Basic Research Needs for Solid State Lighting: LED Science

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Acknowledgements

Basic Research Needs for SSL LED Science Panel

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Tony Cheetham (UCSB)           David Norton (U of Florida)
George Craford (LumiLeds)      Jasprit Singh (U of Michigan)
Mary Crawford (SNL)            Jim Speck (UCSB)
Dan Dapkus (USC)               Stephen Streiffer (Argonne)

Special thanks to...

Jeff Tsao (SNL)
Mary Crawford (SNL)
Mike Coltrin (SNL)
Outline

- Metrics for LED performance
- Approach of the BRN-SSL LED Science Panel
- LED-relevant *Priority Research Directions* (PRDs)

**LED PRDs**

**Cross-Cutting RDs**

http://www.science.doe.gov/bes/reports/list.html
Basic Energy Sciences

Effect of market adoption of 50% efficient SSL

- SSL has the potential, by 2025, to:
  - decrease electricity consumed by lighting by 62%
  - decrease total electricity consumption by 13%

Projected Year 2025 Savings (complete replacement)

<table>
<thead>
<tr>
<th></th>
<th>US</th>
<th>World</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity used (TW-hr)</td>
<td>620/year</td>
<td>1,800/year</td>
</tr>
<tr>
<td>$ spent on Electricity</td>
<td>42B/year</td>
<td>120B/year</td>
</tr>
<tr>
<td>Electricity generating capacity (GW)</td>
<td>70</td>
<td>~200</td>
</tr>
<tr>
<td>Carbon emissions (Mtons)</td>
<td>100</td>
<td>~300</td>
</tr>
</tbody>
</table>
Other performance metrics:

- Lamp power
- Cost
- Lifetime
- Directionality
- Operating temp
- Correlated Color Temp (CCST)
- Color Rendering Index (CRI)

Courtesy E.F. Schubert, RPI
Color Rendering Index (CRI) is a critical factor

“The color rendering index (CRI), is a measure of the ability of a light source to reproduce the colors of various objects being lit by the source (100 is the best CRI).”

<table>
<thead>
<tr>
<th>Light source</th>
<th>CRI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sunlight</td>
<td>100</td>
</tr>
<tr>
<td>W filament incandescent light</td>
<td>100</td>
</tr>
<tr>
<td>Fluorescent light</td>
<td>60 - 85</td>
</tr>
<tr>
<td>Existing Phosphor-based white LEDs/OLEDs</td>
<td>60 - 90</td>
</tr>
<tr>
<td>Na vapor light</td>
<td>40</td>
</tr>
</tbody>
</table>

Courtesy F. Schubert (RPI) and G. Jabbour (ASU)
“Old LEDs never die; they simply fade away.”

Lifetimes of many commercially available LEDs are rated at 50,000 hours. “Lifetime” is defined as time to 70% of original lumen output.
### SSL-LED Technology Roadmap Targets

<table>
<thead>
<tr>
<th>TECHNOLOGY</th>
<th>SSL-LED 2002</th>
<th>SSL-LED 2007</th>
<th>SSL-LED 2012</th>
<th>SSL-LED 2020</th>
<th>Incandescent</th>
<th>Fluorescent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminous Efficacy (lm/W)</td>
<td>25</td>
<td>75</td>
<td>150</td>
<td>200</td>
<td>16</td>
<td>85</td>
</tr>
<tr>
<td>Lifetime (hr)</td>
<td>20,000</td>
<td>&gt;20,000</td>
<td>&gt;100,000</td>
<td>&gt;100,000</td>
<td>1,000</td>
<td>10,000</td>
</tr>
<tr>
<td>Flux (lm/lamp)</td>
<td>25</td>
<td>200</td>
<td>1,000</td>
<td>1,500</td>
<td>1,200</td>
<td>3,400</td>
</tr>
<tr>
<td>Input Power (W/lamp)</td>
<td>1</td>
<td>2.7</td>
<td>6.7</td>
<td>7.5</td>
<td>75</td>
<td>40</td>
</tr>
<tr>
<td>Lumens Cost ($/klm)</td>
<td>200</td>
<td>20</td>
<td>&lt;5</td>
<td>&lt;2</td>
<td>0.4</td>
<td>1.5</td>
</tr>
<tr>
<td>Lamp Cost ($/lamp)</td>
<td>5</td>
<td>&lt;5</td>
<td>&lt;5</td>
<td>&lt;3</td>
<td>0.5</td>
<td>5</td>
</tr>
<tr>
<td>Color Rendering Index (CRI)</td>
<td>75</td>
<td>80</td>
<td>&gt;80</td>
<td>&gt;80</td>
<td>95</td>
<td>75</td>
</tr>
</tbody>
</table>

*The SSL community is just about on target in 2007.*

*Taken from the 2002 DOE/OIDA LED Technology Roadmap*
How to make a white LED

- UV/Blue InGaN LED-pumped phosphors

  ![UV/Blue InGaN LED-pumped phosphors](image)

  Commercial approach to date
  (Up to 150 lm/W achieved*)
  ...relatively low cost
  * Nichia

- Multi-chip/multi-color LEDs (RGB)

  ![Multi-chip/multi-color LEDs (RGB)](image)

  CRI of blue LED + yellow phosphor is ~70

  Potentially most efficient, highest quality white lighting approach
  ...but high cost

Figure courtesy of E. F. Schubert
## Current State of the Art

### Commercial White LEDs are breaking the 100 lm/W barrier

<table>
<thead>
<tr>
<th>Company</th>
<th>Model Details</th>
<th>Current</th>
<th>Lumens</th>
<th>Lumens per Watt</th>
<th>CCT (K)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Nichia</strong></td>
<td>Small area White LED*</td>
<td>20 mA</td>
<td>9.4</td>
<td><strong>150</strong></td>
<td>4600</td>
<td>* 12/20/2006 press release</td>
</tr>
<tr>
<td><strong>Cree Lighting</strong></td>
<td>Small area White LED*</td>
<td>20 mA</td>
<td></td>
<td><strong>131</strong></td>
<td>6027</td>
<td>* 06/20/2006 press release</td>
</tr>
<tr>
<td><strong>Philips Lumileds</strong></td>
<td>High-Power, 1 x 1 mm chip White LED*</td>
<td>350 mA, 2000 mA</td>
<td>136, 502</td>
<td><strong>115</strong>, 61</td>
<td>4685</td>
<td>* 01/23/07 press release</td>
</tr>
</tbody>
</table>
Consider the life-cycle of a “white LED Photon”:

- What stages in the life-cycle are poorly understood and/or poorly controlled?
- Where might increased understanding lead to improved SSL technology?

A major focus is the InGaN materials system.
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\( (injection \ efficiency \ E_{\text{inj}}) \)

(2) Radiative and non-radiative recombination 
\( (internal \ quantum \ efficiency \ \eta_{\text{int}}) \)
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(3) Light extraction from the die (light extraction efficiency $C_{\text{ext}}$)
Approach of the LED Science Panel

Consider the life-cycle of a “white LED Photon”:

- What stages in the life-cycle are poorly understood and/or poorly controlled?
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1. Injection and transport of charge carriers (injection efficiency $E_{\text{inj}}$)
2. Radiative and non-radiative recombination (internal quantum efficiency $\eta_{\text{int}}$)
3. Light extraction from the die (light extraction efficiency $C_{\text{ext}}$)
4. Color conversion and multi-color mixing (optical element & Stokes shift losses)
Challenges for wide bandgaps (GaN)

- Acceptor energy levels are very deep (0.2 - 0.3 ev)
- Tendency for dopant compensation
- Low p carrier concentrations:
  - \( p = \text{mid} \, 10^{18} \, \text{cm}^{-3} \)
  - \( n = \text{mid} \, 10^{19} \, \text{cm}^{-3} \)
- Low p mobilities:
  - \( p = \sim 10 \, \text{cm}^2/\text{Vs} \)
  - \( n = \sim 1000 \, \text{cm}^2/\text{Vs} \)
- p-type contacts have high resistance
  - \( p: 10^{-2} - 10^{-5} \, \Omega \cdot \text{cm}^2 \)
  - \( n: 10^{-5} - 10^{-8} \, \Omega \cdot \text{cm}^2 \)
Because bandgaps tend to increase with bond polarity, most known inorganic wide bandgap semiconductors (including InGaN) are polar. This property is dramatically different from most other III-V materials.

This Priority Research Direction (PRD) proposes a concerted effort aimed at manipulating and understanding the electronic and optoelectronic properties of polar materials and heterostructures. (Includes GaN and others, e.g. ZnO.)

Can we achieve highly conductive p-layers using polarization effects?
Science questions and opportunities

- Can polarization be used for doping and lower resistance p-type contacts and to enhance majority transport?
- Can charge be channeled into the active region under high injection conditions?

Challenges in heavy p-doping for large bandgaps

Minimize contact resistance by exploiting polarization

Polar materials (like LiNbO₃, BaTiO₃…)

Easier to tunnel

Y-R Wu, M. Singh and J. Singh
Challenges:

- **InGaN LED operation in presence of high defect densities (~$10^9$ cm$^{-2}$) little understood.** *(Why do they work at all?)*

- **Rollover of efficiency with high current densities little understood and of great importance**
Another Challenge:

- Internal quantum efficiencies of high-In (green and yellow) LEDs are poor.
PRD: Luminescence efficiency in InGaN

Need to understand how radiative recombination is affected by the complex interplay of:

- charge carrier transport
- quantum confinement
- polarization and strain-induced fields
- point & extended defects
- In alloy phase separation

![Diagram of quantum well, dislocations, and point defects](Image)

Path 1: radiative
Path 2: non-radiative

Courtesy of Jasprit Singh (U. Michigan)

APS March Meeting, Denver, March 5-9, 2007
PRD: Luminescence efficiency in InGaN

Science Questions:

(1) Could the “V-defects” that decorate dislocations be producing energy maxima that repel carriers?

Science Questions:

(2) How does increasing In content affect luminescence? Could In compositional clustering localize carriers away from dislocations and point defects?

This is critical to understanding the green-yellow performance gap!

But recent reports demonstrate In and strain variations caused by TEM materials damage. Are In composition variations in InGaN QWs real?


Smeeton et al., APL 83, 5419 (2003).
Challenges:

- Photons are trapped inside high index layer (total internal reflection). Reflect until absorbed.

- LED light extraction efficiencies remain surprising low: typical state-of-art is at 50-60%

For unencapsulated LEDs:

- Escape cone = 25 deg
- Escape cone solid angle = 4.5% of total (per surface)
Ed & Training: Device physics and light extraction

- TIP-LED Chip 2000
- High-Power TS Chip 1998
- Transparent Substrate 1994
- Absorbing Substrate 1991

*Based on max. measured external quantum efficiency.

Courtesy of M. Krames, Lumileds
Science Questions:

(1) How might nanoscale photonic structures be used to increase light extraction efficiency through geometric effects?

Use photonic crystal to Bragg-scatter waveguided modes
Science Questions:

(2) Can the photon modes and photonic density of states be manipulated to control the direction of emission? *(Avoid waveguiding modes in the first place.)*

(3) Can the internal quantum efficiency be modified?

Resonant Cavity LEDs

Courtesy of Arto Nurmikko (Brown U)

Photonic Crystal LEDs

J. D. Joannopolous, et. al "Photonic Crystals"
CCRD: Innovative Photon Management

Lumileds, Sandia, and UNM (Wierer et. Al., APL 84, 3885 (2004))

- First ever large area (1mm²) III-Nitride photonic crystal LED. (Interferometric litho by S. Brueck.)
- Far field pattern is modified
- External Quantum Efficiency increased by >50%.

Changes in spontaneous emission rates (Purcell Effect) could further increase efficiency.
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Move out at Maturity: Photon Conversion

Challenges:

• Phosphors (developed over decades) for fluorescent lighting absorb near 250 nm and are unsuitable for SSL

• Phosphors for SSL have substantial room for efficiency improvements, especially red.

• Need fast photoluminescence lifetimes (no saturation), high-T operation, low cost, non-toxic, compatibility with encapsulants, and long lived under high UV flux

Blue + Yellow CRI = ~70

Need CRI ≥ 90!

Backscattering of light by large phosphor particles is a significant loss!
Potential Research Approaches

Bulk phosphor materials:
- Eu$^{2+}$ and Ce$^{3+}$ are the only common rare earths with $4f - 5d$ transitions that are parity allowed, and hence intense
- Chemical synthesis of novel oxide & nitride host structures
- *First principles design, not combinatorial methods*

New encapsulants/binder matrices
- Should survive high temps and UV/blue irradiation
- Low-temperature deposited *inorganic* encapsulants (e.g. silica)

Nanocrystalline QDs
- Tunable through size and surface ligand coverage
- Reduced light back-scattering
- Issues of long-term stability, high-T operation
- *Need non-toxic materials!*

Control of excitation and emission energies by manipulation of host structure and chemistry

$\text{Sr}_{2-x}\text{Ba}_x\text{SiO}_4;\text{Ce}^{3+}$
(Le Toquin and Cheetam, pending)

CdS QDs

Single Color  Multicolor/White
Challenges:

Bright GaN LEDs are fairly new (early 1990’s). It is surprising that it has progressed so rapidly.

Could other better materials be out there? But can we atomically engineer a new material that could be even better?

- Non-polar?
- Self-assembled nanoscale components?
- Engineered high conductivity layers?
- Built-in QWs?
PRD: Unconventional Light-emitting Semiconductors

Approaches:

• Designing semiconductors with specific transport and optical properties
  - Use computational design rather than combinatorial methods

• Self-assembly of inorganic nanostructured materials

Example: layered 2D oxychalcogenide crystal structures - self assembled inorganic nanostructured material

Where we’ve been: PRDs, CCRDs, and GCs

**LED PRDs:**
- Polar materials and heterojunctions
- Luminescence efficiency of InGaN structures
- Unconventional light-emitting semiconductors
- Photon conversion materials

**OLED PRDs:**
- Managing and exploiting disorder in OLEDs
- Understanding degradation in OLEDs
- Integrated approach to OLED design

**Cross-Cutting RDs:**
- New functionality through heterogeneous nanostructures
- **Innovative photon management**
- Enhanced light-matter interactions
- Multiscale modeling for SSL
- Precision nanoscale characterization

**Rational design of SSL lighting structures**

**Controlling losses in the light emission process**

Was: “Understanding radiative and non-radiative recombination pathways”
• 50% Energy Efficient Solid State Lighting will replace all conventional lighting in the next 25 years or so.

• This will result in a 10% reduction in global electricity use.

• Much of this revolution will be enabled by discovery-class science.