Final Technical Report

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130 LPW 1000 Lm Warm White LED for Illumination

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1. Executive Summary

An illumination-grade warm-white LED, having correlated color temperature (CCT) between 2700 and 3500 K and capable of producing 1000 lm output at over 130 lm/W at room temperature, has been developed in this program. The high-power warm-white LED is an ideal source for use in indoor and outdoor lighting applications. Over the two year period, we have made the following accomplishments:

- Developed a low-cost high-power white LED package and commercialized a series of products with CCT ranging from 2700 to 5700 K under the product name LUXEON M;
- Demonstrated a record efficacy of 124.8 lm/W at a flux of 1023 lm, CCT of 3435 K and color rendering index (CRI) over 80 at room temperature in the productized package;
- Demonstrated a record efficacy of 133.1 lm/W at a flux of 1015 lm, CCT of 3475 K and CRI over 80 at room temperature in an R&D package.

The new high-power LED package is a die-on-ceramic surface mountable LED package. It has four 2 mm^2 InGaN pump dice, flip-chip attached to a ceramic submount in a 2x2 array configuration. The submount design utilizes a design approach that combines a high-thermal-conductivity ceramic core for die attach and a low-cost and low-thermal-conductivity ceramic frame for mechanical support and as optical lens carrier. The LED package has a thermal resistance of less than 1.25 K/W. The white LED fabrication also adopts a new batch level (instead of die-by-die) phosphor deposition process with precision layer thickness and composition control, which provides not only tight color control, but also low cost.

The efficacy performance goal was achieved through the progress in following key areas: (1) high-efficiency royal blue pump LED development through active region design and epitaxial growth quality improvement (funded by internal programs); (2) improvement in extraction efficiency from the LED package through improvement of InGaN-die-level and package-level optical extraction efficiency; and (3) improvement in phosphor system efficiency by improving the lumen equivalent (LE) and phosphor package efficiency (PPE) through improvement in phosphor-package interactions. The high-power warm-white LED product developed has been proven to have good reliability through extensive reliability tests.

The new kilo-lumen package has been commercialized under the product name LUXEON M. As of the end of the program, the LUXEON M product has been released in the following CCT/CRI combinations: 3000K/70, 4000K/70, 5000K/70, 5700K/70, 2700K/80, 3000K/80 and 4000K/80. LM-80 tests for the products with CCTs of 4000 K and higher have reached 8500 hours, and per IESNA TM-21-11 have established an L70 lumen maintenance value of >51,000 hours at 700 mA drive current and up to 120 °C board temperature.

2. Project Objectives and Actual Accomplishments

A. Original Project Objectives

The objective of this project was to develop high-efficiency LEDs for illumination. The targeted result was a single high-power LED capable of producing 1000 lm of warm-white light with Color Correlated Temperature (CCT) in the range of 2700 K to 3500 K, Color Rendering Index (CRI) > 80, R9 > 20 and luminous efficacy of 130 lm/W, all measured at room temperature (25 °C). The project focus was on design for high performance and low cost. 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.

Intermediate to the final objective, the objective for Phase 1 of this work was to demonstrate 105 lm/W and 850 lm from a warm-white high-power LED with CRI > 80 at 25 °C.

The objective for Phase 2 of this work was to demonstrate 130 lm/W and 1000 lm from a warm-white high-power LED with CRI > 80 at 25 °C.

B. Original Scope of Work

Three key areas of product development were pursued:

1. New LED package development. This work includes: (a) ceramic submount design for 2x2 die attachment; and (b) bolt-down or SMT package development. The focus of this activity was to develop a bolt-down or SMT LED package containing 2x2 dice that can deliver a thermal resistance below 2 K/W.
2. LED encapsulation for improvement in extraction efficiency from the package. This work concentrated on lens integration on the LED package developed for this program. The focus was on the optimization of light extraction efficiency gain, the long-term reliability of the encapsulation material under high current and high flux, and low-cost assembly. The scope included exploration of both compression molding and injection molding techniques for silicone lens formation. Lens size optimization was to be done through optical modeling and statistically designed experiments to strike a balance between cost and performance.
3. Integration of phosphor system for color control. The focus of this effort was on the integration of a high-efficiency warm-white phosphor system into the LED package to achieve the efficacy target at the right CCT and CRI. This work aimed to implement novel ceramic phosphor plates developed by Philips Lumileds called Lumiramic®, which offers an efficient phosphor solution in ceramic form. Other techniques of phosphor integration in the LED package were to be investigated as well.

The scope furthermore included comprehensive reliability test methodology to investigate the reliability of the new LED product throughout the program to make sure the product meets the reliability requirements. Extensive knowledge is available from Philips Lumileds' LUXEON products as well as from the multi-chip high-power warm-white LED development funded by

DOE and Philips Lumileds jointly. Evaluation of progress of each area of improvement was done by fabrication and characterization of LEDs.

C. Major Proposed Milestones

Budget period I:
Prototype warm-white high-power LED with output of 850 lm and 105 lm/W at 25 °C.

Budget period II:
Prototype warm-white high-power LED with output of 1000 lm and 130 lm/W with CCT < 3500K and CRI > 80 at 25 °C.

D. Actual Activities and Accomplishments

(1) New low-cost high-power LED package development

A new high-power surface-mountable white LED package has been developed for general lighting under the program. The LED package operates normally at 8 to 10 W input power emitting over 1000 lm of white light. Figure 1 shows the new LED package. It uses a die-on-ceramic architecture with a 2x2 array of InGaN dice flip-chip attached to a ceramic submount, and has a hemispherical silicone dome lens encapsulating the LED dice. The dimension of the package is 7x7 mm^2. In order to achieve low package cost, a novel hybrid design was developed for the ceramic submount, which combines a high-thermal-conductivity ceramic for die attach and a low-cost ceramic frame surrounding the die attach ceramic for lens formation, as shown in Figures 1 and 2. The high-thermal-conductivity core submount carrying the LED chips provides the heat sink and the electrical connection, while the low-cost plain ceramic frame provides mechanical support for handling and optical lens mount. The hybrid design reduces the size of the expensive ceramic submount in the LED package without sacrificing thermal performance of the package. The typical thermal resistance of the package is measured to be 1.25 K/W from the junction of the chip to the bottom of the ceramic submount. Figure 3 shows the thermal resistance measurement data of two groups of the LED devices mounted on different carrier. The first onset peak of the thermal resistance value is the thermal resistance from junction to the bottom of the ceramic submount; the average value is 1.25 K/W.

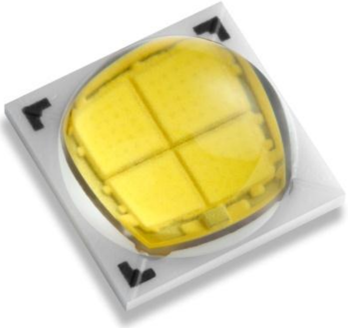

Figure 1: High-power white LED die-on-ceramic package with 2x2 InGaN LED dice covered by phosphor as developed under the program.

Figure 2: Back side view of high-power white LED package.

A hemispherical silicone dome lens is formed on top of the LED array for optical encapsulation to maximize light extraction from the LEDs. The lens diameter was chosen to be 6.4 mm after optical modeling to determine the optical lens size for maximal light extraction efficiency. The silicone lens is formed on the ceramic submount by a compression molding process.

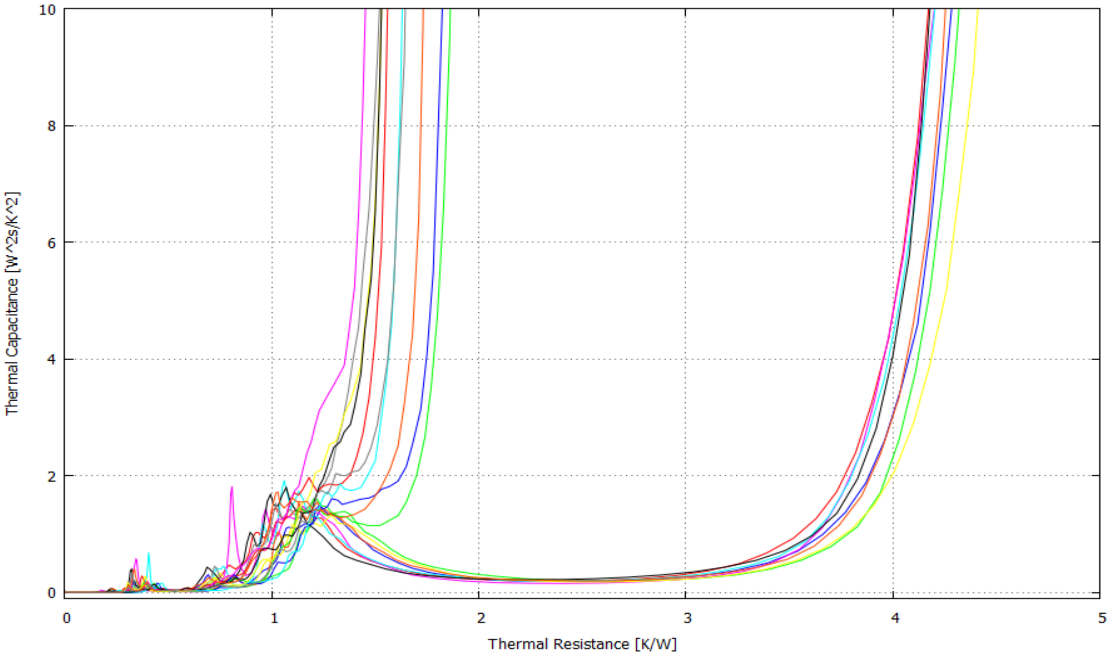

Figure 3: Thermal resistance measurement of two groups of high-power LED packages mounted on different carriers.

(2) Phosphor integration process development

A new phosphor powder batch integration process has been developed to down-convert blue light from the InGaN LED dice into white light. The new phosphor deposition process is done at batch level: a layer of phosphors is applied over a batch of blue dice arrays on ceramic submount. Since the phosphor composition and layer thickness can be well tuned and controlled for any specific color target, the color yield is better than the process currently used in production. As shown in Figure 4, the color point spread (blue dots) for the new phosphor powder batch process is much smaller than the old phosphor process (black dots) for the target point of 3500 K. The tight color distribution enables single color bin specification or freedom from binning. The new phosphor integration process has also been proven to have high conversion efficiency and good color stability under high power and high temperature operation conditions.

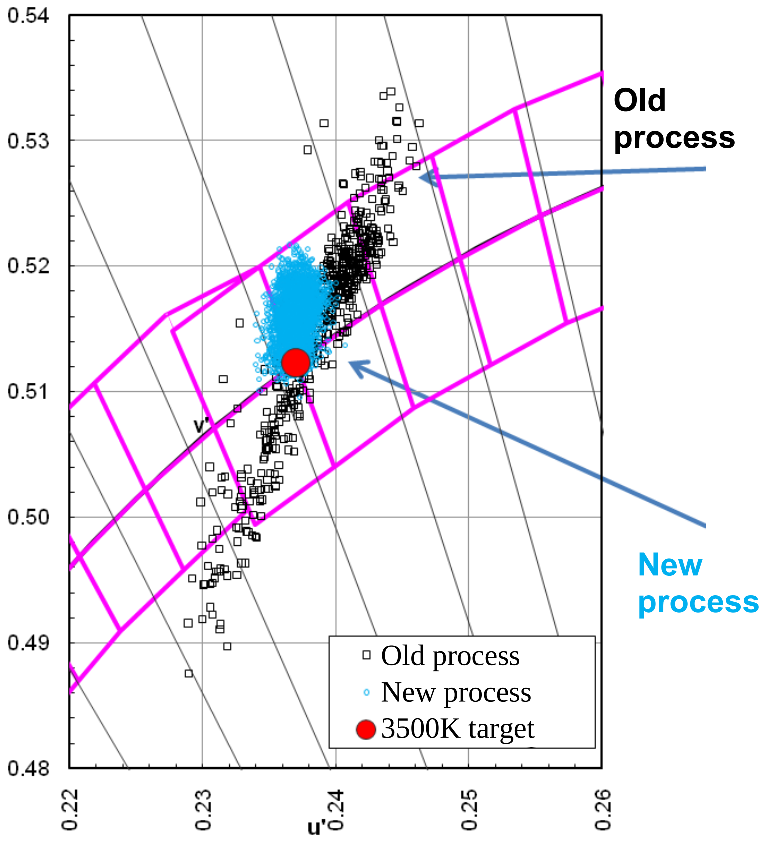

Figure 4: Color distributions of high-power 3500 K white LEDs using the old phosphor process and the new phosphor powder batch process.

(3) 1000 lm High-Power Warm-White LED Prototype Demonstration

Using the high-power array LED package developed in this program, 1000 lm warm-white LED prototype samples were built and tested. The LED package integrates the best available epitaxy and chip technologies and the phosphor integration process developed under the DOE program and internally. Specifically, internal quantum efficiency (IQE) improvement in epitaxy, blue pump chip level electrical injection efficiency improvement and loss reduction, and package level extraction efficiency improvement together contribute to ~25% efficacy gain over the two-year period.

The LED package was tested at room temperature in monopulsed mode in a calibrated integrating sphere tester. At 700 mA, the total flux is 1023 lm with an efficacy of 124.8 lm/W, CCT of 3435 K and CRI of 81.2.

In addition to the productized package, a prototype of an R&D package was tested. This package is shown in Figure 5 and also uses a die-on-ceramic architecture based on four 2 mm^2 InGaN dice. The luminous efficacy of this package is higher than the productized package due to improved package efficiency. The light-emitting surface is also larger.

The R&D package was also tested at room temperature in a calibrated tester at the same conditions as the productized package. Figure 5 shows the flux and efficacy curves as a function of drive current. At 650 mA, the total flux is 1015 lm with an efficacy of 133.1 lm/W, CCT of 3475 K and CRI of 80.5. At 350 mA drive current, the efficacy of the package is 143.9 lm/W and the total light output is 571 lm. This prototype exceeds the program efficacy target of 130 lm/W at 1000 lm and CRI > 80.

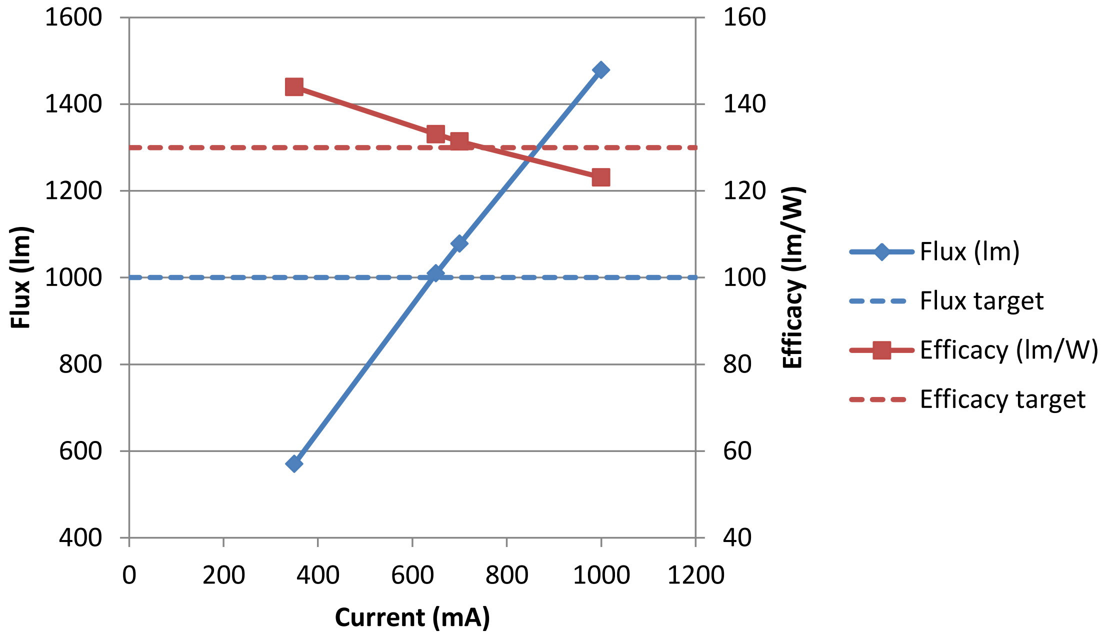

Figure 5: Light output and efficacy curves vs. drive current of R&D prototype high-power white LED tested at 25 °C.

The prototypes of the product package and the R&D package that produced the results above are shown in Figure 6.

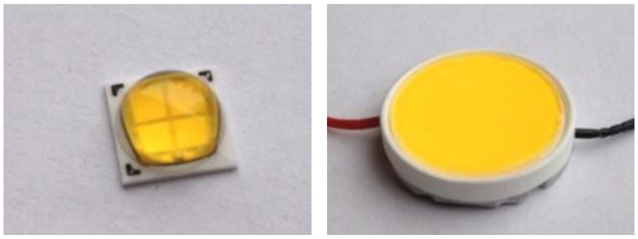

Figure 6: Product package prototype with efficacy of 124.8 lm/W (left) and R&D package prototype with efficacy of 133.1 lm/W (right).

Compared to the performance of high-power warm-white LEDs commercially available, the efficacy of the warm-white LED prototypes developed in this program showed significantly better performance. For example, the top flux bin of Cree's XP-G2 warm-white LEDs has an efficacy of 120 lm/W at a junction temperature of 25 °C and a drive current of 700 mA. Compared to this commercially available product, the warm-white LED product package prototype developed under this program has 4% better efficacy, while the R&D package prototype has 11% better efficacy.

(4) Reliability test

Large quantities of neutral-white LED packages were put on reliability tests. First, operational boundaries for drive current and heat sink temperature were investigated. LED packages were mounted on standardized test substrates, which in turn were mounted on test boards containing 128 to 256 LED packages each. The board temperatures ranged from -40 °C to 115 °C; the drive current ranged from 700 mA to 1050 mA. From this boundary conditions study it was determined that the devices can operate up to 120 °C board temperature under 700 mA drive current, or 105 °C board temperature under 1050 mA drive current.

After this operational boundary study, lumen maintenance and color point stability studies were conducted on the neutral-white LED packages at various board temperatures and a drive current of 700 mA. 80 devices were tested for each board temperature. Figure 7 shows the average lumen maintenance curves. At a board temperature of up to 85 °C, the light output drop is less than 1% during the 6500 hours tested, and a slight increase of the average light output of the order of 2% is observed at completion. Figure 8 shows the color point change of the same groups of devices. The color point shift is less than 0.002 after 6500 hours.

Lumen maintenance and color point stability studies were also started on the warm-white LED packages. Table I shows the status of these studies after 1000 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 maximum color point shift is 0.002 for 700 mA and 85 °C and less than 0.003 for all test conditions.

For the abovementioned tests on both neutral- and warm-white, the color point change meets the reliability requirement for general lighting where the typical heat sink temperature is less than 85 °C.

Additionally, environmental studies were done with 64 units for each test condition. The conditions included low/high temperature storage life, temperature cycle, air thermal shock, powered temperature cycle, moisture operating life, random vibration, and mechanical shock. No failures or large parametric shifts were observed for any of these tests.

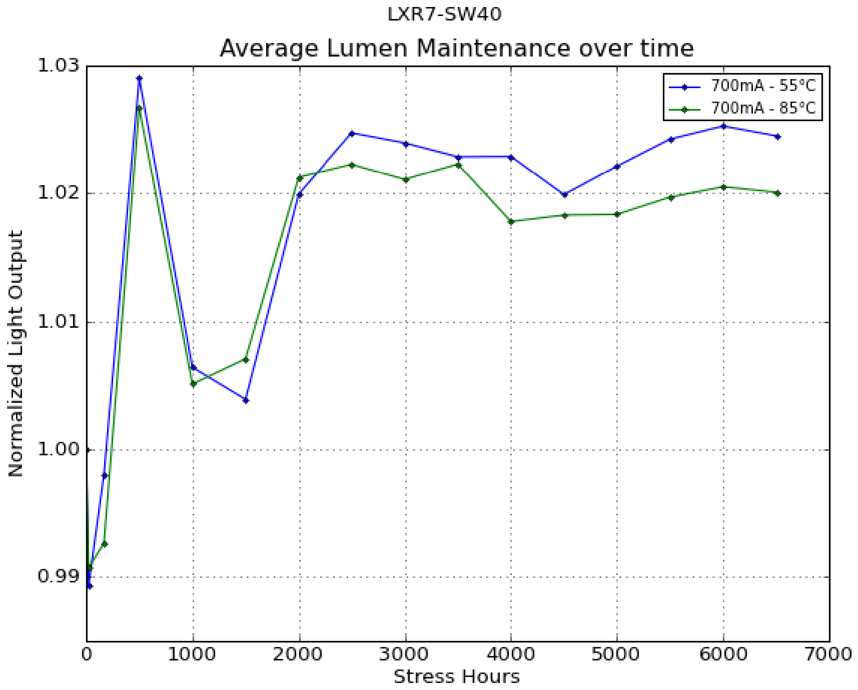

Figure 7: Lumen maintenance over time for high-power neutral-white LEDs at 55 and 85 °C board temperature and 700 mA drive current. Each curve represents an average light output of a group of 80 devices. The device junction temperature is ~19 °C above the board temperature.

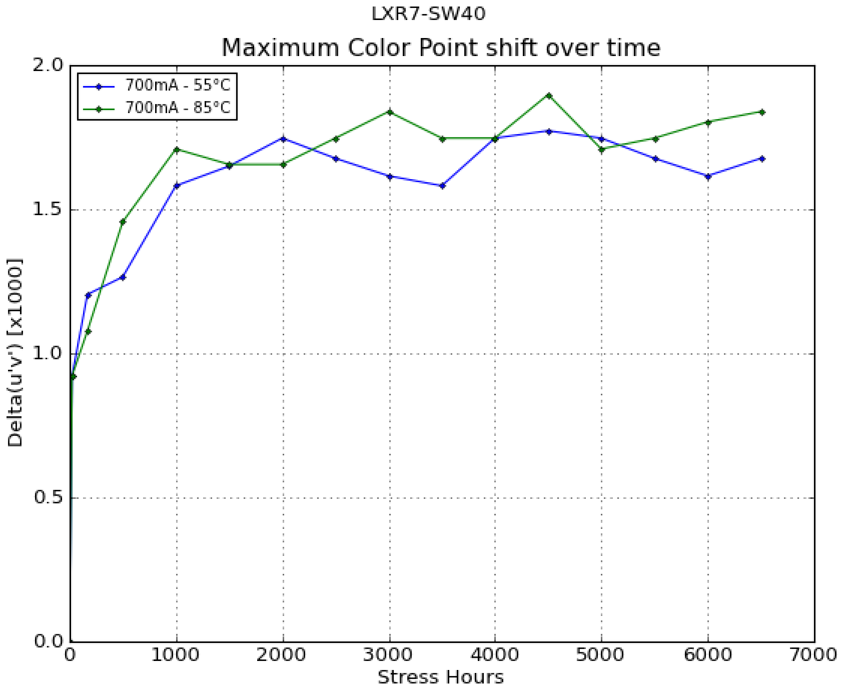

Figure 8: Color point maintenance over time for high-power neutral-white LEDs at 55 and 85 °C board temperature and 700 mA drive current. Each curve represents the maximum color point shift of a group of 80 devices. The device junction temperature is ~19 °C above the board temperature.

Table I: Test results after 1000 hours of high-temperature operating life tests of the warm-white LEDs for the various board temperatures and drive currents. The junction temperature estimate is based on the measured thermal resistance from the junction to the test board. A failure is defined as an LED that is open or shorted or loses more than 30% of light output. A unit with large parametric shifts is defined as having either $|\Delta\phi_V| \geq 15\%$*,* $\Delta(u'v')$ *color point shift* ≥ 0.007*, or* $|\Delta V_F| \geq 10\%$*.*

Stress Test Condition [1,2]	**Units Tested**	**Units Failed [3]** **Units With Large Parametric Shifts [4]**	**Delta Flux after the completion of stress test**	**Delta (u',v') color point after the completion of stress test**	**Delta Forward Voltage after the completion of stress test**
T_{PLATE} = 120°C, I_F = 700 mA, 1,000 hours. $T_{JUNCTION}$ ≈ 140°C	64 units	0 failures 0 units with large parametric shifts	$\Delta\phi_V$ ave = +0.52% $\Delta\phi_V$ min = –0.71% $\Delta\phi_V$ max = +1.86%	Δcp ave = 0.0009 Δcp max = 0.0019	ΔV_F ave = +0.24% ΔV_F min = –0.03% ΔV_F max = +0.52%
T_{PLATE} = 105°C, I_F = 1050 mA, 1,000 hours. $T_{JUNCTION}$ ≈ 136°C	64 units	0 failures 0 units with large parametric shifts	$\Delta\phi_V$ ave = +1.70% $\Delta\phi_V$ min = +0.29% $\Delta\phi_V$ max = +3.35%	Δcp ave = 0.0017 Δcp max = 0.0025	ΔV_F ave = +0.16% ΔV_F min = –0.08% ΔV_F max = +0.58%
T_{PLATE} = 105°C, I_F = 875 mA, 1,000 hours. $T_{JUNCTION}$ ≈ 131°C	64 units	0 failures 0 units with large parametric shifts	$\Delta\phi_V$ ave = +0.98% $\Delta\phi_V$ min = –0.16% $\Delta\phi_V$ max = +4.10%	Δcp ave = 0.0012 Δcp max = 0.0028	ΔV_F ave = +0.20% ΔV_F min = –0.09% ΔV_F max = +5.46%
T_{PLATE} = 105°C, I_F = 700 mA, 1,000 hours. $T_{JUNCTION}$ ≈ 125°C	64 units	0 failures 0 units with large parametric shifts	$\Delta\phi_V$ ave = +0.91% $\Delta\phi_V$ min = –0.27% $\Delta\phi_V$ max = +1.74%	Δcp ave = 0.0013 Δcp max = 0.0021	ΔV_F ave = –0.04% ΔV_F min = –0.25% ΔV_F max = +0.21%
T_{PLATE} = 85°C, I_F = 1050 mA, 1,000 hours. $T_{JUNCTION}$ ≈ 116°C	64 units	0 failures 0 units with large parametric shifts	$\Delta\phi_V$ ave = +1.35% $\Delta\phi_V$ min = +0.52% $\Delta\phi_V$ max = +2.64%	Δcp ave = 0.0012 Δcp max = 0.0022	ΔV_F ave = –0.14% ΔV_F min = –0.26% ΔV_F max = –0.04%
T_{PLATE} = 85°C, I_F = 875 mA, 1,000 hours. $T_{JUNCTION}$ ≈111°C	64 units	0 failures 0 units with large parametric shifts	$\Delta\phi_V$ ave = +0.76% $\Delta\phi_V$ min = –0.03% $\Delta\phi_V$ max = +2.07%	Δcp ave = 0.0014 Δcp max = 0.0022	ΔV_F ave = +0.05% ΔV_F min = –0.04% ΔV_F max = +0.14%
T_{PLATE} = 85°C, I_F = 700 mA, 1,000 hours. $T_{JUNCTION}$ ≈ 105°C	64 units	0 failures 0 units with large parametric shifts	$\Delta\phi_V$ ave = +0.81% $\Delta\phi_V$ min = –1.56% $\Delta\phi_V$ max = +2.05%	Δcp ave = 0.0013 Δcp max = 0.0021	ΔV_F ave = –0.16% ΔV_F min = –0.35% ΔV_F max = –0.02%

3. Product Commercialization

After design and process optimization and extensive reliability tests, the kilo-lumen high-power LED has been released to the market. Based on market demand, neutral-white (4000 K) and cool-white (5700 K) LED products were released at the beginning of 2012 for outdoor and industrial lighting applications. Warm-white LEDs (2700 K and 3000 K) products were released in the second half of 2012 for outdoor/indoor professional and residential applications. The released LED products are called LUXEON M. The data sheet can be found on Philips Lumileds' website at www.philipslumileds.com. All the LED products are single-color binned (5 SDCM ellipse for the 70 CRI products, 3 SDCM ellipse for the 80 CRI products) and hot tested at 85 °C junction temperature. Top-bin products put out as high as 1040 lm at 700 mA and 85 °C junction temperature. The typical operation current is 700 mA with a maximum current of 1050 mA.

The released products are tested following LM-80 test criteria, ensuring accurate lumen maintenance reporting and enabling Energy Star certification for luminaires and lamps containing the product. The LM-80 tests for the products with CCTs of 4000 K, 5000 K and 5700 K have reached 8500 hours, and per IESNA TM-21-11 have established an L70 lumen maintenance value of >51,000 hours at 700 mA drive current and up to 120 °C board temperature.

4. Invention Disclosures and Patent Applications

Decai Sun, "Methods to increase package efficiency of phosphor converted white LEDs", Philips internal invention disclosure, June 2011. No patent application filed.

5. Publications

1. Decai Sun, "High Efficacy Kilo-Lumen Warm White LED Development for Illumination", Invited presentation at DOE SSL R&D workshop, February 1-2, 2011, San Diego, CA
2. Decai Sun, "Kilo-Lumen Warm White LED Development for Illumination", Invited talk at LED Professional Symposium, September 27-29, 2011, Brengenz, Austria
3. Shih Shun Chang and Decai Sun, "Super Bright High Power White LED Development for Illumination", 8th China International Forum on Solid State Lighting, November 8-10, 2011, Guangzhou, China