Final Technical Report

January 24, 2011

100 LPW 800 Lm Warm White LED for Illumination

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1. Executive Summary

An illumination grade warm white (WW) LED, having correlated color temperature (CCT) between 2800 K and 3500K and capable of producing 800 lm output at 100 lm/W, has been developed in this program. The high power WW LED is an ideal source for use as replacement for incandescent, and Halogen reflector and general purpose lamps of similar lumen value. Over the two year period, we have made following accomplishments: developed a high power warm white LED product and made over 50% improvements in light output and efficacy. The new high power WW LED product is a die on ceramic surface mountable LED package. It has four 1x1 mm^2 InGaN pump dice flip chip attached to a ceramic submount in 2x2 array, covered by warm white phosphor ceramic platelets called Lumiramic™ and an overmolded silicone lens encapsulating the LED array. The performance goal was achieved through breakthroughs in following key areas: (1) High efficiency pump LED development through pump LED active region design and epi growth quality improvement (funded by internal programs). (2) Increase in injection efficiency (IE) represented by reduction in forward voltage (V_f) through the improvement of the silver-based p-contact and a reduction in spreading resistance. The injection efficiency was increased from 80% at the start of the program to 96% at the end of the program at 700 mA/mm^2. (3) Improvement in thermal design as represented by reduction in thermal resistance from junction to case, through improvement of the die to submount connection in the thin film flip chip (TFFC) LED and choosing the submount material of high thermal conductivity. A thermal resistance of 1.72 K/W was demonstrated for the high power LED package. (4) Improvement in extraction efficiency from the LED package through improvement of InGaN die level and package level optical extraction efficiency improvement. (5) Improvement in phosphor system efficiency by improving the lumen equivalent (LE) and phosphor package efficiency (PPE) through improvement in phosphor-package interactions. Another achievement in the development of the phosphor integration technology is the demonstration of tight color control. The high power WW LED product developed has been proven to have good reliability. The manufacturing of the product will be done in Philips Lumileds' LUXEON Rebel production line which has produced billions of high power LEDs. The first high power WW LED product will be released to the market in 2011.

2. Project Objectives and Actual Accomplishments

A. Original Project Objectives

We proposed a two-year program for Program Area of Interest 1 – High efficiency LEDs. The result of this program would be a single high power LED capable of producing 800 lm of Warm White light with Color Correlated Temperature (CCT) in the range of 2800 K to 3500 K, Color Rendering Index (CRI) >90 and LED efficiency of over 100 lm/W. Reliability testing would be done through the program to ensure that the approach taken met the requirement for 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 58 lm/W and 500lm from a warm white high power LED with CRI > 90.

The objective for Phase 2 of this work was to demonstrate over 100 lm/W and 800 lm from a warm white high power LED with CRI > 90.

B. Original Scope of Work

Five key areas of product development would be pursued: (1) Increase in Injection Efficiency (IE) represented by reduction in Forward Voltage (V_f). The focus of this work was improvement in the silver based p-contact and reduction in spreading resistance both of which decrease V_f. (2) Improvement in thermal design as represented by reduction in thermal resistance from junction to case for high power LED package. The initial focus of this work was the reduction of thermal resistance due to the die to submount connection in the TFFC LED. (3) Improvement in extraction efficiency from the package. The focus of this work was on increasing the Refractive Index (RI) of the encapsulation materials of the LED through which light must pass from 1.41 to over 1.6. Increase in RI directly improves light extraction efficiency resulting in an increase in extraction efficiency from ~76% today to 85% by the end of this program. (4) Improvement in phosphor system efficiency. Focus of this effort was on improving Lumen Equivalent (LE), Color Rendering Index (CRI) and Phosphor Package Efficiency (PPE) through improvement in phosphor-package interactions. This work used novel ceramic phosphor plates developed by Philips-Lumileds called Lumiramic™. Lumiramic™ plates offer efficient phosphor solutions in ceramic form but these plates must be combined with at least one additional powder phosphor to generate the desired CRI of >90, LE & CCT. Selection of phosphor combinations and methods for integrating phosphors into the package have a direct impact on LED efficiency and even LED LE due to phosphor absorption and reemission. (5) 800 lm high power LED development. The development would be executed on Philips Lumileds high power LED LUXEON® K2 Platform. 2x2 mm2 LED chips would be integrated on high thermal conductivity submount with large area gold to gold interconnect as die attach method. TFFC fabrication process would be developed for large area 2x2 mm2 LED arrays. The 800 lm warm white LED development would combine all the advancement made in the first four areas and continuous IQE improvement in our epitaxial improvement effort funded by Philips Lumileds internally.

C. Major Proposed Milestones

1. Budget period I: Prototype warm white high power LED with output of 500 lm and 58 lm/W.

2. Budget II: Prototype warm white high power LED with output of 800 lm and 100 lm/W.

D. Actual Accomplishments

(1). Injection Efficiency Improvement of InGaN Pump Device

Increase in injection efficiency (IE) of InGaN pump device represented by reduction in forward voltage (V_f) was realized through the improvement of the silver-based p-contact and reduction in spreading resistance inside the device. The injection efficiency was increased from 80% at the start of the program to 96% at the end of the program at 700 mA/mm^2. The V_f of a single 1 mm^2 InGaN pump device was reduced from 3.5V to 2.91V at 700 mA drive current and room temperature.

(2). Thermal Design Improvement of High Power LED

Improvement in thermal design of high power LED as represented by reduction in thermal resistance from junction to case was realized through the improvement of the die to submount connection in the thin film flip chip (TFFC) LED and the selection of submount material of high thermal conductivity. A thermal resistance of 1.72 K/W was demonstrated for the high power LED package with four 1 mm^2 InGaN pump dice.

(3). Improvement in Optical Extraction Efficiency of LED Package

Improvement in extraction efficiency from the LED package was accomplished through improvement of InGaN die level and package level optical extraction efficiency improvement. The optical extraction efficiency increase resulted in more than 10% flux and efficacy gains.

(4). Improvement in Phosphor System Efficiency and Color Control

Progress was made in phosphor system efficiency by improving the Lumen Equivalent (LE) and Phosphor Package Efficiency (PPE) using a phosphor plate called Lumiramic™. Using the Lumiramic technology, tight color control was also demonstrated in WW LEDs. WW LUXEON Rebel LED products using the Lumiramic technology have very tight color distribution with 80% of the parts falling within a 3 MacAdam ellipse area within ANSI bin.

(5). 800 lm High Power WW LED Development

A new high power WW LED product was developed in this program. The LED package integrates all the technologies developed under the DOE program and internally. It has four 1mm^2 InGaN pump dice flip chip attached to a ceramic submount using advanced gold to gold interconnect technology. Thin film fabrication process was developed for the array product to increase light extraction. WW Lumiramic platelets were integrated on top of the thin film flip chip dice for phosphor downward conversion and color control. Silicone lens molding process was done at tile level for optical lens formation. 800 lm light output with an efficacy of 100 lm/W at 700 mA/mm^2 drive current and CCT <3500K. The manufacturing of the product will be done in Philips Lumileds's LUXEON Rebel production line which has produced billions of high quality LEDs. The first high power WW LED product will be released to the market in mid-2011.

3. Project Activities and Progress

(1). Electrical Injection Efficiency Improvement of InGaN Pump LED

At the start of the program, our InGaN pump LED device has relatively low electrical injection efficiency as represented by high forward voltage of the LED at certain drive current. At 700 mA drive current, the forward voltage of an 1 mm^2 InGaN pump LED had a forward voltage of 3.5V at the start of the program, much higher than the theoretical limit of 2.8 V forward voltage limited by the bandgap of GaN material used in the LED structure. The electrical injection efficiency was only 80%.

The development effort started with setting up correct electrical circuit model for the InGaN flip chip device structure. Through numerical modeling, major components contributing to the series contact resistance were identified as shown in Fig 1, where P-contact resistance and spreading resistance in n-layer dominate. In process development, the effort focused on primarily optimizing the Ohmic contact resistance of the silver-based anode contact including deposition conditions and contact annealing process. The reduction of the series resistance of the device was also aided by optimizing the design of the epitaxial layers and doping levels in the n-type GaN layers underlying the InGaN active region which was funded by internal projects.

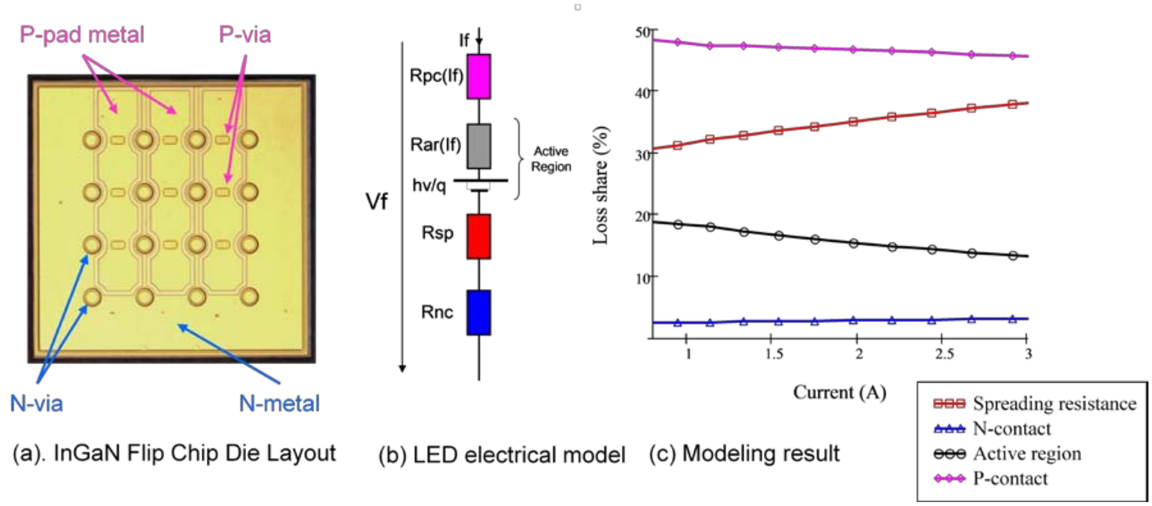


Fig. 1 InGaN flip chip die layout and electrical model

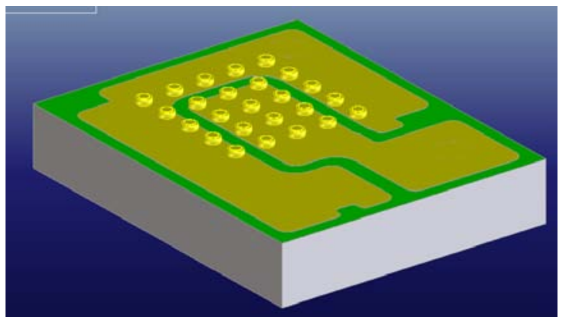
At the end of the program, the forward voltage of 1 mm^2 InGaN pump device was reduced to 2.91 V for a 445nm blue die at an operating current of 700mA. The electrical injection efficiency was at 96%.

(2). Thermal Design Improvement of High Power LED

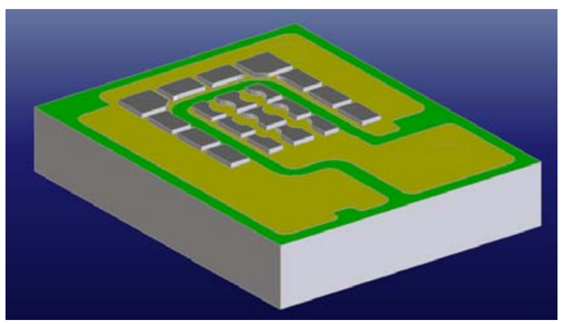
For high-power InGaN flip-chip LEDs, the main determinant of the thermal resistance is the interconnection to the LED package. In a flip-chip device, the interconnection area must be shared between the anode and cathode connections. In practice the combined area of the two electrodes is less than the total die area and is determined by the method and materials used to define the interconnection. The material of the interconnection is also quite critical, with materials of high thermal conductivity providing a low thermal resistance connection. At the start of this program, Philips Lumileds' 1 to 3 Watt LED products use gold-gold interconnections (GGI) based on stud-bumping technology, where the area of the interconnection is limited to only ~15% of the die area. The thermal resistance of the LED is about 10 K/W.

The first phase of the effort focused on increasing the area of the gold-gold interconnection from 15% to 45% through the use of plated gold technology. Large area bumps are plated on a submount carrier where the LED chips will be flip chip attached. Using large area gold to gold interconnect, we have demonstrated 4.2 K/W thermal resistance for a LUXEON K2 device containing 1 mm^2 die.

Using the large area plated gold bumps on a ceramic submount for flip chip die attach, a high power LED containing four 1 mm^2 InGaN pump dice shows a thermal resistance of 1.72 K/W from junction to the bottom of the submount which is below the target thermal resistance of 2 K/W for the program.



(a) LED submount with gold stub bumps



(b) LED submount with large area plated gold bumps

Fig. 2 LED submounts with (a) gold stud bumps and (b) large area gold plated bumps for LED flip chip die attach interconnection

Further reduction of the thermal resistance high power LEDs was developed by increasing the area of the interconnection from 45% to ~90% through the optimization of the gold plating process and the associated die attach technology which is called very large area gold to gold interconnect interconnect technology. The very large area gold bumps are plated directly on InGaN die at wafer level. LUXEON K2 LEDs with such flip chip gold interconnect shows a thermal resistance below 4K/W and less thermal gradient across the die than the die with stud bump or large area gold to gold interconnect method.

(3). Improvement in Optical Extraction Efficiency of LED Package

The proposed approach in the original proposal to increase optical extraction efficiency of a high power LED package such as LUXEON Rebel and LUXEON K2 from ~76% to 85% by increasing refractive index of the encapsulation materials. For example, the overmolded lens dome of LUXEON Rebel is a silicone material of refractive index of ~1.4. When the index of the lens and the glue are raised, the light extraction efficiency goes up as expected. From our investigation, we found the choice in high refractive optical encapsulant is very limited due to the evolutionary requirements on reliability under more and more extreme operation conditions (temperature, flux) and molding compatibility. We have also investigated high index glass lens of 1.8 for LUXEON K2 package, but did not observe much optical extraction efficiency gain because the silicone gel used to fill the gap between the die and the glass lens is still low refractive index material of ~1.4.

In phase II of the program, we altered the approaches to increase optical extraction efficiency of the LED package by focusing on improvement of optical extraction at InGaN pump die and package level. The die level optical extraction efficiency was increased by increasing p-contact reflectivity and reduction of dark contact metal area in the InGaN pump chip. The reduction of dark contact metal area was realized through advanced lithography tool acquired to reduce dark metal (low reflectivity) area. Over 10% flux gain was demonstrated in white LEDs experimentally from the die level extraction efficiency improvement .The optical extraction efficiency at package level is increased by enhancing the reflectivity of the submount surface used for die attach. The surface reflectivity of the submount can be enhanced by applying a white coating to cover the ceramic and gold around the die, which improves the flux by more than 3%.

(4). Improvement in Phosphor System Efficiency and Color Control

The phosphor division of Philips Lighting in cooperation with Philips Lumileds has developed a novel new phosphor in the form of a ceramic wafer that is ideal for use in LEDs. The phosphor wafer is called “Lumiramic™” because it is a high temperature ceramic which luminesces when exposed to blue light of an appropriate wavelength to excite the phosphor. These Lumiramic™ wafers can be fully characterized in wafer form in rapid high volume equipment and can be diced into small plates approximately the size of an LED die as shown in Fig. 3. This allows characterization of the phosphor prior to application to the LED and matching of LED emission wavelength to phosphor plate thus dramatically lowering the spread in color that traditionally results when manufacturing phosphor converted LEDs.

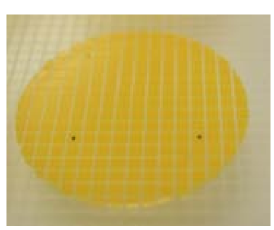


Fig. 3 Lumiramic-™ warm white wafer after dicing

At the start of the program, cool white Lumiramic wafers had been developed and released to production. The focus of this program was on development of warm white Lumiramic wafers which need to combine yellow phosphor plate with red phosphor powder layer and optimization of phosphor integration into the package to hit required Phosphor Conversion Efficiency, CCT and CRI. Both activities have been completed successfully in the end of the program with release of warm white LUXEON Rebel in market place in mid-2010, which demonstrated very tight color control in high volume production, with 80% of the parts falling within a 3 MacAdam ellipse area within ANSI bin as shown in Figure 4.

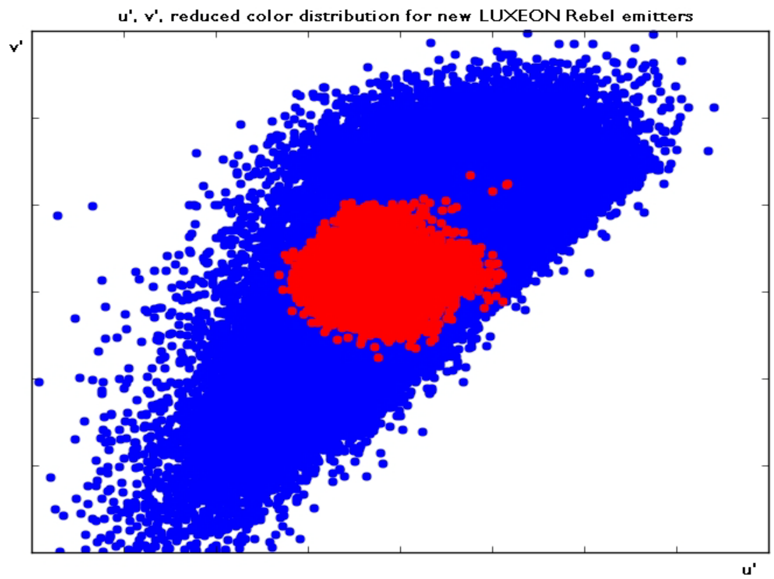


Fig. 4 Color distribution plot of WW LUXEON Rebel: Area in red indicates distribution of LUXEON Rebel LEDs using Lumiramic phosphor technology. Area in blue is a standard distribution of white LEDs.

(5). 800 lm High Power WW LED Development

The original plan for 800 lm high power LED development was to use LUXEON K2 package which is lead frame based. A high power LUXEON K2 containing 2x2 mm^2 pump die flip chip attached to a silicon submount and warm white Lumiramic platelets was developed in the beginning of the program. The LED package emitted over 425 lm at 43 lm/W and CCT of 2700K. The prototype was shown to customers and did not receive good acceptance because of the cost and poor performance. The performance was limited by the package size which was a bit too small for 2x2 mm^2 pump dice.

Based on the customer feedback, we decided to choose die on ceramic with overmolded lens design for the high power WW LED array similar to LUXEON Rebel.

The LED package integrated all the technologies developed under the DOE program and internally. It has four 1mm^2 InGaN pump dice flip chip attached to a ceramic submount using advanced gold to gold interconnect technology in first design as shown in Fig. 5. Thin film fabrication process was developed for the array product to increase light extraction. WW Lumiramic platelets were integrated on top of the thin film flip chip dice for phosphor downward conversion and color control. Silicone lens molding process was done at tile level for optical lens formation. A finished high power LED package is shown in Fig. 6. Device performance exceeding 800 lm light output with an efficacy of 100 lm/W at 700 mA/mm^2 drive current and CCT < 3300K was demonstrated. The color coordinates of the device are shown in Fig. 7. The CRI of the device is 76. We have also designed a high power LED package with four 2 mm^2 InGaN pump dice. The LED package emits over 820 lm at 100 lm/W and CCT of 2845K under 700 mA drive current per die. The CRI of the device is over 80.

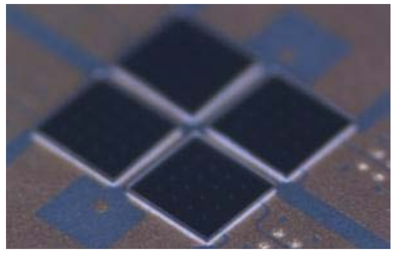


Fig. 5 2x2 InGaN pump dice flip chip attached to ceramic submount

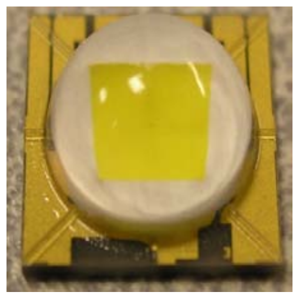


Fig. 6 High power WW LED with 4 1 mm^2 pump die and Lumiramic

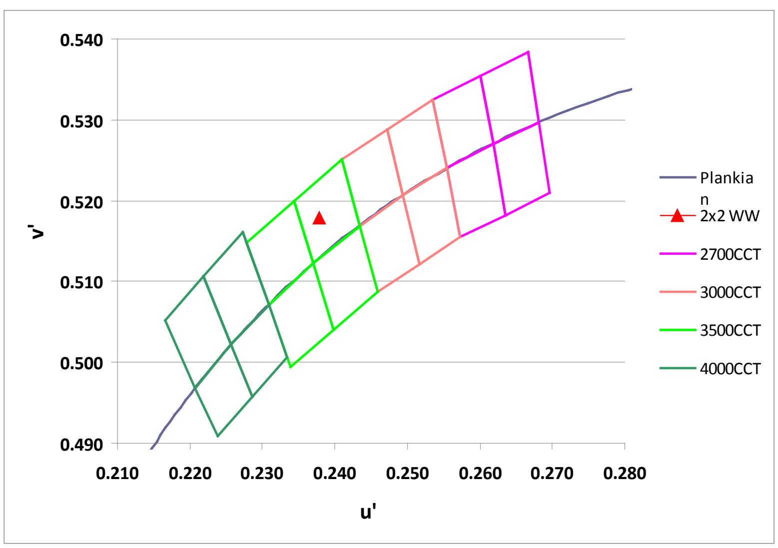


Fig. 7 Color coordinates of high power WW LED with CCT of 3300K

4. Product Commercialization

The product creation process is underway. The manufacturing of the product will be done in Philips Lumileds's LUXEON Rebel production line which has produced billions of high quality LEDs. The first high power WW LED product will be released to the market in 2011.

5. Invention Disclosures and Patent Applications

A. Invention Disclosures

1. ID776116 A Packaging Concept for Ultra-High Power LED Lamp
Inventors: Nanze Patrick Wang,
Internal invention disclosure submission date: January 26, 2009

Summary: In one or more embodiments of the present disclosure, a light-emitting device (LED) package includes an LED die mounted on a support, a high index lens having a refractive index (RI) of 1.5 or greater, and a window element bonded to the lens. The lens with the window element is located over the LED die. The window element may be a wavelength converting element or an optically flat plate. The bond between the window element and the lens may be direct or indirect. A direct bond may be a bond without any intermediate bonding layer between the elements being joined, for example, between the window element and the lens or other optical elements. An indirect bond may be a bond formed with one or more intermediate bonding layers between the elements being joined. The direct or indirect bond has an RI similar to that of the window element, the lens, or both.

Philips Lumileds LLC will retain title in the following countries of filing (plan): US, CN, EP, KR, TW, JP

2. ID775839 High Performance and Low Cost Multi-chip LED Package
Inventors: Nanze Patrick Wang, Gregory W. Eng, Decai Sun, Yajun Wei
Internal invention disclosure submission date: April 21, 2009

Summary: The invention describes a LED module. In one or more embodiments of the present disclosure, an array of housings with housing bodies and lenses is molded, or an array of housing bodies is molded and bonded with lenses to form an array of housings with housing bodies and lenses. Light-emitting diodes (LEDs) are attached to the housings in the array. An array of metal pads may be bonded to the back of the array or insert molded with the housing array to form bond pads on the back of the housings. The array is singulated to form individual LED modules.

Philips Lumileds LLC will retain title in the following countries of filing (plan): US, CN, EP, KR, TW, JP

3. ID775836 Simplified Zener Diode Protection Network for LEDs Connected in Series
Inventor name: Yajun Wei, David Collins, Daniel Steigerwald
Internal invention disclosure submission date: April 22, 2009

Summary: The present invention proposes a novel Zener diode configuration that greatly simplifies TVS network of a multi LED die device for ESD protection. Instead of putting a back-to-back Zener pair for each of the LED diode, by connecting each LED electrode with only one Zener diode, significant reduction of the number of diodes can be achieved. For silicon submount with embedded TVS, it simplifies the design especially the geometry of the ion-implantation regions that is essential to lower diode series resistance with sharper turn on in ESD events and higher current handling capacity. The invention can also be applied to discrete device network.

Philips Lumileds LLC will retain title in the following countries of filing (plan): US, CN, EP, KR, TW, JP

B. Patent Applications

1. 013531: Zener diode protection network in submount for LEDs connected in series. US Patent filing date: September 7, 2009
2. 013562: LED module with high index lens. US Patent filing date: September 17, 2009

6. Publications

1. D. Sun, K. Chang, W. Goetz, M. Holcomb, T. Margalith, S. Schiaffino, O. Shchekin, Y. Wei “100 LPW 800 LM white LED development for illumination”, 2009 US Department of Energy Solid State Lighting Workshop, February, 2009, San Francisco

2. D. Sun, Y. Wei, M. Holcomb, K. Chang, L. Hung, “High power LED development for illumination”, 2009 Philips Solid State Lighting Symposium, March, 2008, Eindhoven, Netherland.

3. D. Sun, Y. Wei, J. Pardo, O. Shchekin, T. Mihopoulos, H. Choy, T. Margalith, S. Schiaffino, W. Goetz, “1000 lumen white LEDs for illumination” White LED conference, Taipei, Taiwan, December 13 – 16, 2009.

4. D. Sun, “ Raising the bar for warm white luminaire performance”, Invited talk at DOE 2010 R&D workshop, Relaigh, NC, Feb 2 to 4, 2010

5. D. Sun, “High power white LED development-enabling high efficacy and high quality luminaire”, Invited Talk at Future of Lighting and Display by Society of Information and Display, Seattle, WA, May 26, 2010

6. D. Sun, “High power white LED development for general lighting”, Invited Talk at Semicon West, San Francisco, July 14, 2010