LUMILEDS

High-Efficacy High-Power LED for Directional Applications

Final Technical Report

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Prime Recipient	Lumileds LLC 370 West Trimble Road San Jose, CA 95131
Principal Investigator	Dr. Wouter Soer wouter.soer@lumileds.com 408-904-3942

1. Executive summary

The efficacy of LEDs has increased to the point where it outperforms all incumbent lighting technologies, driving LED conversion across a wide range of applications. State-of-the-art high-power white LEDs have an efficacy of 130 lm/W (warm white) to 160 lm/W (cool white) under typical operating conditions. Significant further improvements up to the 225-250 lm/W are considered to be possible, but are difficult to realize as many of the individual efficiency components are already approaching their practical limits. Realizing such efficacy gains requires an integrated approach that investigates and takes into consideration the interactions between the technology elements inside the LED device.

In this project, Lumileds has developed a high-power LED emitter with increased efficacy to improve luminaire performance in directional lighting applications. High-power LEDs are particularly suitable for these directional applications as they are optimized for high drive current, high temperature operation and have a small source size and a well-defined radiation profile. An efficacy of 181 lm/W was demonstrated under normalized conditions at a correlated color temperature (CCT) of 4000K and color rendering index (CRI) of about 70, which is a 23% gain over the baseline of 147 lm/W at the beginning of the project. This efficacy gain was realized by an integrated development effort with improvements in each of the LED technology elements: epitaxy, die, phosphor and package.

The realized efficacy improvement will not only result in more direct energy savings, but also encourage faster adoption of solid-state lighting (SSL) by reducing initial and lifecycle cost at a luminaire level and enabling LED conversion of the most demanding applications.

2. Objective and accomplishments

2.1. Objective

The overall goal of this project was to improve luminaire performance by increasing the efficacy of high-power LEDs at representative operating conditions while maintaining a small optical source size and near-Lambertian radiation pattern. The LED efficacy target of the project was set at 200 lm/W at a CCT of 4000K and CRI of 70, measured at a current density J=35 A/cm^2 and junction temperature T_j=85 °C.

The following technology developments were defined in support of this overall goal:

- Substrate and epitaxy based on patterned sapphire substrate flip-chip (PSS-FC) technology with improved external quantum efficiency and extraction efficiency in interaction with the other architecture elements;
- Die technology with a contact design that increases reflectivity with no or minimal penalties on forward voltage and thermal performance;
- Phosphor development based on reduced-bandwidth phosphors to increase luminous efficacy of radiation while maintaining high quantum efficiency;
- Package designs with optical materials that maximize light extraction from the patterned sapphire substrate (PSS) die in a radiation profile optimized for directional applications.

2.2. Summary of accomplishments

Relative to the objectives above, the following key accomplishments were made.

- A next generation of PSS and epitaxy technologies were developed and qualified for use in LED products. An external quantum efficiency (EQE) gain of >5% was demonstrated using this epi technology relative to the baseline at the beginning of the project.
- A new composite p-contact for higher die reflectivity was designed and developed, and demonstrated in functional LEDs.
- A conversion efficiency gain of 2% was realized with a phosphor integration process utilizing phosphors with increased luminous efficacy of radiation.
- A high-reflectivity submount coating was developed and integrated in a package design with geometry optimized for light extraction while maintaining small optical source size. The package efficiency gain due to the submount coating was measured to be up to 7% depending on other package parameters.
- The technology improvements were integrated in an efficacy demonstration build showing an efficacy of 181 lm/W at the normalized operating conditions.
- The first stage of the product creation process of a high-power LED product with upgraded performance based on these technology improvements was successfully concluded.

2.3. Milestone summary

A summary of the milestones and completion status is given in Table 1. All milestones were completed within the project performance period. On the milestones related to the individual technology elements, performance results both higher (Milestones 6.2.2 and 9.1.1) and lower (Milestone 7.2.2) than target were achieved. This reflects the substantial uncertainty in predicting individual technology gains as well as trade-offs that are made between the technology elements to ensure the best package-level performance. The efficacy target of 200 lm/W was not reached in the final performance demonstration, but at 181 lm/W, the demonstrated efficacy is a significant 23% improvement over the 147 lm/W baseline at the beginning of the project and a ~13% improvement over ~160 lm/W state-of-the-art products at the end of the project.

Table 1: Milestone summary table (continued on next page).

Milestone	Description	Verification Process	Target Date	Completion Date and Result
2.1.1	Completion of advanced reflector design	Simulation results of advanced reflector showing a net gain in LED efficacy due to improved die reflectivity taking into account thermal and electrical impact of the reflector design	Nov 2016	Completed Nov 2016
3.1.1	Initial phosphor material definition	Photometric measurement of LER gain (target 2%) with new phosphor in a reference LED architecture over the baseline at the beginning of the project	Feb 2017	**LER gain 1.8%** Dec 2016
1.2.1	Demonstration of 1% EQE gain	Photometric and electrical measurement of a packaged blue PSS-FC LED at $J=35A/cm^2$ and $T_j=85°C$, showing 1% EQE gain over the baseline at the beginning of the project	Mar 2017	**EQE gain 1.0-1.5%** Mar 2017
2.2.1	Completion of first fabrication round	Demonstration of functional LED samples that incorporate the new reflector structure	Apr 2017	Completed Aug 2017

4.2.1	Intermediate efficacy demonstration	NIST calibrated photometric measurement of a packaged white LED at a CCT of 4000K and CRI of 70, measured at $J=35A/cm^2$ and $T_j=85°C$ (target 180 lm/W)	May 2017	**Efficacy 175 lm/W** Jun 2017
5.1.1	Product feasibility demonstration	Prototype performance validation of flux, efficacy and color-over-angle and definition of engineering development required to close any gaps towards specified targets	May 2017	Completed Aug 2017
9.1.1	Package efficiency gain demonstration	Photometric measurement of LED samples with improved package submount showing 2% efficacy gain compared to control samples with same epitaxy, die and phosphor	Jul 2017	**PE gain ~7%** Jun 2017
6.2.2	Demonstration of 3% EQE gain	Photometric and electrical measurement of a packaged blue PSS-FC LED at $J=35A/cm^2$ and $T_j=85°C$, showing 3% EQE gain over the baseline at the beginning of the project	Sep 2017	**EQE gain 5-6%** Jun 2017
7.2.2	Completion of second fabrication round	Photometric and electrical measurements of LED samples incorporating the new reflector showing a 3% performance gain at $J=35A/cm^2$ and $T_j=85°C$ relative to equivalent samples with the baseline reflector	Nov 2017	**Flux gain 1%** Dec 2017
8.1.2	Improved phosphor material definition	Photometric measurement showing 2% LER and flux gain with new phosphor in a reference LED architecture over the baseline at the beginning of the project	Nov 2017	**LER gain 2.2%** **CE gain 2.0%** Oct 2017
10.2.1	Design and process freeze	Completion of DRBFM review and phase 1 reliability including 500 hours WHTOL test	Nov 2017	Completed Apr 2018
9.2.2	Final efficacy demonstration	NIST calibrated photometric measurement of a packaged white LED at a CCT of 4000K and CRI of 70, measured at $J=35A/cm^2$ and $T_j=85°C$ (target 200 lm/W)	Feb 2018	**Efficacy 181 lm/W** Apr 2018
10.3.1	Engineering process validation complete	Demonstrated color targeting capability for targeted CCT/CRI, and completion of phase 2 reliability including 1000 hours WHTOL test	Feb 2018	Completed Apr 2018

3. Project activities

3.1. Substrate and epi development

Epitaxy development focused both on fabricating new patterned sapphire substrate (PSS) geometries for extraction efficiency improvement as well as improving the internal quantum efficiency (IQE) at the targeted current density of 35 A/cm^2.

Stepper reticles were designed and fabricated for photolithography of new PSS geometries, and fabrication processes for these new geometries were set up. In addition to extraction efficiency improvement by optimizing the PSS geometries, changes to the epi design were evaluated that reduce internal absorption losses within the die. Design variations were guided by optical models and experimental data to quantify the losses associated with specific layers of the epi structure. The collective extraction efficiency improvements from this work were evaluated in a controlled build with a baseline package architecture and measured to be approximately 3%.

The target current density of 35 A/cm^2 is in an operating regime where the IQE has strong sensitivities to both Shockley-Read-Hall (SRH) recombination and efficiency droop. Therefore, the IQE improvement effort was directed both toward improving the radiative recombination rate by enhancing electron and hole overlap, and toward improving carrier spreading for better droop and managing the corresponding material quality degradation. This effort was in part guided by results from the project "Improved InGaN LED System Efficacy and Cost via Droop Reduction" (DE-EE0007136), which helped to highlight which types of defects within the active region are primarily responsible for SRH recombination. A net IQE improvement of 2-3% vs. project baseline was measured in a controlled build at T_j = 85 °C and J = 35 A/cm^2.

Next, both improvements were implemented in the PSS-FC package architecture of the targeted product to ensure that the developed EXE and IQE improvements translate to this architecture and are additive. As shown in Figure 1, EXE and IQE gains are indeed additive, and a total of 5-6% EQE improvement was measured. This demonstration exceeds the Milestone 6.2.2 target of 3% EQE improvement.

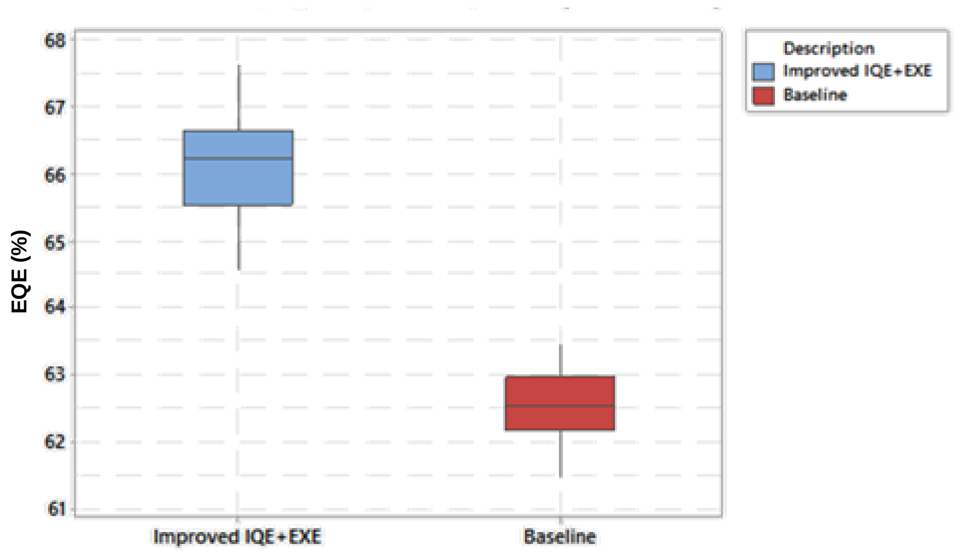

Figure 1: Integrating sphere measurements of packaged blue LEDs at T_j = 85 °C and J = 35 A/cm^2 of the combined improved IQE process and improved EXE process vs. baseline. Total EQE gain of 5-6% over baseline is observed.

Subsequent activities in substrate and epi development focused on the development and validation of manufacturing processes of the demonstrated new epi structure. Evaluations were performed to ensure that the new epi process has sufficient process windows to run in volume manufacturing, and tests were conducted to ensure the process will have robust reliability in the field. The results from these evaluations were all positive. The consistency of the efficacy gains within the final illumination product architectures was confirmed through multiple builds, and process centering was completed for sufficient windows to run in volume manufacturing. Reliability tests were completed without issue, and the development concluded with successfully meeting the process freeze timeline for this epi upgrade.

3.2. Die development

The initial design of an improved composite p-contact mirror was completed in the first quarter of the project, in fulfillment of Milestone 2.1.1. Optical simulations were conducted to optimize the reflectivity of the structure for a wide range of incidence angles and wavelengths. The simulations show a potential efficacy gain of >2% over the baseline, depending on optical quality of the layer materials.

Thin film samples fabricated with two different deposition techniques were collected from several vendors to characterize optical absorption. Using our in-house capability to measure absorption with high sensitivity in very thin layers, we found that layer absorption (*k*) increases in general when the layer is thinner, indicating material quality improves as the layer is deposited. This is true for both deposition techniques that were evaluated. This result was used to update absorption parameters in the optical model for the composite mirror and optimize the design.

Photolithography and etch processes were developed to be compatible with defining small and deep patterns spanning the layers in the composite reflector. The combination of flip-chip technology and the use of insulating dielectric layers as reflector necessitate the patterning and etching of deep structures. These structures, conduits to conduct current to the p- and n-GaN layers through the dielectric mirrors, need to be small in size as they themselves are not reflective and should have smooth sidewalls to ensure high reliability.

The process development focused on forming the challenging structure of small through-vias through the stack. The variety of materials that needs to be etched through within one etch step poses a challenge in forming a good profile. A first version of chemistry was found to form a smooth and gradual sidewall, but resulted in a kink at the foot of the structure, potentially creating problems for the next dielectric layer. A two-step etch process was developed to mitigate this issue, ensuring a flat surface is present at the foot of the mesa at the end of the etching process. Finally, a single-step dry etch process was successfully developed, thereby eliminating the need for the two-step approach which was being pursued as a mitigation.

A first integrated LED structure with a non-optimized version of the mirror design was successfully fabricated and characterized in Q3-2017, passing Milestone 2.2.1. Subsequent characterization of these LEDs showed their performance to be slightly lower than to roughly on-par with their respective control LEDs with baseline composite reflector. Further optimization was conducted with the updated input from the the abovementioned characterization of refractive indices and extinction coefficients measured on thin films of the materials under consideration. The reflectance was optimized for the material stack using a wave optics model, and a mirror loss evaluation was executed for various LED architectures using ray tracing. Four unique optimized designs were down-selected for evaluation and the two most promising designs were included in the next integrated LED structures that were fabricated in fulfillment of Milestone 7.2.2. As shown in Figure 2, these LED structures both showed a gain of approx. 1% across a wide range in current densities. The observation that the gains remain constant over this range indicates that they are indeed coming from an improvement in optical extraction efficiency. In addition, when we measured the ‘encapsulation gain’ calculated from the ratio of the encapsulated (domed) blue LED performance to the un-encapsulated (bare) blue LED performance, we observed that the LED structures with the integrated DBR demonstrate a lower encapsulation gain compared to the standard LEDs with composite reflectors, thereby confirming an improvement in LED extraction efficiency into air.

Further performance improvements are expected to be possible through iterative optimization of the mirror design and the die layout, as well as through improvements to the layer deposition process – specifically, improved thickness control of individual layers, and reduced interfacial roughness.

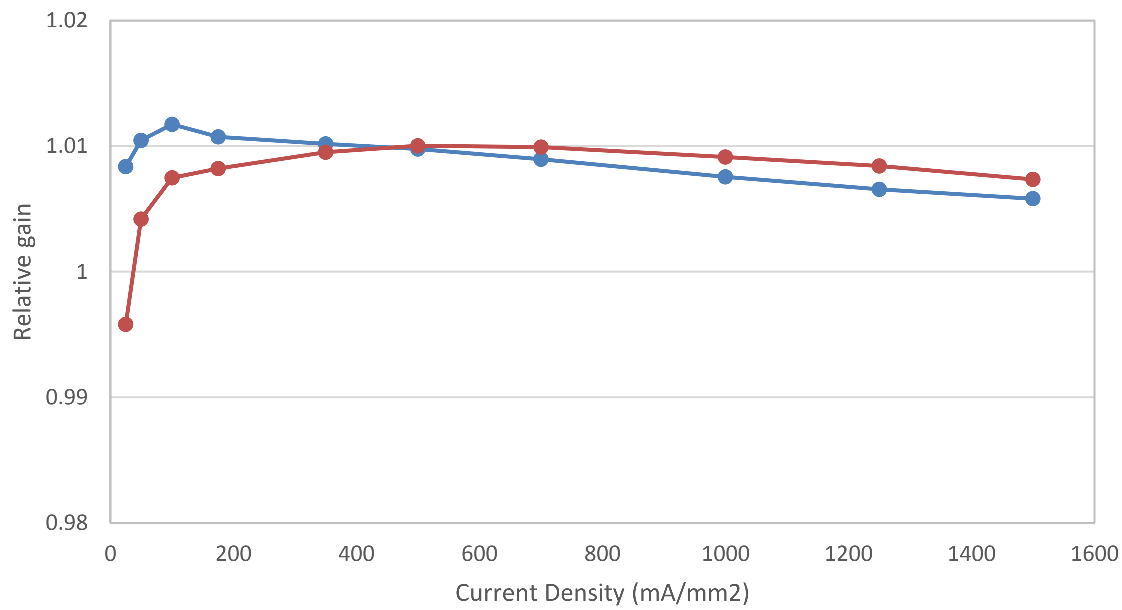

Figure 2: Measured flux gain of LEDs with improved composite mirror (two design variants indicated by blue and red curves) relative to standard LED, plotted as a function of current density. The constant gain across the range of current densities confirms an improvement in optical extraction efficiency.

3.3. Phosphor development

Initial activity in phosphor development in this project focused on evaluation of novel phosphors with higher luminous efficacy of radiation (LER) for both red and green. The tradeoff between LER and quantum efficiency (QE) under operating temperature and blue flux was characterized. A novel green phosphor with higher LER was evaluated in device builds, producing almost 2% LER gain (Milestone 3.1.1). However, the lower quantum efficiency of this material offset the LER gain, giving roughly the same overall conversion efficiency (CE) as the control sample (Table 2).

Table 2: Measurement result of device build with phosphor mix based on novel green phosphor, relative to project baseline phosphor system. QD stands for quantum deficit (Stokes loss).

Measurement relative to baseline phosphor system	**LER**	**QD**	**QE**	**CE**
Test green, control red	1.8%	-0.2%	-1.6%	-0.4%

Phosphor mixtures with novel nitride orange phosphors combined with green garnets were subsequently evaluated. The green garnets are required to maintain an overall higher quantum yield, while a shorter orange phosphor enables a LER gain through lower deep red content. With different formulations of $(Ba,Sr)_2Si_5N_8$:Eu synthesized at Lumileds, the effects of varying both Sr content and Eu concentration were evaluated, and a CE gain of 1% was demonstrated with this approach. This formulation was repeated multiple times and the gains statistically confirmed while maintaining CRI Ra > 70. A CE map of this new phosphor formulation was constructed, showing that the CE changes about +/- 1.5% within the 4000K 5SDCM. This map was used for color targeting of the Budget Period 1 (mid-project) efficacy demonstration.

In Budget Period 2, a test device architecture was designed to allow rapid screening of new phosphor materials by conversion efficacy (CE) measurement under representative operating conditions. The measurements are critical to optimizing the material systems for CE gains of a few percent which are generally within the error margin of our CE models. The test device comprises a thin-film flip-chip (TFFC) die and is designed such that phosphor can be applied on a single part basis rather than the submount tiles (containing hundreds of parts) which are used in production.

The test device was used to evaluate a range of green and red phosphors relative to the phosphors used in the baseline 4000K/70 product. As expected, a negative correlation is observed between color rendering index (CRI) and luminous efficacy of radiation (LER). Furthermore, phosphor combinations with higher LER do not automatically have higher CE as the package efficiency and quantum efficiency may also change. A phosphor system was identified meeting the criteria of Milestone 8.1.2, with a LER gain of 2.2% and a CE gain of 2.0% with CRI Ra>70.

Following these phosphor CE screening experiments with the TFFC based test device, we built a test device based on patterned sapphire substrate (PSS) flip chip die. The PSS die is more representative of the final product in terms of package efficiency and therefore allows for more accurate prediction of CE in the final product. Table 1 below shows the luminous efficacy of radiation (LER) and conversion efficiency (CE) of test devices with different phosphor systems relative to a control device with the phosphor systems used in the mid-project efficacy demonstration, measured at a junction temperature of 25 °C. These results suggest that a CE improvement of 2-3% over the mid-project demonstration is possible. The CE improvement would be mostly attributable to the green phosphor, with a potential minor additional improvement from the red phosphor. The results also show that the CE gain would not be associated with a gain in LER (which is absent or even negative); rather, it would be due to quantum efficiency and/or package efficiency improvements.

Table 3: Normalized LER and CE for test devices with improved phosphor system relative to mid-project baseline, measured at 25 °C junction temperature and translated to the same color point by spectral modelling.

Green phosphor system	**Red phosphor system**	**Normalized LER**	**Normalized CE**	**CCT (K)**	**CRI Ra**	**CRI R9**
Mid-project baseline	Mid-project baseline	1.000	1.000	3985	70	44
Mid-project baseline	Improved	0.986	1.004	3985	71	32
Improved	Improved	0.992	1.027	3985	70	38

The selected phosphor system was implemented in our current phosphor integration process for high-power LEDs and used for the Budget Period 2 efficacy demonstration.

3.4. Package technology development and integration

Improved die submounts were designed to increase package efficiency. Relative to the baseline package, the submounts can accommodate a larger dome, which improves light extraction from the die. Two versions were designed and prototyped; in the first version, the area of the reflective metallization finish on the submount is maximized by reducing the area needed for alignment marks and other features relative to the baseline. In the second version, the surface metallization is limited to the solder pads for die attach only; this version was used to evaluate reflective coatings other than the standard submount metallization finish.

On the version with minimal metallization, experiments were conducted to measure reflectance for different coating thicknesses. The thickest coatings were found to have reflectance substantially higher than the standard metallization finish, indicating a potential for improved package efficiency of the PSS-based emitter architecture. Based on these results, an effort was started to develop a version of this improved submount compatible with manufacturability and reliability constraints. The submount design was optimized to be compatible with high throughput in volume manufacturing. Due to manufacturing requirements additional metal was required on the top surface of the submount. Optical modeling was employed to maximize the package efficiency based on the location of the additional metallization.

At the end of Budget Period 1, a series of packaged LEDs were fabricated combining the performance gains achieved thus far. The purpose of this build was to support the mid-project efficacy demonstration as well as feasibility evaluation of a product implementing these performance gains. The substrate/epi, phosphor and submount improvements described above were included in this build, along with several variations in die design and thickness. Control samples for each of the technology elements were included in the experimental design to validate the individual performance gains and provide a better understanding of the interactions.

Four submount tiles with a total of >1600 parts were built to target maximum performance, with several variations in submount reflector, pump wavelength and phosphor target. All parts comprised a 2 mm^2 die on a 4040 submount with phosphor and 3.6 mm diameter dome. One of the prototype samples is shown in Figure 3. All parts were tested at a current of 700 mA and junction temperature of 85 °C using an automated tile-level photometric tester. Next, about 20 parts from each tile were measured in an integrating sphere calibrated to NIST, and the data from the automated tests was calibrated using the integrating sphere data using a standard correction procedure. Only LEDs with a color point in the 4000K ANSI bin and CRI of 70±1 were considered. Figure 4 shows the data thus obtained for the two parameter variations that resulted in the highest performance. The highest performing parts from these data sets were measured independently in the integrating sphere to eliminate potential errors from the correction procedure.

The highest efficacy part in this mid-project demonstration is indicated by the green circle in Figure 4. This emitter achieved an efficacy of 175.0 lm/W and flux of 347 lm at a current density of 35 A/cm^2 and junction temperature of 85 °C. Figure 5 shows the performance of this prototype LED as a function of drive current, demonstrating peak efficacy well above 200 lm/W.

Figure 3: Prototype high-power emitter for efficacy demonstration.

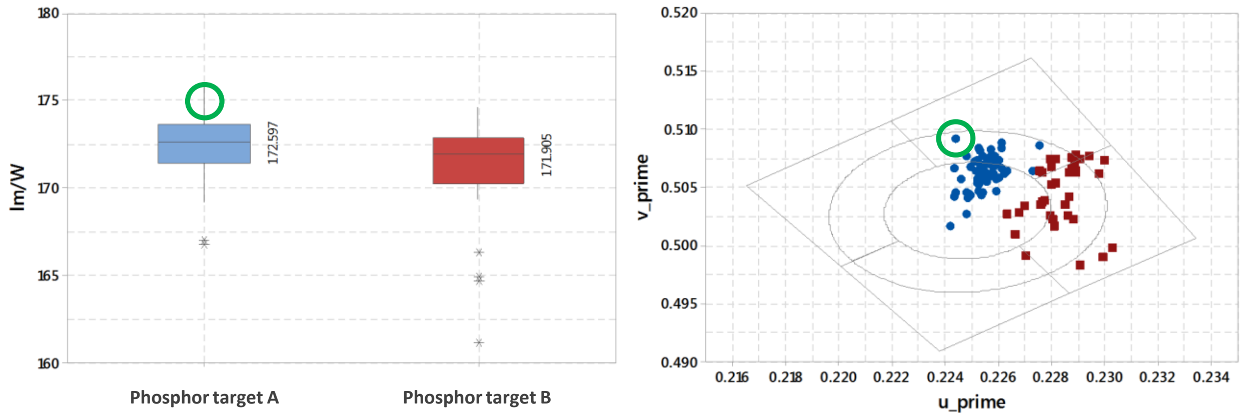

Figure 4: Efficacy boxplot (left) and 4000K ANSI bin color chart (right) showing distribution of prototype devices in mid-project demonstration build with two different color targets at a current density of 35 A/cm^2 and junction temperature of 85 °C. Green circle indicates highest efficacy part.

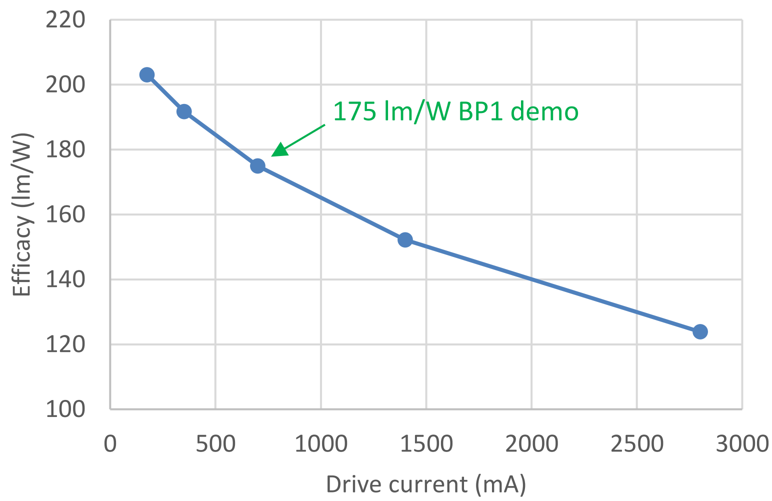

Figure 5: Performance of highest efficacy LED in mid-project demonstration build as a function of drive current at a junction temperature of 85 °C.

Toward the end of Budget Period 2, a similar build plan was executed to incorporate the following further improvements for the final efficacy demonstration:

- A variation of the developed epi design and process with potentially lower V_f;
- A die with modified dielectrics and die layout optimized for efficacy (rather than flux);
- Phosphor with maximized CE based on the screening experiments.

A "pathfinder" wafer fabrication lot was started to evaluate the relative differences between the die design variations. This lot contained 2 epi designs, 5 die layouts with different via designs, 2 variations in composite contact stack, and 3 different die thicknesses. The parts with the largest of the 3 die thicknesses (which gave the highest gains in the Budget Period 1 demonstration) were built into white LED packages for a controlled analysis of the effects of the other design parameters. A ~2% efficacy gain over baseline was observed with the optimal combination of epi and die parameters.

The final efficacy demonstration build used the highest efficacy die design as identified in the "pathfinder" build. Parts were built and characterized in the same manner as described for the mid-project efficacy demonstration, with automated tile-level test data corrected by calibrated sphere measurements, and separate verification of individual parts in the calibrated sphere. Again, parts were measured at a junction temperature of 85 °C, and only LEDs with a color point in the 4000K ANSI bin and CRI of 70±1 were considered. The best performing part was measured to have luminous efficacy of 181 lm/W at the normalized test current of 700 mA, as shown in Figure 1, with a peak efficacy exceeding 220 lm/W.

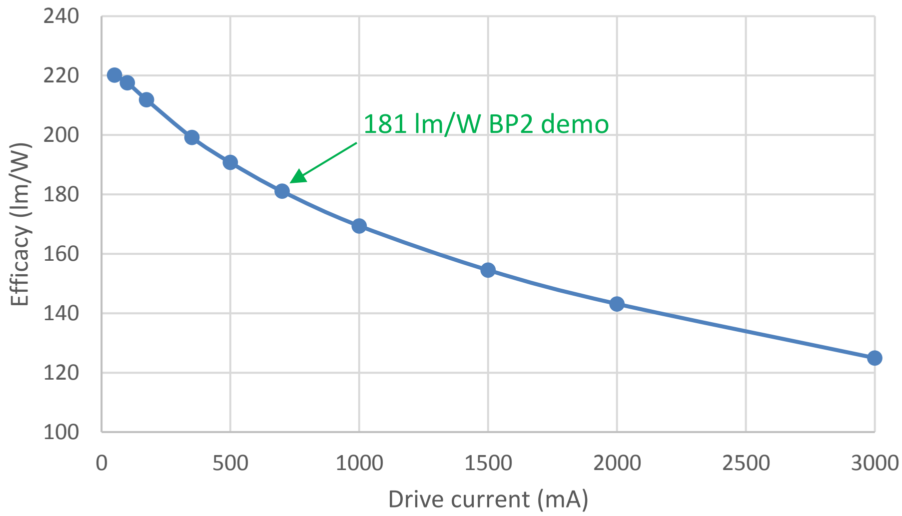

Figure 6: Luminous efficacy as a function of forward current for best performing LED of final efficacy demonstration build, measured at a junction temperature of 85 °C. At the test condition of 700 mA, an efficacy of 181 lm/W is achieved.

3.5. Product creation

In parallel with the mid-project efficacy demonstration, a control build was executed to identify the gain of each parameter/technology change under at least one set of controlled parameters, creating a path with quantified steps from the baseline performance to the mid-project performance demonstration. The performance validation provided by this control build enabled product feasibility demonstration (Milestone 5.1.1) for the product targeted by this project. The scope of the product is a performance upgrade for the baseline 2 mm^2 die high-power LED based on the epi, die and package improvements included in the mid-project demonstration (Milestone 4.2.1). A formal business creation process was started, with subsequent product creation activities focusing on the industrialization of manufacturing processes for the related building blocks, at suppliers as well as in house.

The submount with highly reflective surface went through several iterations of optimization at the supplier. The silicone-based reflective material underwent optimization of the application process in terms of hardness and final surface finish. Reliability tests were started to finalize the surface hardness and surface roughness for high-volume manufacturing.

An alternative phosphor integration process which was initially part of the product plan showed a weakness in the process/material system during initial reliability tests, the root cause of which could not be identified within the timeframe of this product release. The decision was therefore made to proceed based on the baseline phosphor application process established at the beginning of the project.

The doming process was fine-tuned and finalized for high-volume manufacturing. The saw process was optimized for the newly chosen high performance silicone. Pick-and-place and tape-and-reel vacuum pick-up nozzles were designed and the designs were made available to customers.

Pilot runs showed satisfactory yields for the backend processes. These processes go from die attach to substrate to phosphor application to doming and final electrical and optical test followed by binning and tape and reel.

Reliability tests were completed to test for possible interactions of the baseline phosphor application process with preliminary versions of the technology upgrades developed in this project, including the epi, die and submount improvements. These tests, which include standardized high-temperature operating life (HTOL), wet high-temperature operating life (WHTOL), thermal shock (TMSK) and high-temperature storage life (HTSL) tests, passed the 1000 hour mark at the end of this project.

4. Products

4.1. LED products

The technology developed to improve performance of PSS-FC based high-power LEDs has already been incorporated in LUXEON V, a 4 mm^2 PSS-FC high-power LED that was released to the market in August 2017 (https://www.lumileds.com/products/high-power-leds/luxeon-v).

4.2. Publications and presentations

Poster Presentation: "High-Efficacy High-Power LED for Directional Applications", DOE SSL R&D Workshop, Long Beach, CA, January 31 – February 2, 2017

Poster Presentation: "High-Efficacy High-Power LED for Directional Applications", DOE SSL R&D Workshop, Nashville, TN, January 29-31, 2018