Final Technical Report

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High-Power Warm-White Hybrid LED Package for Illumination

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1. Executive Summary

In this project, an integrated warm-white hybrid light engine was developed. The hybrid approach involves combining phosphor-converted off-white InGaN LEDs and direct-emitting red AlInGaP LEDs in a single light engine to achieve high efficacy together with high color rendering index. We developed and integrated technology improvements in InGaN and AlInGaP die technology, phosphor technology, package architecture and encapsulation, to realize a hybrid warm-white LED package with an efficacy of 140 lm/W at a correlated color temperature of 3000K and a color rendering index of 90, measured under representative operating conditions. This efficacy is 26% higher than the best warm-white LEDs of similar specification that are commercially available at the end of the project.

Since the InGaN- and AlInGaP-based LEDs used in the hybrid engine show different behavior as a function of current and temperature, a control system needs to be in place to ensure a stable color point over all operating conditions. In this project, we developed an electronic control circuit that is fully integrated into the light engine in such a way that the module can simply be driven by a conventional single-channel driver. The integrated control circuit uses a switch-mode boost converter topology to control the LED drive currents based on the temperature and the input current of the light engine. A color control performance of 5 SDCM was demonstrated, and improvement to 3 SDCM is considered well within reach.

The combination of high efficacy and ease of integration with existing single-channel drivers is expected to facilitate the adoption of the hybrid technology and accelerate the energy savings associated with solid-state lighting. In the product commercialization plan, downlights and indirect-lit troffers have been selected as the first target applications for this product concept. Fully functional integrated prototypes have been developed for both applications, and the business case evaluation is ongoing as of the end of the project.

2. Project Objectives

This project was a two-year program addressing the “Package Architecture” Area of Interest in the SSL Product Development program area. The original objective of the project was to develop a warm-white LED array package capable of producing 650 lm of warm-white light with Color Correlated Temperature (CCT) in the range of 2700 K to 3500 K, Color Rendering Index (CRI) >85, R9 > 20, and LED efficacy of 130 lumens/Watt (lm/W), all measured at a junction temperature of 85 °C. These objectives were to be realized through a hybrid architecture containing phosphor-converted off-white LEDs and direct-emitting red LEDs. The LED array was envisioned to have a high forward voltage to enable integration with efficient low-cost drivers. Reliability testing was planned throughout the program to ensure that the approach taken meets the requirements of long life and consistent color expected from solid-state lighting solutions.

The project objectives were updated twice during the course of the project. The changes were formally implemented through revisions of the Project Management Plan.

The first update was made in August 2012 and was a result of the high efficacy demonstrated during the first year of the project. An efficacy of 131 lm/W was achieved under the abovementioned conditions, exceeding the original final objective of the project. The final objective was therefore raised to an efficacy of 140 lm/W and flux of 700 lm. Moreover, from our driver integration evaluation in the first year it was concluded that high-voltage die architectures were not critical to achieve the objectives of the project. Rather, integrated color control was considered more crucial to enable integration with cost effective drivers, and the Project Management Plan was updated to reflect this prioritization. The motivation for this change will be explained further in the following sections.

The second update was made in March 2013 during the commercialization phase of the project. From marketing input, the primary target applications for the LED array package developed under the project are high-flux applications such as downlights and troffers. To better fit these applications the target flux for the project was updated from 700 lm to a range of 700-1400 lm.

3. Project Activities and Accomplishments

3.1. Die Development

A major part of the efficacy improvement towards the goals of this project was realized by die development of InGaN and AlInGaP dice for the off-white and red LEDs, respectively. The array architecture envisioned at the beginning of the project was an array of two to four high-voltage low-current (HVLC) InGaN dice, combined with an array of smaller AlInGaP red dice, which would together establish a total forward voltage of 100-200V.

In the area of InGaN die efficacy development, two key improvements were realized during the course of the project:

- A new 2 mm² thin-film flip-chip (TFFC) die design was developed, leading to a flux gain of 3.2%, and an efficacy gain of 2.3%.
- An improved dielectric layer was developed, leading to a flux gain of 2.5%, and an efficacy gain of 2%.

Together with internally funded epitaxy and package development, a total efficacy gain of 15% was realized over the two-year project period.

Towards the HVLC die development objective of this project, a 4-junction 2 mm² TFFC die was developed. The number of junctions was the result of an optimization between die layout and segmentation loss constraints on the one hand, and driver requirements on the other hand. Two ceramic submounts and corresponding die attach processes have been developed. One submount connects the four junctions in two parallel strings of two junctions each, resulting in a total forward voltage of approximately 6V. The other submount connects all four junctions in series, resulting in a forward voltage of 12V. The 4-junction die-on-ceramic is schematically shown in Figure 1a. The die can be used in the same package as Philips Lumileds' LUXEON T product, with a coated phosphor and a compression-molded silicone dome on a ceramic carrier frame (Figure 1b). This packaged 4-junction LED has been commercialized as LUXEON T 6V and LUXEON T 12V and released in August 2013.

Figure 1: (a) Schematic view of 4-junction die on ceramic with integrated TVS (transient voltage suppression) chip; (b) LUXEON T 12V product based on this die (right).

In the area of AlInGaP die development, several die sizes and die designs were evaluated for their potential to reach the efficacy objective of this project. It was found that one of the key factors determining efficacy (at constant current density) in the vertical thin film (VTF) die

architecture is the die area dedicated to p and n contacts, where light cannot escape. Table 1 shows the ratio of the combined contact area to the active die area as a function of die size for the die designs evaluated. As a result from this evaluation, it was determined that a larger die is best suited to meet the efficacy objective. A 1.1 mm^2 die was commercialized in a LUXEON Rebel package and released in November 2013 (Figure 2). The product achieves an efficacy of 110 lm/W and a flux of 90 lm at a drive current of 350 mA, temperature of 25°C and dominant wavelength of 615 nm. Prior to the release of this product, Epistar PX42 dice in a LUXEON Rebel package were used in this project for efficacy demonstration and development purposes. These dice also have an area of 1.1 mm^2 and show an efficacy of up to 130 lm/W at a drive current of 350 mA, temperature of 25°C and dominant wavelength of 610 nm.

Table 1: Contact area relative to active die area as a function of die size for various AlInGaP VTF die designs.

Die size (mm^2)	Ratio of p and n contact area to active die area
0.09	27%
0.12	25%
0.25	19%
1.1	11%

Figure 2: (a) 1.1 mm^2 VTF die; (b) LUXEON Rebel Red product based on this die.

After the first year of the project, it was determined that a high-voltage low-current array architecture, as originally envisioned, was not beneficial to meet the objectives of the project. Two observations contributed to this conclusion. First, the evaluation of efficacy vs. die size for the VTF architecture showed that higher efficacy is obtained for larger dice (and hence, a lower total forward voltage for a given die area). Second, high-flux applications such as downlights and troffers were identified as key target applications for the technology. With typically more than 10 LEDs per luminaire in these applications, sufficient forward voltage for low-cost efficient drivers can be built without the use of high-voltage or small-size dice. Based on this conclusion, an array of single-junction 2 mm^2 InGaN dice and 1.1 mm^2 AlInGaP dice was selected for further product development.

3.2. Package and Encapsulation Development

The package development work package of this project aimed to develop surface mount technology (SMT) die-on-ceramic off-white and red LED packages, and spherical silicone lens encapsulation for the hybrid array made up of these packages.

The SMT packages developed and used in this project leverage package building blocks from similar Philips Lumileds products as shown in Figure 3, in order to facilitate later productization. The off-white LEDs, with 2 mm² die area, have the same package architecture as LUXEON Z ES (for undomed emitters) and LUXEON T (for domed emitters), while the red LEDs, with 1 mm² die area, are based on the package architecture of LUXEON Z (undomed) and LUXEON Rebel (domed).

Figure 3: Philips Lumileds product packages used in this project. From left to right: LUXEON Z ES, LUXEON T, LUXEON Z and LUXEON Rebel.

In the first year of the project, two arrays with different encapsulation architecture were designed and developed as shown in Figure 4. A single-lens array was developed with 2 off-white and 2 red LEDs under a single silicone dome (Figure 4a). This array targets directional applications that require a small source size in order to achieve a narrow angular distribution. For prototypes of this array, the dome was pre-formed and attached to the emitters using a silicone adhesive. As illustrated in Figure 5, the array exhibited significant color-over-angle (CoA) variation. Primary or secondary mixing optics would be required to achieve good color uniformity with this array in directional applications.

Figure 4: (a) Single-lens array design; (b) multi-lens array design (lenses not shown).

Figure 5: Measured color point in CIE1976 coordinates as a function of angle for the single-lens module shown in Figure 4a.

The other array developed is a multi-lens array, designed for non-directional applications, as shown in Figure 4b. Prototypes of this array were made with pre-formed domes of 2.5-3 mm in

diameter, manually attached to the individual emitters. Based on our marketing evaluation, in which several non-directional applications were determined to be key target applications for the hybrid technology, the multi-lens array architecture was selected for further development and efficacy demonstration.

In order to develop a manufacturable encapsulation process for the multi-lens array, two encapsulation concepts were evaluated. The first concept is based on silicone transfer molding at the array level. This approach is currently used in Philips Lumileds' LUXEON K products. This process allows the highest packing density of emitters, but is less flexible towards new board designs since a new mold is required for each design change. A series of hybrid array prototypes with 10 off-white and 6 red LEDs were made with this technology as shown in Figure 6a.

The second concept is based on silicone compression molding at the emitter level. This process utilizes the encapsulation process developed for individual emitters (LUXEON T for off-white and LUXEON Rebel for red) and allows the encapsulated LEDs to be mounted onto the board as shown in Figure 6b. Since there is no board-level encapsulation process, this approach is much more amenable to board design changes. For the non-directional applications targeted in this project, the slightly lower packing density was not deemed to be a significant drawback, and therefore this concept was selected for further product development.

Figure 6: Two packaging options based on Philips Lumileds' existing manufacturing capability; (a) hybrid package with transfer molded lenses; (b) hybrid package with compression molded lenses

3.3. Efficacy Demonstration

Based on the die and package developments described in the previous sections, several efficacy demonstrators were made during the course of the project. In Phase I, an array of four phosphor-converted off-white LEDs and two red LEDs was prototyped. The LEDs were integrated on a metal core printed circuit board (MCPCB) and encapsulated with individual silicone hemisphere dome lenses as shown in Figure 7. The chip size of each InGaN blue LED chip is 2 mm^2 , and that of each red LED chip is 1.1 mm^2 . Figure 8 shows the color point of the array for different operating conditions. At a junction temperature of 85°C , the package shows an efficacy of 131 lm/W and a flux of 763 lm at CCT of 2955K under a drive current of 350 mA for the off-white LEDs and 450 mA for the red LEDs. The CRI is 90 and R9 is 75. This efficacy exceeded the objective for Phase I, which was 110 lm/W , and also the original objective for Phase II, which was 130 lm/W . Therefore, as described in Section 2, the objective for Phase II was raised to 140 lm/W .

Figure 7: Efficacy demonstration prototype made in Phase I.

Figure 8: Measurement results of prototype shown in Figure 7 at a junction temperature of 25 °C (blue line) and 85 °C (purple line).

Figure 9 shows the prototype that was made in Phase II of the project. This array comprises four phosphor-converted off-white LEDs and four red LEDs on an MCPCB. At 85°C junction temperature, this package shows an efficacy of 140 lm/W and a flux of 712 lm at CCT of 3006K under a drive current of 310 mA for the off-white LEDs and 220mA for the red LEDs. The CRI of the device is 91 and R9 is 75. The color point of the device is slightly below the Planckian locus as shown in Figure 10. At 25°C junction temperature, the package shows an efficacy of 161 lm/W and a flux of 747 lm, with a lower drive current for the red LEDs to maintain color point on the Planckian locus.

Figure 9: Efficacy demonstration prototype made in Phase II.

Figure 10: Color point of prototype shown in Figure 9 at a junction temperature of 85°C under a drive current of 310 mA for the off-white LEDs and 220mA for the red LEDs

Comparing to the state of the art, we find that the best conventional phosphor-converted white LEDs commercially available at the end of the project achieve an efficacy of about 111 lm/W at similar specifications ($\text{CCT}=3000\text{K}$, $\text{CRI}>90$) and operating conditions ($J=17.5\text{ A/cm}^2$, $T_j=85^{\circ}\text{C}$). The prototype developed under this project exceeds this performance by 26%.

3.4. Phosphor Integration Development

Following our evaluation of target applications for the hybrid product, four CCTs were selected for further product development: 2700K, 3000K, 3500K and 4000K. Our internal CRI target for each of these CCTs was $R_a > 90$ and $R_9 > 50$. For each of the CCTs, a comprehensive study on phosphor selection was done by numerical simulation. In this study, emission spectra of different types of off-white phosphor are modeled. InGaN and AlInGaP LEDs are modeled according to the production distribution. The result of this modeling work helped us optimize the phosphor selection according to different LED distribution and different CCT targets. Table 2 is an example of the simulation results for 3000K.

Table 2: Simulation results for the 3000K hybrid package: different off-white phosphors and different pump emission wavelengths were modeled. The resulting CRI and R9 of the hybrid system were then calculated to guide the selection of phosphors.

Off-white phosphor	Type 1			Type 2		
Pump wavelength (nm)	445	450	455	445	450	455
System CRI	87	90	92	N/A	91	94
System R9	67	70	74	N/A	81	85

After selecting the phosphor for each CCT, subsequent color targeting experiments were performed using Philips Lumileds proprietary phosphor integration technology. Color targeting is an important step towards mass production. Figure 11 shows the color targeting results for the four different off-white colors corresponding to the selected CCTs. Off-white samples were made on the LUXEON T platform for all these color points. Hybrid arrays were built for the warm-white CCTs of 2700K, 3000K and 3500K, and were confirmed to have CRI $R_a > 90$ and $R_9 > 50$. The 4000K array build was still pending as of the end of the project but is also expected to meet these specifications.

Figure 11: Color targeting results for the four different off-white color points.

3.5. Reliability Study

Since the array architecture selected for product development is based on individually packaged and encapsulated emitters, the reliability for the array is evaluated by reliability tests of the individual emitters. Comprehensive reliability studies were conducted on these two components separately. In these studies, the LED devices are soldered to reliability stress boards that can accommodate up to 160 devices. The LEDs are connected in series strings of up to 20 devices and driven by a constant current source for each series string. Reliability stress boards are mounted in a thermal chamber which provides water or liquid N₂ cooling to the bottom-side of the reliability stress board. The reliability stress board is periodically removed from the thermal chamber, allowed to cool to room temperature, and then tested. The tester consists of a computer-controlled x-y table, integrating sphere, programmable current-source meter, and relay switching-matrix. Each LED is positioned underneath the integrating sphere and driven with a constant-current pulse. Luminous flux, (u', v'), and forward voltage are measured for each LED.

For the off-white LEDs, the reliability study is based on cool-white LUXEON T LED with a CCT of 6500K. These LEDs use the same phosphor system as the off-white LEDs, only at a slightly different color point. A comprehensive reliability study was done on these LEDs and concluded with LM-80 tests up to a total test time of 10,000 hours. Figure 7 shows the average lumen maintenance curves and TM-21 predictions for a drive current of 700 mA, which is the target maximum rated current for the hybrid product. At a board temperature of up to 85 °C, no light output drop is observed during the 10,000 hours tested, and an increase in light output of about 2% is observed at the end of the test. From the L70 extrapolation curve, it is clearly shown that the L70 lumen maintenance is greater than 60,000 hours (limited by the 6x extrapolation prescribed by the TM-21 standard). The color point shift is less than 0.003 after 10,000 hours.

Figure 12: Lumen maintenance over time for LUXEON T LEDs at 55 and 85 °C board temperature and 700 mA drive current. Light output extrapolation is shown up to 100,000 hours.

After reliability study and several process improvements, lumen maintenance and color point stability studies were also started on LUXEON Rebel red packages. Figure 8 shows the status of these studies after 2,000 hours, which was the test duration reached at the end of the program. Again, an increase of the average light output was observed for all test conditions. The average color point shift is less than 0.002 for all test conditions.

Figure 13: Lumen maintenance and color point maintenance over time for high-power LUXEON Rebel Red LEDs at 55, 85 and 105 °C board temperature and 500 mA drive current.

3.6. Integrated electronics development

The hybrid architecture utilizes two different types of LEDs (phosphor-converted blue InGaN LEDs and direct-emitting red AlInGaP LEDs), and the light output ratio of these two components needs to be controlled in order to achieve the desired system color point. Since the dependence of the light output on temperature and drive current is different for the blue and the red LEDs, this control problem is not straightforward. Implementing a fixed drive current ratio between the off-white and red LEDs, e.g. by stringing them together in a series configuration, gives substantial color shift over the operating conditions (as shown in Figure 14), which is unacceptable for many applications. Alternatively, one may design a dual-channel LED package in which the off-white and red LEDs can be addressed separately using a dual-channel driver, but this shifts the problem to the driver side of the system and inhibits integration with low-cost efficient single-channel drivers.

Figure 14: Example of color shift over run-up for a hybrid module with fixed drive current ratio. The color point shifts towards the green as the module warms up since the red LEDs have lower hot/cold factor than the off-white LEDs.

Based on these considerations, as described in Section 2, we directed the driver integration work in this project towards developing an integrated electronics approach to stabilize the light engine's color point. In this approach, the hybrid module is driven by a conventional single-channel driver and the drive currents of the off-white and red LEDs are controlled by an electronic circuit integrated with the hybrid array in order to keep the system's color point within specification. This approach combines the color control performance required for hybrid arrays with ease of integration with low-cost efficient single-channel drivers.

The electronic control topology chosen for integration is a switch-mode boost converter as schematically shown in Figure 15. In this topology, the off-white LEDs are driven at the current

supplied by the driver, and the red LED current is adjusted by the switch-mode converter to stabilize the color point of the module. The stabilization is done by a feed-forward control algorithm based on the drive current and temperature of the board. The control algorithm is implemented on a microcontroller that contains a lookup table specifying the duty cycle of the switch-mode converter as a function of drive current and board temperature.

Figure 15: Schematic representation of the switch-mode boost converter topology used to control the color point of the hybrid module.

To facilitate the initial development of the integrated electronics, an LED board with integrated NTC (negative temperature coefficient) resistor was prototyped as shown in Figure 16. This allowed us to develop the electronics externally while still using the LED board temperature as input. After initial verification of functionality and performance on an electronics breadboard, the electronics were integrated on a separate PCB shown in Figure 16. On this PCB, the control electronics are laid out around the perimeter of the board, while the large connector in the center serves to connect to the LED board shown in Figure 16.

Finally, the LEDs and the electronics were integrated onto one MCPCB to realize a fully integrated hybrid light engine prototype. This prototype is shown in Figure 17. The board can accommodate up to 18 LUXEON T off-white LEDs and 12 LUXEON Rebel red LEDs for a nominal light output of 3750 lm. Lower flux packages can be realized on the same board with the same electronics by mounting fewer LEDs and shorting the empty positions. The particular board shown in Figure 17 has 12 LUXEON T off-white LEDs and 8 LUXEON Rebel red LEDs for a nominal light output of 2500 lm. The integrated prototype array also contains the microcontroller onto which the control program and lookup table can be programmed after assembly through the probe points on the board. Once the module is programmed, all that is needed to drive it is a DC current supplied through the terminal block by a conventional single-channel driver.

Figure 16: (a) LED board with separate off-white and red LED strings and integrated NTC resistor; (b) PCB with electronics to stabilize the color point of this LED board.

Figure 17: Fully integrated hybrid light engine prototype (2700K/2500lm).

Several of these prototypes have been assembled in CCTs of 2700K and 3500K, and nominal light output values of 2500 lm and 3750 lm.

To verify the color stabilization performance, the modules were characterized in a calibrated integrating sphere tester at a representative range of board temperatures and DC drive currents. The results for a 2700K/2500lm module are shown in Figure 18. From this figure it can be seen that the color point excursion is confined within 5 SDCM of the 2700K ANSI bin center for drive currents from 50 mA to 750 mA, and board temperatures from 25 °C to 85 °C. The remaining color shift is relatively minor, and mostly manifests itself at low drive currents of <100 mA. This is attributed to inaccuracy in the LED model at these low currents. This systematic deviation can easily be corrected in further optimization of the algorithm, and doing so is expected to improve the color control further to within 3 SDCM.

Figure 18: Color point of the integrated hybrid light engine prototype (2700K/2500lm) as a function of drive current and board temperature.

4. Product Development and Commercialization

4.1. LED emitter products

The die development work package of this project contributed to the development of a new 4-junction InGaN die as well as a new VTF AlInGaP die. Both dice were commercialized and released to the market in a family of LED emitter products.

The 4-junction InGaN die was commercialized in the same package as the LUXEON T product and released in August 2013. The product features a high-thermal-conductivity ceramic submount for low thermal resistance, and a low-cost ceramic frame to carry the compression-molded silicone dome. The product is available in two forward voltages realized by two different submounts: one submount connects the four junctions in two parallel strings of two junctions each, resulting in a forward voltage of 6 V, while the other submount connects all junctions in series resulting in a forward voltage of 12 V.

The 1.1 mm² VTF AlInGaP die was commercialized in a LUXEON Rebel package and released after the end of the project. The product achieves an efficacy of 110 lm/W and a flux of 90 lm at a drive current of 350 mA, temperature of 25 °C and dominant wavelength of 615 nm.

4.2. Integrated hybrid light engine

Based on the high efficacy and high color rendering offered by the hybrid technology developed in this project, two primary target applications were identified for product development: downlights and indirect-lit troffers.

For the downlight application, the conceptual board design was created to have compact form factor with the LEDs densely packed in the center of a circular MCPCB and the color electronics distributed along the perimeter of the same board. This resulted to the prototype design shown in Figure 17. This design is intended to fit in mixing chambers that are used in many downlight systems. To minimize optical losses, the electronics may be excluded from the mixing chamber by using a reflector that lands on the board around the LEDs. The CCTs specified for the downlight application are 2700K, 3000K, 3500K and 4000K, all at a CRI of 90. Off-white phosphor color targeting was completed for all these CCTs as described in Section 3.4, and integrated module prototypes were built in 2700K and 3500K as described in Section 3.6.

For the indirect-lit troffer application, the product concept consists of a series of identical MCPCB strips with LEDs and an NTC, and a separate PCB with control electronics as shown in Figure 19. This design was chosen to offer more freedom in placement of the control electronics PCB in the troffer luminaire, as well as to keep the LED strip size within practical limits of test and assembly equipment. The CCT specified for this application is 4000K. Prototype LED strips were designed and made as shown in Figure 20. Up to four of these strips can be connected to the control electronics PCB shown in Figure 16b.

Figure 19: Schematic representation of hybrid light engine for troffer applications, consisting of one PCB with control electronics and four MCPCB strips with LEDs and an NTC.

Figure 20: Prototype of one of the MCPCB strips with 6 LUXEON T off-white LEDs, 4 LUXEON Rebel red LEDs and one NTC.

As part of the manufacturing process flow development, a test and programming strategy was laid out that allows for the microcontroller to be programmed with the appropriate lookup table in production, based on test data that are obtained during the LED manufacturing process.

As of the end of the project, all technical requirements of the Product Feasibility phase of the product development process have been met, and the project is ready to pass the Program Plan Commitment gate, pending a positive review of the business case. Customer evaluations of the developed prototypes are ongoing and will help refine the commercialization prospects for this product. The resulting business case will ultimately determine the decision to move forward and bring the product to the market.

5. Patents Applications and Publications

5.1. Patent Applications

Wouter Soer, Rene Helbing, Guan Huang, “Hybrid chip-on-board LED module with patterned encapsulation”, May 2013, US patent application in preparation

5.2. Publications

Decai Sun, Guan Huang, Henry Choy, Dave Kharas, Joseph Juan and Ted Chung, “High Power Hybrid Warm White LEDs for Illumination”, poster presented at DOE SSL R&D Workshop, Atlanta, GA, February 2012

Wouter Soer, Guan Huang, Frank Jin, Han Ho Choi, Dave Kharas, Henry Choy, Frank Wall, “High-Power Warm-White Hybrid LED Package for Illumination”, presented at DOE SSL R&D Workshop, Long Beach, CA, January 2013

Guan Huang, Wouter Soer, Frank Jin, Han Ho Choi, Dave Kharas, Henry Choy, Frank Wall, “High Power Hybrid Warm White LEDs for Illumination”, poster presented at DOE SSL R&D Workshop, Long Beach, CA, January 2013

Wouter Soer, “Smart LED Modules for a Diverse Lighting Market”, presented at SEMICON West, San Francisco, CA, July 2013