Materials and Designs for High-Efficacy LED Light Engines
2017 Building Technologies Office Peer Review

NBD: Narrow-Band Downconverter

NBD Reliability
- Elevated temperature
- Elevated light flux
- High relative humidity

NBD Synthesis
- Reaction conditions
- Precursors
- Particle size control
- Surface control

Light Engine Configuration, Processing
- NBD-chip separation
- NBD distribution
- NBD matrix

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Project Summary

Timeline:
Start date: 7/1/15
Planned end date: 6/30/17

Key Milestones:
1. Month 9: measure red-emitting narrow-band downconverter (NBD) thermal efficiency “droop” of < 10% from room temperature to 85°C.
2. Month 15: confirm <10% LED luminous flux degradation and <0.004 du’v’ color shift at >1,000 hrs. of accelerated testing (high-T, high current).

Budget:
Total Project $ to Date:
- DOE: $1.12M
- Cost Share: $281K

Total Project $:
- DOE: $1.5M
- Cost Share: $375K (20% of total)

Project Outcome:
New red emitting narrow-band down-converter (NBD) materials will enable white solid-state lighting with 10-20% or higher efficacy compared to conventional phosphors.

Cree is overcoming challenges in NBD efficiency and reliability (robustness) in typical LED operating conditions to accelerate these materials toward real applications.
Purpose and Objectives

Problem Statement: simultaneous achievement of red-emitting NBDs with high down-conversion efficiency, high spectral efficiency, and high robustness in application conditions

Target Market and Audience: LEDs integrated into nearly all solid-state lamps and luminaires, particularly warm white (2700-3500K CCT).

Impact of Project:
1. Output: stable and efficient red-emitting NBD materials as drop-in replacements for conventional red phosphors in white LEDs.
2. Primary contribution: increase warm-white LED efficacy in a timeframe that meets or exceeds DOE SSL roadmap goals
   a. Near term: >160 lm/W* in low- to medium-power LED packages
   b. Intermediate term: >170 lm/W* in low- to medium power LED packages
   c. Long term: proliferation into high-power LED packages

*At DOE SSL baseline LED drive current of 35 A/cm² (~1 W/mm²). LED efficacy at lower currents will be significantly higher (>180 lm/W).
**Approach**

**Approach:** Synergistically combine advances in materials synthesis, light engine configuration & processing, and reliability (robustness).

**Key Issues:** primary challenge is achieving high red NBD *reliability* in accelerated testing conditions (high light flux, T, & RH) while maintaining high *down-conversion efficiency* (*i.e.* turning blue photons into red photons).

**Distinctive Characteristics:** a multi-thrust approach with continuous application-centric reliability testing is quickly transitioning NBDs toward commercialization.
Progress and Accomplishments – NBD Synthesis

- NBD synthesis and post-synthesis treatment are being systematically varied and evaluated based on characterization and reliability testing.

- Lessons learned: NBD composition, purity, morphology, and post-synthesis treatment are all factors in optimizing QY. Optimization of some of these parameters may not result in high NBD reliability!
Progress and Accomplishments – Light Engine

• White NBD-containing LEDs fabricated and tested under steady-state conditions at various temperatures.

<table>
<thead>
<tr>
<th></th>
<th>LF</th>
<th>LF gain</th>
<th>CRI Ra</th>
<th>CRI Rg</th>
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<tbody>
<tr>
<td>All Phosphor</td>
<td>23.8</td>
<td>-</td>
<td>92.5</td>
<td>60</td>
</tr>
<tr>
<td>NBD</td>
<td>26.2</td>
<td>+10%</td>
<td>93.0</td>
<td>70</td>
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</tbody>
</table>

• Lessons learned: NBD thermal droop must be factored into “real world” white LED performance. Further white LED luminous flux (LF) gains expected as red NBD QY and thermal droop improve.
Progress and Accomplishments - Reliability

- LED accelerated testing in high-current, high-T, high-RH ambients acts as synthesis feedback and helps define the application space.
- Progressively higher stress currents (and therefore blue flux) are being applied.

- Lesson learned: NBD-containing LEDs often exhibit luminous flux rise early in testing; color point change (namely du’) is a better indicator of NBD stability and lifetime prediction.
Project Integration and Collaboration

**Project Integration**: project R&D staff continually communicate with **Cree LED product development groups** to ensure timeliness and relevance of project goals and achievements.

**Synthesis**: how reproducible is NBD synthesis? How scalable? $/lumen?

**Light Engine**: are NBDs compatible with existing LED fabrication processes and package configurations?

**Reliability**: how does evolving NBD reliability map onto projected lifetime (>50,000 hrs.) in various luminaire application conditions?

**Partners, Subcontractors, and Collaborators**: no external partners.

**Communications**: project results presented at annual DOE SSL R&D Workshops.
Next Steps and Future Plans

Next Steps and Future Plans:

• *By end of project:* package-level evaluation and multiple-condition REL studies to help elucidate NBD failure mechanisms and ways to overcome them. Luminaire-level demonstration for comparison w/ all-phosphor.

• *After project:* continue intensive synthesis/package/REL cycle in the drive to create robust red-emitting NBDs

• *Future:* establish “technical” vs. “fundamental” NBD limitations, and compare to other nascent red down-converter materials systems. Apply “lessons learned” in synthesis and robustness improvements from current project to new materials systems, if applicable.
REFERENCE SLIDES
Project Budget: $1.5M Federal Share / $375K Cree Cost Share
Variances: currently at +$98K (6.7% of combined of Federal + Cost Share budget)
No modifications to project plan.
Cost to Date (as of 2/18/17): $1.25M Federal / $251K Cost Share (83.6% of total)
Additional Funding: none.

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<th>Budget History</th>
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<tr>
<td>7/1/15 – 9/30/16 (project start to end of FY16)</td>
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<tr>
<td>DOE</td>
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<td>$929,459</td>
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Project Plan and Schedule – Past Work

• All Milestones except 3.2 met early or on time.
• Milestone 3.2 deferred (with DOE PM approval) to later in program due to task re-prioritization.

<table>
<thead>
<tr>
<th>Task</th>
<th>FY2015</th>
<th>FY2016</th>
<th>FY2017</th>
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<tbody>
<tr>
<td>Past Work (Year 1)</td>
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<tr>
<td>1.1 RT QY of &gt; 90% @ 600-630nm and &lt; 40nm FWHM</td>
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<tr>
<td>2.1 &lt; 10% QY, &lt; 5nm change @ &gt; 1,000 hrs of REL testing</td>
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<td>3.1 &lt; 5% QY change in cured polymer matrix</td>
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<td>3.2 NBD LED color point: 75%/65% single/5-run yield</td>
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<td>4.1 Spectra w/ LER &gt; 350 lm/W @ CRI &gt; 90 &amp; 3000-3500K</td>
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<td>4.2 NBD LED w/ 145 lm/W @ &gt; 80 CRI (RT, 35 A/cm²)</td>
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See next slide for Current/Future work
### Project Schedule

#### Project Start: 7/1/15

**Completed Work**

#### Projected End: 6/30/17

**Active Task (in progress work)**

- Milestone/Deliverable (Originally Planned)
- Milestone/Deliverable (Actual)

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<thead>
<tr>
<th>Task</th>
<th>FY2015</th>
<th>FY2016</th>
<th>FY2017</th>
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<tr>
<td>Q1 (Oct-Dec)</td>
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<td>Q2 (Jan-Mar)</td>
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<td>Q3 (Apr-Jun)</td>
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<td>Q4 (Jul-Sep)</td>
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### Current/Future Work (Year 2)

1.2 QY thermal droop of < 10% from RT to 85°C

1.3 <10% LF & <2nm peak WL variation for 5 LED runs

2.2 REL testing acceleration factors determined

3.3 NBD-LED FF CAU within 0.004 du’v’ of all-phosphor

3.4 < 10% NBD-LED LF drop, instant on to steady state

4.3 NBD-LED w/ >160 lm/W at >80 CRI, RT, 35 A/cm²

4.4 NBD-LED w/ >180 lm/W peak at >80 CRI, RT

5.1 Down-select demonstration luminaire form factor

5.2 Demonstration Luminaire w/ >150 lm/W, 90 CRI