (SMOLEDs) have been developed and experiments showed that separating emitter layer from cathode enhances EQE. They have also had success with efficient ITO-free OLEDs fabricated on multilayered PSS polymer. A lower index of refraction, higher efficacy and smoother films are some advantages of this technique. OLEDs on chlorinated ITO have also reported very high efficiencies by increasing the work function up to 6.1 eV. Work on outcoupling enhancement using UV laser interference lithography & PDMS molded micro-lens arrays has also shown promise. Outcoupling enhancement is improved to 60% with the use of polystyrene – polyethylene glycol micro-lenses. There have been large advances for OLEDs but there still remain a number of challenges. Longer operating lifetimes and higher efficiency at high brightness is one. Outcoupling from organic to glass or other low-cost substrate is another issue.

Ralph Nuzzo

Assembly and Printing-based Fabrication Methods and Materials for Low Cost, High Performance Lighting Systems

In the application area of flexible and large area optoelectronics for displays and lighting, there are benefits and disadvantages to using thin film OLEDs. Limited lifetime and color degradation are the two largest challenges. Waste in scaling and the efficiency of utilization are also issues. Research is on solution printing of small LEDs onto substrates. Making things smaller offers advantages such as using power better and extracting light easier. It also leads to improved thermal management through greater thermal conduction and heat dissipation. With proper forms of light management there can be a reduction in cost.

Marina Kondakova

Critical areas of research for OLED-based solid-state lighting

Blue OLEDs are the critical component of any white device, so improving them is important. Lifetime and degradation are the major challenges of blue phosphorescent emitters. EQE is the largest hurdle for fluorescent blue emitters. Lower EQE is mainly the result of triplet-triplet annihilation (TTA) processes. Triplets are formed during recombination events and could be quenched at interfaces or by polar ions. The lifetime of triplet state is dependent on molecule structure. Triplet lifetime can change by a factor of 100 but the contribution of TTA is the same. Therefore although it is known that TTA contributes to inefficiency, there is not understanding on how to control it. There is a trade-off between efficiency and lifetime and voltage. A better understanding of physics will lead to the development of highly efficient blue OLEDs with optimal performance lifetimes. Advanced materials are needed for high efficiency devices. Low cost manufacturing is also important. Dopants are extremely expensive. Fast production and low cost and thermally stable materials are important for mass production.

Ian Campbell

Organic/organic interfaces in OLEDs

The highest theoretical efficiency for a phosphorescent single RGB stack is 250 lumens per watt. Currently, using the most state of the art devices, the highest efficacy is 80 lumens per watt. Light extraction is the dominant loss. Drive voltage is also limited. New materials are needed for the improvement of blue devices… can some theoretical design be useful? Tandem structures have a large number of interfaces, but there is still a lot of uncertainty about organic-organic interfaces such as what does the structure look like? There is also a lack of knowledge on the interface between electronic states. The presence of traps and formation of exciplexes at the interface is only known when they are strong, not when they are weak. The function of interface layers is important as they play a role in transport control blocking. LANL has been modeling and investigating molecular dynamics and properties which are relevant for solid state devices.

Jie Liu

Improving light extraction efficiency through OLED material optimization

Light extraction is extremely important for all OLEDs no matter of material or process. Some of the light in trapped in the substrate can be redirected to air using external light extraction films. Within the OLED materials plasmon losses, emission quenching, and losses within the metallic cathodes are related. Caution should be taken when using enhancement factors to classify films. To reduce or eliminate plasmon losses means a gain in enhancement of factor of 1.5 (1.5X increase in efficiency). There are a couple solutions but the most practical one currently is using a thicker ETL layer which in effect increases the distance from emitter to cathode. It works in some degree because thicker layers reduce plasmon losses but substrate losses are increased. The other problem is more layers are more costly. Preferential dipole orientation is another option for conjugate polymer and small molecules in particular.

Ching Tang

Pathways for Blue PhOLED Efficiency and Lifetime Improvements: Emitter materials design, Layer architecture design

Blue phosphorescent OLED efficiency and lifetime needs improvement. This can be achieved through emitter material and/or layer architecture design. Color, luminous efficacy, and lifetime are dependent on emitter layer structure and most importantly the transport layer composition. Blue OLED lifetime is critically dependent on the electron transport layer material selection. The largest costs are associated with the hole transport host materials. Carbazoles are preferred blue host materials. Many blue phosphorescent dopants have a fluorine base which leads to problems with purity and instability. But adding an electron donor-acceptor moiety to a generic structure can produce a very stable blue material. For designing dopant host and transport material, there are three basic junction architectures. Hetero and uniformly mixed junctions lead to sharp HTL/ETL interfaces on either side of the EML which cause charge buildup. A linearly graded mixed junction will eliminate the interfaces improving stability, luminance and lifetime.

Mike Hack

Phosphorescent OLEDs for “Green” Energy Efficient Solid State Lighting

Lifetime and efficiency are the key issues with white phosphorescent OLEDs today. Studying OLED lifetime is difficult without state of the art devices. LER is an area that needs much improvement. Any improvement will probably come from work on emitters. Current IQE is 85% at 1000 cd/m^2 while the goal is 95% at 3000 cd/m^2. Increased voltage at higher lumen output has a larger effect on efficiency drop than current roll off or increased brightness. Electrical efficiency needs to be increased to 90%. Out-coupling efficiency is the low hanging fruit. An improvement from the current 40% out-coupling efficiency will be a significant contribution. Improvements must be made without adding thickness to the device so cost effective thin out-coupling solutions are needed.

Russell Holmes

Scientific challenges for OLED SSL - Opportunities in Engineering Device Architecture

A better understanding of engineering OLED architecture is needed. It would be ideal to reduce complexity and reduce some layers without losing functionality as OLEDS have become extremely complex with the aims of reaching higher efficiencies. Simplifying host materials to a single layer by better understanding how spatial composition affects performance is an example. In the double emissive layer approach the two materials have high hole and high electron mobility getting good excitation at interface with charge confinement. A mixed emissive layer approach allows for a large interface area between hole and electron transport materials. This helps reduce charge buildup which could help improve lifetime and charge roll off. There are other directions besides the multi-layer architecture approach to be explored. It is not necessarily the most optimal one. The graded approach allows higher efficiencies. Single-layer graded emissive layer architecture enables lower carrier leakage and more control over exciton formation and recombination zones. It is important to investigate how changes in architecture impact lifetime and roll off. Exploring these options will help us select the optimum architecture.

Mike Lu

Realizing the Upper Limit in OLED Efficiency

Light extraction is a challenge in reaching the upper theoretical limit of efficiency and has the most room for improvement. The 70% upper limit, which may not even be realizable, necessitates looking into surface plasmons. Another area with room for improvement is electrical efficiency, specifically high conductivity layers, efficiency roll off, and reducing stokes loss. These gains are needed without having chromatic shifts and angular dependence of color. 4500 candelas per meter squared of luminance is the upper limit without causing glare. This is important to consider when thinking about luminaire design and its role in cost and efficiency. A very efficacious panel will be lower in costs but the other implications of this design need to be considered.

Zakya Kafafi

OLEDs and Plasmonics for Solid State Lighting

Currently the theoretical limit of IQE for a fluorescent emitter without doping is achievable. Another challenge is increasing the light output coupling factor. IQE for OLEDs is close to theoretical limit but EQE needs improvement. To improve light emitting factors, periodic nanostructures have been proposed to help eliminate loss from surface plasmons. For example, for organic PV cells absorption, current density, and efficiency of the device have shown improvement by adding nanoholes and a metal alloy cathode to the plasmonic structure. Similarly, for OLEDs plasmonic structures with nanoholes could reduce losses due to surface plasmons, improving the efficiency of the device. Improving light emission using plasmonic structures is the main theme.

Asanga Padmaperuma

Predicting molecular degradation and charge transport in amorphous organic solids

Predicting structure-property relationships to enable energy savings is important. OLED goals focus on maximizing efficiency and stability while minimizing cost. Computational work is also a big part such as predicting geometry and electronic structure. Predicting the electronic structure of a solid is not possible so how can charge transport be predicted? The idea is to predict molecular structure that leads to desired properties in solid phase accompanied by experimental confirmation. OLEDs are very sensitive systems. An enhanced understanding of chemistry is needed to understand and predict degradation.