Roundtable Discussions of the Solid State Lighting R&D Task Structure

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DISCLAIMER

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COMMENTS

The Department of Energy is interested in feedback or comments on the materials presented in this document. Please write to James Brodrick, Lighting R&D Manager:

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1. Introduction

The Multi-year Program Plan (MYPP) for Solid-State Lighting (SSL) forms a basis on which the Department of Energy (DOE) develops research and development (R&D) funding solicitations. This plan is in a process of continual development and is updated annually. The MYPP outlines several overarching goals for the program, a timeline for the goals' achievement and a specific set of R&D tasks to be performed in advancing its objectives. The current task structure[1] has become outdated as it was first developed for a DOE program planning workshop in November of 2003. To address this issue, DOE invited approximately 25 experts in SSL to roundtable discussions in Washington, DC on September 17 and 18, 2008 to reformulate the R&D task structure.

The September roundtables are followed by a series of conference calls to discuss tasks along with suitable metrics and specific targets. At the annual DOE SSL R&D Workshop in February information from the conference calls and this workshop will be used to establish the top priority tasks. Participants will be given an opportunity to revise the tasks and priorities before the final, updated SSL MYPP is targeted for release in March of 2009.

The roundtable discussions began with a brief introduction by James Brodrick, the solid-state lighting program manager at DOE. His introduction was followed by a presentation by Fred Welsh of Radcliffe Advisors. To stress the need for efficient lighting, Welsh highlighted DOE's goal to have the technologies ready to build net-zero energy buildings (ZEB) and homes (ZEH) by 2025. While the development of these technologies is a multifaceted problem, lighting provides the opportunity for a significant advance in energy efficiency. Welsh noted that lighting contributes 25% of commercial building energy consumption and 12% of residential home consumption. DOE's goal for solid state lighting is to halve lighting energy consumption in United States commercial and residential buildings, contributing substantially to the ZEB and ZEH goals.

The focus of the September 17 and 18, 2008 roundtable discussions was the fourth chapter of the MYPP – the Technology and R&D plan – which includes targets, tasks, and schedules. In past MYPP publications, the LED (and OLED) device has been the focus of improvement. However, because the LED device has experienced rapid development in the last few years, more emphasis at the roundtables was placed on the entire SSL luminaire.

As time progresses, product development will have increased emphasis as compared to core technology (applied research), and new metrics and targets may be necessary to continue to improve. The current MYPP contains some confusing and seemingly redundant tasks. The group was charged with working to clarify the distinctions among the tasks. The group was also charged with identifying linkages between product development and core technology tasks in order to help identify critical areas of

[1] Navigant Consulting, Inc., Radcliffe Advisors, and SSLS, Inc. *Multi-Year Program Plan FY'09-FY'14: Solid-State Lighting Research and Development.* March 2008. http://www.netl.doe.gov/ssl/PDFs/SSLMYPP2008_web.pdf

investigation. In addition to identifying linkages among tasks, estimating appropriate resource allocation and task duration estimates are also important, as DOE does not have the resources to fund every task discussed in the roundtables.

Following the introduction to the effort, participants presented their views on research topics of interest to the SSL R&D Program. For more information about these presentations, see Appendix C and Appendix D of this report. Information on the restructured research tasks can be found in Chapter 2 and Chapter 3 of this report.

2. Task Category Identification

The first group activity at the roundtable was identification of the major task categories. In the LED roundtable, the group brainstormed tasks and subtasks crucial to developing a quality LED luminaire and recorded these on the "fishbone" (Ishikawa) diagram shown in Figure 2.1 below. This cause-and-effect diagram gives some indication for later planning on the linkages among tasks. There are a number of principal task categories (the main "bones") and then tasks and subtasks (perhaps several levels of them) that feed into that category. After discussing the tasks and subtasks for the general LED luminaire, the roundtable discussion focused on developing a more detailed diagram of the tasks and subtasks necessary to develop a high quality LED module. This "subfish" is shown in Figure 2.2.

In the OLED roundtable, the participants took a similar approach to the development of the fishbone by identifying tasks and subtasks critical to the successful development of a quality OLED luminaire. A number of the same issues that were raised in the LED roundtable were also raised in the OLED roundtable. Note that the human factors tasks discussed for the LED luminaire are also applicable to OLEDs; thus, they were not included in the OLED task structure. Participants suggested a large number of tasks related to OLED panels, so the OLED panel task was broken into a "subfish" where the group recorded further subtasks.

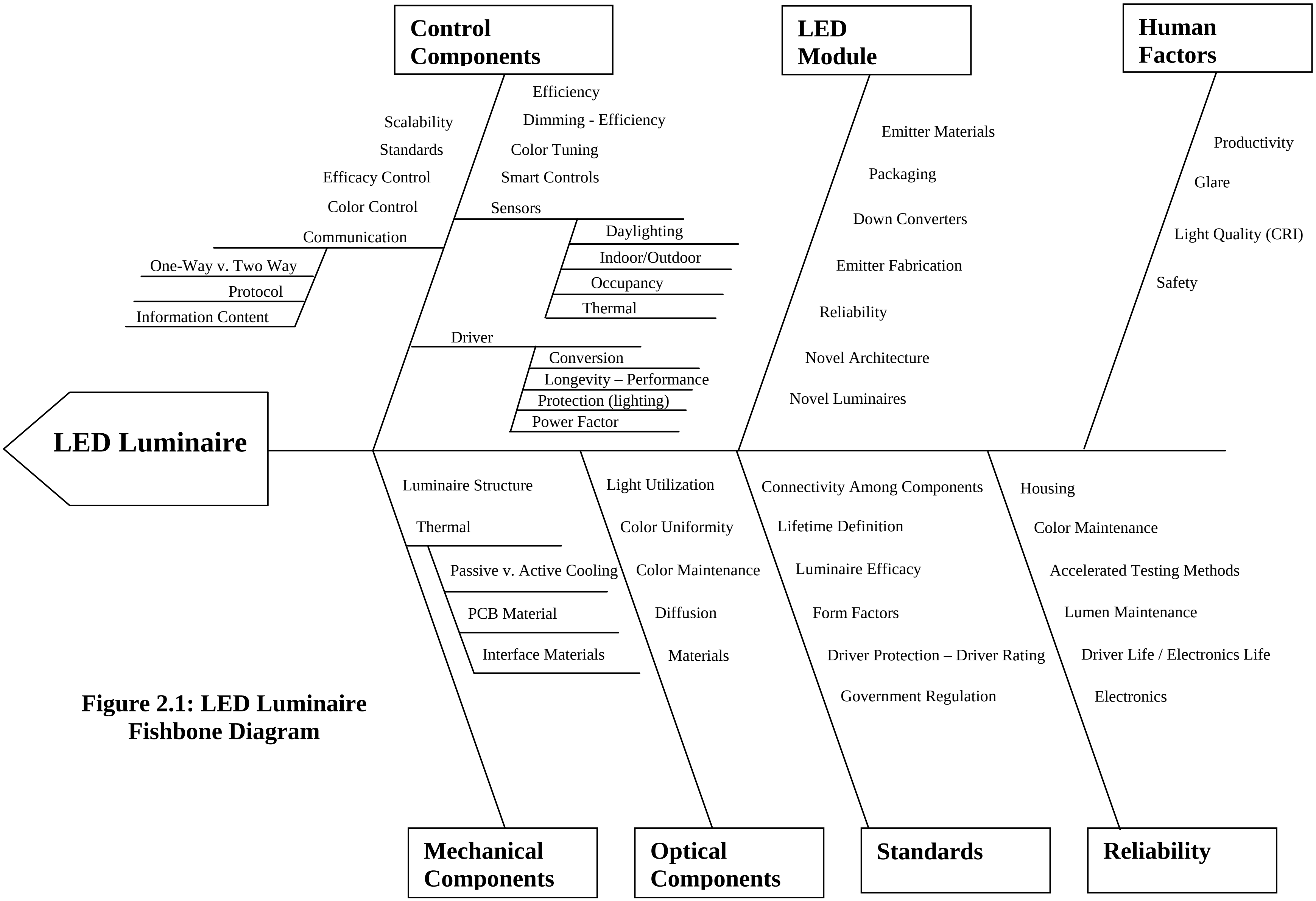


Figure 2.1: LED Luminaire Fishbone Diagram

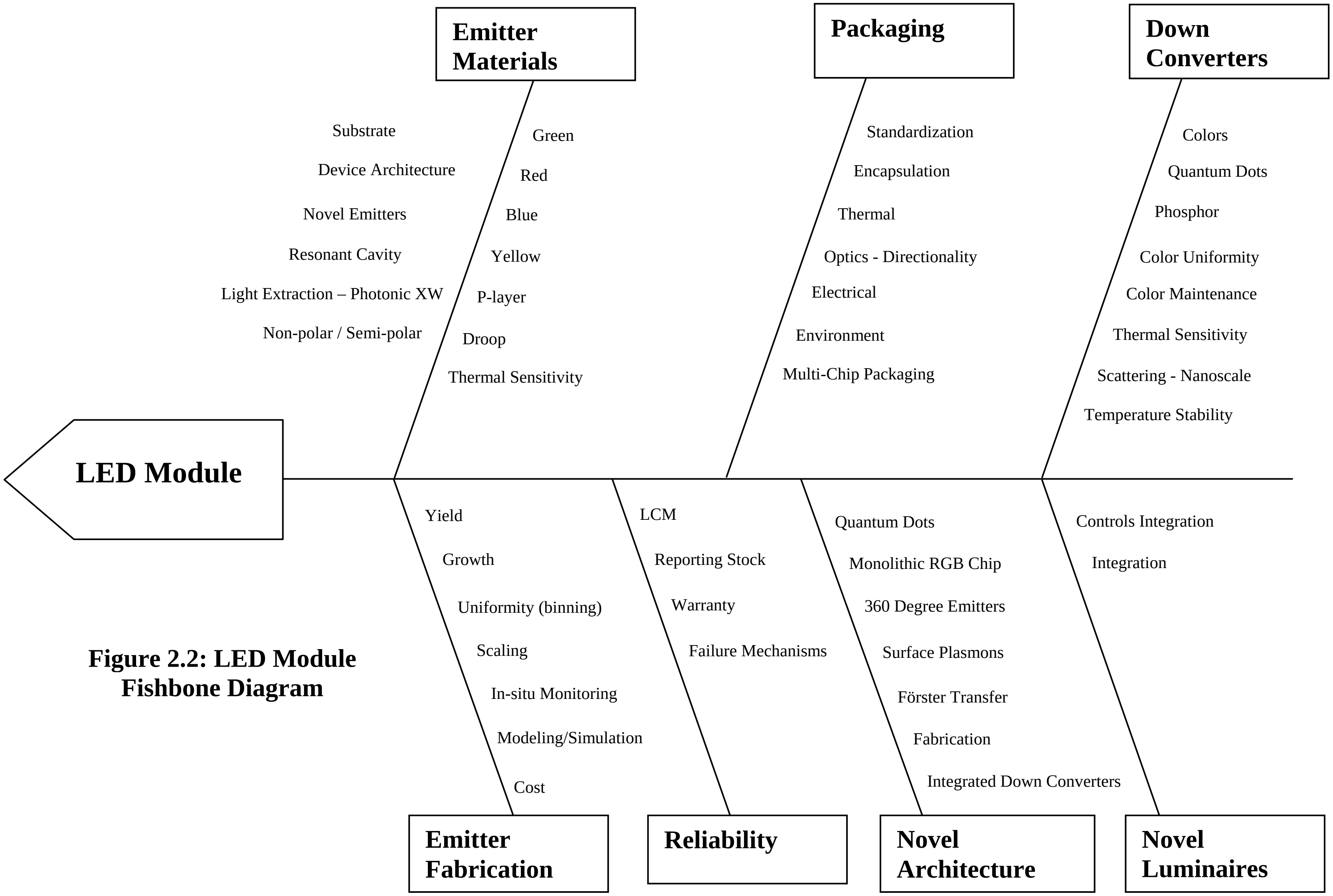


Figure 2.2: LED Module Fishbone Diagram

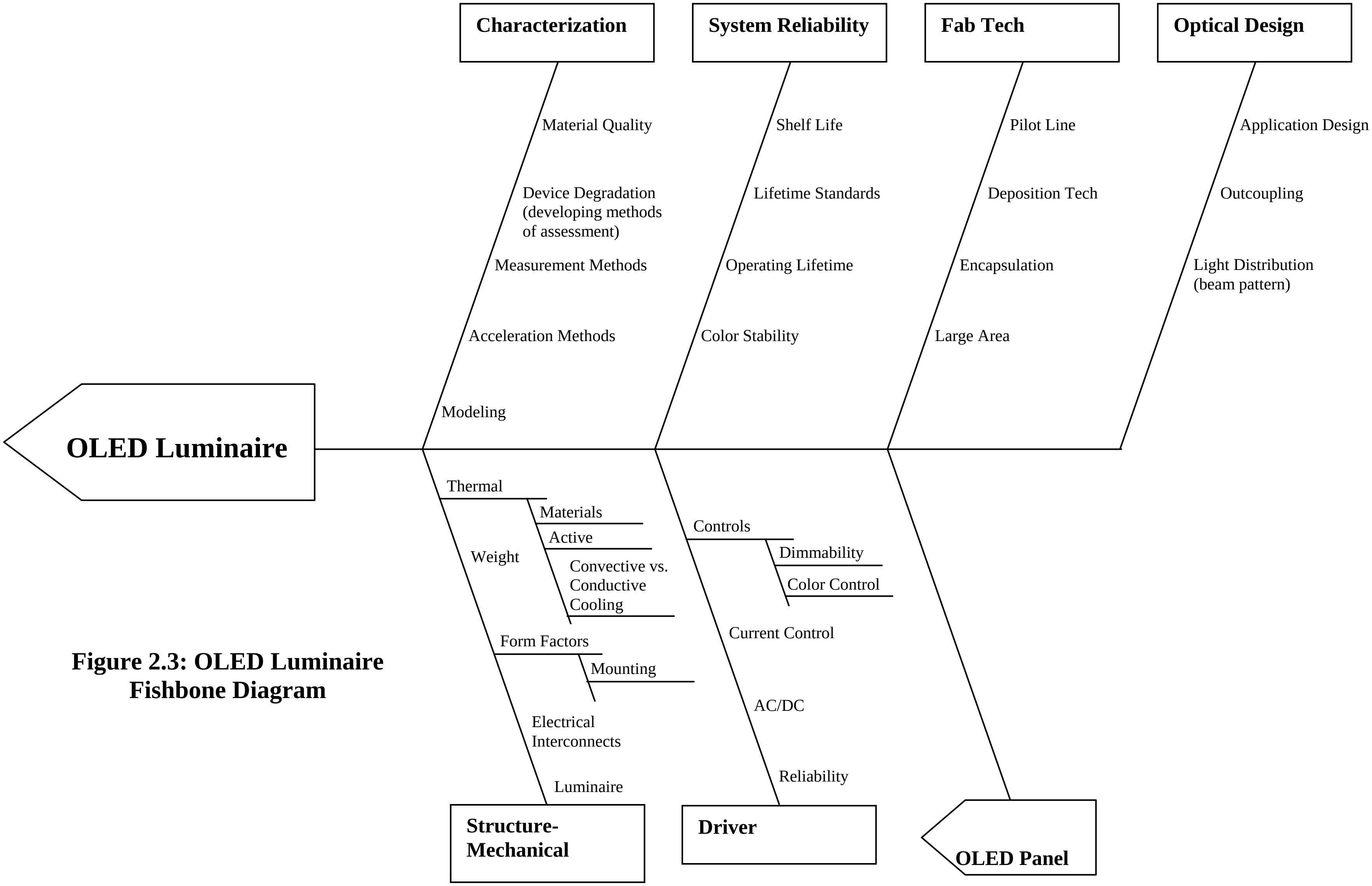


Figure 2.3: OLED Luminaire Fishbone Diagram

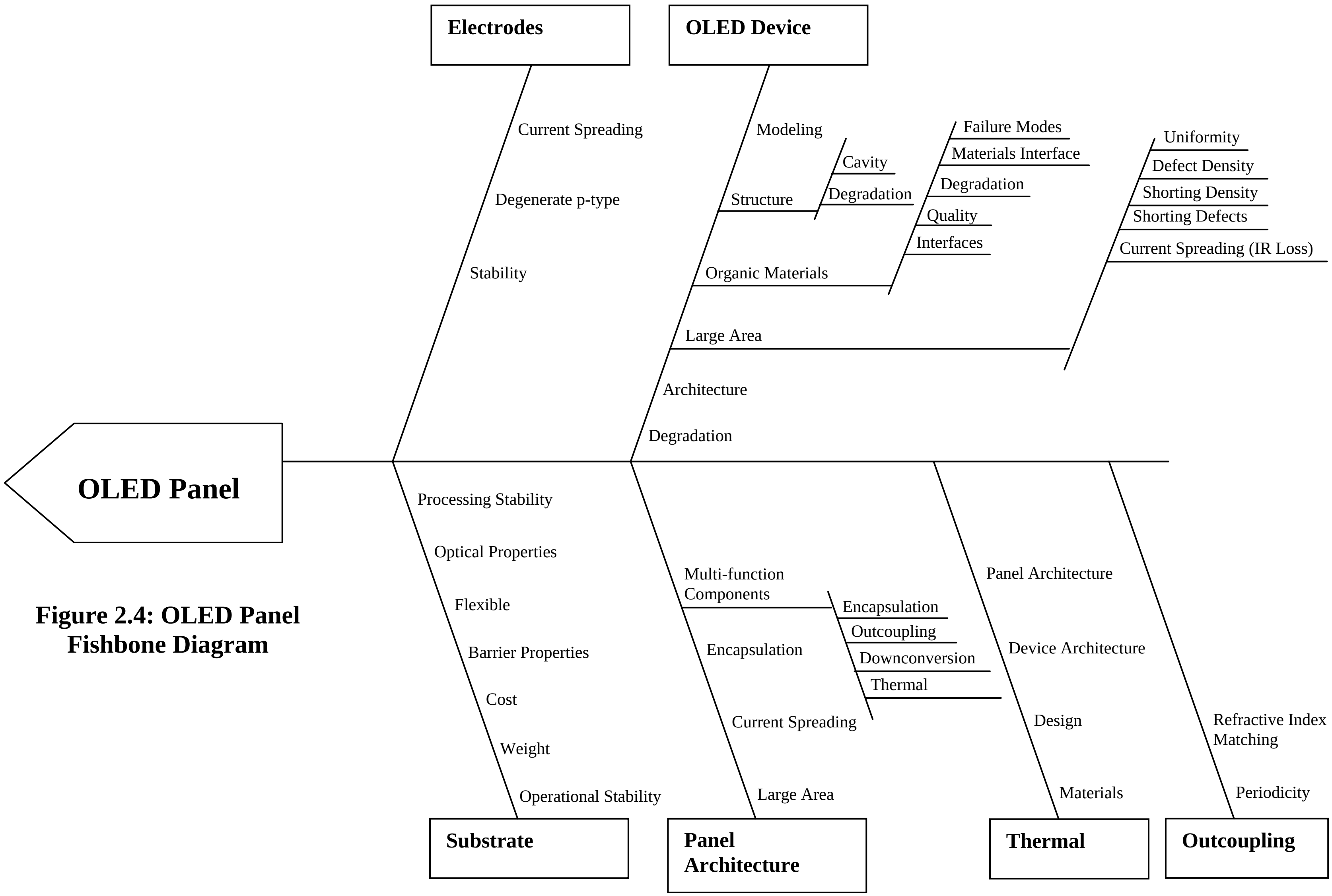


Figure 2.4: OLED Panel Fishbone Diagram

3. Task Information

The next phase was to discuss particular aspects of these tasks. In the LED roundtable, the group discussed what information should be contained in more specific descriptors for the subtasks associated with optical components, reliability, mechanical components, standards, human factors, and controls. For many of these subtasks, the group identified whether the subtask was focused on core technology research or product development. The group also discussed appropriate metrics that could measure progress for many subtasks. Table 3.1 shows tasks common to LEDs and OLEDs that were discussed in detail by roundtable participants. Table 3.2 shows LED luminaire tasks that were discussed in detail. While participants produced a subfish diagram for LED module tasks, only two of those tasks were discussed in further detail. They are included in Table 3.2.

Table 3.1: Common Tasks Discussed During the Roundtable

Task Category	Descriptive Title	Additional Description
Human Factors	Productivity	Investigate how productivity is affected by the quantity of light, quality of light, CRI, and interaction between the three. Understand consumer perception of mixed light sources.
	Glare	Investigate how glare is associated with correlated color temperature, point sources vs. diffuse sources, dark to bright background movement, and physiological differences in human perception.
	Light Quality (CRI)	Investigate redefining CRI for LEDs or develop a new, more meaningful metric.
	Safety	Improve safety and reduce energy consumption using variable brightness based on occupancy.

Table 3.2: LED Luminaire Tasks Discussed During the Roundtable

Task Category	Descriptive Title	Additional Description
Optical Components	Light Utilization	Maximize the ratio of useful light to total light to improve application efficacy.
	Color Uniformity	Eliminate rings of color and create consistency within chips, batches, and years (fewer bins).
	Diffusion	Understand the interaction between glare, intensity, and human perception based on background brightness.
	Material	Develop new materials, or improve current materials. Materials should not be brittle in response to UV light, and should be stable under high temperatures.
Reliability	Lumen Maintenance	Improve the luminaire's ability to operate under a wide range of ambient temperatures. Develop accelerated testing techniques.
	Driver Life / Electronics Life	Develop long life driver topologies.
	Color Maintenance	Improve all components related to color maintenance as any one factor affects the rest.
	Housing	Improve all structural components so no one component is the weakest link.
	Accelerated Testing Methods	Improve accelerated testing methods to make long term prediction possible.

Table 3.2: LED Luminaire Tasks Discussed During the Roundtable (continued)

Task Category	Descriptive Title	Additional Description
Mechanical Components	Thermal - Passive vs. Active Cooling	Develop passive and active cooling strategies.
	Thermal - PCB	Develop printed circuit boards for outdoor use.
	Thermal - Interface Materials	Develop and test materials to increase longevity and thermal performance.
	Overall	Design thermal management tools to protect the luminaire in a variety of environments using real life testing environments. Improve information flow from LED manufacturers to the luminaire manufacturer to enhance the overall process. Consider tests for LEDs that are not used in other forms of lighting.
Standards	Lifetime Definition	Define appropriate lifetime metrics. Determine end of life light function (dim to 50%, turn off, decline uncontrolled, etc.).
	Government Regulation	Support the creation of effective standards.
Controls	Color Control	Investigate methods to maintain color over the life of the unit. Consider dynamic controls to keep the color the same. Consider LEDs capable of producing multiple colors.
	Sensors	Develop controls that reduce a luminaire's power consumption when a location is unoccupied.
	Sensors - Indoor/Outdoor	Develop and improve upon indoor and outdoor occupancy sensors.
	Communication	Develop standard communication protocols. Develop methods of communication that lower costs of implementing control technologies.
	Driver	Improve efficiency of drivers especially at low drive currents.
	Driver - Longevity-Performance	Improve topology of driver to increase driver lifetime.
LED Module	Emitter Materials	Investigate emitter materials like non-polar bulk GaN for high efficiency.
	Standardization	Develop standardized LED Module form.

Similarly, the participants of the OLED roundtable discussed a number of subtasks and the associated descriptors, metrics, and type ("core" vs. "product"). Participants focused on driver, structural-mechanical, characterization, system reliability, fabrication technology, and OLED panel issues related to the development of an OLED luminaire. Tasks that were discussed in detail are shown in Table 3.3. For the OLED panel, participants further developed tasks related to the panel substrate, the panel architecture, thermal and outcoupling issues, and electrode and device issues. The OLED panel tasks that the group discussed in detail are shown in Table 3.4.

Table 3.3: OLED Luminaire Tasks Discussed in Detail in the Roundtable

Task Category	**Descriptive Title**	**Additional Description**
Driver	General	Develop high efficiency drivers suitable for OLED topologies.
Structure-Mechanical	General	Design a structure suitable for converting OLED panels into a luminaire. Weight, form factor, interconnects, and safety issues must be considered.
	Thermal - General	Develop thermal management solutions for luminaire-scale OLED products. These could consist of material technologies as well as active and passive cooling technologies.
	Luminaire	Develop and implement a study of luminaire design tradeoffs. Various factors related to architecture and application can be explored.
Optical Design	Light Distribution (beam pattern)	Explore how to extract light from a fixture in a controlled manner with minimal losses. Optical design may be dependent on application.
Characterization	Material Quality	Define material quality and determine for which materials it is most important. Explore what causes purity problems, and define the relationships between material quality and device performance.
	Device Degradation (developing methods of assessment)	Develop ways to measure degradation. This will aid in advancing the materials/structures development process.
	Acceleration Methods	Develop reliable accelerated testing methodologies that can be employed to study degradation over time.
Fab Tech	General	Develop new technologies for OLED deposition or encapsulation, such as materials and deposition methods.
System Reliability	General	Understand the failure mechanisms of the OLED lighting system. This includes research into environmental conditions or handling issues that may affect operating lifetime.
OLED Panel	See Table 3.4	

Table 3.4: OLED Panel Tasks Discussed in Detail in the Roundtable

Task Category	Descriptive Title	Additional Description
OLED Device	Modeling	Generate model material parameters and device models to accelerate the development of new materials and complicated device structures. This task should be coupled with experimentation.
	Organic Materials - General	Develop new ways of generating a stable, highly efficient blue that are compatible with the ultimate goal of stable white light generation.
	Organic Materials - Degradation	Evaluate the effects of degradation at the material level. This will aid in the understanding of OLED device lifetimes and failure modes.
	Large Area - Current Spreading	Research issues specific to large area devices such as current spreading, IR loss, and shorting defects.
	Structure - General	Develop structure designs that can be manufactured on a large scale at low cost.
	Structure - Degradation	Design a structure that can aid in the evaluation of the effects of OLED device structure degradation.
	Architecture	Investigate the applicability of various device architectures, such as top-emitting and bottom-emitting architectures. Explore the potential for mass manufacturing.
	Degradation	Investigate device-level degradation in OLED devices. This will increase knowledge of device lifetimes and failure modes.
Electrodes	General	Develop high performance, low voltage, low voltage electrodes. Investigate replacements for indium tin oxide (ITO) that are low-cost, flexible, and have the same or better performance.
Substrate	General	Develop low-cost OLED substrates. The substrate type may depend on the structure (e.g. flexible structures may need different substrates).
Panel Architecture	Multi-function Components - General	Investigate multi-functional components that may serve to aid in encapsulation, outcoupling, down-conversion, or thermal management.

4. Critical Issues

Although in principle, a good understanding of tasks, linkages, resources, and durations should identify the critical path for development, certain critical issues with unclear solutions could be major impediments to progress. The groups were asked to suggest potential roadblocks to the development of mainstream solid state lighting solutions.

A number of these roadblocks are common to the LED and OLED field:

- Cost reduction for a variety of system components and processes, from fabrication technology to raw materials, will be a challenge.

- Accelerated reliability testing methods for systems and materials is absolutely necessary for market penetration. Simply waiting for field test results will take too long. In particular, emitter materials have not been tested for long lifetimes. This uncertainty creates risk for manufacturers and consumers, potentially reducing adoption rates. The creation of reliability assessments will require larger quantities of products for testing.

- Consistency from brand to brand and year to year is necessary and will require standardization and improved manufacturing methods. Underwriters Laboratories (UL) standards organization must be made aware of advances in solid state lighting so that standards for LEDs and OLEDs can be developed in a timely fashion.

The roundtable participants identified a few issues specific to LEDs.

- There has been little emphasis on improving red light emission in wavelengths appropriate to lighting and efficiency which could impede LED development in the coming years.

- To meet high efficacy and price targets, the industry must find ways to minimize the amount of "droop" in efficiency that occurs at high drive currents.

The group also identified a number of critical issues specific to OLEDs.

- Development of a long-lasting blue emitter is critical.

- A breakthrough in fabrication technology that can readily produce large area OLEDs at low cost must occur.

- Substrates must be smooth, uniform, and inexpensive.

- The cost and future availability of indium, often used in OLED electrodes, is a concern. Other solutions for low-cost electrodes may be required.

- The development and adoption of LEDs and more mature lighting technologies such as fluorescents may draw attention away from OLEDs as a mainstream lighting technology.

Appendix A. Participants in the LED Roundtable, September 17, 2008

The following individuals participated in the LED SSL MYPP roundtable on September 17 of 2008:

Jim Beck, Optoelectronix

Paul Fini, Inlustra Technologies, LLC

Mark Hand, Acuity Brands Lighting, Inc.

Angela Hohl-AbiChedid, Osram Sylvania, Inc.

Bernd Keller, CREE, Inc.

Mike Krames, Philips Lumileds Lighting Company

Cameron Miller, National Institute of Standards and Technology

Russ Mortenson, QuNano AB

Theodore Moustakas, Boston University,

Gerry Negley, CREE, Inc.

Christopher Ruud, Ruud Lighting, Inc.

Jerry Simmons, Sandia National Laboratories

Jeff Tsao, Sandia National Laboratories

Christian Wetzel, Rensselaer Polytechnic Institute

Appendix B. Participants in the OLED Roundtable, September 18, 2008

The following individuals participated in the OLED SSL MYPP roundtable on September 18 of 2008:

Andy Albrecht, GE Lumination

Peter Djurovich, University of Southern California

Mike Hack, Universal Display Corporation

Mark Hand, Acuity Brands Lighting, Inc.

Russell Holmes, University of Minnesota

Jeff Tsao, Sandia National Laboratories

Lionel Levinson, Vartek Associates, LLC

Gao Liu, Lawrence Berkeley National Laboratory

Samuel Mao, Lawrence Berkeley National Laboratory

Asanga Padmaperuma, Pacific Northwest National Laboratories

Linda Sapochak, National Science Foundation

Joe Schiang, GE Global Research

Gary Silverman, Arkema, Inc.

Yuan-Sheng Tyan, Eastman Kodak Company

Appendix C. LED Participant Presentations, September 17, 2008

Some participants chose to prepare a short presentation outlining their most recent work and suggesting what they saw to be a key issue with LED lighting. The presentations are given below in the order that they were presented, along with short summaries. The final two presentations by Ruud and Keller were extemporaneous. Schowalter submitted a presentation but was unable to attend the roundtable.

Jerry Simmons, Sandia National Laboratory
Thoughts for EERE SSL LED Roundtable (Presentation 1)
Also presented in the OLED session by Jeff Tsao
Simmons noted that we need research into how people perceive color and whether they prefer wide or narrow band colors. He noted that red and blue should be narrow band colors so that the energy would not be wasted outside the visible spectrum. Finally, Simmons thought there is still efficacy (lm/W) headroom in LED development.

Mark Hand, Acuity Brands Lighting, Inc.
DOE SSL Roundtable
Hand discussed the debate of scotopic versus photopic vision and suggested that cool lights could be more efficient and more highly demanded by the market. Hand also spoke on standardization of the LED driver lifetime specifications. He stressed that currently the driver lifetime appears shorter than LEDs. In addition, stated that brightness specifications that consider glare are necessary for LEDs.

Angela Hohl-AbiChedid, Osram Sylvania
Color Shifts over lifetime in LED system
Hohl-Abichedid called for focus on increased longevity optical materials that were more resistant to color shift and heat damage. She also noted the challenge in the lengthy process of reliability testing and looked forward to accelerated testing procedures.

Jeff Tsao, Sandia National Laboratory
Thoughts for EERE SSL LED Roundtable (Presentation 2)
Also presented in the OLED session
Tsao looked at the macroeconomic impacts of a change to SSL, targeting the interaction between GDP, productivity, and the cost of energy. He saw that increased cost of energy would decrease GDP unless SSL could reduce energy consumption and increase productivity – leading to increased GDP. Tsao noted that effective usage of SSL through sensors and timers will determine how revolutionary the new technology can be.

Paul Fini, Inlustra Technologies, LLC
Non-polar & Semi-polar GaN Substrates for UHB-LEDs
Fini noted that polarization is the largest contributor to droop, a key performance limiter for high brightness LEDs. He discussed several approaches to resolving the issue of droop. In addition, Fini discussed the benefits to using GaN as a substrate for ultra-high brightness LEDs.

Theodore Moustakas, Boston University
Materials issues responsible for the green gap
Moustakas addressed possible origins of the reduced efficiency of InGaN LEDs. In particular, he stated that there may be both device and materials issues. With regard to materials issues, he discussed how atomic ordering may affect efficiency.

Christian Wetzel, Rochester Polytechnic Institute
Contributions to Solving the "Green Gap" in LED Technology
Wetzel stated that fundamental LED research is not complete and may require radically different approaches. In particular, he discussed several recent research areas on improving the efficiency of green LEDs.

Christopher Ruud, Ruud Lighting
Ruud emphasized the importance of recognizing the scotopic versus photopic response of the eye. He agreed that glare is a major problem with human perception and technical specifications on brightness of LED luminaires are important. He also mentioned that lumen maintenance has yet to be defined at the luminaire level for LED systems.

Bernd Keller, CREE
Keller suggested that DOE should be interested in the scalability and manufacturability of both the LED device and luminaire in order to help improve market penetration. Keller also warned against the industry depending on overseas infrastructure to manufacture LEDs.

Leo Schowalter, Crystal IS, Inc.
Though Schowalter was unable to attend the roundtable, his presentation was shown to the participants. The presentation highlighted Crystal IS's capability to fabricate low defect density AlN substrates and GaN on AlN substrates. Crystal IS also shared its plans for future work including GaN growth on m-plane AlN and developing a process for m-plane crystals for growth up to two inches.

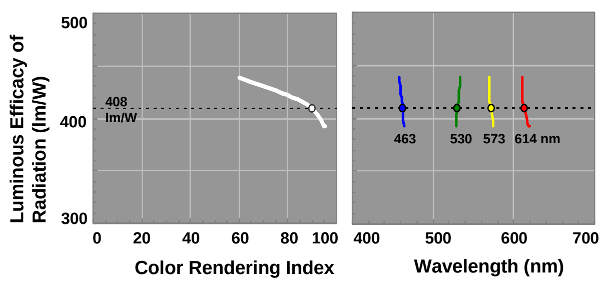
Thoughts for EERE SSL LED Roundtable

Jerry Simmons · Jeff Tsao
Physical, Chemical and Nano Sciences Center
Sandia National Laboratories

1. lm/W headroom
2. Red has been a forgotten challenge: Narrower linewidths and shorter wavelengths
3. EERE program emphasis can have big effect on cumulative energy savings

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Security Administration under Contract DE-AC04-94AL85000.

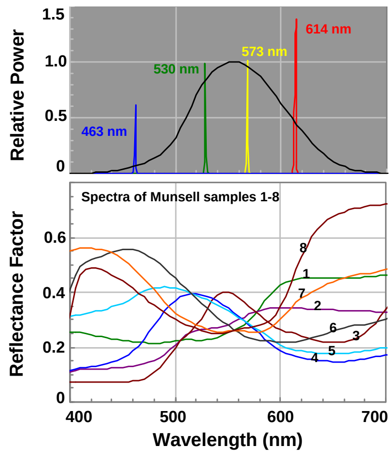
lm/W: may have more headroom than previously thought…



Reference	CCT (K)	CRI	Δλ (nm)	# Colors	LER (lm/W)	
Zukauskas App Phys Lett 2002	4,870	80	30	3	320	
Ohno SPIE 2004	3,300	80	20-30	3	359	MMY Plan
Ohno SPIE 2004	3,300	91	20-30	4	347	
Phillips/Ohno Las Phot Rev 2007	3,000	90	1	4	408	Latest

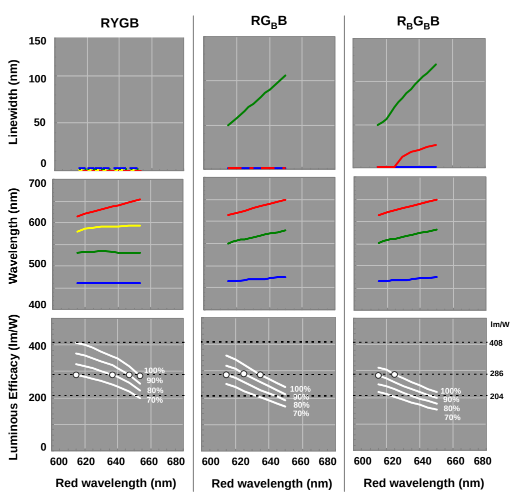
- Simulations using NIST CQS v7.1
- LER = 408 lm/W (higher than previous results in 320-360 lm/W range)
- Lower CCT and narrower linewidths
- Caveat: CRI metric…

Want narrower linewidths (especially in the red)



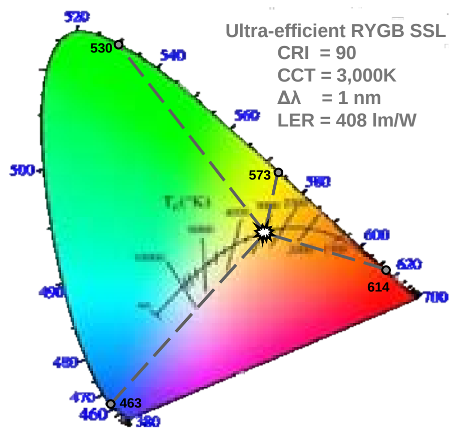
- Light sources with < 20 nm linewidths
  - are essentially delta functions against the Munsell samples' broad spectra
  - hence give similar CRIs regardless of linewidth
- Light sources with < 5 nm linewidths are
  - especially important in the red, to avoid spill-over into the deep red, where the human eye isn't very sensitive
  - less important in the blue, because low CCT implies less blue than red
  - Much less important in the green and yellow, where the human eye response is broad

Want shorter-wavelength red and RYGB or RG_BB



- The shorter the red wavelength, the higher the lm/W (until CRI 90 becomes difficult to maintain)
- With optimal red (614 nm), 286 lm/W = 70% of 408 lm/W requires individual light sources that are
  - RYGB: 70% efficient
  - RG_BB: 80% efficient
  - R_BG_BB: 90% efficient

The light source worth leapfrogging towards?



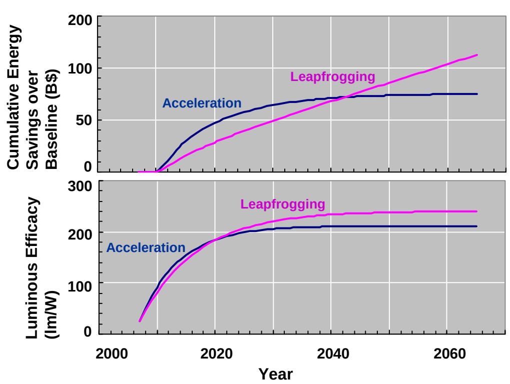
Critical S&T challenges for 286 lm/W

- High internal radiative efficiency in the shallow red (615 - 625 nm) from a primary semiconductor
- High internal radiative efficiency in the yellow-green (530 - 570 nm) from a primary semiconductor
- High (~100%) internal radiative efficiency in the blue (460 - 465 nm)
  - InGaN semiconductors: Understanding and ameliorating effects of
    - Extended defects
    - Point defects
    - Polarization effects
    - Compositional inhomogeneities (?)
    - High current injection
  - AlInGaP semiconductors
  - Other semiconductors: II-VIs?

Critical S&T challenges for 286 lm/W (cont.)

- Efficient narrowband (< 20 nm linewidth) shallow red (615 - 625 nm) emission from a phosphor that can be pumped in the blue (460 - 465 nm)
  - Micron-sized phosphors
  - Nanophosphors - effects of surface-active ligands, metal precursor ratios, dopant concentration
  - Quantum dots - toxicity, readsorption, monodispersion
  - Photon recycling semiconductors?
  - Direct energy transfer architectures (Forster transfer)?
- High efficiency (> 90%) and directional light extraction techniques
  - Photonic crystals to manipulate extraction and IQE
  - Stimulated emission - RCLEDs and LDs
  - Strong coupling regime
  - Plasmonic effects, including metamaterials

Accelerating vs Leapfrogging

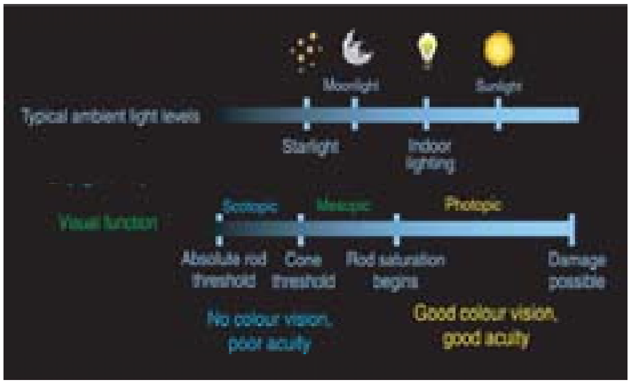


EERE program emphasis	Acceleration	Leapfrogging
Philosophy	Solving problems within existing materials and device paradigm	Exploring new materials and device paradigms
Time constant of progress	Faster than baseline SSL	Same as baseline SSL
lm/W at long times	Same as baseline SSL	Higher than baseline SSL
Cumulative energy savings	Saturates	Doesn't saturate


THINK
INNOVATION
FORM
ENERGY
SOLUTIONS
DOE SSL Roundtable
Presented by: Mark Hand
AcuityBrands
Lighting


AcuityBrands
LITHONIA LIGHTING
SPECLIGHT
HOLOPHANE
gotham
AEL American Electric Lighting
MetalOptics
HYDREL
PEERLESS
mark architectural lighting
ANTIQUE Street Lamps
CARANDINI
Synergy LIGHTING CONTROLS
SAERIS
ROAM

Scotopic vs. Photopic



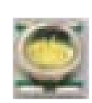
- Which is better?
- Physiological differences?
- Legislative issues?

NEED: Data to end the debate and direct development appropriately

LED Life vs. Driver Life

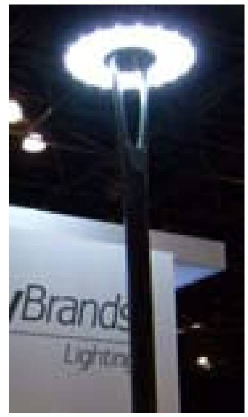

- LED life - 70% Lumen Maintenance
- Driver Life – MTBF, B10, L70?
- Driver life appears shorter than that of LEDs
- Luminaire Maintenance Costs



NEED: Driver technology to equalize LED and Driver life

Glare



- Multiple point sources vs. Single large light source
- Optical efficiency vs. Aesthetic effectiveness
- Lumens on task vs. Luminaire functionality

NEED: Data to end the debate and direct development appropriately

Color Shifts over lifetime in LED system

Color Maintenance

The change of chromaticity over the lifetime of the product shall be within 0.007 on the CIE 1976 (u'v') diagram.

? How to predict color shift over 35,000 hours?

? How do plastic materials/ Si change transmission properties as a function of wavelength and intensity.

Thoughts for EERE SSL LED Roundtable

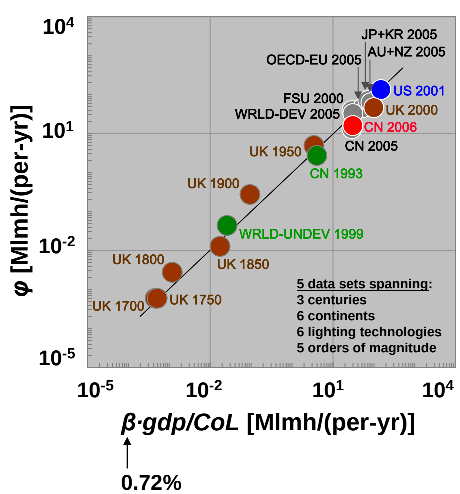
Jeff Tsao · Jerry Simmons
Physical, Chemical and Nano Sciences Center
Sandia National Laboratories

1. *φ* is more than *é*, it's also *gdp*
2. so *CoE*↑'s impact on *gdp* can be offset by η_φ↑
3. provided η_φ↑ is accompanied by lighting productivity↑

Opportunity for EERE to broaden its scope to include not just lighting efficiency, but lighting productivity?

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Security Administration under Contract DE-AC04-94AL85000.

φ is more than just *é*, it's also *gdp*



per capita light consumption
per capita productivity
cost of light

- *φ*, *gdp* and *CoL*: two equivalent, empirical relationships
  - *φ* = *β·gdp/CoL*
  - *gdp* = *φ·CoL/β*
- Consistent with textbook economics' maximization of profit
  - *gdp* = $A\cdot\chi^\alpha\cdot\varphi^\beta$ (Cobb-Douglas)
  - *cost* = *χ·CoX* + *φ·CoL* (linear costs)
  - *profit* = *gdp* - *cost*

so *CoE*↑'s impact on *gdp* can be offset by η_φ↑

Energy intensity

$$\frac{\dot{e}}{gdp} = \frac{1}{CoE}\cdot\left[\frac{\alpha}{1+\kappa_\chi}+\frac{\beta}{1+\kappa_\varphi}\right]$$

per capita gross domestic product

$$gdp = A^{\frac{1}{1-\alpha-\beta}}\cdot\left[\frac{\alpha}{CoE\cdot(1+\kappa_\chi)/\eta_\chi}\right]^{\frac{\alpha}{1-\alpha-\beta}}\cdot\left[\frac{\beta}{CoE\cdot(1+\kappa_\varphi)/\eta_\varphi}\right]^{\frac{\beta}{1-\alpha-\beta}}$$

- **An increase in *CoE***
  - is the only sure way of decreasing *ė/gdp*
  - but also decreases *gdp*
- **An increase in η_φ**
  - can offset (or more than offset) the decrease in *gdp*

provided η_φ↑ is accompanied by lighting productivity↑


REVIEW

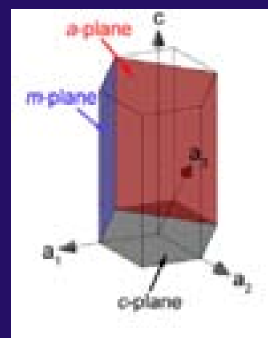
Solid-State Light Sources Getting Smart

- **Previous lighting transitions improved productivity enormously**
  - Cleanliness
  - Fast turn-on/turn-off
  - Decreased room heating
  - Reduced fire hazard
- **Will the SSL transition improve productivity similarly?**
  - Maybe: compactness, ruggedness, …
  - Maybe not: affordable real-time IP-addressable control of light characteristics (positioning, directionality, flux, color point, color rendering, luminous efficacy)?

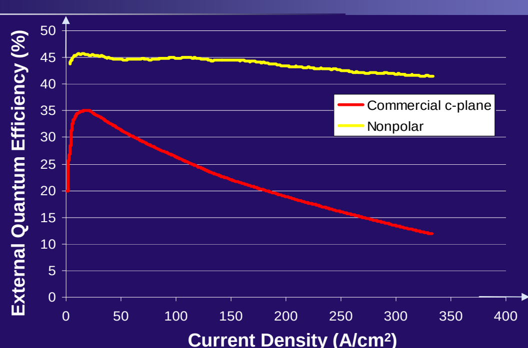
Non-polar & Semi-polar GaN Substrates for UHB-LEDs

Paul Fini
Inlustra Technologies

September 17, 2008



A key HB-LED performance limiter for SSL is "Droop"



Commercial c-plane

- Efficiency peaks at low drive current; drops as current increases
- Current approach: bigger chips; costly light extraction
- Lower wafer yields (larger chips) result in higher $ / lumen / chip

Non-polar material

- Higher peak efficiency
- Significantly less droop
- Smaller chips at higher current: increase lumens per area
- Cost reductions in fabrication, packaging

Polarization is likely the biggest contributor to droop

Theories

Polarization

- Supported by UCSB, RPI, Samsung
- Eliminating polarization minimizes EQE droop
- Supported by experimen[...] results

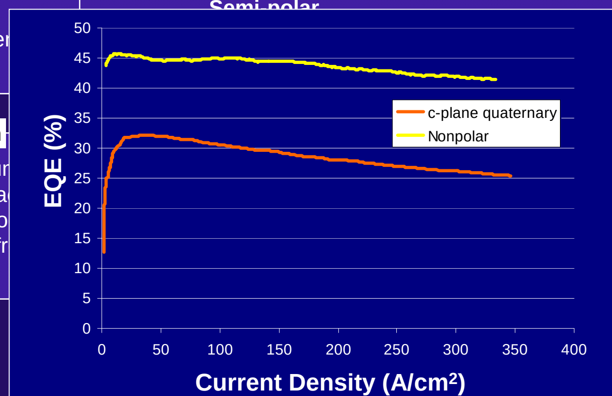
Auger Recombination

- Proposed by Philips Lu[...]
- Modification to device a[...] region could reduce dro[...]
- Disputed by modeling fr[...] other groups

Approaches to resolve droop

Non-polar
- No polarization for any composition

Semi-polar



Inlustra Technologies -- Proprietary and Confidential

GaN Substrates for UHB-LEDs

	Foreign Substrates	GaN Substrates
Lattice Matching	• Sapphire, Si: bad • SiC: better, but still high TDD	• Minimal mismatch with device layers
Thermal Expansion	• Sapphire: compressive • SiC, Si: tensile → cracking • Wafer bowing a real problem	• CTE closely matched to device layers
Growth	• LT buffer/nucleation layers • 2-4 µm 'base' n-GaN layer	• Direct re-growth with minimal buffer layer
Electrical Conductivity	• Sapphire: insulating • SiC, Si: acceptable	• Customized doping: SI, n, p • Back-side contacts: maximize device area, minimize etching

Inlustra Technologies -- Proprietary and Confidential

Materials issues responsible for the "green gap"

Theodore D. Moustakas

Electrical and Computer Engineering / Physics / MSE

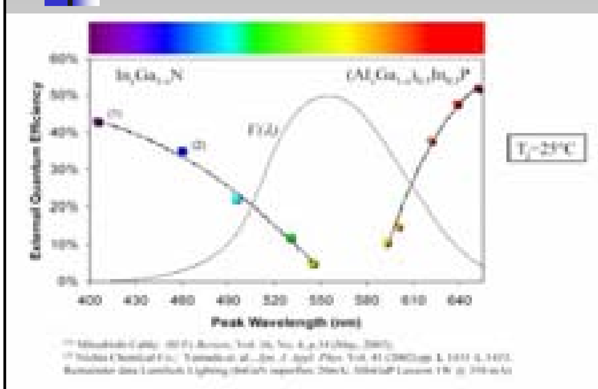
Boston University

DOE LED roundtable
Washington
Sept.17, 2008

Boston University

Wide Bandgap Semiconductors Lab

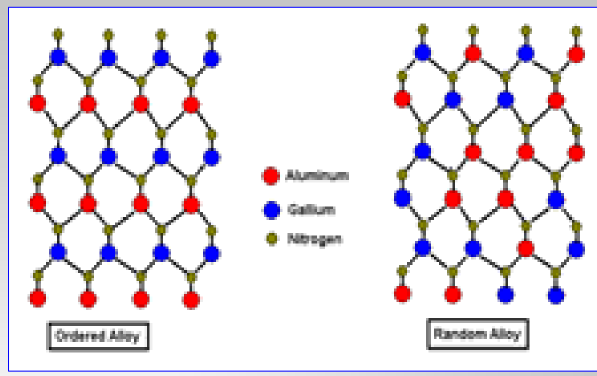
External Quantum Efficiency of Nitride and Phosphide LEDs



There is no consensus as to the origin of reduction of the efficiency of InGaN green LEDs

- Materials issues
- Device issues

Ordering in Nitride Alloys

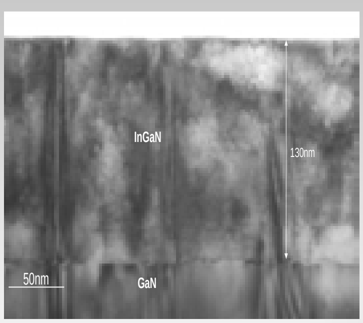


Origin of atomic ordering in Nitride alloys

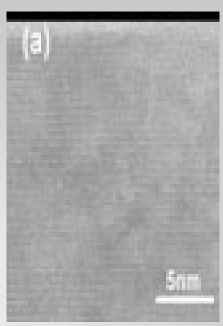
- To relief_due to the difference in the size of the group-III atoms
- The problem is more prominent in InGaN alloys because the In-atom is 11% larger than the Ga-atom

Boston University **Wide Bandgap Semiconductors Lab**

Nanoscale ordering in InGaN alloys



InGaN film grown on GaN



Random Domain

Ordered Domain

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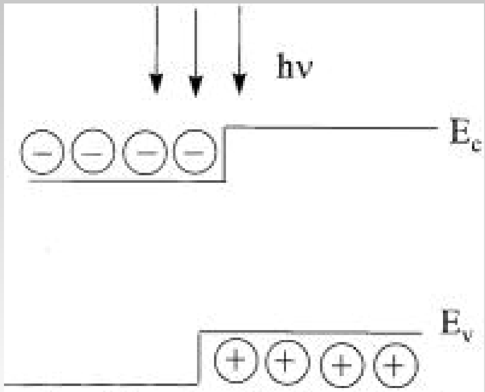
Band alignment of ordered and random domains in Nitride alloys (Type-II heterostructure)



Ordered domain   Random domain

Experimental Evidence:

Misra et al., *Appl. Phys. Lett.* **74**, 2203 (1999)

Theory

S. V. Dudiy and Alex Zunger, *Appl. Phys. Lett.* **84**, 1874 (2004)

- Transition from type-I to type-II heterostructure occurs at x=40 %

This charge separation reduces the rate of spontaneous radiative recombination, which is detrimental to LED efficiency

Boston University   Wide Bandgap Semiconductors Lab

Contributions to Solving the "Green Gap" in LED Technology

Christian Wetzel and Theeradetch Detchprohm

Future Chips Constellation
Department of Physics, Applied Physics and Astronomy
Rensselaer Polytechnic Institute
Troy, NY

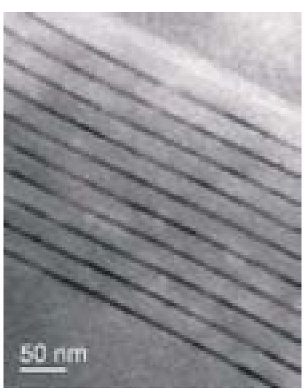
DOE
Solid State Lighting
Roundtable

Washington, DC, Sept. 17, 2008

Performance Polar c-Plane Green LED on Sapphire

bare fabed die

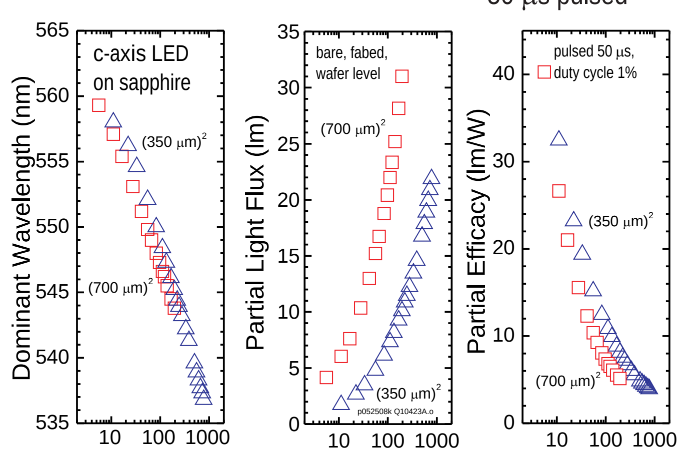
Transmission Electron Microscopy (TEM)



No V-defects

No misfit dislocations

50 µs pulsed

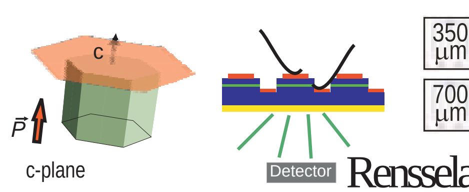


C. Wetzel, et aL J. Cryst. Growth *accepted* (2008)

bare 700 µm fabed die,

un-thinned, wafer level

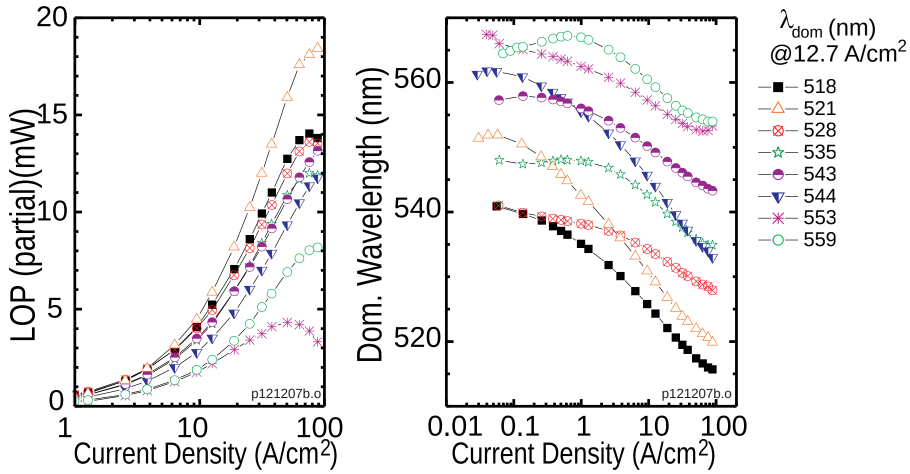
700 mA: 544 nm dom.
31 lm partial
8 lm/W partial

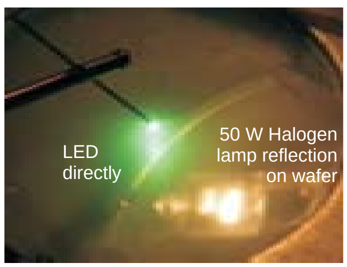


M. Zhu *et al*. Mater. Res. Soc. Symp. Proc. 1040E, 1040-Q03-02 (2008).

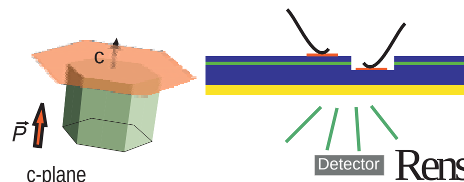
Green Performance without V-Defects

scratch diodes





T. Detchprohm, *et al.*
phys. stat. sol. (2008 *in print*)

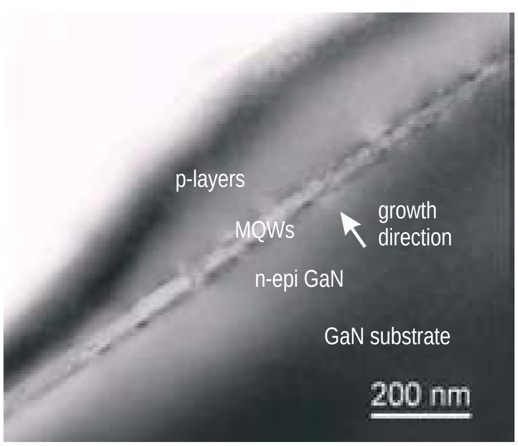


Rensselaer
Future Chips Constellation

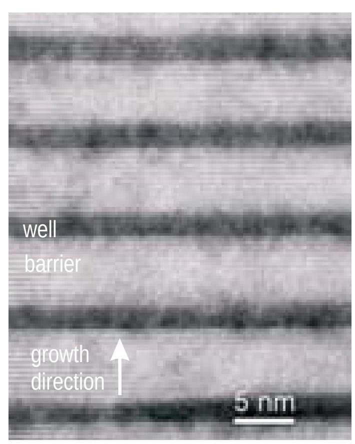
C.Wetzel
P080408a.c

Green c-Axis LED Epi on GaN

current status, scratch diode



TEM

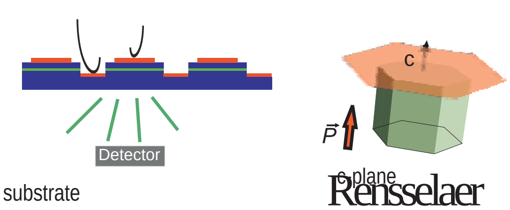


High resolution TEM

M. Zhu, *et al.*
Mater. Res. Soc. Symp. Proc. 1040E (2008)

M. Zhu, *et al.*
J. Electron. Mater. **37**(5), 641-645 (2008).

Current Dens. (A/cm^2)	Wavel. (nm)	FWHM (nm)	LOP (mW)	Lum. (L)	Efficacy (L/W)
2	531.5	55	3.79	1.86	15.38
5	520.1	58	11.01	4.90	5.49



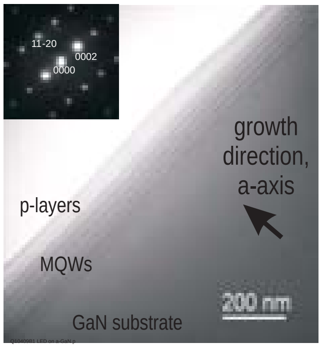
Rensselaer
Future Chips Constellation

C.Wetzel
P080408a.c

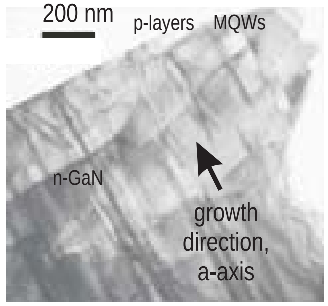
Non-Polar a-Plane Homoepitaxial LED

control polarization

TEM

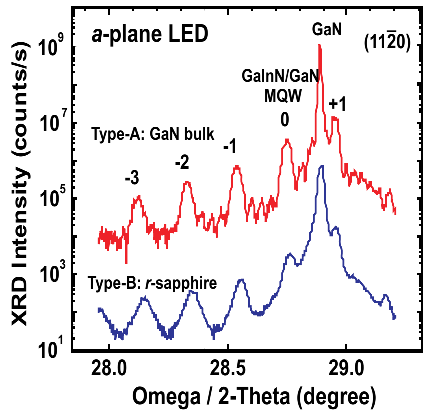


on a-plane bulk GaN



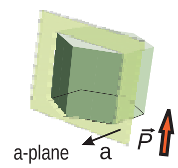
on r-plane sapphire

XRD



T. Detchprohm *et al.*
Appl. Phys Lett. **92**, 24119 (2008)

C. Wetzel, *et al.*,
J. Cryst. Growth **310**, 3987-91 (2008)

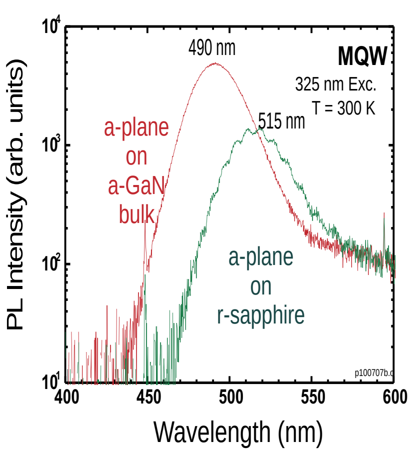


C.Wetzel P080408a.c Rensselaer Future Chips Constellation

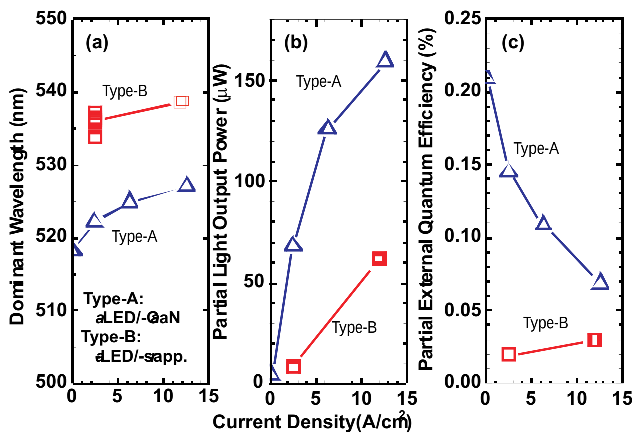
Non-Polar a-Plane Homoepitaxial LED

first green non-polar LED

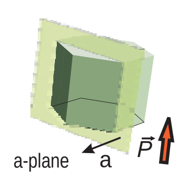
PL MQW



EL LED



T. Detchprohm *et al.*
Appl. Phys Lett. **92**, 24119 (2008)
C. Wetzel, *et al.*,
J. Cryst. Growth **310**, 3987-91 (2008)



C.Wetzel P080408a.c Rensselaer Future Chips Constellation

Crystal IS
Innovative Semiconductors

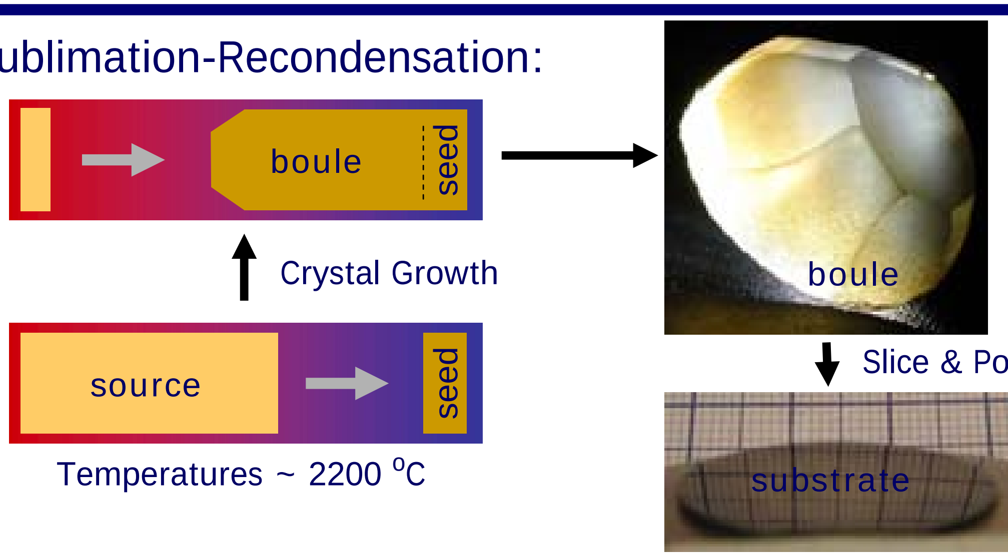
Company Overview

- Crystal IS is the world leading manufacturer of low defect aluminum nitride (AlN) substrates
  - Defect Densities are <1E+4cm^{-2} on c-plane
- We have epitaxial growth capabilities in house and have demonstrated low defect gallium nitride (GaN) grown on our AlN substrates
  - Defect Densities demonstrated <1E+6cm^{-2}
  - Further development work is required
- We have 10x10mm substrates commercially available and have demonstrated 2-inch AlN
  - C-plane and m-plane available in 10x10mm
  - 2-inch has been demonstrated in c-plane

Crystal IS
Innovative Semiconductors

AlN Bulk Crystal Growth

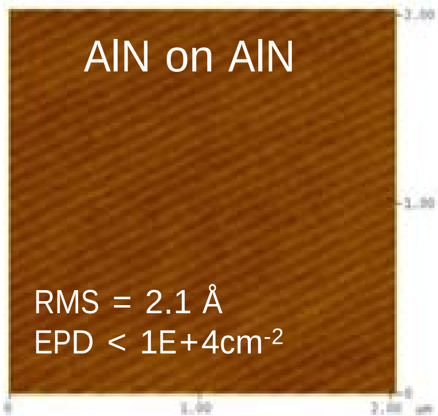
Sublimation-Recondensation:

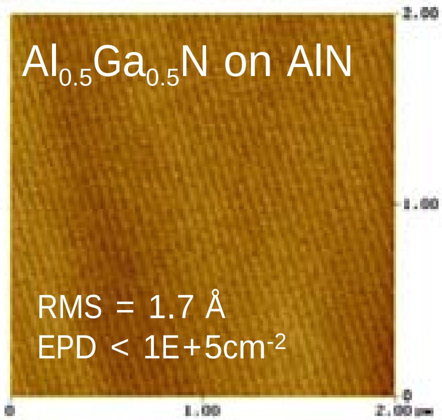


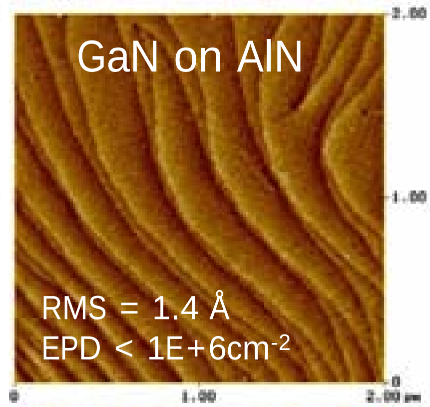
Crystal IS has a unique and patented process for growing high purity AlN crystals and manufacturing high quality AlN substrates from these crystals

- Crystals are currently grown in c-plane
- Because they are bulk crystals, they can be cut in c-plane or m-plane
- Feasibility of m-plane crystal growth has been shown, but more development is required

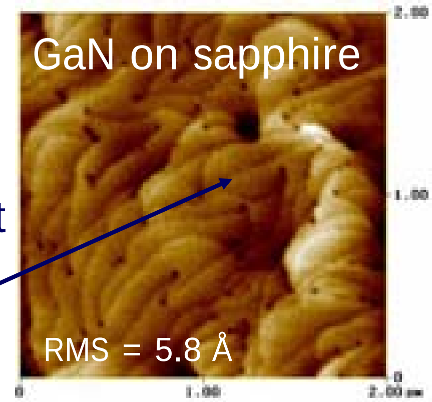
High Quality Epitaxy on AlN Substrates







- Significantly fewer dark pits evident and good smooth surfaces for epitaxy grown on AlN substrates.
- EPD of epitaxy on AlN measured after hot KOH etch.



Threading dislocation estimated from AFM images ~ 2 x 10^9 cm^{-2} on sapphire

Further Work

Development Program	Current Status	Further Work Required
Low Defect GaN growth on c-plane AlN	Demonstrated <1E+6cm^{-2}	Improve reproducibility of GaN growth and demonstrate benefits of low EPD substrates in devices (work underway through DOE award DE-FE26-08NT01578)
Low Defect GaN growth on m-plane AlN	Initial work started	Understand defects in m-plane GaN on AlN and demonstrate low defect growth. Demonstrate device benefits.
m-plane crystal growth	Feasibility study conducted successfully	Develop process and expand growth to 2-inch

Appendix D. OLED Participant Presentations, September 18, 2008

Several participants in the OLED roundtable chose to give presentations outlining their work or their thoughts on key issues in the OLED lighting field. The presentations are given below in the order that they were presented, along with short summaries. The final presentation by Linda Sapochak was extemporaneous.

Mark Hand, Acuity Brands Lighting, Inc.
OLED Device Luminance Specifications for Interior Lighting of Commercial Spaces
Hand provided tables of OLED sizes necessary to provide the same amount of light as a variety of fluorescent lighting system layouts. Hand used California's Title 24 watt/sq. meter energy requirements for office buildings as an upper limit on the amount of energy the systems can consume. He expressed that there are some benefits to creating smaller devices, but smaller devices must produce more light per unit area to achieve the equivalent foot-candles as larger devices.

Mike Hack, Universal Display Corporation
Enabling an Energy Savings OLED Lighting Industry
Hack presented a variety of technology and industry areas of focus for enabling an OLED lighting industry. He expressed that in order for OLEDs to become mainstream lighting sources, a diverse array of technology and industry issues must be resolved first.

Gary Silverman, Arkema, Inc.
Out-coupling Improvement of "Substrate/Grid Components"
Silverman discussed conductivity and transmission issues for net anodes and presented research into zinc oxide (ZnO) as a material for net anodes. Silverman stressed that the conductivity and processing cost of net anodes must be improved, with the conductivity of copper being a desirable goal.

Jeff Tsao, Sandia National Laboratory
Thoughts for EERE SSL LED Roundtable (Presentation 1)
Also presented in the LED session by Jerry Simmons
Tsao noted that research is needed to determine how people perceive color and whether they prefer wide or narrow band colors. He noted that red and blue should be narrow band colors so that the energy would not be wasted outside the visible spectrum. Finally, Tsao thought there is still efficacy (lm/W) headroom in LED development.

Jeff Tsao, Sandia National Laboratory
Thoughts for EERE SSL LED Roundtable (Presentation 2)
Also presented in the LED session
Tsao looked at the macroeconomic impacts of a change to SSL, targeting the interaction between GDP, productivity, and the cost of energy. He saw that increased cost of energy would decrease GDP unless SSL could reduce energy consumption and increase productivity – leading to increased GDP. Tsao noted that effective usage of SSL through sensors and timers will determine how revolutionary the new technology can be.

Asanga Padmaperuma, Pacific Northwest National Laboratory
2009 Multi-Year Project Plan Update Kickoff Roundtable
Padmaperuma presented considerations for improving the stability of OLEDs by developing more stable materials as well as barriers. He stated that much of the DOE SSL progress has been on device efficiency, but to meet the DOE goals of increasing usage in buildings, the SSL field must focus on widespread adoption. This necessitates a focus on product stability.

Gao Liu, Lawrence Berkeley National Laboratory
Advanced Characterization Methods for OLED Devices
Liu presented a variety of complementary advanced characterization methods that may be able to answer how devices degrade differently on different substrates. Liu stressed the need to assess degradation in devices before and after their operation and discussed the variety of advanced characterization methods already available to perform such assessments. He also stated that collaboration between industry and national laboratories may lead to the development of improved characterization methods.

Yuan-Sheng Tyan, Eastman Kodak Company
Roadmap & Future Predictions Consistent with ENERGY STAR Requirements
Tyan discussed ENERGY STAR performance requirements, which emphasize luminaires rather than lamps, along with data showing that luminaire efficacies are much lower than lamp efficacies for a variety of lamp technologies. He also showed that ENERGY STAR color requirements have efficacy implications, as high efficacy OLED devices reported today may not always meet ENERGY STAR color requirements. Tyan stressed that the cost and efficacy implications of ENERGY STAR at the OLED device and luminaire level must be explored.

Samuel Mao, Lawrence Berkeley National Laboratory
Two Topics: OLED Core Research
Mao presented Hewlett-Packard's research into hybrid devices, which combine organic materials with inorganic semiconductors. He showed the performance of a hybrid OLED with a nanocrystal inorganic semiconductor. Mao also discussed some useful inputs and outputs for device-level simulation and stated that device simulation capabilities must be improved through collaboration.

Linda Sapochak, National Science Foundation
Sapochak discussed the implications of material purity on device lifetime. She stated that the relative purity of commercially available phosphors varies widely and that the OLED industry must understand material purity in order to take this variance into account. Sapochak also stressed that the OLED industry must understand which of the various types of material impurities have an effect on device lifetime.

OLED Device Luminance Specifications for Interior Lighting of Commercial Spaces

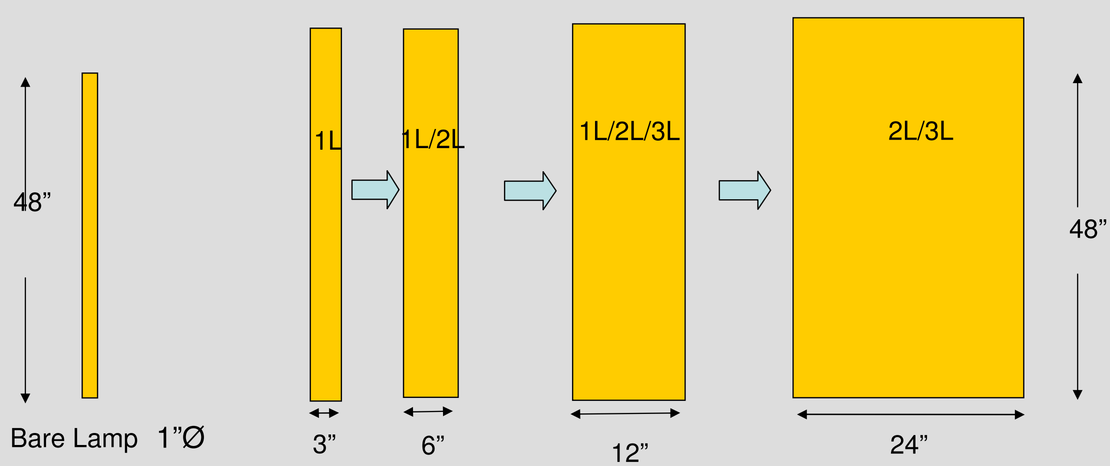
Peter Ngai
Innovation and Technology
Acuity Brands Lighting
Berkeley, CA

September 18th, 2008

Methodology of Analysis

Commonly Specified Luminaire Configurations in Commercial Spaces Lighting

T8 Bare Lamp Luminance = 9,000 cd/m² Lumen Output= 3000 L/Lamp



OLED SIZE ft²	1	2	4	8
OLED SIZE m²	0.1	0.2	0.4	0.8

Lighting Analysis

Size (0.1 m² , 0.2 m², .4 m², 0.8 m²)

Layout (W X L 8' X 8', 8 X 10',8' X 12')

Total Light Output – Lumens

Maintained Illuminance (FC)

Energy Consumption (W/ft²)

Luminance of OLED (cd/m²)

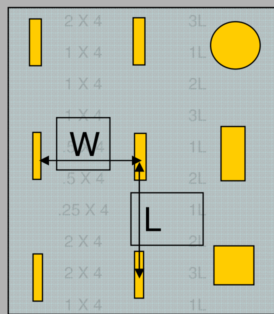
Efficacy :OLED =Fluorescent Assumed@100L/W

Values are approximate

No Optical Loss or Optical Control considered

Units of Measure are mixed

for easy of illustration



Layout of Luminaire W X L:

8' X 8', 8 X 10', 8' X 12'

O Lord, Four Slides Only!

>=20FC and <= 0.75 w/ft² (2010)

OLED Size Square Meter	Fluorescent Equivalence Size	#Lamps	wattage	Lumen	Layout	Area Illuminated	watt/sq.ft	Maint. FC	Luminance cd/m2
2 X 0.4	2 X 4	2L	60	6000	8X10	80	0.75	50	2250
2 X 0.4	2 X 4	2L	60	6000	8X12	96	0.63	41	2250
0.4	1 X 4	1L	30	3000	8X8	64	0.47	31	2250
0.4	1 X 4	1L	30	3000	8X10	80	0.38	25	2250
0.4	1 X 4	1L	30	3000	8X12	96	0.31	20	2250
2 X 0.2	1 X 4	2L	60	6000	8X12	96	0.63	41	4450
0.2	.5 X 4	1L	30	6000	8X8	64	0.47	31	4450
0.2	.5 X 4	1L	30	3000	8 X 10	80	0.38	25	4450
0.2	.5 X 4	1L	30	3000	8X12	96	0.31	20	4450
2 X 0.1	.5 X 4	2L	60	6000	8X10	80	0.75	50	8900
2 X 0.1	.5 X 4	2L	60	6000	8X12	96	0.63	41	8900
0.1	.25 X 4	1L	30	3000	8X8	64	0.47	31	8900
0.1	.25 X 4	1L	30	3000	8 X 10	80	0.38	25	8900
0.1	.25 X 4	1L	30	3000	8X12	96	0.31	20	8900

>= 20FC and <= 0.65 w/ft² (2011 Forward)

OLED Size	Fluorescent Equivalence					Area		Maint.	Luminance
Square Meter	Size	#Lamps	wattage	Lumen	Layout	Illuminated	watt/sq.ft	FC	cd/m2
2 X 0.4	2 X 4	2L	60	6000	8X12	96	0.63	41	2250
0.4	1 X 4	1L	30	3000	8X8	64	0.47	31	2250
0.4	1 X 4	1L	30	3000	8X10	80	0.38	25	2250
0.4	1 X 4	1L	30	3000	8X12	96	0.31	20	2250
0.4 m^2 (24"x24") Specifications: 2,500 cd/m^2 7,5000L/m^2 75W/m^2@100L/W									
2 X 0.2	1 X 4	2L	60	6000	8X12	96	0.63	41	4450
0.2	.5 X 4	1L	30	3000	8X8	64	0.47	31	4450
0.2	.5 X 4	1L	30	3000	8 X 10	80	0.38	25	4450
0.2	.5 X 4	1L	30	3000	8X12	96	0.31	20	4450
0.2m^2 (7"X17") Specifications:5,000cd/m^2 15,000L/m^2 150W/m^2@100L/W									
2 X 0.1	.5 X 4	2L	60	6000	8X12	96	0.63	41	8900
0.1	.25 X 4	1L	30	3000	8X8	64	0.47	31	8900
0.1	.25 X 4	1L	30	3000	8 X 10	80	0.38	25	8900
0.1	.25 X 4	1L	30	3000	8X12	96	0.31	20	8900
0.1m^2(12"X12") Specifications:10,000 cd/m^2 30,000L/m^2 300W/m^2@100L/W									

AcuityBrands Lighting

VISION | INNOVATION | REALITY

Enabling an Energy Savings OLED Lighting Industry

Universal Display Corporation

Sept 18, 2008

UNIVERSAL DISPLAY CORPORATION

PHOLED Lighting examples

PHOLED Ceiling Lighting

UNIVERSAL DISPLAY CORPORATION

Critical Elements for OLED Lighting

- Energy saving products
- Cost effective products
  - Initially niche
  - Followed by general illumination
- Infrastructure and supply chain
- Consumer education and acceptance

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Areas of Focus - Technical

- Higher performance OLED devices
  - Lifetime
  - Power efficacy over large areas
- Low cost substrates
- Lower resistance anodes (uniform and smooth)
- Cost effective outcoupling solutions
- Heat management schemes
- Thin Film Encapsulation
- Different form factors

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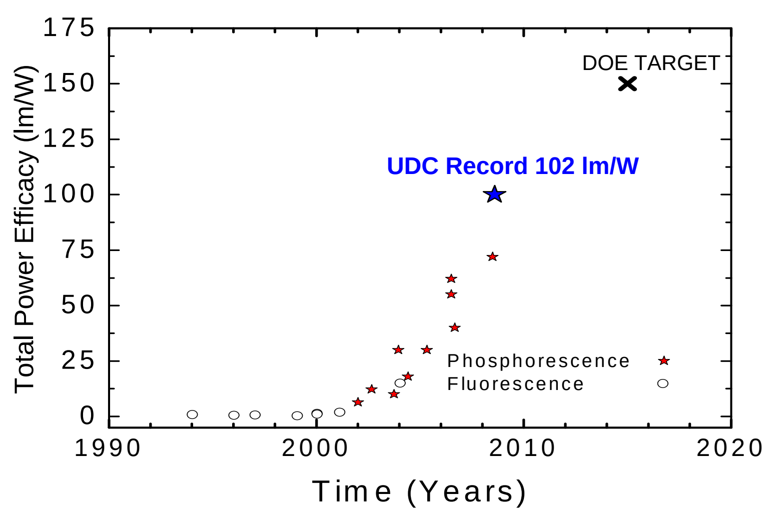
Areas of Focus - Industry

- High Utilization & Yield OLED Deposition Equipment
- PHOLED lamp manufacturers
- Prototypes
- Customer focus
- Creative product designers for industry launch
- Niche products for consumer awareness
- Driver electronics
- Luminaire integrators

PHOLED™ : The Low Power Advantage



2009 Multi-Year OLED Roundtable

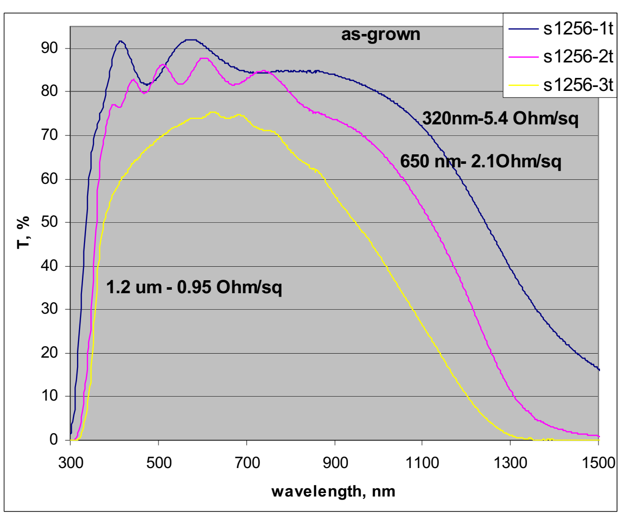
Out-coupling Improvement of “Substrate/Grid components”

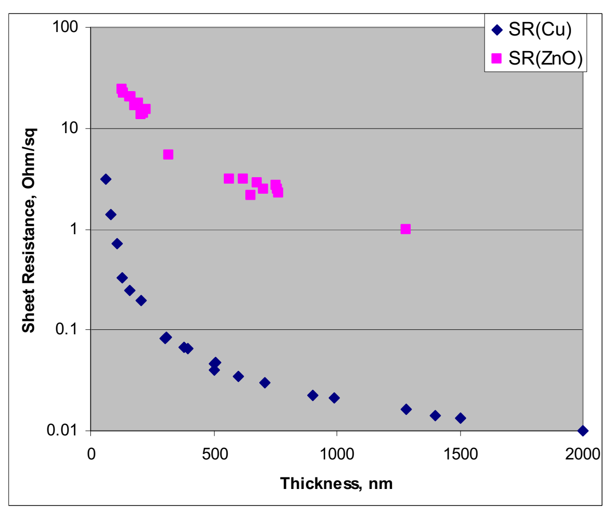
Gary S. Silverman, Ph.D.
Arkema, Inc.

September 18, 2008

ARKEMA

Issue – Obtaining conductivity & transmission targets for large area OLED lighting





- Metal grids work, but lose significant light out-coupling and processing cost.
- TCOs have limitations to get true metal-like conductivity

Targeted Solicitation Need

- Net anode structures that improve light out-coupling
- Improve net anode processing cost
- Combination of both

Thoughts for EERE SSL LED Roundtable

Jeff Tsao · Jerry Simmons
Physical, Chemical and Nano Sciences Center
Sandia National Laboratories

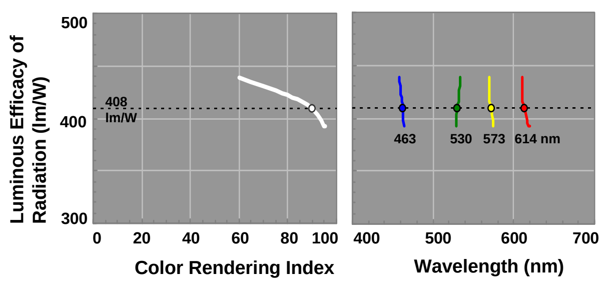
1. lm/W headroom

2. Red has been a forgotten challenge: shorter wavelengths and narrower linewidths

Opportunity for EERE to increase emphasis on the highest possible lm/W?

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Security Administration under Contract DE-AC04-94AL85000.

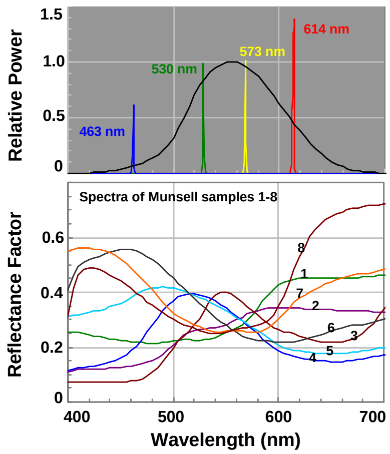
lm/W: may have more headroom than previously thought…



Reference	CCT (K)	CRI	Δλ (nm)	# Colors	LER (lm/W)	
Zukauskas App Phys Lett 2002	4,870	80	30	3	320	
Ohno SPIE 2004	3,300	80	20-30	3	359	**MMY Plan**
Ohno SPIE 2004	3,300	91	20-30	4	347	
Phillips/Ohno Las Phot Rev 2007	3,000	90	1	4	408	**Latest**

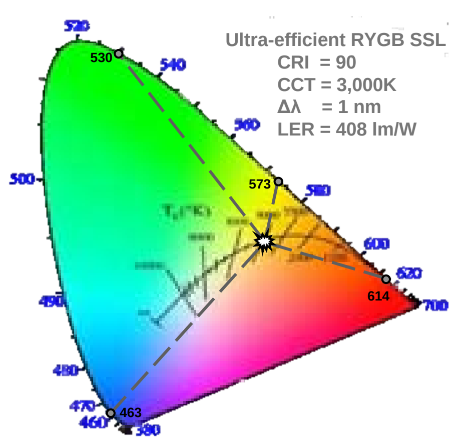
- **Simulations using NIST CQS v7.1**
- **LER = 408 lm/W (higher than previous results in 320-360 lm/W range)**
- **Lower CCT and narrower linewidths**
- **Caveat: CRI metric…**

Red has been a forgotten challenge: shorter wavelengths and narrower linewidths



- More lumens in red than in any other color
- Shorter red wavelengths
  - avoid the deep red, increasing lm/W
  - until CRI 90 becomes difficult to maintain
- Narrow (< 5 nm) red linewidths
  - Again, avoid spill-over into the deep red
  - OK for CRI based on Munsell samples' broad spectra

The light source worth leapfrogging towards?



Thoughts for EERE SSL LED Roundtable

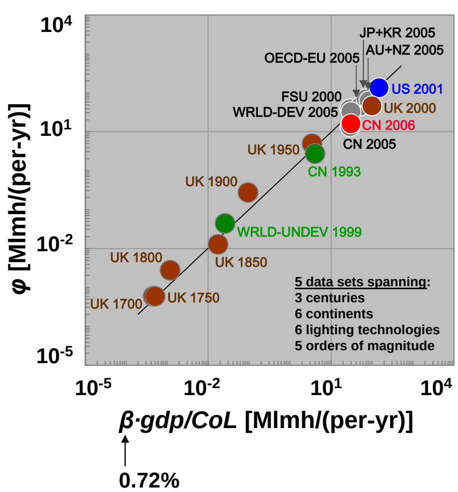
Jeff Tsao · Jerry Simmons
Physical, Chemical and Nano Sciences Center
Sandia National Laboratories

1. ***φ* is more than *é*, it's also *gdp***
2. **so *CoE*↑'s impact on *gdp* can be offset by η_φ↑**
3. **provided η_φ↑ is accompanied by lighting productivity↑**

Opportunity for EERE to broaden its scope to include not just lighting efficiency, but lighting productivity?

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Security Administration under Contract DE-AC04-94AL85000.

φ is more than just *é*, it's also *gdp*



↑
0.72%

per capita light consumption
per capita productivity
cost of light

- ***φ*, *gdp* and *CoL*: two equivalent, empirical relationships**
  - $\varphi = \beta \cdot gdp/CoL$
  - $gdp = \varphi \cdot CoL/\beta$
- **Consistent with textbook economics' maximization of profit**
  - $gdp = A \cdot \chi^{\alpha} \cdot \varphi^{\beta}$ **(Cobb-Douglas)**
  - $cost = \chi \cdot CoX + \varphi \cdot CoL$ **(linear costs)**
  - $profit = gdp - cost$

so *CoE*↑'s impact on *gdp* can be offset by η_φ↑

Energy intensity

$$\frac{\dot{e}}{gdp} = \frac{1}{CoE} \cdot \left[\frac{\alpha}{1+\kappa_\chi} + \frac{\beta}{1+\kappa_\varphi} \right]$$

per capita gross domestic product

$$gdp = A^{\frac{1}{1-\alpha-\beta}} \cdot \left[\frac{\alpha}{CoE \cdot (1+\kappa_\chi)/\eta_\chi} \right]^{\frac{\alpha}{1-\alpha-\beta}} \cdot \left[\frac{\beta}{CoE \cdot (1+\kappa_\varphi)/\eta_\varphi} \right]^{\frac{\beta}{1-\alpha-\beta}}$$

- **An increase in *CoE***
  - **is the only sure way of decreasing *ė/gdp***
  - **but also decreases *gdp***
- **An increase in η_φ**
  - **can offset (or more than offset) the decrease in *gdp***

provided η_φ↑ is accompanied by lighting productivity↑


REVIEW

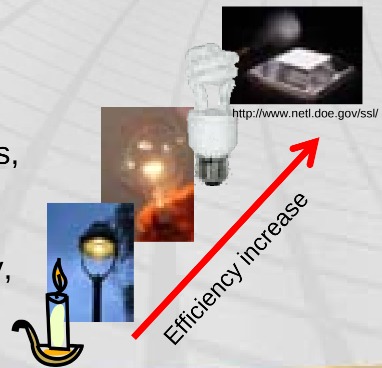
Solid-State Light Sources Getting Smart

- **Previous lighting transitions improved productivity enormously**
  - **Cleanliness**
  - **Fast turn-on/turn-off**
  - **Decreased room heating**
  - **Reduced fire hazard**
- **Will the SSL transition improve productivity similarly?**
  - **Maybe: compactness, ruggedness, …**
  - **Maybe not: affordable real-time IP-addressable control of light characteristics (positioning, directionality, flux, color point, color rendering, luminous efficacy)?**

2009 Multi-Year Project Plan Update Kickoff Roundtable

Asanga B Padmaperuma, Daniel J Gaspar, Gordon L Graff, Mark E Gross, Lelia Cosimbescu, Philip Koech

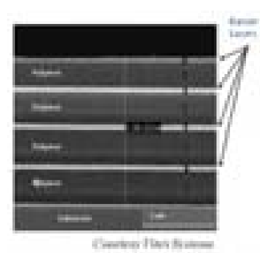
Pacific Northwest National Laboratory, Richland, WA



Pacific Northwest
NATIONAL LABORATORY

Low Cost Thin Film Barrier Solution for OLEDs

- **Identified need – develop a barrier**
  - High-volume, low-cost
- **Proposed solution**
  - Develop high volume techniques
  - Improve on barrier techniques for displays
  - Reduce the cost by order of magnitude
  - Increase the active area
- **Expected impact**
  - Commercial manufacture and widespread adoption of SSL products
- **Time frame**
  - Effort to begin immediately
  - Deliver to industry within 3-4 years
  - Incorporate added functionalities to the barrier

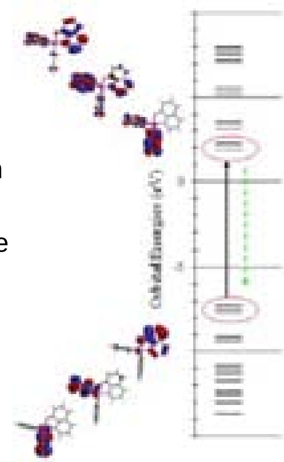


2

Pacific Northwest
NATIONAL LABORATORY

Continued work on stability and efficiency of OLEDs through material engineering

- **Identified need – develop materials**
  - That improve charge balance in OLEDs
  - That are stable under OLED operation
- **Proposed solution**
  - Degradation modes for some devices are known
  - More studies on degradation are needed
  - Not limited to post mortem analysis – real time measurement of device properties
- **Expected impact**
  - Higher power efficiency and longer lifetimes
  - Widespread adoption of OLED SSL products
- **Time frame**
  - Degradation be addressed immediately



3

Pacific Northwest
NATIONAL LABORATORY

Advanced Characterization Methods for OLED Devices

Solid-State Lighting Round Table Discussion
Building Technology Department
US DOE
September 18th, 2008
Washington DC

Gao Liu

Building Department
Environmental Energy Technology Division
Lawrence Berkeley National Laboratory

What and Why?

What included?

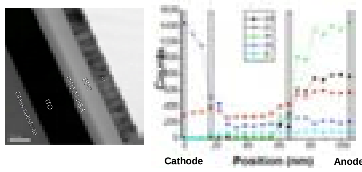
•Electron microscopy techniques.
•Synchrotron (Soft and hard x-ray based characterization, neutron diffraction, XPS etc.)
•Spectroscopic techniques. (UV, IR, Raman)
•Mass spectrum
•Chemical analysis ?

Why now?

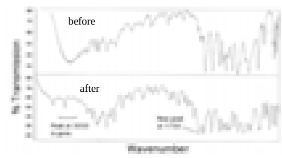
•Materials and device structures that can satisfy the performance for display applications are available, but how to push this technology for 50k hrs lifetime at a reasonable cost?
•Manufacture has to be simplified including low cost packaging technique.
•Understand long-term performance degradation mechanism.
•Understand degradation at various manufacture (including packaging) conditions.
•Literatures on the characterization techniques applied on the OLED are limited.
•Because of the unique structure of the OLED device, each available characterization techniques need to be refined.

What can they do?

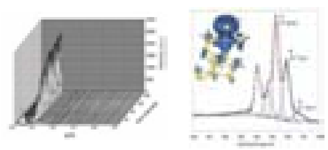
Electron Microscopy
Device Structure change and elemental distribution



Spectroscopy
Chemical structure –functional groups



Synchrotron
New phase formation, Chemical structure and interface



Mass spectrum
Segments of chemical structure.

Chemical analysis by NMR etc.
Chemical structure post-dissolution.

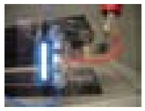
Why they haven't been done?

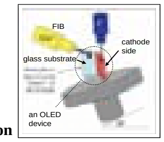
- Device failure study has always been part of the research of new material discovery and device design.
- We've already known some of the general failure mechanisms in OLED devices.

- We may need a major effort to study this if we want to accelerate the development of the OLED towards SSL applications.
- Experts in OLED may not be experts in the characterization methods.
- Advanced electron microscopy, synchrotron source are not easily available to many researchers, and may not be much interest to the manufacturers.
- Some routine analyses in other areas such as TEM for studying solid structures and MS in proteinomic are not routinely used in OLED research.
- OLED thin film device has unique structure properties that need significant, sometime novel, methodology development to adopted in studying OLED.
- Samples that suitable for long term stability analysis only available to the entities that with tight manufacture control.

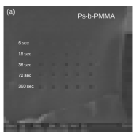
An Example

2. Device testing

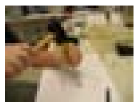


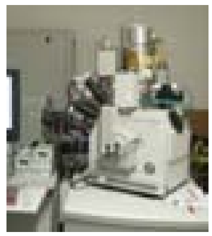


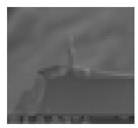
3. Sample preparation



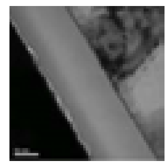
1. Stability study







4. TEM analysis



How can we do it and do it better?

National Labs
Characterization

Facilities and process developed in National Labs

Electron microscopy
Synchrotron
Materials
etc.

Industry
Device

Manufacture capabilities

Material development
Fabrication
Characterization
etc.

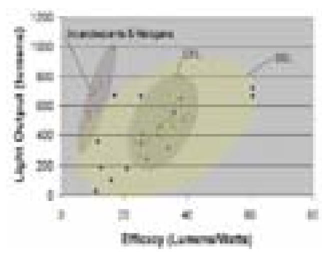
Roadmap & Future Predictions

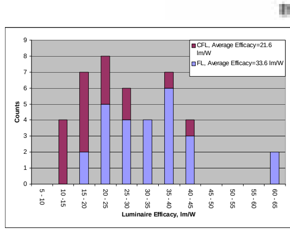
Consistent with Energy Star Requirements

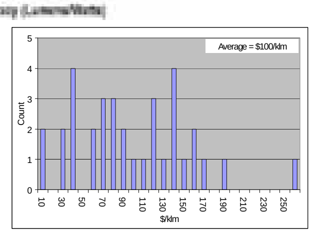
- Luminaire based
  - Performance
  - Cost
- Tolerance quadrangle for color

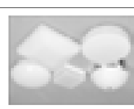
Competing Lighting Technologies

Source: DOE CALiPER Report



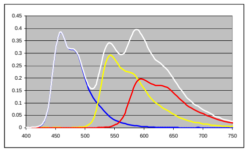


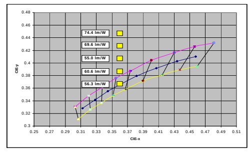


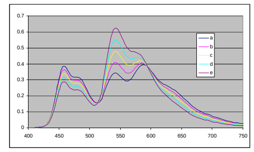


Source:

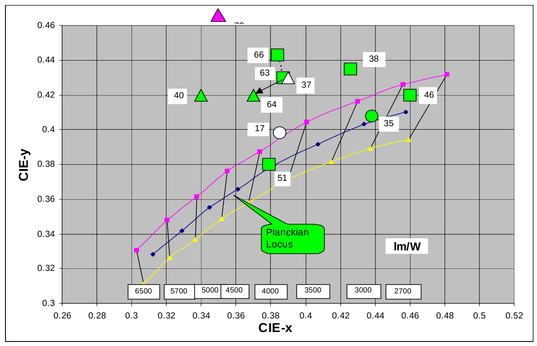
Color & Efficacy







675 lm/A; @ EQE = 25%; Voltage = 3.0 V; 56.3 lm/W



Funding Priorities

- Breakthrough manufacturing technology for vacuum deposited, small molecule OLED devices.
  - Beyond Aixtron, Vist
  - Low capital cost, high throughput
  - Complicated device structure

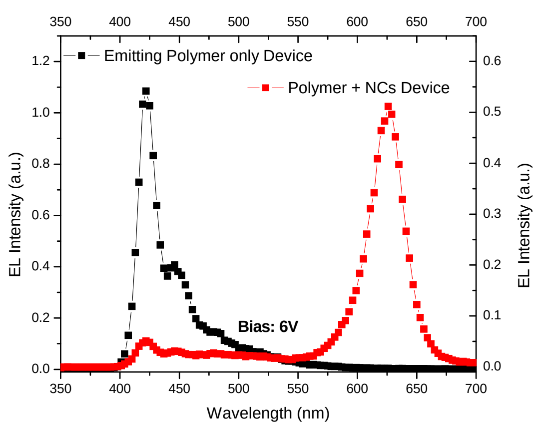
Two Topics: OLED Core Research

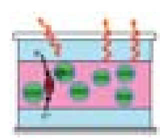
Samuel S. Mao
Lawrence Berkeley National Laboratory

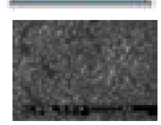
September 18, 2008

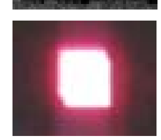
Opportunity: Hybrid Devices

<u>Efficient energy transfer between organic-inorganic semiconductors</u>









nearly 100% energy exchange

Opportunity: Device Simulation

<u>Comprehensive device-scale simulation</u>

Input
Comprehensive material property
Designed device architecture

Output
Charge distribution in device
Photon distribution in device
Current-Voltage curve
Luminance-Voltage curve
Device efficiency/efficacy