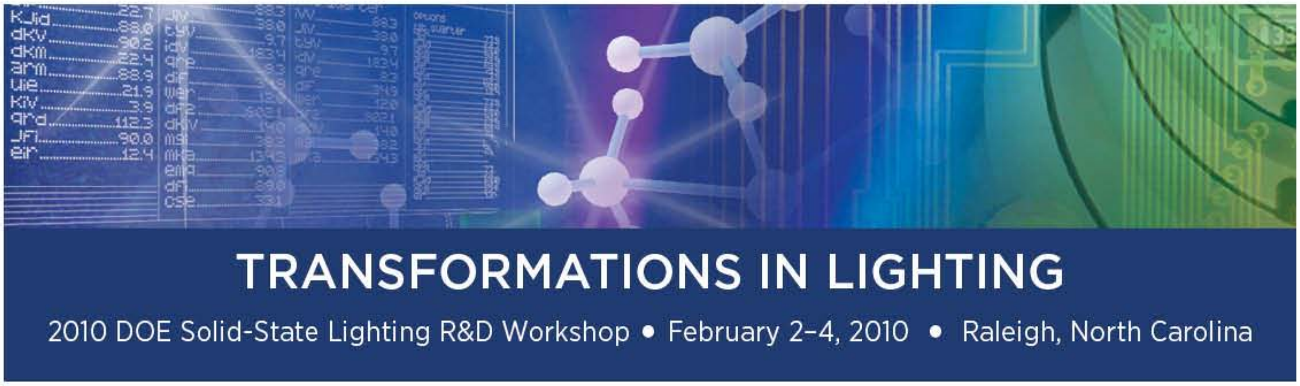

SOLID-STATE LIGHTING R&D WORKSHOP REPORT

Lighting Research and Development
Building Technologies Program
Office of Energy Efficiency and Renewable Energy
U.S. Department of Energy

March 2010

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1. Introduction

More than 350 lighting technology leaders gathered in Raleigh, North Carolina, February 2–4, 2010, to participate in the seventh annual Solid-State Lighting (SSL) R&D Workshop hosted by the U.S. Department of Energy (DOE). Researchers, manufacturers, and other industry insiders and observers joined DOE to share perspectives on the rapid evolution of SSL technology. Entitled "Transformations in Lighting," the workshop provided a forum for building partnerships and sharing strategies for continuing advances in high-efficiency, high-performance SSL technologies.

Opening plenary session of Transformations in Lighting 2010

2. Strategies for "Transformations in Lighting"

2.1 Welcome

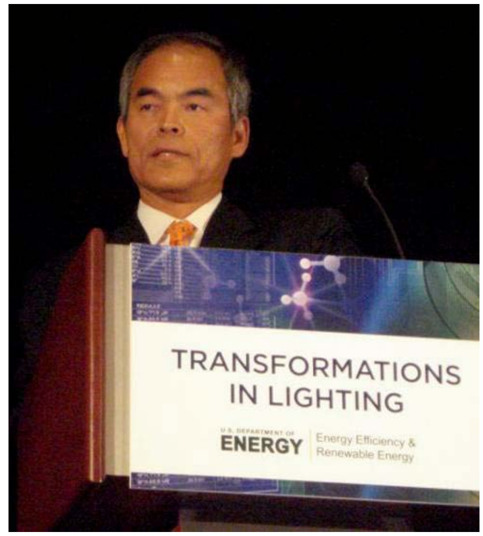
James Brodrick, U.S. Department of Energy

Brodrick kicked off Day 1 by noting the tremendous progress that's been made over the past decade, which has seen SSL evolve from a technology limited to traffic signals to one that can compete with incumbent lighting for certain applications. He observed that the easy problems have already been solved, and that today's challenges require new ways to climb whatever "wall" stands in the way. Brodrick framed the two questions that would serve as the workshop's main themes: "What are the limits of SSL?" and "How can we overcome them?"

2.2 What Are the Limits of SSL?

Shuji Nakamura, University of California, Santa Barbara

In his keynote talk, Nakamura answered the questions Brodrick posed by reviewing the multiple threads being explored in the UCSB laboratories. Nakamura described how he and his team are working to better understand the green gap issue, prevent efficiency droop, improve extraction efficiency, develop high quantum efficiency phosphors, and explore bulk growth of GaN. He said it will take improvements in all of these areas to achieve the full energy-saving potential of SSL. Nakamura noted that while DOE's current efficacy target is 200 lm/W for LED devices, he and his team feel that 250 lm/W is feasible and are aiming that high.



Keynote Speaker Shuji Nakamura

2.3 A Fresh Look at Priorities – The DOE SSL R&D Multi-Year Plan

Fred Welsh, Radcliffe Advisors

Welsh previewed the proposed updates to the DOE SSL R&D Multi-Year Program Plan (MYPP), which include more information on price targets and progress, clarification of some of the tasks and metrics, reprioritization based on needs and progress, and coordination with DOE's manufacturing initiative.

3. Panel 1: The Limits of Efficacy

Christian Wetzel of Rensselaer Polytechnic Institute examined how eliminating defects can improve LED efficiency. Focusing on avoiding efficiency droop in green LEDs, he explained how improving the metal organic vapor phase epitaxy (MOVPE) processes from blue, through green, to yellow is a key to closing the "green gap," and how avoiding non-uniformity, V-defects, and impurities also plays an important role.

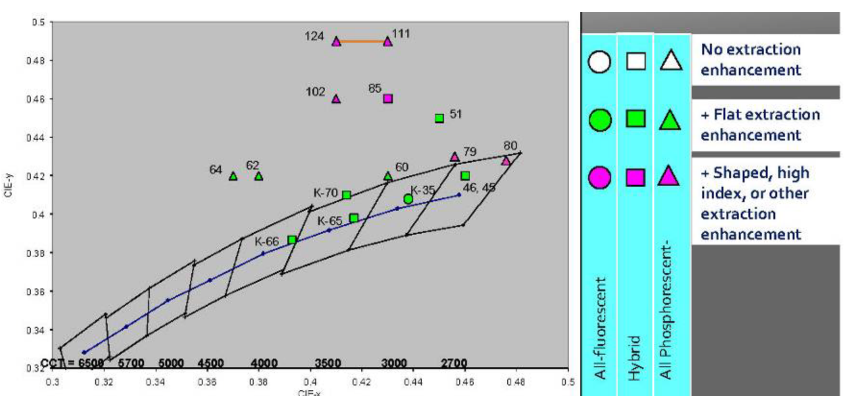
Steve Paolini of Lunera Lighting, Inc. discussed whether current packaging technology limits LED device efficacy. He concluded that it does, but only near the limit. Paolini made the point that LED packages trap light and heat, and that the two main ways to increase package efficiency are to dispose of the heat and increase the encapsulant's refractive index. He explored the question of voltage, the use of phosphors, and the issue of big chips vs. small chips, and also examined the role played by the driver, optics, and thermal resistance.

Yoshihiro Ohno of the National Institute of Standards and Technology (NIST) followed with a presentation on how improving the color spectrum can increase LED efficacy. He explained luminous efficacy and reviewed the relationship between light spectra and color quality, noting that narrow-band RGB peaks can enhance color to the point where, from an end user's perspective, it gives a reasonable approximation of sunlight. Ohno discussed the drawbacks of the color rendering index (CRI) as a metric for SSL and described a proposed new metric developed by NIST, the color quality scale (CQS), that is more appropriate for SSL than CRI.

Narrow-band RGB peaks can enhance color.

Mike Hack of Universal Display Corporation and Yuan-Sheng Tyan of Eastman Kodak Company (formerly) each discussed the barriers to developing OLEDs with an efficacy of 150 lm/W. Hack stated that while there are many challenges, he doesn't believe there are any fundamental barriers. He identified outcoupling efficiency as "the main issue with OLEDs today" but noted that UDC and Kodak have already come close to achieving the target for this, and that other targets for developing a 150 lm/W OLED are also within reach.

Tyan compared three types of state-of-the-art OLED devices: all-fluorescent, all-phosphorescent, and hybrid (see figure below). He calculated the theoretical maximum efficacy of a phosphorescent single-stack OLED and a hybrid double-stack OLED, and examined the major loss mechanisms. Tyan stated that "the first hurdle to good efficiency is to have a good blue phosphorescent system."



Efficacy of state-of-the-art OLED SSL devices

Joe Shiang of GE Global Research concluded the panel with a discussion of OLED lifetime. He made an important distinction between shelf lifetime and operating lifetime and observed that many of the pieces are in place for long OLED shelf life, but that we need more systems demonstration and integration so we can understand the whole chain. Shiang noted that while the operating lifetime of OLEDs is currently at about 20,000 hours, there is a super-linear tradeoff between lifetime and brightness, “so we need better tools to understand what goes into that curve.”

Question and Answer Session
In the Q&A session, Shiang was asked what his own laboratory’s experience with polymers has been. Shiang observed that polymers vary all over the map, noting that “unfortunately they don’t always give you the color you’d like, so there’s a tradeoff. A lot of it depends on the processing.” Responding to the question of whether anything is being done to fabricate OLEDs with microsurfaces, Hack said, “I think it’s a great topic for upcoming solicitations.”

4. SSL in the Real World

4.1 Walking Tour of Local LED Lighting Installations

Sponsored by Cree, Inc., and Progress Energy

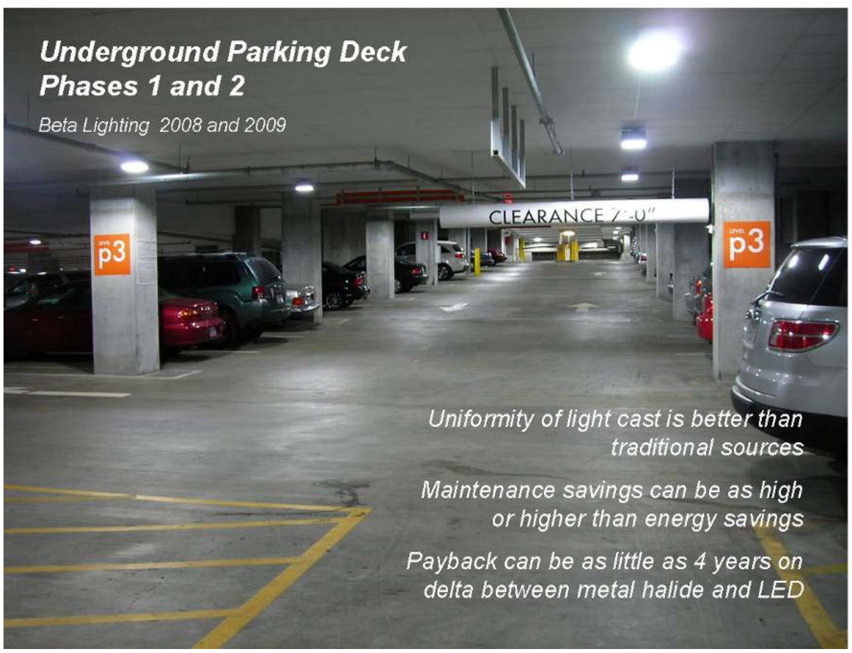
Day 1 closed with a tour of Raleigh municipal LED lighting installations. Led by Raleigh assistant city manager Dan Howe, attendees first visited the Convention Center’s underground parking facility, which features two separate LED installations, one of them incorporating motion detectors. The tour then passed through nearby streets lit with LEDs on the way to City Plaza, a park featuring LED uplighting in bollards and landscape beds as well as four decorative towers lit with programmable LEDs. Nearby was an outdoor ice-skating rink with LED area lights powered by flexible solar film on the poles, followed by LED canopy fixtures in front of Progress Energy’s former corporate headquarters, and an opportunity to compare three different kinds of LED street lighting.

Top: Raleigh Convention Center underground parking garage, featuring two LED installations. Bottom: One of four City Plaza towers lit with programmable LEDs.

The tour continued to the Raleigh Municipal Complex, where attendees saw a mobile solar area light and compared several different LED installations in the parking garage. Next came a temporary outdoor parking lot at Campbell University School of Law that was lit by solar-powered LED fixtures. Walking back to the hotel, attendees passed the colorful Cree Shimmer Wall, featuring 80,000 breeze-activated aluminum squares lit by programmable LEDs. This installation has transformed a functional side of the Raleigh Convention Center into a major landmark.

4.2 Panel 2: Lessons from the Field

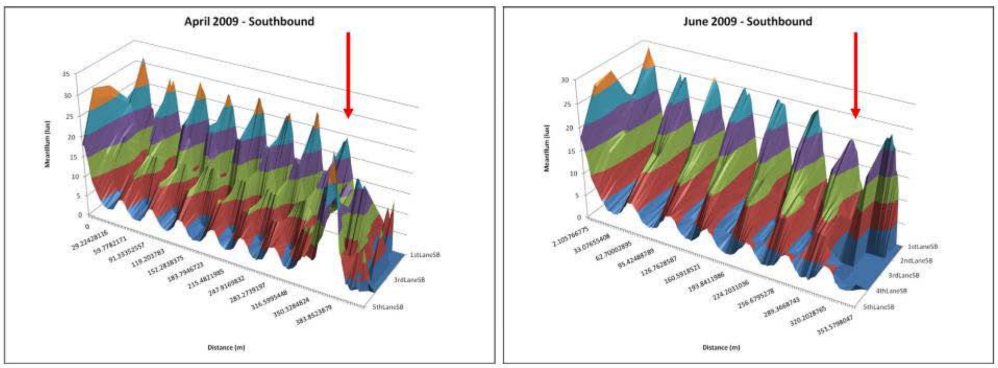
Day 2 began with a panel discussion sharing varied perspectives on lessons learned from recent real-world LED lighting installations. Dan Howe described Raleigh's broad municipal experience with SSL, which dates back to 2007, when it became the country's first LED City. Raleigh's use of LEDs ranges from parking garage, to public plaza, to greenway underpass, to street lighting and includes decorative applications as well as a number of solar-powered fixtures. Howe noted that overall, user satisfaction has been high, maintenance costs have been low, and lifetime performance has been better than expected. He reviewed the savings LED installations are bringing the city but observed that the economics have not yet reached the tipping point for street lighting and interior office lighting.



SSL used in Raleigh municipal underground parking deck

Chip Israel of Lighting Design Alliance gave a lighting designer's perspective on SSL. He stressed that designers can't just focus on the economics but must take architectural and human needs into consideration. He urged manufacturers to develop LED fixtures for directionality, which he considers "a huge opportunity" for SSL. Israel cited the poor performance of LED luminaires in Round 9 of CALiPER testing as illustrating one of the reasons designers are still hesitant about specifying them, noting that in one of his projects 40 percent of the LED fixtures failed. "As designers, we need to have the ammunition to say to the client 'this is right for you,'" he said.

Bruce Kinzey of Pacific Northwest National Laboratory (PNNL) provided an update on the I-35W Bridge in Minneapolis, which was rebuilt with LED lighting and is now being monitored as part of DOE'S GATEWAY demonstration program. Kinzey noted that ongoing monitoring detected a 12 percent reduction in the bridge's light levels just a few months after its September 2008 reopening. Investigating further, DOE and the manufacturer identified two main causes: a bubbling problem in the optical gel of the luminaires that was subsequently corrected by the manufacturer, and dirt depreciation. "These 'learning curve' issues are to be expected in the early years," he said. "But we should refrain from using phrases like 'maintenance-free' when describing SSL."



Summary of illumination depreciation data for two GATEWAY outdoor installation sites

Mark Schulkamp concluded the panel by sharing his perspective as an electrical contractor. As the installer whose job it is to "make it work," he observed that LED lighting products do not always live up to their promises, such as being dimmable or being "plug and play." This leaves him and other electrical contractors with all sorts of unanticipated obstacles to overcome, which he illustrated by describing four LED installation jobs. However, Schulkamp thinks LED lighting that is easier to install and service is on the horizon and that SSL is probably the "wave of the future."

Question and Answer Session

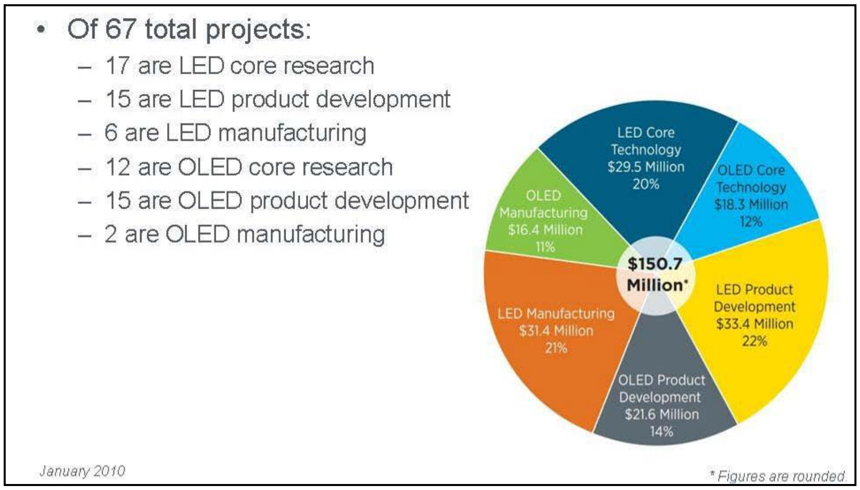
In the Q&A session, one attendee asserted that making lighting more efficient is not enough, and that manufacturers need to understand that unless they make sure the lighting quality is high, the pushback from the consumer will be significant and LEDs will fail. Asked whether there have been any negative responses to Raleigh's LED lighting from neighbors, Howe said that while he and his colleagues had been concerned about glare, "what we've found so far is that people think LED lighting is better than what was there before."

5. DOE's SSL R&D Program

5.1 Program Update

James Brodrick, U.S. Department of Energy

Brodrick began the next session with an overview of the DOE SSL R&D portfolio budget and areas of focus, with recognition for project teams making significant contributions in 2009.

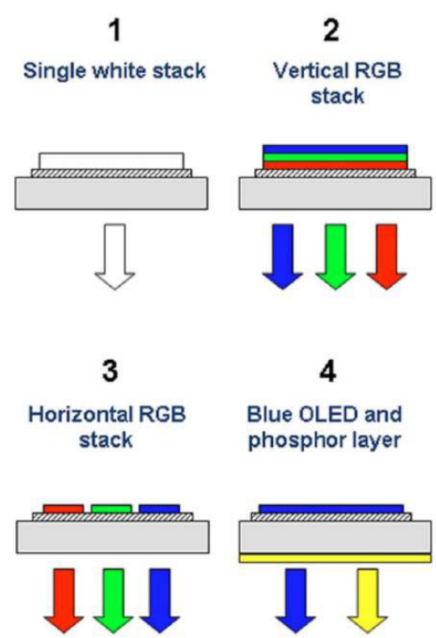


DOE SSL funding by program pathway

5.2 Invited Presentations on Significant DOE SSL R&D Projects

Andy Armstrong discussed how Sandia National Laboratories is closing the "green gap" in multichip white LEDs by increasing efficiency of deep green-emitting LEDs through InGaN defect reduction. He described Sandia's deep level optical spectroscopy (DLOS) technique, which helps improve understanding of how defects can degrade a device.

Franky So provided an overview of how white OLEDs are made (see figure, right) and described the University of Florida's effort to achieve high efficiency OLEDs by fabricating the devices in microcavity structures with down conversion phosphors. Using high triplet electron transporting materials, his team was able to achieve blue OLEDs with efficiency up to 59 lm/W. By fabricating OLEDs in microcavity structures, the emission can be tuned to match the excitation spectrum of the down conversion phosphors, and the resulting OLEDs have a power efficiency of 68 lm/W and a CRI of 83. Using a macrolens to further enhance light extraction, the team achieved a maximum efficiency of 99 lm/W.



Christopher Summers offered an overview of PhosphorTech Corporation's efforts using advanced phosphor systems for warm, efficient LEDs. He explained that these materials have tunable color spectra and have shown quantum yields as high as 88 percent, and that certain compositions of these phosphors become even more efficient at higher temperatures — a property known as thermal anti-quenching. Typical phosphors used in SSL have limited color flexibility, and the efficiency quenches rapidly at higher temperature operation. With these new phosphors, LEDs will potentially operate more efficiently at higher temperature and experience less color shift due to the drop-off in phosphor efficiency. PhosphorTech is currently working to improve the chemical stability of these materials and to better understand the anti-quenching effect in order to implement it in other phosphor compositions.

Tony Burrell presented Los Alamos National Laboratory's research to develop a cost-effective electrode for OLED general illumination. He reviewed the different techniques for the growth of thin films, including physical deposition, chemical vapor deposition, and chemical solution deposition. Burrell discussed using the Polymer Assisted Deposition system (PAD) to examine known transparent conductors and evaluate their feasibility for cost-effective production and material quality. PAD is a solution method for the production of high-quality thin films of oxides, nitrides, and carbide. Burrell also talked about the production of nitride-based films as transparent conductors and the development of methodologies suitable for producing it on glass, as well as a combinatorial approach.

Monica Hansen discussed how Cree, Inc. is improving LED efficiency and performance. She reviewed the challenges of developing warm-white LEDs, including the fact that efficacy drops at real-life operating temperatures, that the color-point shifts at high temperatures, and that there are reabsorption losses. Hansen noted that Cree is focusing on two areas: improving the wall-plug efficiency of the chip, and improving the phosphor and package efficiency at high temperatures. As to the former, Cree has managed to reduce the voltage to less than 3.1 V. As to the latter, they've developed LED phosphor solutions with improved color stability and improved efficiency at high temperatures while maintaining a CRI of 90.

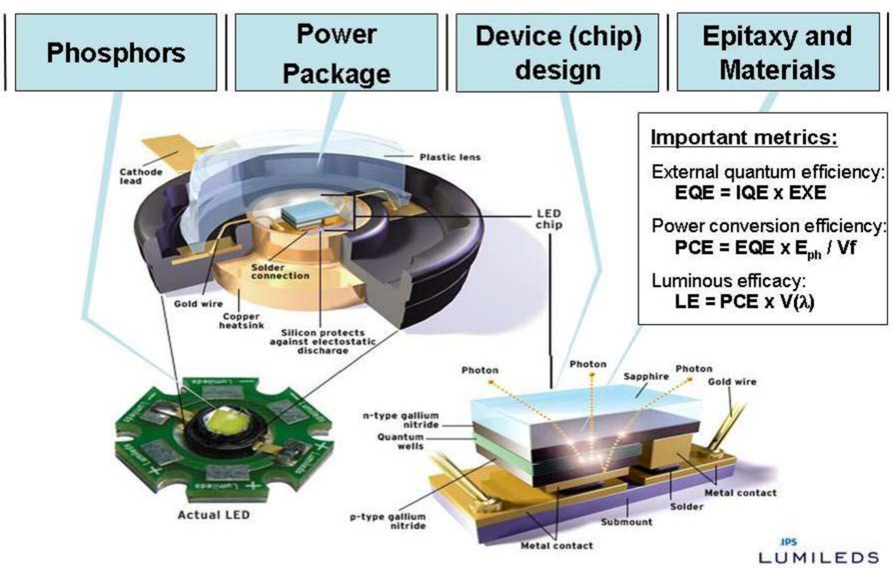
Gary Silverman described Arkema Inc.'s progress toward commercially viable OLED devices, through their search for less expensive transparent conducting oxides (TCO) as a replacement for the current anode, indium tin oxide (ITO). He explained that he and his team are focusing on using atmospheric pressure MOCVD (Metal Organic Chemical Vapor Deposition),[*] which is a more economical and higher throughput process than those previously used and involves technologies borrowed from energy-saving windows. Arkema has established that doped zinc oxide can be used for OLEDs and has demonstrated two approaches to mitigate surface roughness. Silverman observed that zinc oxide has excellent optoelectronic properties and is stable to substrate and OLED processing conditions.

[*] Also referred to as APCVD (Atmospheric Pressure Chemical Vapor Deposition)

Robert Harrison reviewed Osram Sylvania Development Inc.'s efforts to develop a high-efficiency LED downlight. He discussed how his team has demonstrated an efficient LED light engine with a 3500 K CCT and CRI greater than 80. The light engine consists of a compact array of blue LEDs on a circuit board covered by a phosphor-coated disk. The phosphor coating on the disk converts the blue light into a warm white light. The project results support Osram Sylvania's goal to develop a highly efficient LED downlight by improving the phosphor, optical, electronic, and thermal systems of the luminaire. This latest performance improvement was due to a new red phosphor that allowed both a higher efficacy and CRI to be achieved.

Mike Hack discussed Universal Display Corporation's work to develop commercially viable OLED panels. He noted that UDC has fabricated a white OLED 5cm x 5cm panel that achieves 68 lm/W and a CRI of 80. This is a significant milestone that ties lifetime and color quality to efficiency while moving towards a commercially available OLED panel. The device was measured in an integrating sphere using an outcoupling lens, and results were met at lighting brightness at a color temperature of 2860 K. With this project, UDC will team with Armstrong World Industries to incorporate an OLED lighting panel into Armstrong's TechZone™ Ceiling System.

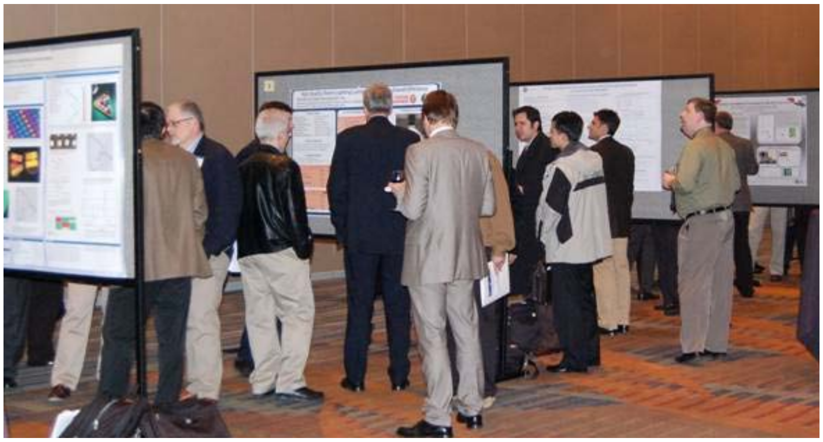
Decai Sun talked about how Philips Lumileds Lighting is raising the bar for warm white LED luminaire performance. He described how his team has demonstrated a warm white LED with a light output of 811 lumens, an efficacy of 99 lm/W, a CCT of 3307 K, and a CRI of 75. The LED was 2x2 mm^2 and was driven at a current density of 0.7 Amp/mm^2. The goal of this project is to demonstrate a 100 lm/W warm white LED with a light output of 800 lumens and a CRI of 90. Smaller, more efficient light sources that have higher light outputs would give luminaire manufacturers more flexibility when designing lighting products.



Four key areas of high-power LED development at Philips Lumileds

5.3 Poster Session for All Current DOE-Funded R&D Projects

A Wednesday evening poster session and reception for all DOE SSL projects provided additional opportunities to share research results, identify needs, and build relationships. Poster topics and presenters are given in Appendix B.



Participants share project information at the poster session showcasing 46 SSL R&D projects.

For an overview of all current DOE-funded SSL R&D projects, including a brief description, partners, funding level, and proposed timeline, see the 2009 SSL Project Portfolio on the DOE SSL Web site at www.ssl.energy.gov/projects.html.

6. Panel 3: Reliability and Lifetime

Moderator Fred Welsh of Radcliffe Advisors introduced the topic of reliability and lifetime, noting that a DOE-industry working group on the topic expects to publish guidelines in the coming months.

Kevin Dowling of Philips Color Kinetics examined the question of luminaire lifetime, which he called "one of the biggest issues we face in solid-state lighting." He referred to the improvements over the past few years in CRI and other key parameters, but decried the lack of quality due to reliability issues as revealed by CALiPER testing and field experience. Dowling emphasized that reliability and lifetime problems need to be addressed by looking at the underlying causes. He stressed that these are not issues that can be tackled individually, but require a collaborative, industry-wide effort.

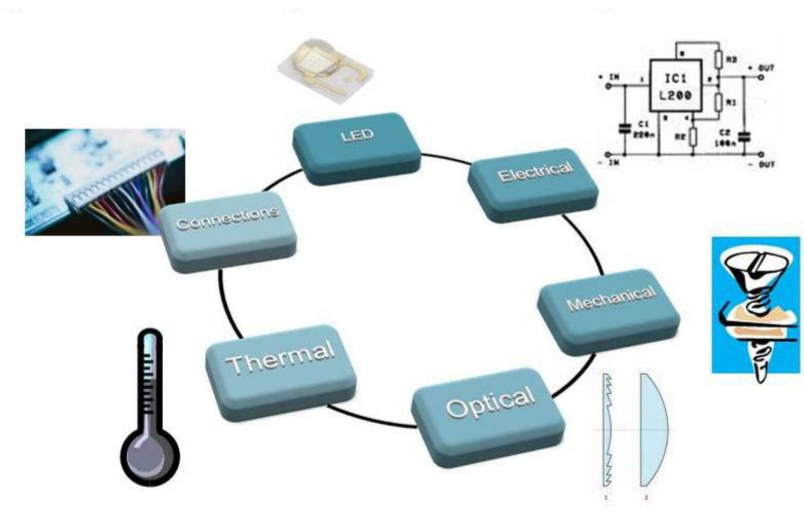
David Szombatfalvy of GE Lighting Solutions talked about how lifetime can be demonstrated. He explained the process steps he and his colleagues use at GE, including

Reliability Requirements		Targets: Rel Goal	Rel Test Plan	Development Activity: Initial Review →		Final Review
Demonstrated Functional Life	Required Hours	65K	Goal	Goal Verify	Goal Verify	Goal Verify
	LED Module	99.5%	99.0%	95.0%	96.0%	99.0%
	LED Driver	97.5%	98.6%	96.0%	97.0%	98.6%
	Xconn & Harness	98.0%	98.0%	95.0%	96.0%	98.0%
	System Rollup	95.1%	95.7%	86.6%	89.4%	95.6%
	Rel Spec	95.0%	Pass	Unproven	Unproven	Pass
	Conf Level	95.0%				
Lumen Maintenance	Life Target at xx hrs	LM Level		Lumen Maintenance Over Time		
1K Hours on Test	LM Goal (%)	Level 1				
3K Hours on Test		Level 2				
6K Hours on Test		Level 3				

LED luminaire reliability scorecard used by GE identifying reliability targets, performing a gap assessment to identify risk and drive risk mitigation, and then allocating and tracking reliability by means of a “scorecard” to roll up available supplier and field data. Szombatfalvy made the point that reliability is more than just lumen maintenance, and emphasized that testing only tells you what you actually have, and that reliability should be designed into both product and process.

Terry Clark of Finelite underscored the importance of color quality and consistency over the life of the product. He explained that color shift is an issue regardless of the type of light engine, and that it is very application-dependent. Clark called color shift a “daunting” problem for LED-based luminaires, noting that LEDs shift color, that different luminaires do so at different rates, and that testing for color consistency and fixing color shift are expensive. He called for the creation of a working group on color shift for high-volume bulb and lamp replacements, with separate groups focused on standard- and specification-grade luminaires.

Mark Hodapp of Philips Lumileds Lighting reviewed his company’s reliability modeling and discussed how it affects complete luminaire systems. He stressed that system reliability has to be designed into the product, and that it goes beyond LEDs to include optical, mechanical, thermal, electrical, and other elements. He noted that Philips will soon post an online system modeling tool that lets the user input drive conditions and calculates the probability for lumen maintenance and catastrophic failures as well as expected system lifetime.



$$R_{system} = R_{electrical} * R_{connections} * R_{LEDs} * R_{optical} * R_{thermal} * R_{mechanical}$$

Components of system reliability for an LED luminaire

Question and Answer Session

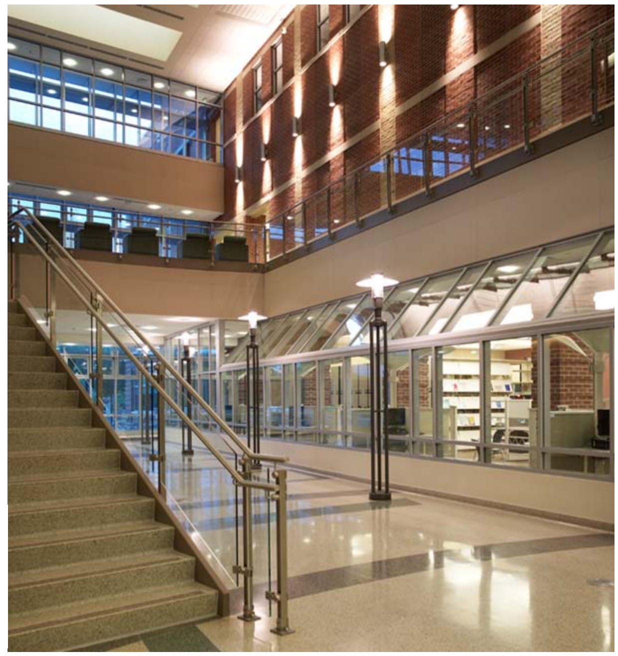
In the Q&A session, one attendee asked Szombatfalvy whether he’d had a chance to look into the reasons behind failures that don’t appear on the scorecard, especially color shift. Szombatfalvy said most of his company’s issues with color shift are LED-related, so he refers those failures back to the LED manufacturer. Another attendee asked whether the testing referred to by the panelists is a complete test to fail or is testing to pass. Hodapp said his company tests LEDs on 1,000-hour intervals on a continuous basis, while Szombatfalvy noted that his company tests some products to try to precipitate failures.

7. SSL in the Marketplace

7.1 What Designers Want From SSL

Naomi Miller, Pacific Northwest National Laboratory

Miller offered insights on the challenges of specifying today's LED lighting products. She called for better communication about product performance as well as for the standardization of SSL terminology. Miller stressed the need for products to be easily installable and serviceable, and for the luminaire manufacturer to serve as the single point of responsibility for the entire system, rather than there being a different point for each component.



Architectural lighting products may be in use for decades, so specifiers are concerned about availability of replacement parts that provide the same light output, color, and distribution.

Question and Answer Session

In the Q&A session, Miller was asked about the large time gap between specifying a product and its actual use. She acknowledged this as "an enormous problem," noting that products specified today may not be ordered for two or three years, by which time the manufacturer is producing a new generation of products. She said that because of this gap, manufacturers should keep product versions available over an extended period of time rather than discontinue them as soon as newer versions come out.

7.2 Panel 4: Recognizing Quality in the Marketplace

Ruth Taylor of PNNL discussed two lighting design competitions that spotlight product manufacturers who are "getting it right" with commercial and residential luminaires. *Lighting for Tomorrow* is a residential lighting design competition sponsored by DOE, the American Lighting Association, and the Consortium for Energy Efficiency. *Next Generation Luminaires*™ is a commercial luminaire design competition sponsored by DOE, the International Association of Lighting Designers, and the Illuminating Engineering Society of North America. Taylor highlighted the 2009 *Lighting for Tomorrow* winners,[*] noting that the 2009 *Next Generation Luminaires* winners[**] would

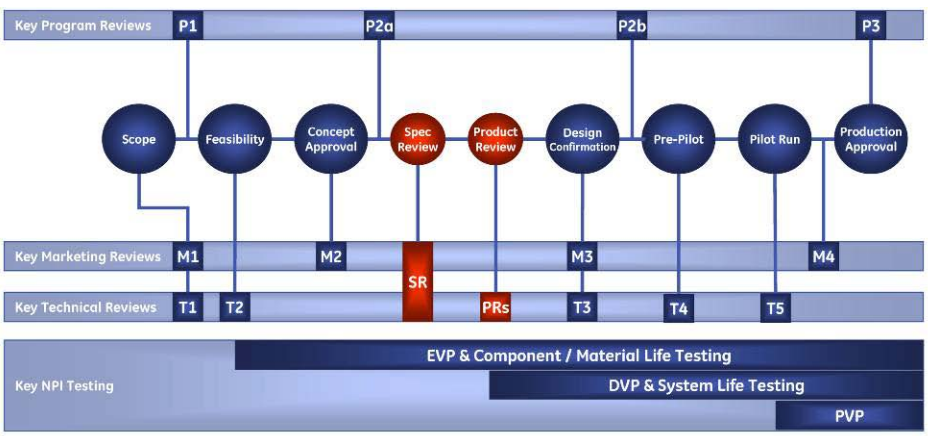
[*] Details on 2009 *Lighting for Tomorrow* awards are available at www.lightingfortomorrow.org.

[**] Winners of the 2009 *Next Generation Luminaires* awards were announced February 11, 2010, at the Strategies in Light Conference in Santa Clara, California. More details at www.ngldc.org.

be announced at the 2010 Strategies in Light Conference.

Taylor added that the *Next Generation Luminaires* competition is inclusive rather than exclusive, with all qualifying products recognized, and that the number of entries and recognized products doubled in 2009 over the previous year. She then introduced representatives from three manufacturers of winning products, who talked about the development process.

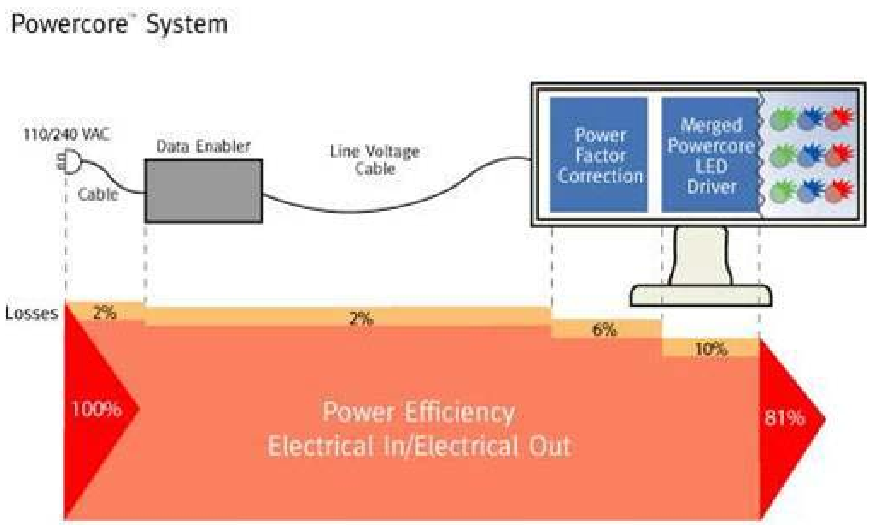
Ravi Kaushik of GE Lighting explained that the development of the Immersion™ display case lighting system, used primarily for jewelry displays, was a natural extension from lighting systems for refrigerated display cases and leverages the directionality of LEDs. He noted that in testing, LEDs proved superior to fluorescent light sources, with less drop-off, and had better uniformity and distribution than halogens. Kaushik then described GE's tollgate process for new product development. He also discussed the AZARA™ LED lighting module (another NGL winner), the rights to which GE recently purchased from Journée Lighting. Kaushik remarked that market research showed the need for field-replaceable modules that an end user can easily navigate without tools, if a component within the LED driver, or the LED itself, happens to fail.



GE's tollgate process for new product introduction

Gary Trott of Cree, Inc. talked about the four key questions Cree focused on in developing the LR6 DR1000 Six-Inch Downlight: what is the lighting problem, what is the competing solution, who is the primary customer, and what is the maintenance strategy. "Don't assume that what's out there being used (i.e., already available on the marketplace) is good and right," he told the audience. "You can find ways to substantially improve on incumbent solutions." Trott made the point that electrical engineers rather than lighting designers drive the majority of projects, and emphasized that replaceable integrated modules allow for future improvements as the technology develops.

Kevin Dowling of Philips Color Kinetics described some of his company's early LED cove light offerings and traced the evolution of that product line. "We discovered how hard these products were to install, and we learned a lot from this," he said, adding that Philips continued to build and improve these devices so they could be offered at various price and performance levels. Dowling noted that Philips began investing in controls, so that the systems were self-addressable. He emphasized the integration of power factor correction as a key factor in the development of the company's eW Cove Powercore, which raised the cost of the fixture but lowered the overall system cost and the cost of installation.



The integration of power factor correction was key to the development of Philips Color Kinetics' Powercore system.

Question and Answer Session

In the Q&A session, one participant observed that many jewelry stores use linear halogen lights, and Kaushik explained that these are mounted outside the display cases, since the heat generated by linear halogen lights would raise the temperature of the jewelry. GE has focused on developing a light that can be mounted inside display cases. Trott was asked whether a high CRI would be a primary requirement in office spaces, and he said that while a higher CRI is more crucial in retail applications, it's also advantageous in an office setting because it enables people to discern facial expressions better.

8. Breakout Group Discussions

On Wednesday and Thursday afternoons, workshop participants divided into separate LED and OLED track sessions to explore the proposed priority tasks for DOE's next update to the SSL R&D Multi-Year Program Plan (MYPP).

These breakout tracks are part of DOE's annual, ongoing R&D planning process, which includes structured dialogue with SSL stakeholders. In November 2009, DOE invited SSL technology experts to participate in roundtable discussions to advise DOE on priority research needs to advance SSL products and recommended updates to the 2009 MYPP. The outcomes of the roundtables[*] were presented to a larger group of interested stakeholders for further discussion in the LED/OLED track sessions at the Raleigh SSL R&D Workshop.

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[*] 27 technology experts participated in DOE's November 2009 roundtable discussions. The report, *Roundtable Discussions of the Solid State Lighting R&D Task Priorities*, is posted on the SSL Web site at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl-rd-roundtable-report_nov09.pdf.

The recommendations from these track sessions will inform the final updates to the 2010 MYPP, which DOE expects to publish in April 2010, and will guide DOE and NETL in developing upcoming R&D competitive solicitations. DOE expects to issue the next round of competitive solicitations in April 2010.

At this workshop, the first LED track session continued the Panel 1 discussion on the limits of efficacy and considered how R&D can lead to higher packaged device efficacies through substrate development, emitter materials, down conversion, and novel architectures. The second LED track session addressed overall luminaire performance, especially reliability. Participants emphasized reliability methods and optimization, electronics reliability, and color maintenance options.

The first OLED track session addressed the limits to OLED efficiency, with an emphasis on materials considerations, electrode design and materials, outcoupling methods, and other issues related to basic device efficacy. The second OLED track session addressed design optimization of OLED lighting. Considerable discussion on the tradeoffs between lifetime, cost, and brightness has occurred in the past year, and this session considered these issues in terms of panel design for practical OLED lighting.

9. Wrap-up

Brodrick concluded the three-day workshop by thanking participants for their input and participation. He noted two additional DOE SSL workshops in 2010:

- SSL Manufacturing R&D Workshop, April 20–21, in San Jose, California
- SSL Market Introduction Workshop, July 20–22, in Philadelphia, Pennsylvania.

He also encouraged attendees to stay apprised of DOE SSL program activities by visiting www.ssl.energy.gov.

Workshop presentations and materials referenced in this report can be found on the SSL Web site at www.ssl.energy.gov/past_conferences.html.

APPENDIX A: 2010 SSL R&D Workshop Participants

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Vadim Adamovich
Universal Display Corporation

John Adinolfi
Lighting Technologies

Diane Allard
Akoya

Steven Allen
Osram Sylvania

Frazer Anderson
TDI / Oxford Instruments

James Anderson
Philips Color Kinetics

Tom Anderson
AVX Corporation

Chris Andrews
Renaissance Lighting, Inc.

Mehmet Arik
GE Global Research Center

Andrew Armstrong
Sandia National Laboratories

Teresa Bair
EYE Lighting International of North America

Karen Baker
OptoLum, Inc.

Troy Baker
Kyma Technologies

Norman Bardsley
Bardsley Consulting

Tom Barnett
Masco Corporation

Jay Bartek
Task Lighting Corporation

Pallab Bhattacharya
The University of Michigan

Robert Biefeld
Sandia National Laboratories

Karen Blackmore
Los Alamos National Laboratory

Stephen Bland
SB Consulting

Chris Bohler
Cooper Lighting

Peter Bolan
Universal Lighting Technologies

Harshad Borkar
Lavalux LED

Scott Bowden
Sharp

Dennis Bradley
GE Lumination

Michael Bremser
Permlight Products

James Brodrick
U.S. Department of Energy

Kate Buck
ICF International, in support of ENERGY STAR

Roger Buelow
Energy Focus, Inc.

Pam Bullock
Kichler Lighting

Chad Bulman
Midwest Energy Efficiency Alliance

Anthony Burrell
Los Alamos National Laboratory

Nelson Caldani
Toyota Tsusho America

Michael Callahan
GreenTech Solutions

Martha J. Carney
Outsourced Innovation

Anthony Catalano
TerraLUX

Joel Chaddock
U.S. Department of Energy-NETL

Michael Chan
Digital Lighting Inc.

Tony Chao
Applied Ventures

Jian Ping Chen
Add-Vision

Xiaolan (Anna) Chen
Novellus Systems, Inc.

Samuel Chen
TSMC

Terry Clark
Finelite, Inc.

Mike Coltrin
Sandia National Laboratories

Jason Cook
Howard Lighting Products

Keith Cook
Philips Lighting

Cason Coplin
EcoFit Lighting

Lelia Cosimbescu
Pacific Northwest National Laboratory

Robert Crane
C. Crane Company Inc.

Garry Cunningham
RTI International

Jack Curran
LED Transformations, LLC

Ku'uipo Curry
Ku'uipo Curry Lighting Design

Robert Davis
Carnegie Mellon University

Lynn Davis
RTI International

Gilbert DeFreitas
Progress Energy Florida

Jon DeGroot, Jr.
Dow Corning Corporation

Steven DenBaars
UCSB Solid State Lighting and Energy Center

Mark D'Evelyn
Soraa

Charles DeVries
Texas Instruments

Peter Di Maso
Texas Instruments

Gerald DiBattista
Bayer MaterialScience

Erhan Dikel
National Research Council Canada

Brian Dlugosch
AIXTRON Inc.

Brian Dotson
DOE National Energy Technology Laboratory

Kevin Dowling
Philips Color Kinetics

Shawn Du
Nichia

Gerald Duffy
GE Lighting

Anil Duggal
GE Global Research

Kevin Elsken
Bayer MaterialScience

Judelson Enriquez
Southern California Edison

Sean Evans
U.S. Department of Energy-NETL

Robert Ewald
Applied Materials

Ronald Farmer
US LED LTD

Ian Ferguson
UNC Charlotte

Neill Ferrill
Intertek ETL

Curtis R. Fincher
DuPont Displays

Annette Finsterbusch
Applied Ventures

Peter Ford
United Luminous International

Melissa Ford
Vektrex

Michael Fusco
LED Specialists

John Gach
Cooper Lighting

Jim Gaines
Philips Lighting Company

Robert Galli
Panasonic

Francisco Galvez
Los Angeles Department of Water and Power

Geoff Gardner
Dow Corning Corporation

Raiford Garrabrant
Cree, Inc.

Daniel Gaspar
Pacific Northwest National Laboratory

Gary Gatesman
ElectraLED, Inc.

Michael Gaydos
Lumastream LLC

Thomas Gehrke
Micron Technology, Inc.

Austin Gelder
Halco Lighting Technologies

Robert Gerlach
ETC

Amal Ghosh
eMagin Corporation

Ashok Gidwani
Lavalux LED

Robert Glass
Cree, Inc.

Wendy Graves
Akoya

Michael Green
DuPont Company

Derek Greenauer
D&R International

Garrett Grega
Philips Lighting Company

Scott Griffith
WF Harris Lighting

Tom Griffiths
Solid State Lighting Design Online

Jason Guo
Fairchild Semiconductor

Shiping Guo
IQE RF LLC

Mahima Gupta
Navigant Consulting

Michael Hack
Universal Display Corporation

Kent Hafemann
Facility Solutions Group (FSG)

Mark Hand
Acuity Brands Lighting

Jay Handley
General Microcircuits, Inc (GMI)

Monica Hansen
Cree, Inc.

Uwe Happek
The University of Georgia

Kei Haraguchi
Nichia America Corporation

Gerard Harbers
Xicato Inc.

Robert Harrison
Osram Sylvania

Eric Haugaard
Ruud Lighting

Andrew Hawryluk
Ultratech

Bob Henderson
Progress Energy

Tanya Hernandez
HART Design Group

Eric Higgs
Lumastream LLC

Frank Hoang
Virtium

Mark Hodapp
Philips Lumileds

Hideyoshi Horie
NIST

David Horn
SuperBulbs

James Horsman
Lockheed Martin

Bob Householder
Fraen OMG

Daniel Howe
City of Raleigh, North Carolina

Li Huang
Carnegie Mellon University

Charles Huber
Lynk Labs, Inc.

Bedwyr Humphreys
IQE-NanoGaN Ltd

James Ibbetson
Cree Santa Barbara Technology Center

Chris Isaacson
Numinus

Chip Israel
Lighting Design Alliance

John Ivey
Ilumisys

Steve Jackson
Tyco Electronics

Chris James
Cree, Inc.

Philip Jessup
The Climate Group

Jianzhong Jiao
Osram Opto Semiconductors

Ray Johnston
3M Company

Keith Kahen
Eastman Kodak Company

Ravi Kaushik
GE Lighting

Gregory Kay
Edge Lighting

Philip Keebler
EPRI

Shawn Keeney
Cree, Inc.

Ronald Kelley
Green Gap Solutions

Youjin Kim
ETRI

Bruce Kinzey
Pacific Northwest National Laboratory

Harry Kirk
Sigen

Warren Kleinsmith
Optiled Technology LLC

David Knapp
Firefly Green Technologies, Inc.

Hyunchul Ko
Illumitex, Inc.

Daniel Koleske
Sandia National Laboratories

Dave Krutek
Arrow Electronics

Michael Kurtz
Sternberg Lighting

Jeff Lagaly
Intematix Corporation

Karen Leak
Energy Focus, Inc.

Jay Lewis
RTI International

Ming Li
Osram Sylvania

Minghang Li
University of North Texas

Michael Lim
Luminus Devices

Ming-Te Lin
University of North Texas

Geoffrey Ling
Gallium Lighting

Gao Liu
Lawrence Berkeley National Laboratory

Jie Liu
Duke University

Daniel Loftus
Maria Energy Group

Bill Long
WF Harris Lighting

Joe Lorenzo
USAF

Mike Lu
Sagitta Research, LLC

Chun Lu
SiliconCore Technology Inc.

Theron Makley
Seoul Semiconductor, Inc.

Ehsan Maleki
PacifiCorp

Kishore Manghnani
Marvell Semiconductor, Inc.

Douglas Mar
Liquidia Technologies

Karen Marchese
Akoya

Angelo Mascarenhas
NREL

Mathew Mathai
Plextronics, Inc.

Deanna Matthews
Carnegie Mellon University

Fredric Maxik
Lighting Science Group Corporation

Amy Mayers
Philips Vista Lighting

Mike Mazloom
Glosynergy

Robert McAnally
Appalachian Lighting Systems, Inc.

Mark McClear
Cree, Inc.

Michael McGehee
Lighting Technologies

Terry McGowan
American Lighting Association

William McGrath
LEDdynamics, Inc.

Joanna McKittrick
UC San Diego

Chad McSpadden
H.E. Williams

Hisham Menkara
PhosphorTech

Brent Meyer
The Nassau Group, Limited

Jeffrey Miller
International Association of Lighting Designers

Naomi Miller
Pacific Northwest National Laboratory

Mary Miller
Sandia National Laboratories

Brian Miloski
Caris & Company

Silvia Mioc
Smart Lighting Engineering Research Center
Rensselaer Polytechnic Institute

Kailash Mishra
Osram Sylvania

Sergey Monakov
JSC Kvazar

John Montgomery
Ringdale, Inc.

John Morreale
Illumitex, Inc.

Chris Morris
Vossloh-Schwabe, Inc.

Russ Mortenson
GLO

Wayne Myrick
Sharp Electronics

Shuji Nakamura
University of California

Balraj Narang
Catalina Lighting

Jeff Nause
Cermet, Inc.

David Neal
Seoul Semiconductor, Inc.

Scott Newman
U.S. Army Research Laboratory

Chris Nitz
Corning Incorporated

Orlando E. Nova
City of Los Angeles/Bureau of Street Lighting

Arto Nurmikko
Brown University

Aaron O'Brien
Pure Lighting

James O'Connor
Carclo Technical Plastic Inc.

Yoshi Ohno
NIST

Mohammad Omary
University of North Texas

Amy Oriss
Akoya

Julian Osinski
Woodside Advisors

Brian Owen
greenTbiz / LEDs Magazine

Asanga Padmaperuma
Pacific Northwest National Laboratory

Hash Pakbaz
Cambrios

Bob Pantalone
Jabil

Steve Paolini
Lunera Lighting, Inc.

Ajit Paranjpe
Veeco Instruments, Inc.

Rizwan Parekh
Cyber Tech Lighting, Inc.

Kitae Park
Samsung Electronics

Ian Parker
DuPont Displays

Nag Patibandla
Applied Materials

Morgan Pattison
SSLS, Inc.

Lisa Pattison
Technical Consulting & Patents

Bruce Pelton
Tyco Electronics

Michael Pena
NXP Semiconductors

James Perkins
QD Vision, Inc.

Jeffrey Perkins
Yole, Inc.

James Petroski
GrafTech International

Edward Petrow
Lincoln Technical Services, Inc.

Christiane Poblenz
Kaai, Inc.

Jason Pomante
Arkema Inc.

Jeff Popielarczyk
General Electric

Michael Poplawski
Pacific Northwest National Laboratory

George Powch
Versatilis LLC

Apurba Pradhan
Luxim Corporation

Chris Primous
Permlight

Gopalan Rajeswaran
Moser Baer Technologies Inc.

Mark Reed
LSI Industries

Meredith Reed
U.S. Army Research Laboratory

Rick Regan
South Star Solutions

John Richard
DuPont

Michael Riebling
Philips HADCO

Scott Riesebosch
CRS Electronics Inc

Kurt Roberts
DuPont CPM

Sean Robillard
General Microcircuits, Inc. (GMI)

Clark Robinson
DOE National Energy Technology Laboratory

Jeffrey Roeder
CT Thin Film Technologies

Kyle Rogers
Cree LED Lighting

Steven Rosenblum
Corning Incorporated

Vsevolod Rostovtsev
DuPont CR&D

Jae-Hyun Ryou
Georgia Institute of Technology

Amin Sabbagh
Kichler Lighting

Mikhail Sagal
TSR

Luis Sano
Republic ITS

Pat Sapinsley
Good Energies

Frank Schaffer
Sharp Microelectronics of the Americas

Leo Schowalter
Crystal IS, Inc.

Mark Schulkamp
Mark W. Schulkamp Electric Co.

Thomas Schuller
Schuller

Anant Setlur
GE Global Research

Mehdi Shafaghi
Los Angeles Department of Water and Power

Sudeep Sharma
Clean Lighting Solutions, LLC

Eddie Shaw
Duke Energy

Yijian Shi
SRI International

Joseph Shiang
GE Global Research

Ahmed Shuja
Progressive Cooling Inc.

Gary Silverman
Arkema Inc.

Brook Simmons
TDI, Inc. / Capitol Decisions, Inc.

Marc Sims
DuPont Displays

Franky So
University of Florida

Dan Sperling
Akoya

Mark Spizzo
Acuity Brands Lighting

James Stanton
The Nassau Group, Limited

James Steedly
MaxLite

Lindsay Steele
Pacific Northwest National Laboratory

David Stein
Sandia National Laboratories

Michael Stevens
Georgia Power Company

Matthew Stevenson
QD Vision, Inc.

Edward Stokes
UNC Charlotte

Matthew Stough
Osram Sylvania

Lawrence Stout
Army Research Laboratories

Todd Straka
Intertek

David Sturdy
Sturdy Corporation

Christopher Summers
PhosphorTech

Decai Sun
Philips Lumileds Lighting

Suresh Sunderrajan
NN-Labs

Rajendra Swamy
OSRAM Opto Semiconductors

David Szombatfalvy
GE

Aijaz Taj
Lights of America

Yiqing (Laura) Tang
Toyota Tsusho America

Paiboon Tangyunyong
Sandia National Laboratories

Nelson Tansu
Lehigh University

Chingez Tarar
Lights of America

Daniel Taub
Applied Materials

Ruth Taylor
Pacific Northwest National Laboratory

Thomas Taylor
The Dow Chemical Company

Eric Teather
WhiteOptics LLC

Paul Thurk
ARCH Venture Partners

Yongchi Tian
Lightscape Materials, Inc.

Jacquelyn Tran
Southern California Edison

Bruce Trimbur
Trimbur Group LLC

Gary Trott
Cree, Inc.

Tom Trovato
Trovato Mfg., Inc.

Ralph Tuttle
Cree, Inc.

Yuan-Sheng Tyan
Eastman Kodak Company

Craig Updyke
NEMA/NGLIA

Graham Upton
Endicott Research Group

Adil Vakil
Lights of America

Farooq Vakil
Lights of America

Steve Van Slyke
Technocorp Energy

Eric Virey
Yole, Inc.

Helen Vydra Roy
New Streetlights

Peter Wagner
Powerbox USA

Ying Wang
DuPont

Mike Waters
Delta Products Corporation

Ronald Weber
Tyco Electronics

Warren Weeks
The Compound Group

Bill Weiss
Power Integrations

Fred Welsh
Radcliffe Advisors

Jason West
D&R International

Russ Westerman
Plasma Therm

Christian Wetzel
Rensselaer Polytechnic Institute

Michael Wilcox
Nuventix

Kevin Willmorth
Lumenique LLC

Greg Wilson
MEMC Electronic Materials

Larry Wilson
Philips

Shelby Wilson
Hypergrowth!

Brian Witzen
SHARP

Mark Wolff
Optiled

Howard Wolfman
Lumispec Consulting

George Woodbury
Republic ITS

Derek Wotring
Interep Associates Inc.

Craig Wright
Progress Lighting

Jiangeng Xue
University of Florida

Hirsohi Yagi
IMAnet, Inc.

Jeremy Yon
Litecontrol

Barry Young
OLED Association

Charles Zhang
NN-Labs

Jun Zhang
Solid Technology, Inc.

Wanfeng Zhang
Marvell Semiconductor, Inc.

Scott Zimmerman
Goldeneye

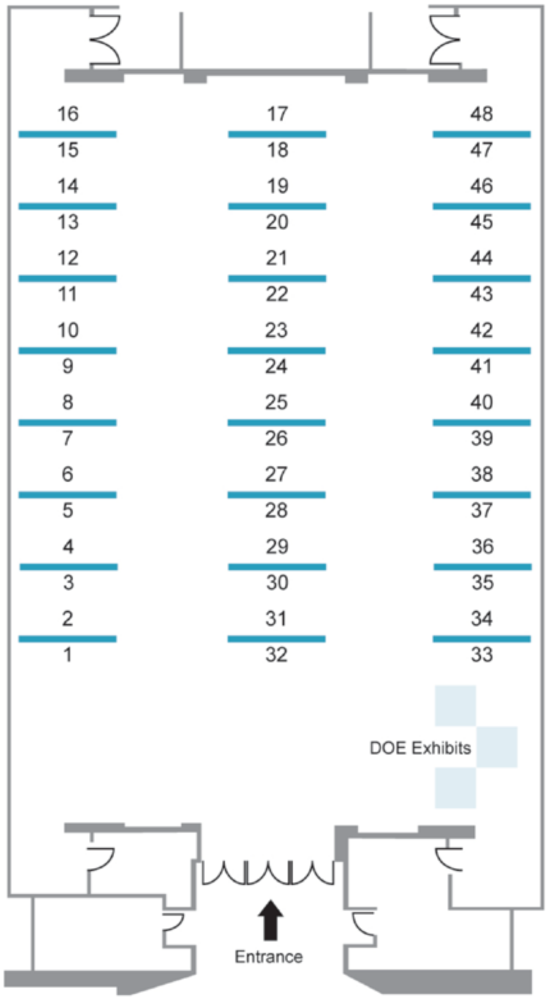
Ellen Zmithrovitch
Energizer

Robert Zona
Philips Lumileds

APPENDIX B: DOE-Funded SSL R&D Project Posters

Transformations in Lighting
SSL R&D Workshop LED Poster Session

FEBRUARY 3, 2010 • 5:30 PM – 7:30 PM

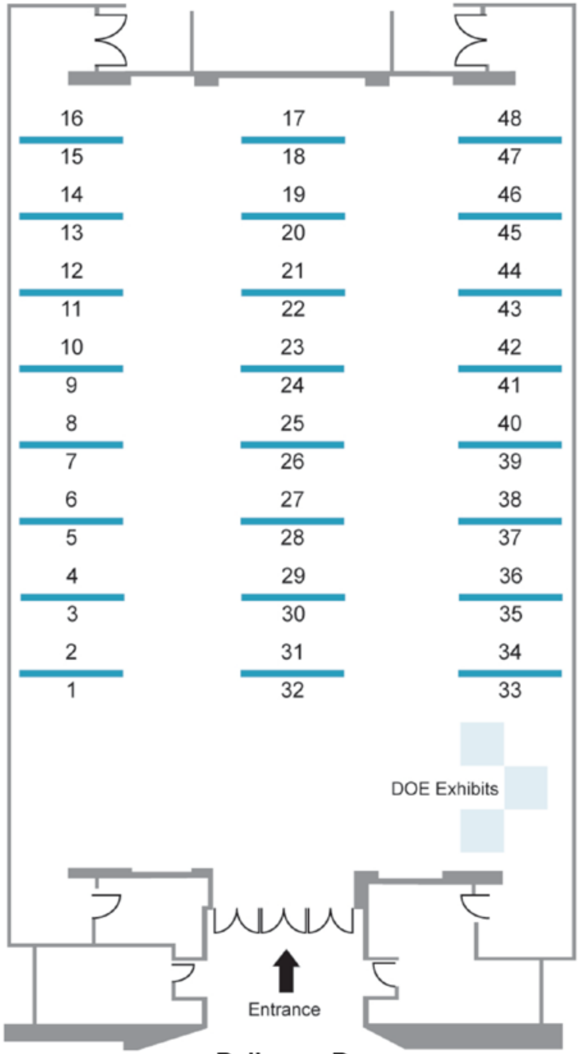


Ballroom B
Raleigh Convention Center

DISPLAY NUMBER	LED PROJECTS	PRESENTER
1	Photoluminescent Nanofibers for High Efficiency Solid-State Lighting Phosphors	**Lynn Davis** Research Triangle Institute
2	Highly Efficient Small Form-Factor LED Retrofit Lamp	**Steven Allen** Osram Sylvania Products Inc.
3	High Quality Down Lighting Luminaire with 73% Overall System Efficiency	**Robert Harrison** Osram Sylvania Products Inc.
4	Affordable High-Efficiency Solid-State Downlight Luminaires with Novel Cooling	**Mehmet Arik** GE Global Research
5	Phosphor Systems for Illumination Quality Solid State Lighting Products	**Anant Setlur** GE Global Research
6	Novel Defect Spectroscopy of InGaN Materials for Improved Green LEDs	**Andrew Armstrong** Sandia National Laboratories
7	Semi-polar GaN Materials Technology for High IQE Green LEDs	**Daniel Koleske** Sandia National Laboratories
8	Novel Heterostructure Designs for Increased Internal Quantum Efficiencies in Nitride LEDs	**Robert Davis** Carnegie Mellon University
9	An Integrated Solid-State LED Luminaire for General Lighting	**Kevin Dowling** Color Kinetics Incorporated
10	Fundamental Studies of Higher Efficiency III-N LEDs for High-Efficiency High-Power Solid-State Lighting	**Russell Dupuis** Georgia Institute of Technology
11	Epitaxial Growth of GaN Based LED Structures on Sacrificial Substrates	**Ian Ferguson** Georgia Tech Research Corporation
12	High Efficiency Driving Electronics for General Illumination LED Luminaires	**James Gaines** Philips Lighting
13	100 LPM 800 LM Warm White LED for Illumination	**Decai Sun** Philips Lumileds Lighting, LLC
14	SSL Luminaire with Novel Driver Architecture	**Sten Heikman** Cree, Inc.
15	Efficient White SSL Component for General Illumination	**Ronan Le Toquin** Cree, Inc.
16	Multicolor, High Efficiency, Nanotextured LEDs	**Jung Han** Yale University
17	High Efficiency Colloidal Quantum Dot Phosphors	**Keith Kahen** Eastman Kodak Company
18	Lattice Mismatched GaInP Alloys for Color Mixing White Light LEDs	**Angelo Mascarenhas** National Renewable Energy Laboratory
19	Phosphors for Near UV-Emitting LEDs for Efficacious Generation of White Light	**Joanna McKittrick** University of California, San Diego
20	High-Efficiency Nitride-Based Photonic Crystal Light Sources	**James Speck** University of California, Santa Barbara
21	Development of High Efficiency m-Plane LEDs on Low Defect Density Bulk GaN Substrates	**Christiane Poblenz** Kaai, Inc.
22	Exploiting Negative Polarization Charge at n-InGaN/p-GaN Heterointerfaces to Achieve High Power Green LEDs without Efficiency Droop	**Meredith Reed** ARL
23	GaN-Ready Aluminum Nitride Substrates for Cost-Effective, Very Low Dislocation Density III-Nitride LEDs	**Leo Schowalter** Crystal IS, Inc.
24	High Extraction Luminescent Materials for Solid-State Lighting	**Christopher Summers** PhosphorTech Corporation
25	Enhancement of Radiative Efficiency with Staggered InGaN Quantum Well LEDs	**Nelson Tansu** Lehigh University
26	High Efficacy Green LEDs by Polarization Controlled MOVPE	**Christian Wetzel** Rensselaer Polytechnic Institute

Transformations in Lighting
SSL R&D Workshop OLED Poster Session

FEBRUARY 3, 2010 • 5:30 PM – 7:30 PM



Ballroom B
Raleigh Convention Center

DISPLAY NUMBER	OLED PROJECTS	PRESENTER
27	Embodied Life Cycle Energy for SSL Products	**Deanna Matthews** Carnegie Mellon University
28	High Quality Low Cost TCOs	**Anthony Burrell** Los Alamos National Laboratory
29	High Efficacy Phosphorescent SOLED Lighting	**Vadim Adamovich** Universal Display Corporation
30	Efficient Large Area WOLED Lighting	**Rui-Qing (Ray) Ma** Universal Display Corporation
31	High Efficacy Integrated Under-Cabinet Phosphorescent OLED Lighting Systems	**Mike Hack** Universal Display Corporation
32	Development of High Efficacy, Low Cost Phosphorescent OLED Lighting Ceiling Luminaire System	**Mike Hack** Universal Display Corporation
33	Quantum Dot Light Enhancement Substrate for OLED Solid-State Lighting	**Seth Coe-Sullivan** QD Vision, Inc.
34	Investigation of Long-Term OLED Device Stability via Transmission Electron Microscopy Imaging of Cross-Sectioned OLED Devices	**Gao Liu** Lawrence Berkeley National Laboratory
35	Materials Degradation Analysis and Development to Enable Ultra Low Cost, Web-Processed White P-OLED for SSL	**Devin MacKenzie** Add-Vision Inc.
36	Low Cost, High Efficiency Polymer OLEDs Based on Stable p-i-n Device Architecture	**Devin MacKenzie** Add-Vision Inc.
37	Charge Balance in Blue Electrophosphorescent Devices	**Asanga Padmaperuma** Pacific Northwest National Laboratory
38	Development of Stable Materials for High-Efficiency Blue OLEDs through Rational Design	**Asanga Padmaperuma** Pacific Northwest National Laboratory
39	High Stability Organic Molecular Dopants for Maximum Power	**Daniel Gaspar** Pacific Northwest National Laboratory
40	Multi-Faceted Scientific Strategies Towards Better Solid-State Lighting of Phosphorescent OLEDs Phosphors	**Mohammad Omary** University of North Texas
41	Solution-Processed Small-Molecule OLED Luminaire for Interior Illumination	**Ian Parker** DuPont Displays, Inc.
42	High Quantum Efficiency OLED Lighting Systems	**Joe Shiang** GE Global Research
43	Application of Developed APCVD Transparent Conducting Oxides and Undercoat Technologies for Economical OLED Lighting	**Gary Silverman** Arkema, Inc.
44	High Triplet Energy Transporting Materials and Increased Extraction Efficiency for OLED Lighting	**Franky So** University of Florida
45	Top-Emitting White OLEDs with Ultrahigh Light Extraction Efficiency	**Jiangeng Xue** University of Florida
46		
47		
48		