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Lighting R&D Program:

LED Materials and Devices R&D Meeting

October 2020

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DOE Lighting R&D Program, "LED Materials and Devices R&D Meeting," October 2020.

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Comments

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1 Introduction

On August 25 & 26, 2020, twenty experts on light emitting diode (LED) based lighting gathered at the invitation of the Department of Energy (DOE) Lighting R&D Program to help identify critical research and development (R&D) topic areas for both LED materials and devices, including down-converters and packaging. This small group discussion meeting is one forum for experts to provide technical input to the DOE Lighting R&D Program. The DOE Lighting R&D Program also collects inputs from stakeholders at the annual Lighting R&D Workshop, via a Lighting R&D Request for Information (RFI), and other means. The guidance provided by stakeholders in these various forums helps identify critical R&D areas which may be incorporated into DOE's technical roadmaps.

This year, for the first time, the meeting was held virtually due to travel difficulties and concerns related to the ongoing COVID-19 pandemic. The meeting commenced with "soapbox" presentations where each participant was invited to give a short presentation describing what they believed to be the key technology challenges for solid state lighting (SSL) over the next three to five years. This was followed by a general discussion of the most critical technology challenges facing the industry today. Following these discussions, the participants were asked to contribute ideas regarding program content for the upcoming R&D Workshop to be held February 1-4, 2021.

The meeting format provided an opportunity for LED experts across the research spectrum to exchange ideas and explore collaborative research concepts. Participants included invited experts in LED-relevant science and technology disciplines drawn from academia, National Laboratories, and industry. They included DOE-Lighting R&D-funded researchers and non-DOE-funded researchers.

This report summarizes the outcome of the discussions on critical technology challenges and identifies corresponding R&D tasks. Outlines of the participants' soapbox presentations and related remarks are included in Appendix A of the report.

1.1 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 research areas that could lead to significant breakthroughs in SSL performance. These themes are as follows and are outlined in more detail in Section 2:

- Longer Wavelength LEDs
- Materials Discovery
- Micro-LEDs
- Tunnel Junctions
- Down-Converters
- Encapsulants

2 Critical R&D Topic Areas

2.1 Longer Wavelength LEDs

Considerable improvements in green and amber LED efficiency are needed to unlock the full potential of color-mixed LED lighting architectures and move beyond the performance limits inherent with phosphor-converted white LEDs. The level of understanding of the mechanisms that limit performance in longer wavelength InGaN LEDs continues to make major progress. Fundamental performance differences between the blue and green LEDs are caused by larger polarization charges and carrier transport barriers at longer wavelengths. These polarization-induced barriers at the InGaN/GaN quantum well (QW) and barrier interface leads to sequential filling of the QWs and contributes to large forward voltage in multiple quantum well (MQW) green LEDs. There is an opportunity to improve power conversion efficiency via volumetric injection into the MQW active region using “V-defects” to bypass the voltage barriers suffered by the normal injection of carrier vertically into the QWs. Additionally, there is the opportunity to engineer the QWs to increase the radiative recombination rate relative to Auger recombination rate.

Prospects for improving the performance of AlGaInP LEDs for the amber and red wavelengths were also discussed. The challenges for this material system include a diminishing internal quantum efficiency at shorter wavelengths due to the lack of current confinement as it approaches the indirect band gap crossover energy, and the low extraction efficiency due to the higher index of refraction. Recent R&D results show that tensile-strain barriers can be used to overcome the limited carrier confinement in lattice-matched AlInGaP in amber wavelength and provide more design freedom to optimize the structure for performance. Pursuing this avenue of research requires combined efforts in material growth (defects), strain engineering, and device design. Participants discussed the opportunity to leverage knowledge in other technology areas such as III-V multi-junction solar cells, which have made progress on the foundation of semiconductor materials control, to inform a path forward for improving LED efficiency and thermal performance with AlGaInP materials.

2.2 Materials Discovery

While potential R&D pathways were clearly recognized for improving LEDs with conventional III-V semiconductor materials, further research into new materials beyond InGaN and AlGaInP may be necessary for additional improvements in the yellow/amber and red wavelengths. There are many less-studied materials that can be integrated with GaN (or AlN). II-IV-nitrides are one family of possibilities being explored; other candidates include the addition of boron into InGaN to reduce the lattice mismatch to GaN, or adding antimony into GaN to reduce the bandgap. These and other ternary nitride compounds can be realized by heteroepitaxial integration on GaN, but there may also be the possibility to use polycrystalline materials or other substrates such as silicon. In addition, the exploration of new materials, as well as the relationship between modeled performance and experimental results, can enable advancements in understanding and performance of conventional LED materials and devices.

Materials discovery is hard to predict, and participants discussed the challenges with identifying new materials and their applicability to SSL. A new materials checklist rule of thumb was proposed to recognize key factors that can help distinguish contenders for LED emitters. Knowing the band gap range, band offsets, alloy and dopant possibilities, and polarization effects are important to realize the potential of the material for device architectures. Another major consideration is determining if the material quality and synthesis possibilities are amenable for bright emission and whether it can be improved or if there are fundamental limits. Once known compounds are classified to have met the criteria required for the applications, then the materials design process begins with the development of composition-gradient thin-film synthesis and fine tuning of properties – often by alloying. Finally, when existing materials candidates do not provide a pathway to meeting the required properties, the computational materials discovery approach may yield new options to explore.

2.3 Micro-LEDs

Micro-LEDs are being developed to improve brightness, high dynamic range, color gamut, and energy efficiency of next generation display technology. While display applications are currently driving the R&D, these small LED device form factors are being considered for illumination applications for their ability to offer improved directional lighting and new lighting functions using adaptive pixels for wayfinding, emergency lighting, and information display. Critical to implementation in either lighting or displays, the micro-LED performance needs to improve to meet the applications requirements and enable greater energy savings.

As the LED device dimensions shrink, the LED efficiency decreases in both InGaN and AlGaInP material systems. This effect is driven by the fact that perimeter to area ratio increases, allowing carriers to reach defects at the device sidewalls and recombine nonradiatively. The efficiency falloff with LED size reduction is especially pronounced for AlGaInP material system, where surface recombination velocities are an order of magnitude higher than for InGaN. This has led to a 'red gap' in the micro-LED space where both AlGaInP and InGaN are inefficient for red micro-LEDs. In addition, these small devices operate at much higher current densities making current density droop an important consideration in device performance. Technology investment is required to further study and mitigate the efficiency reduction that arises as a consequence of die miniaturization. Advances in device processing, characterization, epitaxial growth should be explored. Additionally, manufacturing developments in the display industry should be leveraged for micro-LED lighting in terms of die testing, die transfer, circuit designs, and control schemes.

2.4 Tunnel Junctions

Tunnel junctions have been implemented in optoelectronic devices in conventional III-V semiconductors, but they are not yet used in mass production of III-nitride devices to due high excess voltages because of the challenges with p-type doping and activation in metal-organic chemical vapor deposition (MOCVD) grown tunnel junctions. Tunnel junctions can be used to improve the current spreading limitations of p-type GaN in LED structures, and also can enable novel device structures like the cascaded multi-junction LEDs to mitigate the impact of current density droop in LEDs by scaling output power at low current densities. The performance of MOCVD tunnel junctions has improved considerably over the past few years leading to smaller excess voltages of approximately 0.2 V that make a cascaded multi-junction LED structure more feasible. New innovations in the implementation of tunnel junctions have also been realized, such as selective area growth (SAG) of tunnel junctions in a micro-LED scale device. This has led to more size-independent micro-LED voltages than experienced with traditional contacts or tunnel junctions. The breakthroughs of achieving a low voltage penalty for an all MOCVD-grown tunnel junction provides an opportunity to employ new LED device structures aimed at improving LED efficiency at a broader range of operating conditions.

2.5 Down-converters

Phosphors

Advances in phosphor materials R&D continue to target different spectral needs in applications such as lighting for human health, horticulture, and displays. Participants highlighted the on-going work for developing phosphors that can emit at specific regions of the spectrum including the cyan region for impacting circadian responses and alerting effects, and the far-red region for horticulture. Moreover, display trends are driving phosphor research towards narrow-band green phosphors and particle size reduction for use with micro-LEDs. As the industry moves towards LED miniaturization for lighting applications, R&D is needed to shrink the size scale of phosphor particles to submicron levels without impacting efficiency or environmental stability. Some of this work is occurring in phosphor R&D for displays, but other spectral regions and phosphor spectral widths will be necessary to optimize for the color quality requirements in lighting applications.

Additional R&D opportunities include 1) particle coating development that can expand the design space for phosphors to meet maintenance and reliability requirements at higher drive currents (red phosphors are vulnerable in humid conditions); and 2) computational techniques (e.g., machine learning) for new material discovery. Participants reminded DOE of the 8-10 year innovation time scale for previous phosphor materials innovations, such as the development of KSF with the performance and stability requirements for lighting and display applications. They cautioned that new materials development work can be in this same 8+ year time scale and sustained R&D effort is required.

Quantum Dots

Quantum dots (QDs) continue to progress rapidly for their use as wavelength down-converters, as evidenced by the availability of LED products with on-chip QDs. CdSe-based QDs have made great progress in improving environmental stability to withstand the flux and thermal stressors in the LED package. Photoluminescent quantum yield (PLQY) and reliability are highly dependent on the surface layer and barrier coating, encapsulation, and the barrier coating/QD interface. More development work is needed on coatings and encapsulation to allow QDs to be used in a wider range of LED operating conditions and lighting applications.

While CdSe-based QDs can provide state of the art performance, the use of cadmium (Cd) in electronic devices is regulated by the European Union (EU) under the Restriction of Hazardous Substances (RoHS) Directive. This regulation provides an opportunity to improve the performance of Cd-free QDs like the InP materials system. InP QDs are heavily used in displays, but require improvements in the flux and thermal stability to make them viable for on-chip LED application. Participants advised DOE to consider progress over a longer timescale for new QD materials developments and implementation in products, similar to the timescale discussed above with the KSF phosphors.

For LED products incorporating QDs, a combination of phosphors and Cd-based QDs are implemented in the package to improve efficacy at higher color quality and stay below the Cd limit. This combination opens up an opportunity for engineering new phosphors + QD systems that offers a new degree of freedom in LED down-converter design. Combining QDs with phosphors can provide unique solution level benefits such as fine tuning the spectrum for efficiency improvements or creating more temperature stable light emission at varying temperatures.

2.6 Encapsulants

The properties of the encapsulant have a strong impact on the thermal and optical properties of an LED package. The low thermal conductivity of current silicone encapsulants can lead to heating of phosphor particles and rapid degradation of phosphor conversion efficiency when the LED is operated under high current conditions. In addition, silicone materials can discolor and breakdown, thus limiting their lifetime and the lifetime of the LED under high photothermal stress. Increasing refraction index of silicones can enable better light extraction but comes with the tradeoff of a lower gas permeability and transparency after aging.

R&D is needed in new materials or additives that can improve the thermal conductivity and photothermal stability of LED encapsulants. Current encapsulants are limiting the amount of light output power out of the LED package. Advancements in encapsulants could enable a much higher light output from each package, thus strongly impacting the cost of LED lighting. A better understanding of interactions of the encapsulant with the package, within the phosphor composite, and with aging can lead to better designs. Better control of the process, including the degree of cure and stress build up/relief, can help define proper lifetime estimates. Improved material stability correlation with accelerating testing can help shorten the development cycle. Attendees discussed improvements to conventional silicone encapsulants and the possibility of developing other materials systems such as glass encapsulants. The big challenge with further innovation is obtaining sufficient R&D investment to improve the long-term quality of the product. Funding from DOE is important to help fill this gap of R&D investment (long development cycles with a hard to quantify payoff).

3 Suggestions for the DOE Lighting R&D Workshop

The 2021 Lighting R&D Workshop, which is to be held February 1-4, 2021, offers another opportunity to continue the discussion on critical R&D challenges. Another goal of this R&D meeting was therefore to gather input and suggestions for suitable topics and speakers, and ideas for panel discussions. Participants suggested the following topics:

1. Display technology, display energy efficiency, and display eye safety.
2. UV-LEDs and germicidal UV lighting for disinfection.

Appendix A: Participant Presentations

Jim Speck, University of California Santa Barbara: V-Defects for Low VF Green LEDs, and Polarization Field Screening

Jim Speck, Seoul Viosys Distinguished Professor of Materials at UC Santa Barbara, discussed carrier transport mechanisms in green LEDs. Their work on a funded DOE Lighting R&D project found that polarization induced barriers at the GaN/InGaN (lower barrier/QW) interface and sequential filling of QWs contributes to the large excess voltage in MQW green LEDs. His team is exploring a ‘V-defect’ engineering approach for volumetric injection of carriers into the active region using the semipolar sidewall of the QWs with low polarization barriers. This can improve hole injection into the deeper QWs (n-side) and the resulting LED forward voltage. He also highlighted findings using polarization screened QWs in LEDs to improve external quantum efficiency (EQE).

Rob Armitage, Lumileds: Efficient Green and Yellow LEDs for Solid State Lighting Applications

Rob Armitage, Senior Staff Development Engineer at Lumileds, highlighted the need for large improvements in green LED efficiency to make color mixing competitive in efficacy and how efficient yellow/amber emitters are further required for high color rendering index (CRI) lighting systems. He discussed the approaches of the DOE Lighting R&D project at Lumileds for improving green and yellow LED efficiency with epitaxy optimization. The project team will use predictive modeling to suggest experiments to improve the radiative/Auger recombination balance and characterization techniques to provide specific and actionable learning for different LED designs. Furthermore, new device structures such as cascaded LEDs will be explored on the project.

Manos Kioupakis, University of Michigan: New Nitride Alloys for Efficient Light Emission

Manos Kioupakis, Associate Professor in the Department of Materials Science and Engineering at the University of Michigan, explained the origin of efficiency droop, which is due to indirect Auger recombination, compounded in the green wavelengths by polarization fields and localization. He then discussed how these difficulties might be circumvented by implementing thicker QWs while avoiding the complications of lattice mismatch. The addition of boron into InGaN reduces the lattice mismatch with GaN, allowing for thicker QWs; boron does not increase the bandgap, so it allows for the luminescence in the visible spectrum. Another approach he proposed was exploring dilute $GaN_{1-x}Sb_x$ alloys where the introduction of <1% Sb into GaN dramatically reduces the bandgap, thus enabling luminescence in the visible range while preserving lattice matching. This system is a more ordered material than InGaN so a reduced Auger recombination would be expected.

Andrew Armstrong, Sandia National Laboratories: Solving Current Droop Via Cascaded Multi-Junction LEDs

Andrew Armstrong, Senior Member of the Technical Staff in the Semiconductor Material and Devices Sciences Department at Sandia National Laboratories, examined cascaded MJ-LEDs as a path to circumvent efficiency droop. Stacking multiple LED junctions in an LED allows the improvement of wall plug efficiency by operating the cascaded multi-junction (MJ) LED at low current densities (where droop from Auger recombination has a minimized effect). His team has demonstrated a MJ-LED proof-of-concept device grown by MOCVD and showed that the EQE scales linearly with number of junctions up to 3 junctions. The voltage penalties of the tunnel junctions in their devices were too high for product implementation, so they will explore InGaN-based tunnel junctions to reduce the voltage penalty, while minimizing any absorption by the InGaN.

Siddharth Rajan, The Ohio State University: Ultimate Limits for Interband GaN Tunnel Junctions – Theory and Experiment

Siddharth Rajan, Professor of Electrical and Computer Engineering and Materials Science & Engineering, at The Ohio State University, discussed tunneling-based cascaded multiple active region LEDs and their ability to bypass the main issues driving current density droop – carrier overflow and Auger recombination. Significant progress has been made with MOCVD-grown tunnel junctions over the past several years. He discussed the challenges with low voltage penalty tunnel junctions (< 0.2 V) including accurate placement and timing when injecting the delta doping is critical. A current focus is on MOCVD-grown tunnel junctions, to make the tunnel junction process compatible with the MOCVD process used to grow the LED devices. His team has demonstrated state-of-art low tunnel junction voltages of 0.18 V for InGaN interlayer junction and 0.45 V for GaN homojunction at 100 A/cm^2.

Steve DenBaars University of California Santa Barbara: Development of Low Voltage Tunnel Junctions and Strain Engineering in RGB Micro-LED Devices

Steve DenBaars, Mitsubishi Distinguished Professor of Materials and of Electrical and Computer Engineering at UC Santa Barbara, described the implementation of tunnel junctions in micro-LED device structures to address current spreading and droop using an innovative MOCVD-based selective area growth (SAG) of the tunnel junctions. An SiO_2 mask was patterned on the LED structure to allow for the growth of the tunnel junction in pillars. When the SiO_2 is removed, the tunnel junction grown by SAG technology enables the removal of hydrogen (which passivates the p-type Mg dopants) through the aperture on top of the p-GaN layer. The current spreading in micro-LEDs with SAG tunnel junctions was more uniform than with conventional tunnel junctions and led to size-independent forward voltage in micro-LEDs.

John Whiteman, Plessey Semiconductors: Demands Display Requirements Place on Micro-LEDs

John Whiteman, the Senior Vice President of Development at Plessey, discussed the performance and implementations challenges with micro-LEDs. He highlighted the display requirements of pixel size, frame rate, individual pixel brightness control with dynamic range and duty cycle, and the requirement for deep sub-micron CMOS backplanes. Micro-LEDs need to be cost competitive with liquid crystal display (LCD) + quantum dots LED (QLED), and OLED displays, demanding cost reductions available from larger size growth substrates. He then detailed the performance trends in micro-LEDs. InGaN on silicon shows reduced peak EQE and higher current density with reducing LED size. This is due to the increasing perimeter to area ratio with smaller LEDs leading to surface recombination and higher non-radiative recombination. Improving this EQE at small sizes requires optimized epitaxial structures and device processing. The green gap is negligible for very small pixels as seen in 4 micron LEDs with the blue devices showing 37% EQE and the green devices at 36%. On the other hand, there is a "red gap" for micro-LEDs. Red AlGaInP micro-LEDs on GaAs substrates see the EQE reduces rapidly below 70 µm size due to surface recombination (worse than for InGaN LEDs); InGaN red LEDs have a similar EQE ~ 2.5% at all sizes (1mm to 4um). Approaches to understand the performance cross-over for red LEDs of different sizes and material systems are needed.

Hongping Zhao, The Ohio State University: Development of II-IV-N_2 for High Performance LEDs

Hongping Zhao, Associate Professor of Electrical and Computer Engineering Associate Professor and Bertha Lamme Development Chair at The Ohio State University, discussed the implementation of II-IV-nitride semiconductors within the LED heterostructures to increase the wavelength of the InGaN LEDs to the green/amber/red regions without requiring heavy indium concentrations that can degrade performance. For example, inserting a small layer of $ZnGeN_2$ can change the emission wavelength of InGaN LEDs by greater than 100 nm with the same indium composition. The exact position of the layer in QW impacts how much the wavelength is altered. The growth of these II-IV-nitrides is compatible with InGaN though requires a dual-chamber MOCVD reactor – one chamber for each of the two materials.

Stephan Lany, National Renewable Energy Laboratory: Discovery and Design of Ternary Nitrides with Potential for LED Application

Stephan Lany, a computational materials scientist of the National Renewable Energy Laboratory, explained the processes of materials discovery and materials design and its function in specific applications such as LED emitter materials. He identified several potential new ternary nitride compounds for SSL use including

$ZnGeN_2$ and $MgSnN_2$. Next, he addressed the design approach process by discussing band gap engineering using alloys; ZnSnN2:ZnO shows short range order impact on the electronic structure and localization effect; $ZnGeN_2$/GaN interfaces show the effect of polarization and disorder.

Adele Tamboli, National Renewable Energy Laboratory: Discovering New Emitters for Solid State Lighting

Adele Tamboli, a researcher at the National Renewable Energy Laboratory, stated the need for a full suite of emitter materials – from the UV to the IR – which requires more materials to supplement existing semiconductor solutions. She identified the opportunities to explore many less-studied nitride materials that can be integrated with GaN (or AlN). She also proposed a new materials checklist to ensure the right characteristics are being classified in potential candidates including band gap range, band offsets, and polarization (all three will determine device architecture). Another important question to answer is if the material quality is sufficient for bright emission, if it can be improved, or if there are fundamental limits to material quality.

Kirstin Alberi, National Renewable Energy Laboratory: Red and Amber LEDs, Leveraging capabilities for Improvements

Kirstin Alberi, a researcher at the National Renewable Energy Laboratory, considered the progress and challenges of red and amber emitter materials. Recent progress in red LEDs has been made through improvements in the emitter materials and other device components, but additional approaches are needed to overcome fundamental loss mechanisms that limit device performance at amber wavelengths. She highlighted the opportunity in learning from the adjacent photovoltaic (PV) industry whose III-V multi-junction solar cells have advanced on the foundation of semiconductor materials control (epitaxy, compositional homogeneity, doping, non-radiative recombination centers, access to lattice-mismatched compositions, extended defects, tunnel junctions, and device design). Areas for leveraging semiconductor knowledge and capabilities from PV to improve AlGaInP based red and amber emitters include: developing better material control during epitaxy, understanding loss mechanisms, better close-coupling between epitaxy and characterization, access of desired compositions through lattice-mismatched growth, alternative perspectives on device design, and computational capabilities to understand electronic structure, defects, etc.

Ted Chung, Lumileds: AlInGaP Epi for Direct Red & Amber LEDs

Ted Chung, Senior Manager AlInGaP epi group at Lumileds, expounded on the AlInGaP emitter performance challenges for red and amber LEDs. This materials system exhibits an efficiency drop at shorter wavelengths (amber region) due to low internal extraction efficiency (IQE) when approaching direct-indirect bandgap region, and the low extraction efficiency due to the high refractive index and low IQE limiting the photon-recycling effect. Another fundamental issue is the thermal sensitivity of the emitter materials due to the IQE droop from lack of carrier confinement as it gets closer to indirect band (shorter wavelengths). Lumileds' DOE funded project to address these challenges found that tensile-strain barriers can be used to overcome the limited carrier confinement in lattice-matched AlInGaP in amber wavelengths. This provides more design freedom to optimize the structure for performance, but it requires combined efforts in material growth (defects), strain engineering, and device design. He also emphasized that the markets do not incentivize the required R&D investment in amber and red LEDs to reach DOE SSL goals, but instead prioritize efforts in blue LEDs for the phosphor-converted white LED solution. He stressed that DOE R&D investment is required to increase red and amber efficiency for high efficacy SSL systems based on color mixing.

Jim Murphy, GE Research: Phosphors for Next Generation Solid-State Lighting/Displays

Jim Murphy, a Senior Scientist at GE Research, considered the phosphor technology crossover between the display and lighting industries. He highlighted three color conversion trends for the display industry that are relevant to SSL. The first trend presented was narrow band phosphors for higher color gamut for displays, but relevant to SSL for higher luminous efficacy while maintaining color quality. The second trend was display size diversity hence smaller LEDs and smaller phosphor grain sizes. The third trend was the increasing importance of physiological responses such as circadian response, which is important both for displays and for SSL. He recommended DOE should invest in submicron phosphors and/or QDs development to combine with blue micro-LEDs and that investment around optimization and reliability (coating development) is especially needed. He also asked whether DOE should consider funding or studying display power consumption, color quality, and physiological response.

Erik Swenson, Nichia: Novel Color/Spectral Tunable LED Solution to Balance Circadian Rhythms

Erik Swenson, General Manager of Nichia America Corporation, discussed the idea of pursuing ideal light sources by pointing out how the spectral content of LEDs was optimized to target different lighting applications like museum or retail lighting, horticultural lighting, and lighting for health and well-being. He noted that most phosphor-converted LEDs do not have a strong cyan spectral contribution, though it is an important wavelength range to stimulate responses for the circadian system. A new SAE phosphor (strontium aluminate doped with europium) is being implemented with a cyan luminescence that closely matches the spectral sensitivity of the intrinsically photosensitive retinal ganglion cells (ipRGCs). Combining the SAE phosphor with a white tunable LED allows a spectrally tunable solution that can adjust the blue-green component to help balance human circadian rhythm, while also balancing other key metrics like efficacy and CRI.

Bill Cohen, GE Current, a Daintree company: Phosphors for General Illumination

Bill Cohen, the Specialty Materials Business Leader at GE Current, a Daintree company, reviewed the benefits of using the narrow-band red KSF phosphor which provides a more efficacious solution at improved color quality. He addressed the value of developing a narrow-band green phosphor to improve efficacy, but noted that it cannot be too narrow, or it will be detrimental to desired color performance in lighting applications. He also recognized an opportunity to develop phosphors for far-red emission required in horticultural lighting.

Jonathan Owen, Columbia University: Downconversion Using QDs “On Chip”

Jonathan Owen, an Associate Professor of Chemistry at Columbia University, highlighted the benefits of a narrow-band QD down converter to LED performance. He showed examples of how replacing a conventional red phosphor with a red QD can improve the luminous efficacy of an LED with CRI 90 by 25%. That large efficacy jump has motivated research into QDs as down-converters for LEDs. While the spectral performance boost is undeniable, the environmental stability has limited QD implementation into LED packages. PLQY and reliability are highly dependent on surface layer and barrier coating, encapsulation, and the barrier coating/QD interface. Better barrier layers must be developed to electronically passivate the QD surface, provide moisture barrier, ion-barrier, and pH buffer, in order for QDs to be better utilized in LED packages for lighting applications.

Juanita Kurtin, OSRAM Opto Semiconductors: Combining Phosphors and Quantum Dots: On-chip Operation and Solution Tailoring

Juanita Kurtin, the Director of Materials Research at OSRAM Opto Semiconductors, discussed the benefits of combining phosphors and QDs in a hybrid solution to help narrow the overall emission linewidth while maintaining the reliability and cost benefit of phosphors. Tuning the phosphor emission peak in tandem with the QD peak helps fine tune the spectral range and put more photons into the optimum areas (more overlap with the human eye response) and put less photons in the deep red to reach higher efficacies. Additionally, the combination of phosphors and QDs can be used for creating a more temperature stable LED emission by balancing the red shift of the QD and LED at higher temperatures to the blue shift of the phosphor with increasing temperature. Tailoring the right combination of phosphors and QDs offers a new degree of freedom in solution design which can drive higher performing LED solutions. She advocated that research on both down-converter technologies should continue to be pursued.

Ruiqing (Ray) Ma, Nanosys: Cd-Free QD Optical Down-Converters for LED Lighting: Narrow Red and Cyan

Ray Ma, Senior Director at Nanosys, talked about the challenges of developing Cd-free QDs that can withstand the operating conditions of on-chip integration. The QD stressors include temperature and flux density. The ability to withstand higher temperatures has improved faster for InP QDs than the progress in withstanding higher optical flux densities. As the flux density increases for InP QDs, the biexciton emission takes over from the single-exciton making it the dominant mechanism for an on-chip architecture. He also discussed the opportunity to develop cyan QDs to fill a gap in spectrum from 480-520 nm common in phosphor converted white LEDs. Multiple QD material systems are available to address the cyan region including InP, InGaP, and ZnTe, though they face the same challenges with stability as green or red QDs.

Gregoire Denis, Lumileds: Silicones & Beyond

Gregoire Denis, Director of the Phosphor and Converter team at Lumileds, reviewed the state of the art in silicone materials, which are ubiquitous in LEDs in phosphor particle binders, ceramic platelet attach, side-coats, dome materials, and underfill materials. The properties of the silicone materials change with the R-group (functional group), molecular weight, cross-linking, catalysts and additives. There are trade-offs, though, with the different R-groups. Methyl-based silicones have lower refractive index than phenyl-based silicones, but they also have a higher gas permeability and better aging robustness. He then discussed pathways to quality improvement including understanding the key interactions with the package and phosphor composite, the influence of the process (e.g., degree of cure, stress build up and release), and improving accelerated testing correlation to LED reliability. He asked, “Can we understand how to ‘fail faster’ to run through more experiments?” Silicones are still on the learning curve of the performance/quality trade off and investment is needed to develop the long-term quality of silicone materials. The amount of investment in R&D from the market is minimal since the volume of silicone materials sold are not high enough to drive the chemical industry into R&D for this application, despite the leverage being very high in terms of LED performance and reliability.

Rajiv Pathak, Lumileds: Mini-LED Application View

Rajiv Pathak, Director of Die Technology Development at Lumileds, discussed benefits of using smaller LEDs in lighting. Mini and micro-LEDs can improve directional lighting by allowing for dynamic beam shaping, low glare, a thin form factor, and better color mixing. They also enable lighting systems with new functionality like basic projection display for way finding, emergency lighting and information display. He illustrated the differences between a micro-LED for display and a micro-LED for lighting. A lighting system requires higher lumen output and efficacy compared to displays; the spectral requirements are also different with the displays maximizing color gamut, whereas illumination systems are designed for color rendering. As LED device dimensions shrink, the perimeter to area ratio increases resulting in EQE decreases in both InGaN and AlInGaP material systems. The reduction in EQE is especially pronounced for AlInGaP material system where surface recombination velocities are an order of magnitude higher than for the InGaN material system. Technology investment is required to further investigate and mitigate the reduction in efficiency that arises as a consequence of die miniaturization through advances in processing (etch/dielectric), characterization, and epitaxy.

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