Development & Industrialization of InGaN/GaN LEDs on Patterned Sapphire Substrates for Low Cost Emitter Architecture

2015 Building Technologies Office Peer Review

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Project Summary

**Timeline:**
Start date: August 1, 2013
Planned end date: July 31, 2015

**Key Milestones:**
1. Repeatable demonstration of PSS emitter performance within 1.5% of the TFFC counterpart;
   - met January 2014
2. Demonstration of PSS emitter performance exceeding TFFC counterpart by 2%:
   - met January 2015
3. Industrialization of PSS flip-chip process with light output equal to or better than TFFC devices in a low-cost package: target: July 31, 2015

**Budget:**
Total DOE $ to date: $1,299,711 (Feb 2015)
Total future DOE $: $591,179

**Key Partners:** None

**Project Goal:**
Develop Patterned Sapphire Substrate (PSS) - based LEDs with performance matching the best thin-film flip-chip devices to enable next-generation, low-cost LED products.

**Target Market/Audience:**
Commercial products are targeted for the high-brightness illumination markets.
Purpose and Objectives

Problem Statement:

• In Lumileds’ traditional products, the highest Lm/W performance has been from thin-film flip-chip (TFFC) LED architectures.

• Production of TFFC emitters requires a number of complex processing steps and necessitates mounting the LED to an intermediate (Level 1) package.

• This DOE-assisted project is developing next-generation LED emitters using patterned sapphire substrates as an alternative to TFFC to enable size and cost reduction while maintaining state-of-the-art performance.

Target Market and Audience:

The LED components pursued in this program are targeting indoor and outdoor illumination markets which demand the most competitive Lm/W and Lm/$ characteristics in small footprint components.
1. The endpoint of this project is commercialization targeted in 2015 of PSS-based components with best-in-class Lm/W performance at a 20% cost reduction over last year’s TFFC product counterparts targeted for high-output, small-footprint illumination products.

2. The achievements of this project are measured by:
   a. Near-term (performance improvements in PSS products)
   b. Intermediate-term (commercialization of low-cost LEDs based on PSS die)
   c. Long-term (utilization of PSS architectures in extended applications and higher levels of integration)
Problem Statement

- In Lumileds’ traditional products, the best Lm/W performance has been from thin-film, flip-chip (TFFC) LEDs.
- In TFFC texturing the surface of the GaN enables 40% greater light output relative to a smooth surface.
- Production of TFFC devices requires removing the sapphire substrate and additional complex processing.
- The use of patterned sapphire substrates allows the sapphire substrate to remain in place and enables chip-scale packaging.

Epitaxy & Wafer Fabrication
LED layers are grown and processed on sapphire substrates.

LED Die Fabrication
Singulated die are “flip-chip” attached to a metallized ceramic carrier.

TFFC process adds complexity and cost to the LED product!

TFFC Process steps
LED layers are separated from their substrate and roughened.
Approach: Design and establish optimized patterned sapphire substrate geometries and improved LED epitaxial growth processes to enable a chip-scale package LED with state of the art performance with a >20% reduction in cost.

Key Issues: Our second generation PSS structure and process has resulted in an 8% improvement in Lm/W over our first generation PSS, thus demonstrating the potential of performance on par with the best TFFC products. This achievement is enabling Lumileds to develop the Next-Generation LED architectures for smaller and less expensive components for illumination productions in the second phase of this project.

Distinctive Characteristics: Two Next-Generation Emitter product applications are under development:

(1) a low-cost, direct-attach, chip-scale packaged part
(2) a small foot-print, high-drive packaged part for high directionality and high Lm/$.
LEDs on Patterned Sapphire Substrates Enables Simplification

Traditional TFFC requires roughening the LED surface after removing the sapphire, leaving a thin film device which requires mechanical support provided by an L1 tile.

Patterning the sapphire before LED fabrication provides a robust die which can be directly attached to an L2 board. (chip on board solution)

Luxeon K 1100 lm lamp

L2 board
• Design and fabrication of optimal PSS features for high light extraction and LED yield.
• Growing smooth, high-quality epitaxial layers on highly patterned PSS wafers.
• Engineering high-performance, low-cost package architectures which best exploit the features of the PSS LED die.
• Implementing high-volume manufacturing capabilities for the above.

Tradeoff of Patterned Area vs Epitaxial Layer Quality

Original PSS1 Recipe

AFM

10x Optical

Good yield

Good yield

Good yield

Poor yield

Confidential
Progress and Accomplishments

- Down-selection and industrialized manufacturing of new “PSS2” patterns.
- Established methods for automated visual inspection during PSS substrate manufacturing.
- Established LED epitaxial growth methods on all major reactor platforms.
- Wafer-level LED fabrication yield-data showing comparable performance to “process of record” epitaxial wafers.
- Demonstrated initial data showing PSS2 emitter performance in 1mm² LUXEON Q package exceeding its LUXEON Rebel TFFC counterpart in multiple epitaxial growth and wafer fabrication runs.
- ~4-5% gain in light output attributed to PSS2 added to ~4% gain in LUXEON Q through Gen2 die design.

**Commercial release of the PSS2 pattern and epitaxial growth process into LUXEON Q products, with the official product data sheet updated for higher flux specifications (>12% gain in flux for 3000K 80 CRI at 35A/cm²).**

- Down-selection of candidate packaging concepts for next-generation emitter architecture.
Market Impact of Project

- 5-8% higher Wall Plug Efficiency by optimizing the PSS substrate and epitaxy.
- Largest improvements are seen at highest drive current.
- These improvements have been released in Luxeon Q products and are enabling our “Next-Generation Emitters”

![Graph showing Relative WPE at 35A/cm², 85°C](image)

<table>
<thead>
<tr>
<th>λ bin</th>
<th>350mA</th>
<th>700mA</th>
<th>1000mA</th>
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<tr>
<td>41</td>
<td>5.9</td>
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<td>42</td>
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<td>Avg</td>
<td>5.4</td>
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U.S. DEPARTMENT OF ENERGY
Energy Efficiency & Renewable Energy
Advancements in PSS pattern design and LED die architecture have improved the light output performance of Lumileds LUXEON Q product by more than 8% allowing future expansion of this technology to more applications.

**Market Impact of Project**

- **LUXEON Q** is the first generation PSS product from Lumileds – introduced in 2013
- Product is a PSS flip-chip die attached to reflective submount (not a CSP product)
- At introduction the initial efficacy lagged behind the TFFC product leader LUXEON
- Product Spec sheet revised in 2014 for LUXEON Q based on improved flux!

**LUXEON Q**  *Increase in flux from 2014 to 2015 (data sheet values)*

<table>
<thead>
<tr>
<th>Luxeon Q Product</th>
<th>May 2014</th>
<th>Jan 2015</th>
<th>PSS2-G2 effect</th>
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<tbody>
<tr>
<td>Lumileds Part Number</td>
<td>Nominal CCT (K)</td>
<td>Typical Luminous Flux (lm) 350 mA</td>
<td>Typical Luminous Flux (lm) 350 mA</td>
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<tr>
<td>L1Q0-2780000000zzz0</td>
<td>2700K</td>
<td>100</td>
<td>113</td>
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<tr>
<td>L1Q0-3080000000zzz0</td>
<td>3000K</td>
<td>102</td>
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<td>L1Q0-3580000000zzz0</td>
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<td>L1Q0-4070000000zzz0</td>
<td>4000K</td>
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<td>L1Q0-5770000000zzz0</td>
<td>5700K</td>
<td>127</td>
<td>134</td>
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The PSS2 die in a LUXEON Q package offers performance on par with best TFFC products.

- 1mm$^2$ die in a 3.5x3.5 mm ceramic package,
- non-Lambertian radiation profile.

We are presently working toward achieving the same PSS performance in smaller packages to meet targeted market applications in the illumination markets.

- 2.5x2.5mm and smaller packages
- Option for direct-attached and unpackaged devices
- Lambertian radiation profiles.
- $>130$Lm/W for warm white (3000K/80 CRI) at 350mA/mm$^2$
Project Integration and Collaboration

Project Integration:
• This project is a collaboration of Lumiled’s staff in (1) Technology Development (2) Manufacturing Operations and (3) Product Development and (3) Sales and Marketing.
• The demands of our customers and emerging applications are identified by the Marketing and Product Development teams and drive the future requirements for size, performance and cost.
• Lumileds Technology Development and Manufacturing teams have collaborated closely to ensure timely industrialization of new processes and methods developed in this program.
• All funded work has been performed internally at our San Jose, CA facility without subcontracts.

Communications:
Results have been communicated in regular reports to DoE SSL division, annual peer review meetings and SSL’s R&D workshops.
Next Steps and Future Plans

- Establish low-cost next generation emitter architectures for illumination products.
- **Applications are demanding smaller footprints, lower profiles, higher performance and lower cost!**

Current Tasks and Challenges of PSS architectures

- Maintaining high Lm/W in smaller package sizes
- Obtaining high-efficacy with directional illumination (managing side-emission).
- High ESD robustness in direct attach products
**Project Budget**

**Project Budget:** Total allocated budget for 2 years is $3,781,783 with 50% cost share

**Variances:** As of February 2015 there is a variance of $402,026.

**Cost to Date:** $2,599,424 out of $3,781,783 has been spent through Feb 2015 (DOE portion is 50%).

**Additional Funding:** None

<table>
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<th>Budget History</th>
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<td><strong>August 1, 2013 – FY2014 (past)</strong></td>
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<tr>
<td>DOE</td>
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<td>$1,048,732</td>
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# Project Plan and Schedule

**Project start:** August 1, 2013  
**Project finish:** July 31, 2015

<table>
<thead>
<tr>
<th>Task and Milestone Description</th>
<th>3Q 2013</th>
<th>4Q 2013</th>
<th>1Q 2014</th>
<th>2Q 2014</th>
<th>3Q 2014</th>
<th>4Q 2014</th>
<th>1Q 2015</th>
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<tbody>
<tr>
<td>Predictive Modeling</td>
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<td>Optimize PSS Fabrication</td>
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<td>Optimize PSS Epitaxy</td>
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<td>Validate Performance (Yield, LOP)</td>
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<td><strong>Demonstrate Gen 1 PSS lamps with light output within 1.5% of TFFC</strong></td>
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<td>Validate Gen 2 Performance (Yield, LOP)</td>
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<td><strong>Demonstrate Industrialized Equivalent performance of FC-PSS die to TFFC (within 0.5%)</strong></td>
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<td>Investigate PSS-FC low-cost packaging architecture</td>
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<td>Explore further enhancements to PSS design and fabrication methods</td>
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<td>Produce and compare PSS LED devices to established TFFC baseline</td>
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<td><strong>Demonstrate Gen 2 PSS lamps with light output greater than TFFC by 2.0%</strong></td>
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<td>Establish low-cost, high-efficiency package architecture for warm white PSS-FC</td>
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<td><strong>Industrialization of FC-PSS emitter with equivalent performance to TFFC at reduced cost</strong></td>
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