High Efficiency LED Lamp for Solid-State Lighting

Final Report

Period Start Date:	**October 1, 2003**
Period End Date:	**December 31, 2006**
Principal Investigator/Author:	**James Ibbetson**
Date Report Issued:	**April 18, 2007**
DOE Award Number:	**DE-FC26-03NT41943**
Project Manager:	**Ryan Egidi**

Cree Santa Barbara Technology Center
340 Storke Road
Goleta CA 93117

(805) 968-9460

DISCLAIMER

ABSTRACT

This report contains a summary of technical achievements during a three-year project to demonstrate high efficiency, solid-state lamps based on gallium nitride/silicon carbide light-emitting diodes. Novel chip designs and fabrication processes are described for a new type of nitride light-emitting diode with the potential for very high efficiency. This work resulted in the demonstration of blue light-emitting diodes in the one watt class that achieved up to 495 mW of light output at 350 mA drive current, corresponding to quantum and wall plug efficiencies of 51% and 45%, respectively. When combined with a phosphor in Cree’s 7090 XLamp® package, these advanced blue-emitting devices resulted in white light-emitting diodes whose efficacy exceeded 85 lumens per watt. In addition, up to 1040 lumens at greater than 85 lumens per watt was achieved by combining multiple devices to make a compact white lamp module with high optical efficiency.

Table of Contents

EXECUTIVE SUMMARY

The objective of this three-year project is to develop new chip technology, fabrication processes, and lamp prototypes based on gallium nitride (GaN) light-emitting diodes (LEDs) in order to demonstrate 1000 lumens lamps that could be viable replacements for energy inefficient incandescent light sources. The ultimate goal of the program is to deliver to the Department of Energy solid-state lamp prototypes that produce 1000 lumens of white flux at an efficacy of 100 lumens per watt, with the potential of 150 lumens per watt beyond the time frame of the project. A summary of project milestones by Year and Task is shown in Table 1, below.

Summary Table of Project Goals

Task	**Attribute**	**End of Year 1**	**End of Year 2**	**End of Project**	**Lumens/$ Improvement**
1	GaN LED Quantum and Wall Plug Efficiency	QE: 35%	QE: 40%	QE: 50% WPE: 42%	2x
2	White Lamp Efficiency and Light Extraction (1000 Lumens Lamp)	65 lm/W	80 lm/W	100 lm/W	2-3x
	Current Density	50 A/cm^2	75 A/cm^2	100 A/cm^2	2x

This report contains a summary of technical progress made during the three-year project. For the sake of clarity, the report is divided into two main parts according to the two main tasks in the statement of work. Each part contains background, experimental, results and discussion, and conclusion sections.

Section I describes progress on an ultra-thin LED chip design that, relative to the start of the project, represents a radical departure from conventional nitride LED designs. The performance of the ultra-thin LED was shown to exceed that of conventional designs by a significant margin, resulting in the demonstration of a blue LED with quantum efficiency of 51% and 45% wall plug efficiency. While great progress was made, the final results are shy of the Year 3 milestone for Task 1 since they were demonstrated at 50 A/cm^2 not 100 A/cm^2.

Section II describes the fabrication and performance of white LEDs made using blue chips developed under Task 1. Individual white lamps using a commercial LED package were demonstrated with an efficacy of 85 lumens per watt at a current density of 50 A/cm^2. White lamp modules, comprised of multiple chips, achieved 1040 lumens output at an efficacy of 87 lumens per watt, which fell somewhat short of the Year 3 milestone target for Task 2.

Two related products were commercialized during the course of the project. Cree's EZBright™ chip product family targeting solid-state lighting was introduced. The blue EZBright1000 power chip, measured as a bare die, exhibits power output up to 370mW at 350mA of drive current and 800mW at 1A of drive current. A second-generation XLamp 7090 LED product has been released incorporating the EZBright power chip. This new XLamp LED, available in volume quantities, produces luminous flux of up to 95 lumens or 85 lumens per watt at 350 mA, and up to 160 lumens at 700 mA. Both products incorporate technology elements that were partly developed under this project, in conjunction with NIST ATP-funded and Cree internal development efforts.

SECTION I

Task 1 - High Efficiency, High Current Density LEDs

PROBLEM BACKGROUND

One of the key problems to be addressed under Task 1 is illustrated in figure 1, which shows the optical characteristics for a state-of-the-art blue power LED at the start of the project. Note that the peak quantum efficiency was only 32% at the time. Moreover, the device was designed to operate at a current density of ~50 A/cm^2 where the quantum efficiency dropped to ~25%. Technical goals for Task 1 during the project were to double the designed operating current density while boosting the quantum efficiency at ~100 A/cm^2 to 50%.

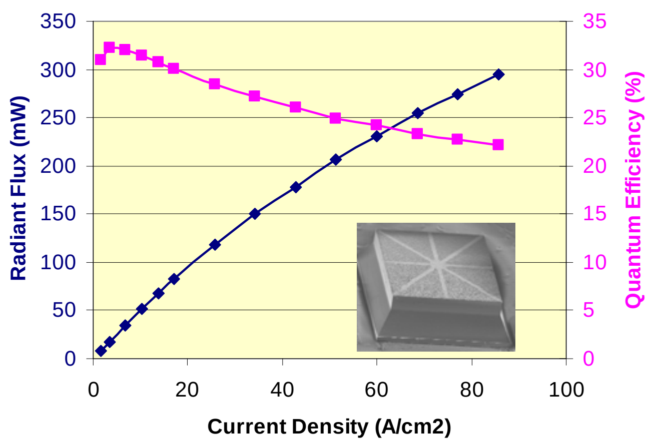


Figure 1. Optical characteristics of a conventional, 460 nm GaN/SiC power LED (inset) indicative of the state-of-the-art at the beginning of the project.

LED quantum efficiency is a product of the internal quantum efficiency, or how many photons are generated inside the semiconductor per unit of current (essentially materials quality), and the light extraction efficiency, or the fraction of generated photons that escape from the chip. In principle, improvements to the net efficiency can be achieved by improvements to either component. At the start of the project we performed a theoretical analysis of state-of-the art GaN/SiC LEDs using optical modeling of the photon paths inside the chip, which suggested the light extraction efficiency was in the range of 35-50%. So, while the roll-off in efficiency at higher current density in figure 1 is certainly a materials issue, it was evident that a major portion of the targeted efficiency gains would have to be achieved through improved light extraction. For that reason, the focus of the work on Task 1 was on developing an advanced chip design for improved light extraction.

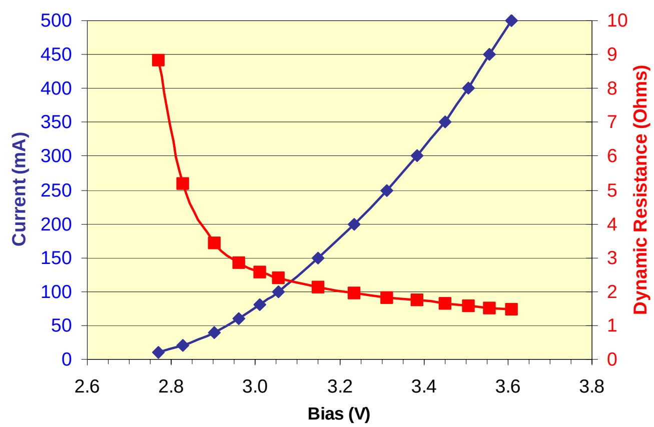


Figure 2. Electrical characteristics of a conventional blue GaN/SiC power LED, representing the state-of-the-art at the beginning of the project.

Operating voltage is also important for overall device efficiency. The operating voltage of a blue LED with an emission wavelength of 460 nm cannot be less than 2.7 V for any useful current density since this value corresponds to the active region band gap energy. Figure 2 shows the current-voltage (*I-V*) curve for the same GaN/SiC LED whose optical characteristics were plotted in figure 1. Note the LED turns on at slightly above 2.7 V, but its voltage is significantly higher (3.45 V) at the operating current of 350 mA. The difference of 0.75 V represents an excess – or parasitic – voltage that directly impacts the wall plug efficiency of the device. Moreover, the excess voltage continues to increase as the operating current is increased. In order to meet the project's ultimate LED efficiency goals, we estimated it would be necessary to reduce the excess voltage by approximately 50% over the three years of the project.

Based on calculations described in the project's annual technical reports, approximately one third of the excess voltage comes from the p-side of the diode, approximately two thirds from the n-side, while the active region appears to have little impact. When evaluated in more detail the specific contact resistance of the metal contact to p-GaN is relatively high and the contact itself is more critical than the bulk resistivity of p-GaN. On the n-side of the junction the SiC substrate and n-GaN/SiC interface resistances contribute a majority of the excess voltage. Thus, another area of focus on Task 1 has been aimed at reducing or eliminating these sources of excess voltage.

Ultra-Thin LED Design

An analysis of existing chip designs suggested there was limited scope for dramatically improving the light extraction through incremental improvements. A completely new approach was called for. Figure 3 is a schematic of a very different kind of LED design taken from the scientific literature [1]. In this design, a highly reflective mirror contact is provided on the original LED epiwafer, which is then bonded to a conductive carrier. The substrate is then thinned to reduce bulk absorption, and a textured surface is applied to the remaining material. The underlying principle is that texturing – or micro-lenses – on the surface promotes efficient light extraction by randomizing the paths of any light rays that undergo total internal reflection.

Figure 3 also shows a plot of the calculated light extraction as a function of the mirror contact reflectivity for the micro-lens LED design with and without surface texture. In principle, with a mirror reflectivity of ~90% and suitable texturing, light extraction efficiency could reach 75%, which would be a

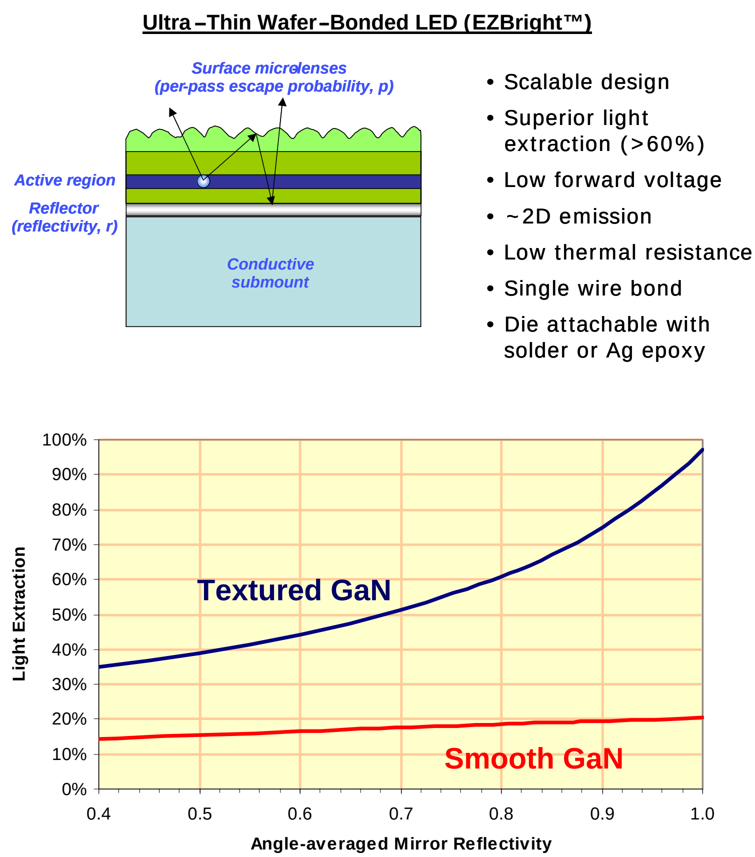


Figure 3. (Top) Schematic of the ultra-thin LED concept showing its salient features. (Bottom) Calculated fraction of light that escapes from a ultra-thin GaN LED, per reference 1. The calculations take into account bulk absorption and mirror losses.

significant improvement over conventional nitride LED designs.

Such ultra-thin or micro-lens designs have been implemented in the AlInGaP and AlGaAs materials systems, and indeed variations on the theme are available as commercial red and amber LEDs [2]. However, at the start of the project we were not aware of any successful demonstration of the concept in the nitride system. During the project's first year, much effort was put into developing many of the basic fabrication process steps required to realize such a design. During the second year, the fabrication process and baseline materials had been improved, and nitride micro-lens LEDs with record performance had been successfully achieved as a result. During the final year, new designs for improving the LED light extraction and the subsequent fabrication processes for these designs were investigated. Details of that work are provided below.

EXPERIMENTAL

MOCVD Growth and Materials Characterization

The GaN/SiC epi-material is the starting point for the LED devices. LED structures were grown by depositing successive layers of (Al, In, Ga)N of varying composition and doping on SiC substrates. In large part we were able to make use of epi-material as grown for Cree's existing LED products. However, due to the very different device architecture, changes to this baseline structure were also evaluated and developed as needed.

All materials growth and development work was conducted on production scale metal organic chemical vapor deposition (MOCVD) equipment, which allowed for a concurrent assessment of the manufacturability of any new process concepts.

Wafer-level characterization techniques such as photoluminescence, x-ray diffraction, atomic force microscopy (AFM), *L-I*, *C-V*, *I-V*, and Hall effect measurements were used to provide quick feedback. Select wafers were then passed for LED fabrication.

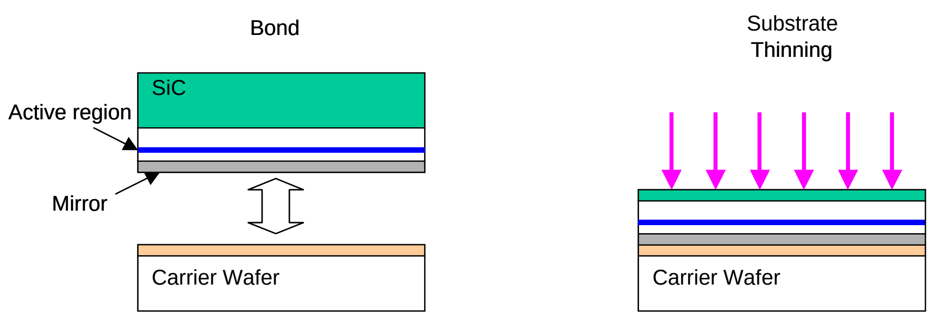


Figure 4. Key initial process steps leading to a micro-lens LED based on GaN/SiC

Device Fabrication and Characterization

Briefly, the main process steps for the micro-lens LED design were: wafer metallization, wafer-wafer bonding, substrate thinning, etching, including the texturing process, and contact formation. These steps are shown schematically in figure 4.

Prior to bonding, a mirror contact metal was applied to the p-GaN surface of the GaN/SiC LED wafers using conventional semiconductor process techniques such as photolithography, e-beam and sputtered metal deposition, etching, and contact annealing. Then, bond metal stacks were deposited on both the LED wafers and the mechanical carrier wafers to which they would be bonded.

For the bonding process, the LED and carrier wafers were placed face-to-face in a wafer-bonding tool, in which bond parameters such as temperature, pressure, and ambient atmosphere could be carefully controlled.

After bonding came the substrate thinning process, using a proprietary SiC removal process.

Further wafer-level processing was carried out to complete the LED device, namely:

- Definition of the device active junction area.
- Deposition and patterning the metal n-contacts.
- Application of the surface micro-lenses.

Again, these steps involved various conventional semiconductor process techniques, including photolithography, e-beam and sputtered metal deposition, etching (e.g. RIE), and contact annealing. The final step in the fabrication process was individual die separation.

The surface texturing was a critical area of the process on which a great deal of effort was focused during the project for the simple reason that the LED brightness was empirically observed to be very sensitive to the texture properties. We developed and refined several proprietary etch techniques in order to 'tune' the size and density of the surface texture features. Optical microscopy, scanning electron microscopy (SEM), and AFM tools were used to characterize the surface morphology, although the ultimate arbiter was the final LED lamp efficiency.

For the various process steps, progress was assessed on a continual basis using wafer and chip-level electrical (*I-V*) and optical (*L-I*) characterization. Other characterization techniques included optical microscopy, AFM, SEM, and electron diffraction spectroscopy (EDS). Metal/n-GaN and metal/p-GaN contact resistances were determined by conventional *I-V* measurements, using the so-called transfer length model (TLM), at the wafer-level using specific test devices fabricated with variable-spaced contact pads arranged in a linear geometry [3].

Lamp Builds and Testing

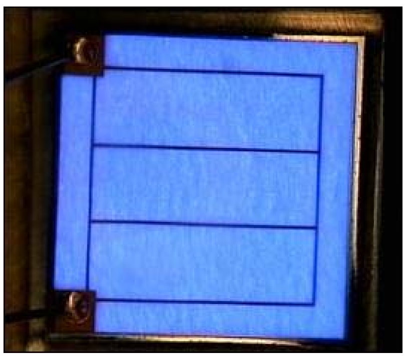
As needed, individual LED chips were packaged into lamp form. At the start of the project, devices were mounted to reflective TO-39 headers using silver epoxy, followed by encapsulation using a transparent material such as epoxy resin or silicone. The TO-39 header is a simple, optically efficient package whose limitations (poor thermal resistance, and not surface mountable) are not an issue for t=0, chip testing purposes. Towards the end of the project, LEDs were also packaged in Cree's XLamp® 7090 package, which has good thermal resistance and is surface mountable.

Electrical and optical characteristics of finished lamps were measured using a calibrated integrating sphere combined with a spectrometer and digital current-voltage multi-meter. Typically, the critical device parameters of interest were the radiant flux (optical output power) and device operating voltage (electrical input power). To compare LED brightness between multiple process runs, we use a parameter termed "relative flux", which normalizes the measured LED flux to that of a Cree standard device.

RESULTS AND DISCUSSION

Blue LED Efficiency Status

As a result of continuous design and process improvements during the project, blue (450 nm) LEDs have been achieved with external quantum efficiency of 51% at 350 mA, corresponding to 495 mW of output power. At 800 mA (100 A/cm^2), the efficiency was over 42%, with output of 950 mW, which is shy of the key project milestone for Task 1. The external quantum and wall plug efficiencies of a representative device are plotted as a function of current in figure 5, below. Overall, we note that the blue LED performance has almost doubled compared to the start of the project. The specific areas that led to these improvements are described in more detail next.



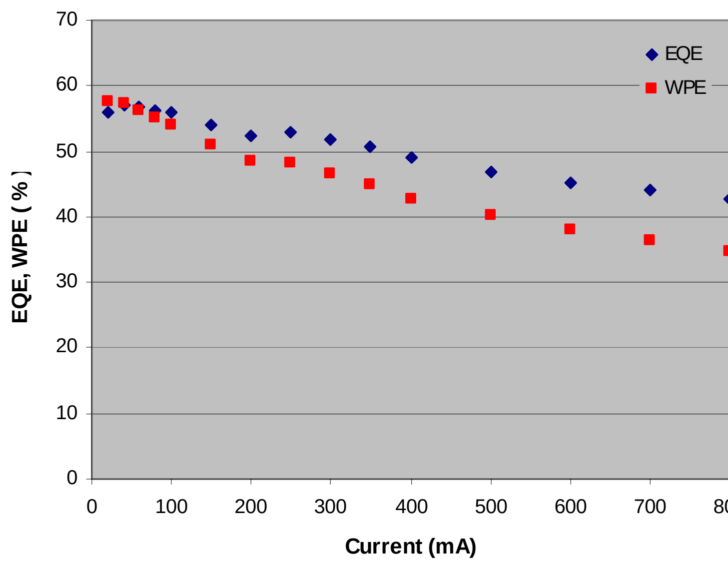


Figure 5(a) Microscope image of 1 x 1 mm^2 blue, ultra-thin LED chip with micro-lens roughening; (b) Status of LED efficiency after encapsulation as a function of current (QE = quantum efficiency, WPE= wall plug efficiency).

High Efficacy LED Materials and Chip Fabrication

The project leveraged, where possible, off materials work conducted at Cree's Durham manufacturing facility. Several improvements were demonstrated:

- Improved LED materials and heterostructures resulted in material approximately 20% brighter than what was available at the start of the project.
- Improved buffer layers, resulting in lower diode voltages and enabled better control of the LED fabrication process (especially the surface texturing described in the next section).

A number of general process issues needed to be resolved during the project including:

- Reproducible wafer bonding up to 2" diameter GaN/SiC to a carrier wafer using a metal-metal bond process.

- Robust mirror contact metallization (survives high temperature wafer bond) process on the p-GaN with high reflectivity and low series resistance.

Micro-Lens Surface Texturing

This subtask represented a sizable fraction of the technical effort during the project due to the importance of the micro-lens features to the LED performance. A great deal of time and effort went into forming micron- and submicron-scale features on the LED surface, as well as developing an understanding of the relationship between surface morphology and LED brightness. We developed an etch process that imparted a surface texture with features roughly 0.2 to 1 μm (width and height), depending on the etch conditions and duration. In principle, the range of surface feature sizes that can be achieved with this particular etch process covers the range generally considered to be optimal for scattering light. Qualitatively, the scattering nature of the textured surface was quite evident when observed in an optical microscope.

Many different etch processes have been investigated over the course of the project. In general, we found that the LED brightness was very sensitive to the etch process, to the etch duration for a given process, and to the evolution of the LED surface morphology resulting from each etch. Changes to the material quality (per subtask 1.1) also impacted the etch behavior and we found it was necessary to re-optimize a given process for different generations of material. Figure 6 shows some representative data of the sort used to characterize the surface morphology after each etch process, while figure 7 shows the range of resulting morphologies that can be seen. Figure 8 shows actual brightness data, the ultimate decider, for several sets of LED lamps

Figure 6: (a) Example of optical micrograph of surface of LED subject to one particular roughening etch process. (b) Same except longer etch time. (c) Atomic force micrograph of 20 x 20 μm^2 portion of surface in (b).

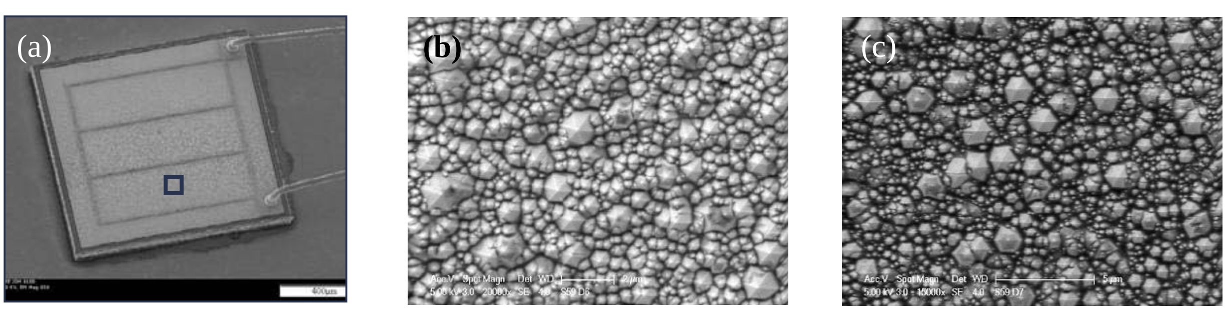


Figure 7: SEM images of (a) LED device with surface texture etch and (b) – (c) images of resulting surface textures from process conditions.

whose micro-lens surfaces were fabricated with different etch processes. For reference, Cree's conventional XB900™ GaN/SiC LED operating at 350 mA has a relative flux value of ~34. We have achieved relative flux values as high as 46 at the same current for the best LEDs fabricated under the program

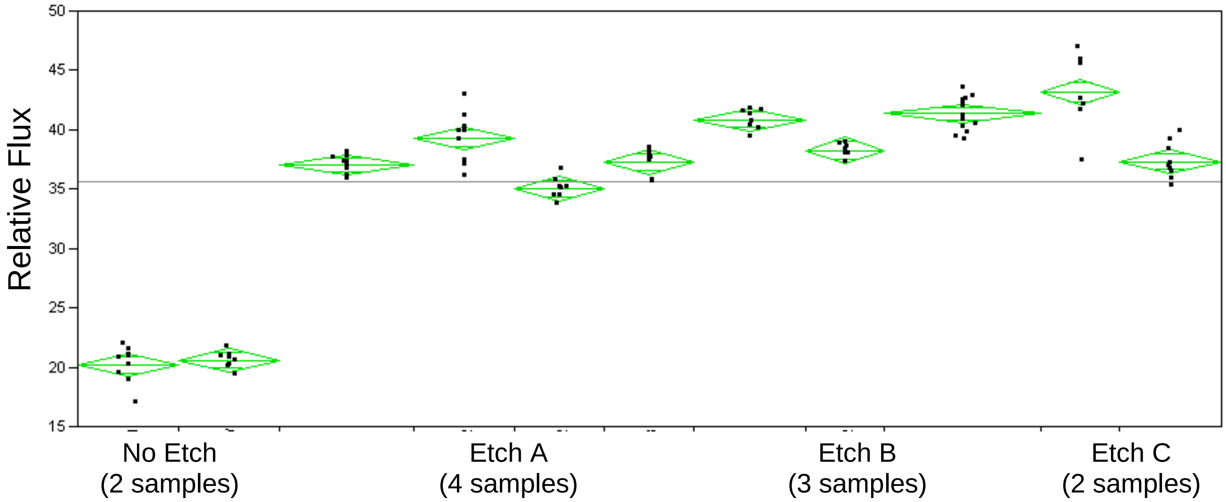


Figure 8: Compilation plot showing the impact of several etch experiments on LED brightness. Note doubling or more of the brightness as a result of the morphology that the various etches add to the LED surface. Each dot represents an individual LED lamp.

Periodic Nano-Scale Surface Patterning

One of the keys to further brightness improvements may lie in the details of the LED surface texture. The random texture etch processes demonstrated may not allow adequate, independent control over the critical surface feature parameters - such as density, size, height, and shape – to optimize the photon extraction from the LED chip. Thus, we believe it might be useful to be able to control these parameters more or less independently. The use of *periodic* surface features rather than the random arrays investigated to date, may offer additional benefits. The random surface texture features extract ~25% of incident photons per pass, & randomly scatter the rest. In order to improve the overall light extraction efficiency, the amount of first pass light escaping from the chip must be increased, and the random element reduced. Periodic surface features created by nano-scale patterning can potentially improve the light output by using diffraction effects to "steer" the photons out of the chip more efficiently (using the "photonic crystal" effect).

During the third year of the project, we successfully developed a fabrication process that allows us to create periodic, high density, high aspect ratio nano-scale patterns in GaN films. Etched features up to 1 µm tall with a ~350 nm pitch have been successfully demonstrated. Figure 9 shows SEM images of representative patterns. The ability to faithfully reproduce the mask pattern in the GaN film was achieved through modifications to the mask materials and the etch conditions.

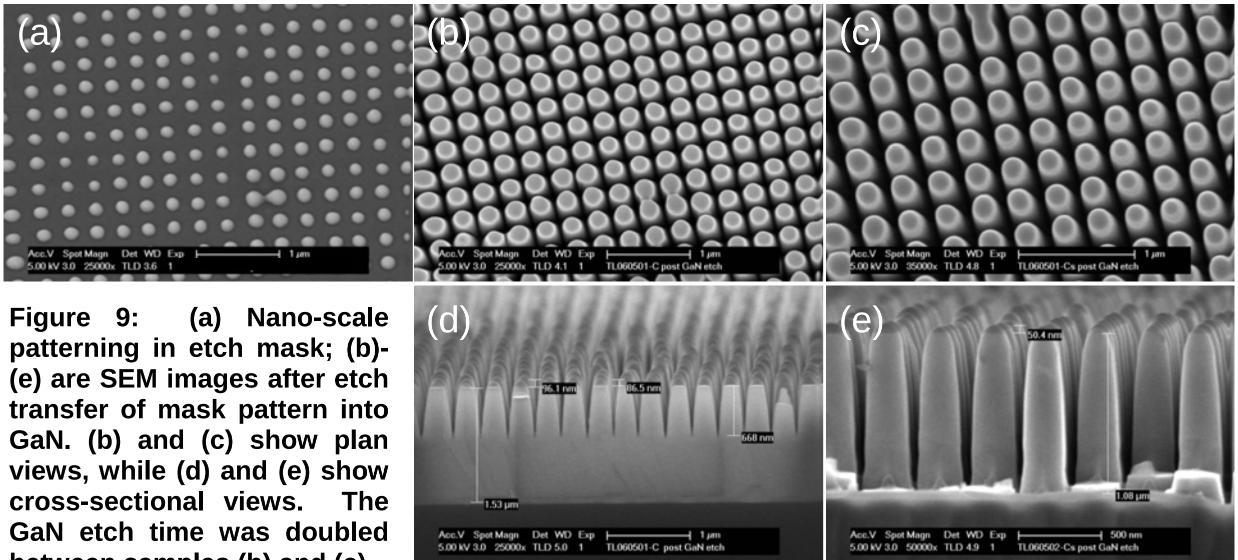


Figure 9: (a) Nano-scale patterning in etch mask; (b)-(e) are SEM images after etch transfer of mask pattern into GaN. (b) and (c) show plan views, while (d) and (e) show cross-sectional views. The GaN etch time was doubled between samples (b) and (c).

LEDs were then fabricated incorporating the periodic nano-scale surface texture that was developed. Patterns with different pitches (or periodicities) in the 300 nm – 500 nm range were targeted. Figure 10 on the next page shows scanning electron micrograph images of portions of the patterned GaN surface, and the corresponding far-field radiation patterns – intensity as a function of viewing angle – for representative devices. Compared to a randomly textured surface, which results in lambertian emission (i.e. a simple cosine dependence), the periodic nature of the surface texture in these devices resulted in intensity features at certain emission angles, depending on the pattern pitch. In particular, there was relatively more light being emitted at 45-60 degrees compared to on axis. In effect, we are observing a type of diffraction pattern as the photons generated inside the LED interact with the refractive index modulation at the semiconductor/air interface. For this particular set of experiments we observed that the effect became stronger as the pattern pitch decreased. Upon further investigation it was determined that the texture depth and shape was also varying so it was not clear at this point if pitch is the defining variable or if the other factors also played a role. In terms of integrated intensity (i.e. the sum of emitted power over all angles as measured in an integrating sphere), the devices with periodic surface patterning were found to be slightly (~10%) inferior to devices fabricated from the same wafer with random surface texture instead.

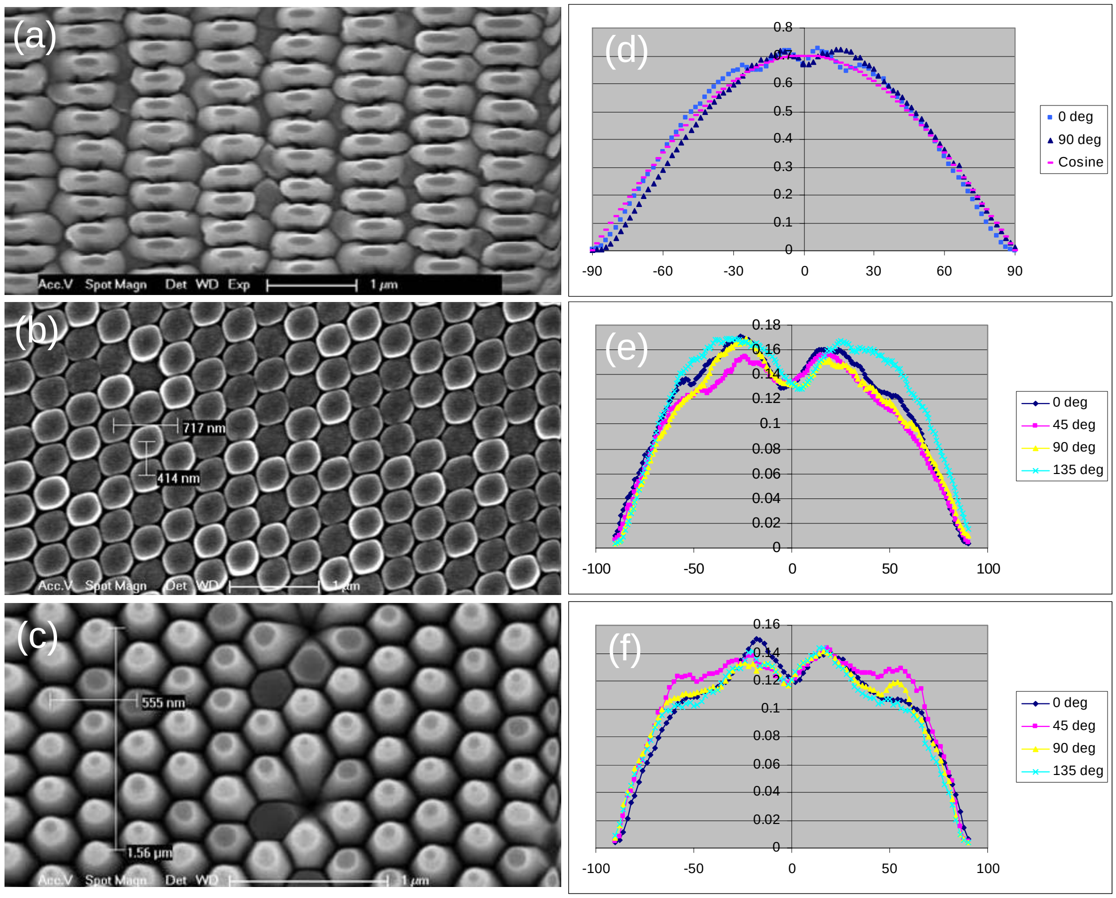


Figure 10: (a)–(c) Scanning electron micrographs of GaN LED surfaces after nano-scale patterning. 3 different pattern pitches were fabricated. (d)–(f) Measured far-field radiation pattern from corresponding LEDs mounted on a reflective header. Note the relative increase in intensity near 45-60 degrees in (e) and (f) compared to (d).

<u>Improved N-Contact Schemes</u>

The project statement of work requires doubling the operating current of the LED by a factor of two, while keeping the active area constant. Increasing the current density leads to additional efficiency losses due to the finite electrical resistance of the LED. The n-contact side of the junction is believed to be responsible for a significant fraction of these parasitic electrical losses so the n-contact was another area that received attention over the course of the project. Several improvements were demonstrated:

- New n-contact geometries reduced the operating voltage of test structures by as much as 250 mV compared to the conventional contact design. An analysis of the data showed that the improvement was primarily due to improved current spreading.
- Changes to the n-contact metals reduced the voltage on test structures by ~100 mV.
- Improved contact metal deposition process conditions reduced the voltage on test structures by ~110 mV.

The low voltage potential of the ultra-thin LED design was clearly demonstrated during the project. Figure 11 compares the measured voltage-current (*V-I*) behavior of a state-of-the-art XB900 chip and an ultra-thin LED fabricated. In both cases the LED chips were soldered to a metal-core printed circuit board to minimize self-heating effects and the measurements were performed using a four-probe method. The electrical behavior of the two chips was very similar at low currents, indicative of comparable material quality and emission wavelength. However, at currents above ~100 mA the dynamic resistance of the new LED design continuously decreased (evident from the rollover of the *V-I* curve in figure 11), while that of the XB900 saturated. As a result, the operating voltage of the ultra-thin device was only 3.15 V at 700 mA, compared to 3.6 V for the conventional chip.

Figure 11: Four-probe voltage-current curves for conventional and ultra-thin blue GaN/SiC LEDs. Note the similar behavior at low currents, indicating comparable material quality for both types. The divergence at high currents is due to the much lower parasitic resistance of the latter.

Technology Commercialization

In August 2006, Cree announced it has successfully commercialized the ultra-thin LED design as the EZBright™ chip product family targeting solid-state lighting. Product is available in volume quantities and its introduction came out as a result of the work described in this report, (primarily laboratory scale proof-of-concept devices), in conjunction with NIST ATP-funded and Cree internal development efforts. The EZBright chip family currently consists of four different chip products ranging in size from 290 μm x 290 (EZBright290) μm up to 1 mm x 1 mm (EZBright1000) in the 450 – 470 nm wavelength range. The blue EZBright1000 power chip, measured as a bare die, exhibits power output up to 370mW at 350mA of drive current, and 800mW at 1A of drive current. The support provided by DOE was gratefully acknowledged in a press release issued announcing the chip product (see appendix).

TASK I – CONCLUSIONS

In summary, during this three-year project we have successfully taken a novel, ultra-thin LED design from a paper concept (at least for nitride materials) and shown that its performance exceeds that of conventional LED designs by as much as 40%. Novel chip design elements and fabrication processes, together with improved materials work conducted outside the scope of this project, resulted in 1-watt class blue LEDs with – at the time – record performance for comparable devices. Specifically, blue LEDs have been achieved with external quantum efficiency of 51% at 350 mA, yielding 495 mW of output power. The wall-plug efficiency for these devices was 45%. Unfortunately the Year 3 goal for Task 1 was not quite met since these efficiencies were at a current density of 50 A/cm^2 instead of the targeted 100 A/cm^2. Further technical breakthroughs are still needed to meet this ambitious target.

Furthermore, Cree has been able to commercialize the ultra-thin LED design in the form of its EZBright chip product family targeting solid-state lighting applications. The EZBright chip incorporates elements partly developed and first demonstrated on the DOE project.

SECTION II

Task 2 – White Solid State Lamp Development

PROBLEM BACKGROUND

The key project deliverables are solid-state lamp prototypes with luminous output of ~1000 lumens with progressively higher efficacy each year. Figure 12 shows a prototype lamp developed under a previous NETL/DOE project [4], which used 16-36 individual high power LED chips as the primary emission source. By comparison, the challenge for the current project is to improve both the thermal and optical performance while simultaneously reducing the number of LED chips (roughly by a factor of four). Meeting the project goals involves:

- Improving the chip efficiency, the focus of Task 1.
- Optimizing the heat dissipation through careful system design and choice of materials.
- Demonstrating high system optical efficiency by optimizing the combination of chips and down-converter material (phosphors).

The last two bullets are the subjects of work conducted on Task 2, which is described in this section of the report.

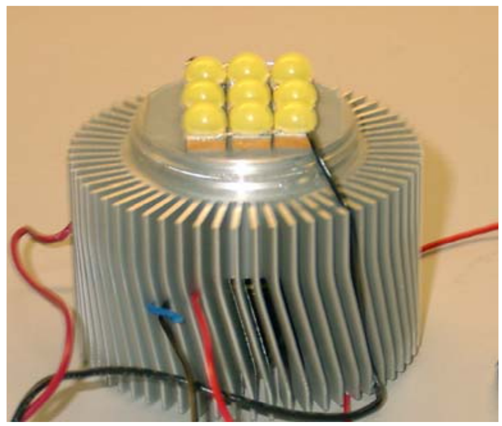


Figure 12. A prototype, 1000 lumens solid-state lamp indicative of the state-of-the-art at the start of the project.

The project's first efficacy milestone was a 1000 lumen lamp with 65 lm/W by the end of Year 1. In addition, the end of Year 2 efficacy milestone was to achieve 80 lm/W at a current density 50% higher than in Year 1. Finally, the end of project efficacy milestone was 100 lm/W at a current density 2x higher than year 1 (100A/cm^2). Our progress towards meeting these goals is described below.

EXPERIMENTAL

For optical modeling of white lamps, we used a commercial ray-tracing software package that allows three dimensional volumes and surfaces, and takes into account all the necessary optical constants: absorption, refractive indices, surface reflectivity, etc. We have previously used the software extensively to model the behavior of light inside GaN/SiC chips.

Individual white LEDs were fabricated using the experimental blue LED chips from Task 1. The chips were mounted to Cree's XLamp® 7090 package using solder paste. (The XLamp 7090 package with conventional type LED chips is commercially available in multiple colors.) Devices were then wire bonded and finally encapsulated with either silicones or epoxy resins. A commercial broadband yellow phosphor was premixed and dispensed with the portion of the encapsulant in the immediate vicinity of the chip.

For the high-lumen white lamps that were comprised of multiple individual lamps, custom components (e.g. circuit boards, heat sinks, encapsulation molds) were procured from various outside vendors. Otherwise, the fabrication process was similar to the individual lamp case.

Electrical and optical characteristics of the finished lamps were measured using a calibrated integrating sphere, spectrometer, and digital current-voltage multi-meter. Typically, the critical device parameters of interest were luminous flux, efficacy, and white color coordinates. Far-field radiation measurements were made using a commercial dual axis goniometer with a 50 cm source-detector spacing.

RESULTS AND DISCUSSION

White Lamp Performance Status

Figure 13 shows a picture of a 7090 XLamp mounted to a circuit board. The best blue chips described in Section I were put into the XLamp package. At a drive current of 350 mA, output from the XLamp devices averaged 91 lumens, with individual devices as high as 93 lumens. The efficacy of the lamps averaged 82 lumens per watt, with individual devices as high as 86 lumens per watt. The lamps' color coordinated temperature was ~5900 K, with the color point lying at or near the black body locus.

Lamps built using TO-39 headers were roughly 5-10% brighter than the XLamps with the same chips, showing the potential for the chips themselves. (The TO-39 header is a simpler, and

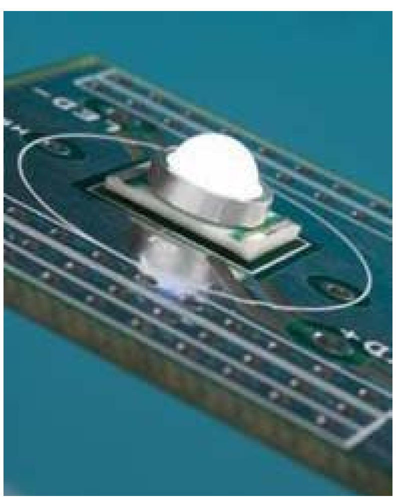


Figure 13: White-emitting 7090 XLamp built with latest generation blue LED chip and yellow phosphor. Up to 94 lumens at 86 lumens per watt was achieved at a drive current of 350 mA.

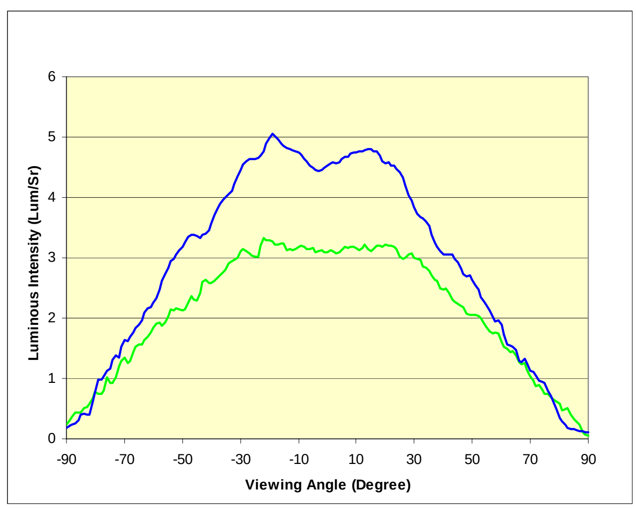


Figure 14: Far field emission pattern of white LED lamp built using a micro-lens LED with phosphor on a TO-39 header. The green and blue curves correspond to before and after encapsulation, respectively.

therefore slightly more efficient, package but it isn't suitable for practical use as it cannot effectively dissipate the heat generated by the LED.) The far-field radiation pattern of a typical TO-39 header lamp is shown in figure 14. Of particular note is the near perfect lambertian emission pattern, a result of the micro-lens LED design, which is considered particularly desirable for optical design purposes.

Year 3 Milestone Lamp Demonstrator

At the end of Year 3, we demonstrated high flux white lamp modules with output as high as 1040 lumens at an efficacy of 87 lumens per watt when operated at a drive current of 350 mA per chip (~ 50 A/cm^2). Figure 15 shows a picture of the finished module. The array of emitters was mounted to a metal core printed circuit board attached to a finned metal heat sink for efficient heat dissipation. As far as possible, the modules utilized materials (e.g. solder, phosphor, clear encapsulant) developed for Cree's XLamp products since they have demonstrated proven reliability under high flux operating conditions. The modules' total emitting area was kept within a 4" diameter circle, i.e. the same footprint as a PAR 38 incandescent light source.

Figure 16 shows plots of the total luminous output and the efficacy of the module as a function of current density. At a current density of ~ 50 A/cm^2, the luminous output was 1040 lumens, corresponding to 87 lm/W at an input power of 12 watts. At higher current desities of 100 A/cm^2 even higher luminous flux was realized, up to 1960 lumens, though the efficacy decreased to 66 lm/W. Table 2 summarizes the module's performance when operating at the three target diode current densities of 50, 75 and 100 A/cm^2 for the various project milestones. The color point of the lamps was close to the black body curve, with color coordinated temperature in the range of 5800-6000 K.

Figure 15: Experimental high flux lamp module consisting of an array of individual emitters on a metal core circuit board.

Metric	Array Results		
Diode Current Density (A/cm^2)	50	75	100
Array Input (W)	12.0	21.5	29.6
Light Output (lumens)	1040	1600	1960
Efficacy (lm/W)	87	74	66
CCT (K)	5850	5900	5950

Table 2: High flux lamp module performance at the target diode current density of 52 A/cm^2. Array #2 has higher efficacy but lower total luminous output.

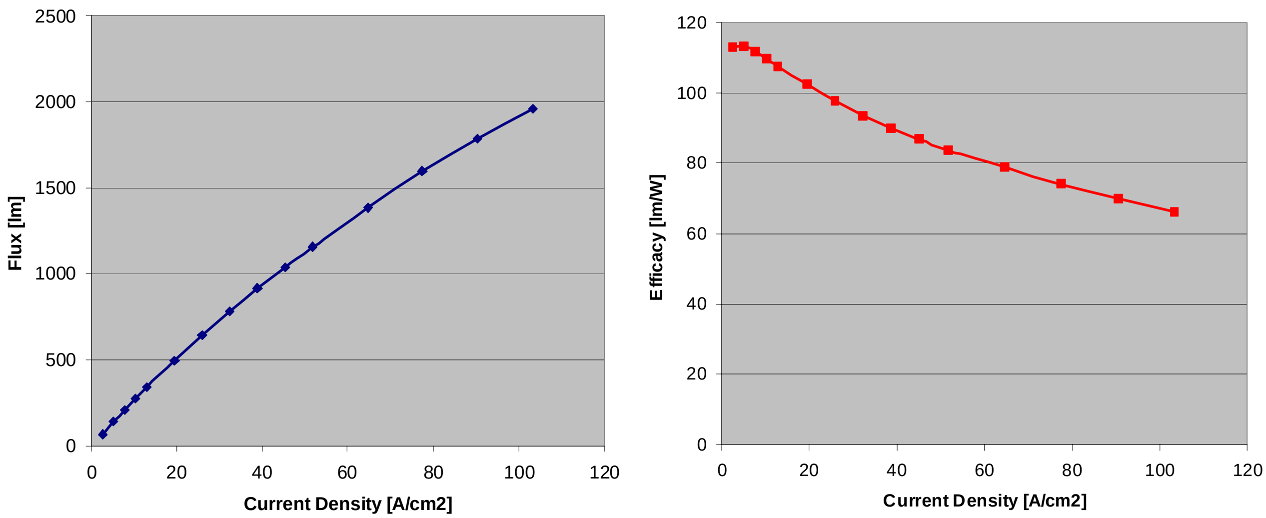


Figure 16: High flux lamp module (a) output and (b) efficacy as a function of current density.

Technology Commercialization

We are also pleased to be able to report that Cree released a second generation XLamp 7090 LED product (figure 13) incorporating the EZBright power chip. This new XLamp LED, available in volume quantities, produces luminous flux of up to 95 lumens or 85 lumens per watt at 350 mA, and up to 160 lumens at 700 mA. At the time, this represented a significant step up in performance of commercially available LEDs. The new product introduction came about as a result of this work, in conjunction with a NIST ATP-funded project and Cree's internal development efforts. The support of DOE was acknowledged in a press release issued announcing the new XLamp product (see appendix).

TASK II - CONCLUSIONS

In summary, at the end of the project we demonstrated individual white LEDs with efficacy as high as 86 lumens per watt, and a compact LED lamp module using multiple chips with output of 1040 lumens at 87 lumens per watt with a 350 mA drive current (~ 50 A/cm^2). At a current density of 100 A/cm^2, the luminous flux was up to 1960 lumens, though at a slightly lower efficacy of 66 lumens per watt. The major source of the improvement in lamp efficacy over the course of the project came from the increased brightness of the blue chips that were developed on Task 1. Unfortunately, our ambitious Year 3 goal for Task 2 of demonstrating a white lamp with 1000 lumens output with an efficacy of 100 lumens per watt at an operating current density of 100 A/cm^2 was not quite achieved, pending further technical breakthroughs on chip performance.

In addition, Cree's launch of its XLamp 7090 XR-E series high power white LED means the high efficacy levels that were demonstrated on the project are now commercially available for solid state lighting applications.

REFERENCES

[1] I. Schnitzer, E. Yablonovitch, C. Caneau, .J. Gmitter, and A. Scherer, "30% external quantum efficiency from surface textured, thin-film, light-emitting diodes", *Appl. Phys. Lett.* vol. 63, 2174–2176, 1993.

[2] R. Windisch, P. Altieri, R. Butendeich, S. Illek, P. Strauss, W. Stein, W. Wegleiter, R. Wirth, H. Zull, and K. Streubel, "InGaAlP Thinfilm LEDs with high luminous efficiency", *Proc. SPIE* vol. 5366, 43–52, 2004.

[3] See, for example, R. Williams, *Modern GaAs Processing Methods* (Artech House, Boston, 1990).

[4] J. Ibbetson, "Final Report DOE Contract DE-FC26-00NT40985", unpublished.

APPENDIX

Copy of Cree Press Release 8/31/06

Contact:
Deb Lovig
Marketing Communications Manager
Email: Deb_Lovig@cree.com
Phone: (919) 287-7505
Fax: (919) 313-5615

Cree Launches EZBright™ LED Power Chip for Lighting Applications

DURHAM, NC, August 31, 2006 — Cree, Inc. (Nasdaq: CREE), a leader in LED solid state lighting components, today announced the release of its new EZBright™ LED power chip. The new EZBright1000™ LEDs are twice the brightness of Cree's current power chips. The EZBright1000 power chip is designed for general lighting applications, such as home and office lighting, auto headlamps, streetlights, and garage and warehouse low bay lighting, as well as consumer applications including flashlights, camera flash and projection displays.

"This is an important milestone for power LEDs. For the first time, these chips should enable solid-state lamp makers to challenge the efficacy of not only incandescent, but also fluorescent lamps," said Chuck Swoboda, Cree chairman and CEO. "The EZBright1000 LED power chip is one of several advancements we are working on to help drive LEDs into more mainstream lighting applications."

"The blue EZBright1000 power chip, measured as a bare die, exhibits power output up to 370mW at 350mA of drive current and 800mW at 1A of drive current," stated Scott Schwab, Cree vice president and general manager of optoelectronics. "This product should enable our customers to reach new levels of power output and efficiency from a single chip and redefine what is possible with power LEDs."

The EZBright1000 power chip is the third product released based on the Cree EZBright platform, which features a proprietary optical design that delivers an optimal Lambertian radiation pattern, with low emission losses and high efficiency. This product incorporates technology that was in part developed with support provided by the U.S. Department of Energy, National Energy Technology Laboratory, and the U.S. Department of Commerce, National Institute of Standards and Technology, Advanced Technology Program.

EZBright1000 LEDs are now available in commercial quantities. Additional EZBright products are targeted for release over the next several months. For additional information on Cree EZBright LEDs, please call (800) 533-2583 or visit www.cree.com.

About Cree, Inc.
Cree is a market-leading innovator and manufacturer of semiconductors and devices that enhance the value of solid-state lighting, power and communications products by significantly increasing their energy performance and efficiency. Key to Cree's market advantage is its world-class materials expertise in silicon carbide (SiC) and gallium nitride (GaN) for chips and packaged devices that can handle more power in a smaller space while producing less heat than other available technologies, materials and products.

Cree drives its increased performance technology into multiple applications, including exciting alternatives in brighter and more tunable light for general illumination, backlighting for more vivid displays, optimized power management for high-current switch-mode power supplies and variable-speed motors, and more-effective wireless infrastructure for data and voice communications. Cree customers range from innovative lighting-fixture makers to defense related federal agencies.

Cree's product families include blue and green LED chips, lighting LEDs, LED backlighting solutions, power-switching devices and radio-frequency/wireless devices. For additional product specifications please refer to www.cree.com.

This press release contains forward-looking statements involving risks and uncertainties, both known and unknown, that may cause actual results to differ materially from those indicated. Actual results may differ materially due to a number of factors, such as the risk we may encounter delays or other difficulties in ramping up production of our new products; the risk we may be unable to manufacture products with sufficiently low cost to offer them at competitive prices or with acceptable margins, the rapid development of new technology and competing products that may impair demand or render our products obsolete; the potential lack of customer acceptance for the products; variations in demand for Cree's products and its customers' products; the risk we may encounter delays or other difficulties in developing and commercially releasing additional new products for mainstream lighting applications; and other factors discussed in Cree's filings with the Securities and Exchange Commission, including its report on Form 10-K for the year ended June 25, 2006, and subsequent filings.

# # #

Cree is a registered trademark and EZBright and EZBright1000 are trademarks of Cree, Inc.

Copy of Cree Press Release 10/9/06

Contact:
Deb Lovig
Marketing Communications
Ph: (919) 287-7505
Fax: (919) 313-5943
Email: Deb_Lovig@cree.com

Cree Delivers the First 160-Lumen White Power LED

— XLamp LEDs now as efficient as fluorescent sources —

DURHAM, NC, October 9, 2006 — Cree, Inc. (Nasdaq: CREE), a leader in LED solid state lighting components, today announced new benchmarks for power LED brightness and efficacy with the release of the newest white Cree XLamp® 7090 power LED. This new XLamp LED, available in volume quantities, produces luminous flux of up to 95 lumens or 85 lumens per watt at 350 mA, and up to 160 lumens at 700 mA.

Typical luminous flux for the new Cree XLamp 7090 LED is 80 lumens at 350 mA, yielding 70 lumens per watt. The new XLamp LED was designed to enable general lighting applications, such as street lighting, retail high bay lighting and parking garage low bay lighting, as well as to vastly improve the light quality in consumer applications such as flashlights. LED technology has been sufficiently bright for many general illumination applications for some time. The new XLamp 7090 LED, however, offers the efficiency and reliability needed to make LEDs cost-effective for more of these applications. The new XLamp 7090 LED is the first power LED based on the company's

EZBright™1000 LED chip, which provides the industry's highest efficacy at 350 mA.

"Cree LEDs are achieving efficacy levels formerly delivered only by the most efficient traditional lighting sources, including fluorescent bulbs. We have established a new class of LED performance," notes Mike Dunn, Cree general manager and vice president, lighting and backlighting LEDs. "Our goal at Cree remains to aggressively increase the brightness and efficacy of our LEDs to ensure that LEDs become a cost-effective, energy-saving alternative for all lighting applications."
"The Department of Energy is pleased to have been a contributing partner in the Cree research and development efforts that have achieved a new level of performance for power LEDs," notes Alexander Karsner, Department of Energy Assistant Secretary for Energy Efficiency and Renewable Energy. "Now, more than ever, our nation needs energy-saving technology that is top-quality and cost-effective. The Department will continue to work with Cree and other lighting-industry partners to turn advanced energy-saving technology into commercially available and successful products that save energy for consumers."

The Cree LED research and development efforts were enabled in part through funding from the Department of Energy's Building Technologies Program, within the Office of Energy Efficiency and Renewable Energy, and also in part through funding from the Department of Commerce's National Institute of Standards and Technology's Advanced Technology Program. Cree is also a charter member of the Department of Energy's Solid-State Lighting Partnership with the Next Generation Lighting Industry Alliance, an organization of lighting manufacturers that provides input to enhance the manufacturing and commercialization focus of the Department's solid-state lighting portfolio.

For additional information on Cree XLamp 7090 power LEDs and Cree EZBright LED chips, please call (800) 533-2583 or visit www.cree.com.

About Cree, Inc.
Cree is a market-leading innovator and manufacturer of semiconductors and devices that enhance the value of solid-state lighting, power and communications products by significantly increasing their energy performance and efficiency. Key to Cree's market advantage is its world-class materials expertise in silicon carbide (SiC) and gallium nitride (GaN) for chips and packaged devices that can handle more power in a smaller space while producing less heat than other available technologies, materials and products.

Cree drives its increased performance technology into multiple applications, including exciting alternatives in brighter and more-tunable light for general illumination, backlighting for more-vivid displays, optimized power management for high-current, switch-mode power supplies and variable-speed motors, and more-effective wireless infrastructure for data and voice communications. Cree customers range from innovative lighting-fixture makers to defense-related federal agencies.

Cree's product families include blue and green LED chips, lighting LEDs, LED backlighting solutions, power-switching devices and radio-frequency/wireless devices. For additional product specifications please refer to www.cree.com.

This press release contains forward-looking statements involving risks and uncertainties, both known and unknown, that may cause actual results to differ materially from those indicated. Actual results may differ materially due to a number of factors, such as the risk we may encounter delays or other difficulties in ramping up production of our new products; the risk we may be unable to manufacture products with sufficiently low cost to offer them at competitive prices or with acceptable margins, the rapid development of new technology and competing products that may impair demand or render our products obsolete; the potential lack of customer acceptance for the products; variations in demand for Cree's products and its customers' products; and other factors discussed in Cree's filings with the Securities and Exchange Commission, including its report on Form 10-K for the year ended June 25, 2006, and subsequent filings.

About the Department of Energy
The Department of Energy's Office of Energy Efficiency and Renewable Energy invests in a diverse portfolio of energy technologies to provide American consumers with a greater choice of energy-efficient products and enhance quality of life. The Building Technologies Program works with a wide array of industry, state, and university partners to accelerate the development and use of advanced building technologies such as solid-state lighting (SSL). SSL has the potential to more than double the efficiency of general lighting systems, saving energy costs for consumers and reducing overall U.S. energy consumption.

The unique attributes of SSL drive the need for a coordinated Federal approach that encompasses research, development, and commercialization support. In partnership with industry, the Department has developed a comprehensive R&D plan to ensure that DOE funds appropriate research topics that will improve efficiency and move SSL from the laboratory to the marketplace. To ensure that DOE R&D investments result in technology commercialization, the Department also implements commercialization-support strategies including lighting design competitions and the development of ENERGY STAR® criteria for SSL products. The Department works closely with the Next Generation Lighting Industry Alliance, utilizing the expertise of this organization of manufacturers to enhance the manufacturing and commercialization focus of the SSL portfolio.

For more information on the DOE solid-state lighting portfolio, visit www.netl.doe.gov/ssl.

# # #