SSL Luminaire with Novel Driver Architecture

Final Report

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ABSTRACT

Cree has developed a new high-efficiency light emitting diode (LED) technology platform capable of providing low-cost, high performance luminaires that can be adopted across a variety of SSL applications. This development is built on Cree's high brightness LED platform to design a novel LED chip that enables a high-efficiency driver architecture to improve the overall luminaire system efficacy. These system efficiency gains were realized using an integrated approach tailoring the LED chip characteristics to allow for the high-efficiency driver technology platform. The reliability of the new LED design was robust at the component level under accelerated testing conditions. Luminaires were assembled integrating the novel LED and driver technology to demonstrate the system improvement.

Cree has successfully completed this project by developing a novel LED architecture that enables a new driver design with 93% efficiency. This technology was showcased in an LED luminaire that produced 725 lumens at an efficacy of 87.4 lumens per watt (LPW). The correlated color temperature (CCT) of the luminaire was 2708 K with a color rendering index (CRI) of 91. The novel LEDs and driver led to a 9% system performance improvement compared to the standard LEDs and driver scheme.

DISCLAIMER

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PROJECT OBJECTIVE

The goal of this project was to develop an 81 lumen per watt (LPW) light emitting diode (LED) luminaire that emits white light at a color temperature of 2700K. By the end of the two year project, Cree aimed to establish production-capable, efficient warm-white LED luminaires that maintain high performance levels at 'real-life' operating conditions. This development will enable significant site energy savings by initially targeting retail and commercial applications, which are most sensitive to the lifetime operating costs.

To achieve this objective, Cree built on its high brightness LED platform to design a novel LED chip that enabled a high-efficiency driver architecture to improve the luminaire system efficacy. The ultimate goal was to deliver to the Department of Energy a proof-of-concept warm-white luminaire prototype that produces 700 lumens at correlated color temperature (CCT) of 2,700K and a CRI > 90 with an efficacy of 81 LPW.

This report contains a summary of technical progress made during the two year project.

PROBLEM BACKGROUND

Solid-state LEDs have emerged as the long-term, cost-effective and environmentally-friendly alternative for inefficient conventional lighting, by combining one or more saturated color LEDs with a phosphor or other light down-converting media to achieve lighting-class white broad-band illumination. In spite of the short bulb life, lack of robustness and low overall efficiency of 8-20 LPW associated with incandescent and halogen lighting, it has became entrenched due to the extremely low cost (low dollars per lumen and initial cost) and historical infrastructure of the fixture design. To become viable, more energy-efficient replacement solutions need to deliver system efficacies of greater than 80 LPW with excellent color rendition (CRI ≥ 90) at a cost structure that enables payback cycles of 2-3 years for commercial applications.

To improve the luminaire system efficiency, a comprehensive, integrated development effort is needed. Without an integrated development effort, it is unlikely the optics, thermal and driver technology will arrive independently to achieve these goals. For example, the recent trend for high power LEDs has been to increase the drive current to raise the light out per LED for cost reduction. Similarly, as brighter LEDs are available, the number of LEDs in a fixture may be reduced. However, this approach puts an increasing burden on the driver electronics to convert high input voltages to very low output voltages at higher currents.

This project developed an integrated solution of novel LEDs and driver electronics to create a more efficient luminaire system. One key to improving driver efficiency is to reduce the resistive losses: power loss in a circuit due to resistive elements with resistance R is equal to I^2R, where I is the drive current, providing significant reductions in power delivery losses at lower currents. Therefore, scaling drive voltage instead of current for the LEDs therefore provides a path to improving the overall driver and system efficiencies, and provides design flexibility for different luminaire configurations. Cree proposed a novel LED design that operates at high voltage and low current to allow the use of a more efficient driver topology and thereby increase the overall lighting system efficacy.

TECHNICAL APPROACH

The project builds on Cree's expertise in thin-film InGaN LED technology using its high brightness EZBright® LED platform to design the novel LED chip. This new chip architecture will enable a new, more-efficient driver topology that can improve the overall driver efficiency to 93%, thereby increasing the system efficiency. Cree's focus was developing a novel chip architecture that has an equivalent overall performance (optical flux out vs. electrical power in) compared to the state-of-the-art EZBright chip. Cree explored different fabrication methods and materials for the new chip design. Multiple approaches investigating various trade-offs were evaluated with modeling and experimental results. The layout of chip was optimized for yield and defect tolerance. The new chip design and processes were developed to be compatible with Cree's evolving high-speed SSL component manufacturing lines.

As with any new LED chip design, long term reliability was a key metric. This is especially true for the final luminaire product, with an expectation for 35,000 - 50,000 hours of operation (depending on application). Cree conducted studies to investigate the reliability of the new LED devices. The materials and fabrication processes used for the LED chip were examined to ensure they perform under accelerated testing conditions. Failure analysis was performed to gain feedback for improving the chip design and fabrication to withstand the stressed testing conditions.

Utilizing the new chip architecture, a new driver topology was designed and optimized for fabrication to achieve an efficiency of 93% – a 12 percent relative improvement in driver efficiency from the 82-84% typical in LED luminaires at the start of the program. After initial design testing, the driver circuitry and various discrete elements were integrated into a custom application specific integrated chip (ASIC). Power factor correction was incorporated into the driver design.

TECHNICAL PROGRESS

SECTION I - Novel LED Architecture

Device Design and Fabrication

Cree established the fabrication processes for a novel LED architecture which enables a new, more efficient driver circuitry. The goal for this task was to develop the same net lumens output per chip as the benchmark EZBright® chip platform.

Developing the novel blue LED chip fabrication process was the focus of the first year. The primary goal was to maintain equivalent external quantum efficiency (EQE) and wall plug efficiency (WPE) in the new design to ensure the chip does not diminish overall system efficiency. Continued improvement to the fabrication processes during the first year led to a packaged novel blue LED with a peak EQE of 58.7%.

With a solid baseline process in place, Cree began focusing on improving the yield and repeatability of the novel LED fabrication processes. Two lots of wafers were processed to fabricate the novel LED chips. Chips from four different wafers were packaged in Cree's XLamp test bed and their performance measured using an integrating sphere (to measure total flux and average color point) and a spectrometer (to measure the intensity as a function of wavelength). To compare LED brightness over multiple process runs, Cree used a parameter termed "relative flux", which normalizes the measured LED flux to that of a historical Cree standard device and eliminates the effects of wafer-to-wafer variations.

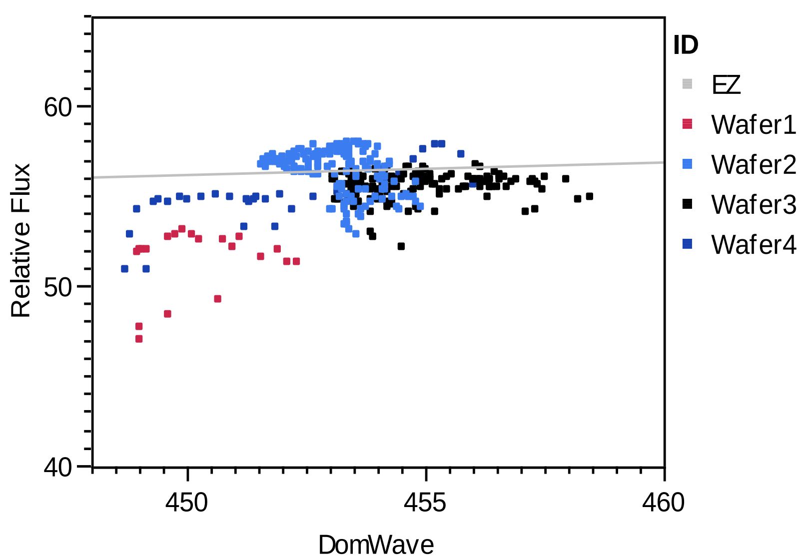

Figure 1: Relative flux at 350 mA equivalent (1mm^2 chips) as a function of wavelength for novel blue LEDs compared to the EZBright LED production average flux value. The novel LED was on average 3% dimmer compared to the benchmark EZBright LED.

The novel LED chips from the two different process lots showed an average relative flux nearly matching that of the benchmark EZBright low voltage chips. The average flux of the novel blue LEDs was nominally 3% lower than the average EZBright LEDs, as seen in Figure 1. This is an important proof-of-concept showing the novel chip design can be as bright as the conventional EZ Bright benchmark. In addition, three of the four wafers showed very good brightness repeatability with the fourth a little lower flux. The average flux for each of the four wafers was within 8% of each other showing respectable run-to-run reproducibility, giving Cree further confidence in the results.

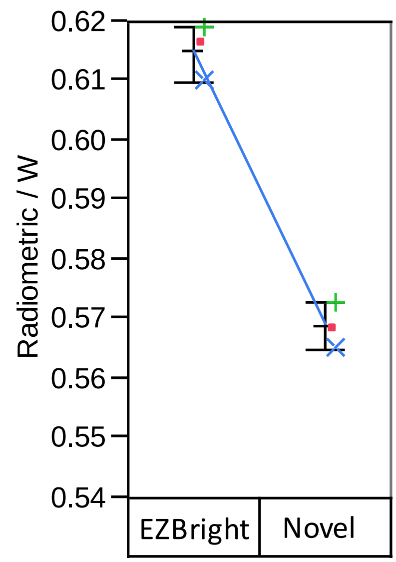

Figure 2: The novel LED had an average flux around 7.5% lower than the benchmark LED when processed on the same epi material. Further process development was needed since the efficiency gap was larger than anticipated.

In the project's second year, Cree continued to refine the novel LED design and fabrication processes. As part of this work Cree compared the novel LED and the benchmark EZBright LED using the same epi material to get an accurate comparison (Figure 2). The average flux for the novel LED wafers was found to be 7.5% lower than the benchmark LED, a larger difference than expected and correction from our first year batch–to-batch comparison. Only a 2% flux difference was expected due to slightly different active area dimensions between the two designs (not a fundamental issue just a result of this particular design spin).

Cree identified potential causes of the lower than expected flux of the novel LEDs and altered the fabrication processes on subsequent lots. Cree implemented two different alternate

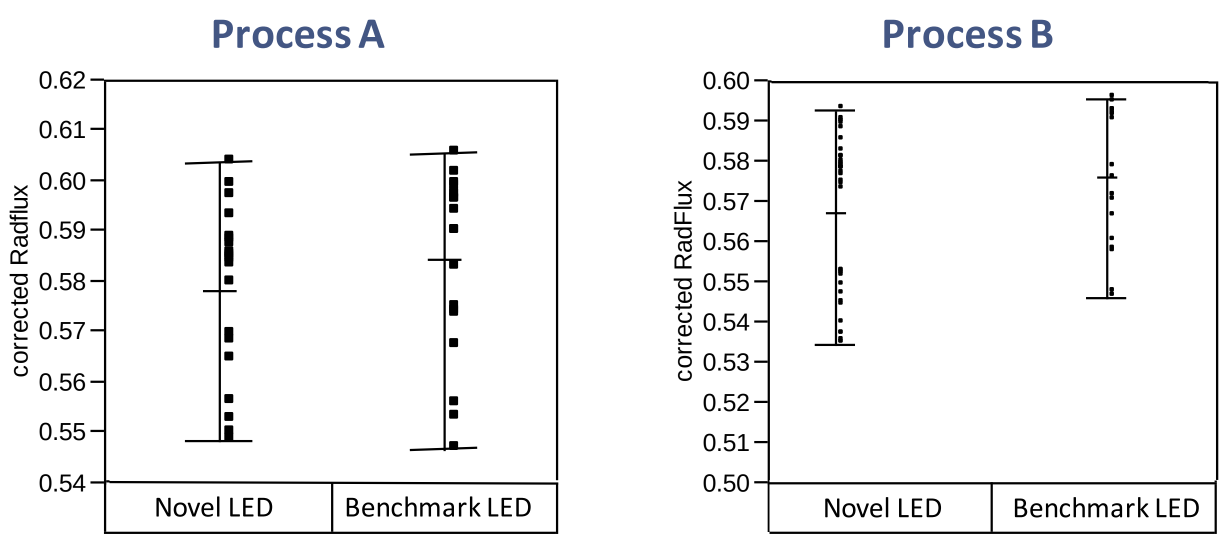

Figure 3: The novel LED (using both alternative fabrication processes A and B) provides nearly the same flux as the benchmark LED when processed on the same wafer. The efficiency gap between the novel process and the benchmark LED process is 1.7% for Process A and 1.5% for process B.

fabrication processes, A and B, in parallel to reduce the efficiency gap between the novel LEDs and the benchmark LEDs. Process A and B showed similar performance when compared to each other, and both processes were nearly as bright as the benchmark single junction LEDs – within 2% – now confirming our model expectations. Figure 3 shows the performance of the two processes compared to the benchmark LED. The samples were fabricated using on-wafer splits to reduce the variability of the blue LED wafer brightness.

The best performing novel blue LEDs fabricated on the project showed a peak EQE of 63%. These novel LEDs were fabricated using high-quality epi material but not on the very best epi material Cree can produce. For reference, blue EZBright LEDs based on the very best epi material show a peak EQE of 71%, so it is expected that the novel LEDs have the potential to reach 70% EQE if the brightest epi material is used.

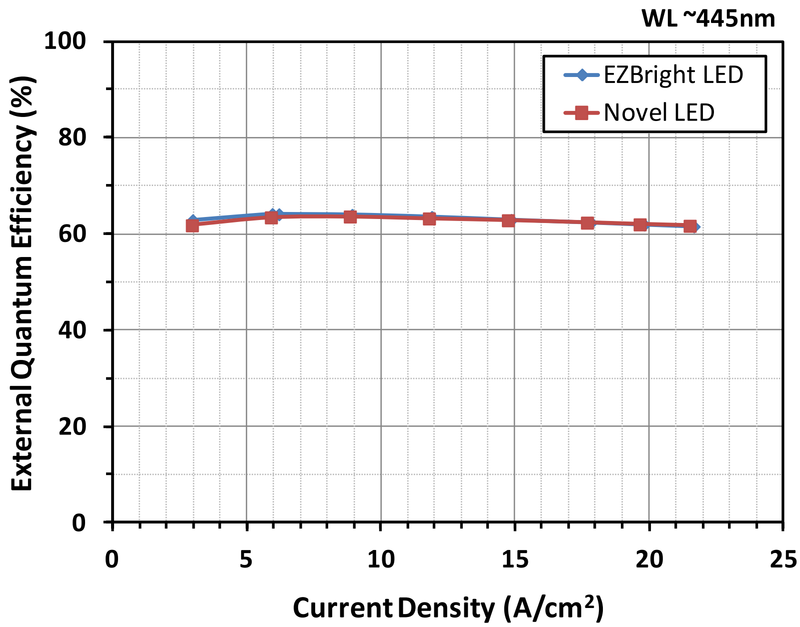

Figure 4: External quantum efficiency as a function of current density for the novel and benchmark EZBright LEDs from the same epi material. EQE for the novel LED peaks at 63.6%, whereas the EZBright LED, which used brighter epi material, peaks at 64% EQE. Note: the two curves overlap.

Novel White LEDs

Novel blue LED chips were combined with a phosphor to fabricate white LEDs to ensure there are no additional losses when converting the blue light to white. Again, it is essential to maintain comparable brightness to the benchmark LED in order to reap the efficiency gains achieved through the new driver design enabled by the novel LEDs.

Both warm white and cool white novel LEDs show comparable luminous flux to white LEDs utilizing the benchmark EZBright chips, the same trend seen with the blue LEDs. This is an important proof-of-concept showing the novel configuration can provide similar conversion efficiency as the benchmark chip design. Figure 5 shows the relative brightness for the novel white LEDs compared to the benchmark.

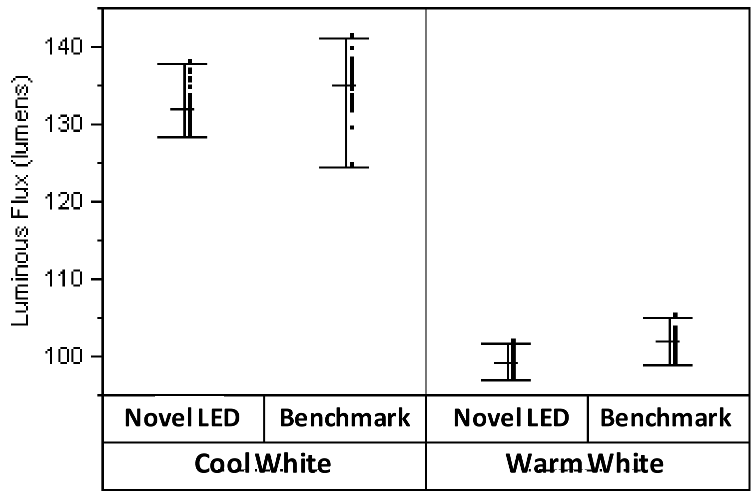

Figure 5: Novel white LEDs provides comparable luminous flux to the benchmark LEDs for both cool and warm white color points. The novel LED output is within 2.2% for cool white and 2.7% for warm white.

The average luminous flux of the cool white novel LEDs was 132 lumens at a color temperature of ~ 6500 K with an average efficacy of 125 lumens per watt (LPW) at a 35 A/cm^2 current density. The warm white novel LEDs provided an average of 99 lumens at a color temperature of ~ 3000 K with an efficacy of 96.6 LPW at a 350 mA equivalent. On average, the benchmark LEDs had a slightly higher luminous flux of 2.2% and 2.7% for cool white and warm white, respectively. The color points of the different samples fall in the same chromaticity range, which allows for direct comparison of luminous flux. In addition, the samples were fabricated using on-wafer splits to eliminate variability from the underlying blue LED wafer brightness.

Reliability of Novel LED Architecture

Cree performed reliability testing on the novel LEDs to ensure the new materials and fabrications steps of the chip designs would perform consistently over its lifetime. Accelerated environmental testing was performed using industry-standard test methods for stressed conditions (high temperature and high humidity).

The first year's reliability goal was to achieve greater than 90% lumen maintenance after 500 hours under wet high temperature operating life (WHTOL) tests. Before subjecting the novel LEDs to WHTOL testing, a less stringent room temperature lifetime (RTOL) test was performed as an initial check of the new chip architecture. Novel LED chips were packaged in Cree's XLamp test bed (with proven reliability) for RTOL tests. The LEDs were checked for changes in luminous flux, changes in color point, increases in forward voltage, and increases in forward leakage currents at various intervals throughout the RTOL testing.

Preliminary RTOL data from Batch 4 of novel LED testing shows a large improvement from the first batch of novel LEDs (Table 1). Initially, failure rates were high, so Cree performed detailed failure analysis to identify the root cause of the failures. This information was then used to redesign the process steps leading to gradual improvements. Batch 4 of the novel LEDs showed 98% passing lamps after 504 hours of RTOL testing; at this point, Cree commenced

WHTOL testing. Batch 4 showed 92% passing lamps after 336 hours of WHTOL testing in the first year of the project.

Table 1: Summary of the initial RTOL testing on the novel LEDs. Early batches had a sizeable failure rate that was addressed by process improvements resulting in a high passing rate. Passing RTOL is an important step toward being able to pass the more stringent WHTOL testing.

Novel LEDs	Test	Length	Passing Lamps
Batch 1	RTOL	336 hours	50%
Batch 2	RTOL	336 hours	30%
Batch 3	RTOL	336 hours	80%
Batch 4	RTOL	504 hours	98%
	WHTOL	336 hours	92%

Reliability testing continued in the second project year as more refinements were made to the novel LED fabrication processes. Cree was continually evaluating the reliability of the new process spins during the second year. Process improvements made in conjunction with the reliability results and failure analysis led to the improved results from the first year. Four novel LED wafers from two different process lots underwent WHTOL testing, resulting in 99.5% passing devices after 1000 hours. This is for the so-called "standard" process (with 7.5% flux deficit to the benchmark). Cree has also evaluated the reliability of devices using the two alternate fabrication processes, A and B, which reduced the efficiency gap between the novel LEDs and the benchmark LEDs to within 2%. Two Process A wafers, each from two different lots, showed 98.7% passing devices after 1000 hours of reliability testing. Three Process B

Table 2: Summary of the second year's accelerated testing of the novel LEDs. Multiple wafers from a number of lots have demonstrated greater than 98% passing devices after 1000 hours of WHTOL testing indicating the that the novel LED platform can be inherently reliable.

Fabrication Process	# Wafers / Lots	Length	Passing Lamps
Standard	4 wafers / 2 lots	1008 hours	99.5%
Process A	2 wafers / 2 lots	1008 hours	98.7%
Process B	3 wafers / 2 lots	1008 hours	98.3%

wafers from 2 different lots showed 98.3% passing devices after 1000 hours of reliability testing. This shows that fundamentally the process modifications can provide good reliability. These results are summarized in Table 2 above.

By the end of the project, a number of wafers from seven different process lots consisting of different processes have demonstrated greater than 98% passing devices after 1000 hours accelerated testing. The fact that the reliability is high with the different process variations in multiple process lots shows the novel LED platform can be inherently reliable.

SECTION II – Efficient Driver Development

Cree fabricated a first generation driver using a preferred topology design for high efficiencies. The first generation prototype provided an 85% driver efficiency, while operating prototype novel LED chips. Cree cataloged the losses in each prototype converter and made the necessary design changes to support efficiency improvements. New prototype test boards were assembled implementing these design improvements. The resulting second generation prototypes were assembled into an LR6 housing (6" inch downlight) along with the novel LEDs for prototype testing of the driver. The second generation prototype driver resulted in a higher efficiency of 90.6%. This is an important proof-of-concept that the new driver topology in combination with the prototype LEDs can deliver a significantly higher efficiency than the conventional luminaire driver.

In the second year of the project, third generation driver prototypes resulted in higher efficiencies with a combined driver efficiency of 93% and a power factor correction of 0.97. This represents a 12% relative efficiency improvement compared to the driver technology used at the start of the project. For the third generation driver prototype, Cree used the same methodology of cataloging the losses in the Generation 2 prototype and made the needed design changes to improve the efficiency. The new prototype test boards and the novel LEDs were again assembled into an LR6 housing for prototype testing of the driver.

Table 3: Summary of progress indriver efficiency over the project. The third generation driver provided 93% efficiency and a power factor correction of 0.97. This represents a 12% improvement over the driver technology at the start of the project.

Driver	Efficiency
Generation 1	85%
Generation 2	90.6%
Generation 3	93%

SECTION III – Luminaire Integration

Proof-of-Concept Luminaire Demonstration

A proof-of-concept luminaire was assembled to showcase the novel LED and driver technology of this DOE project. The housing from a Cree A-lamp prototype (developed under internal Cree funding) was used in combination with the new LED components and driver developed in this project. (The prototype A-lamp retained the original optics and fixture design). Two different prototypes were assembled targeting different operating ranges. Figure 6 shows a photograph of one of the lamp prototypes.

Figure 6: Image of Cree's A-lamp prototype used to showcase the novel LED and driver technology developed in this program.

The novel LEDs and driver led to a 9% system performance improvement compared to the standard LEDs and driver scheme. One of the lamps produced a flux of 827 lumens at 83.6 LPW with 91 CRI at a CCT of 2817 K. The second prototype yielded 725 lumens at 87.4 LPW with 91 CRI at a CCT of 2708 K. The LM-79 testing was performed on the lamps by a CALiPER approved Photometric Test Laboratory.

TECHNOLOGY COMMERCIALIZATION

Cree is pursuing commercialization of a novel LED component for integration into luminaires based on technology developed in part under this program. Cree's LED Lighting business unit is designing products using this type of novel component architecture in combination with the novel driver topology. Cree also plans on offering LED components based in part on this novel platform to OEM manufacturers.

Figure 7: Cree's novel LED and driver platform is applicable to many different light applications. A few such examples are shown above, including bulbs, downlights and troffers.

The technology developed under this project will help maintain Cree's leadership in the adoption of LED lighting in general illumination. Products from a growing number of LED fixture makers utilize Cree's lighting-class LEDs to deliver real energy savings and economic benefits over a range of general illumination applications, both domestically and internationally.

CONCLUSIONS

The project's ultimate objective was to produce an 81 LPW LED luminaire that provided 700 lumens at 2700K and 90 CRI. In addition, the goal was to develop a 93% efficient driver for the LED luminaire. Cree has successfully completed this project by developing a novel LED architecture that enables a new driver design with 93% efficiency. The new technology was showcased in an LED luminaire that produced 725 lumens at 87.4 LPW with 91 CRI at a CCT of 2708 K. The novel LEDs and driver technology resulted in a 9% system performance improvement compared to the standard LEDs and driver scheme.