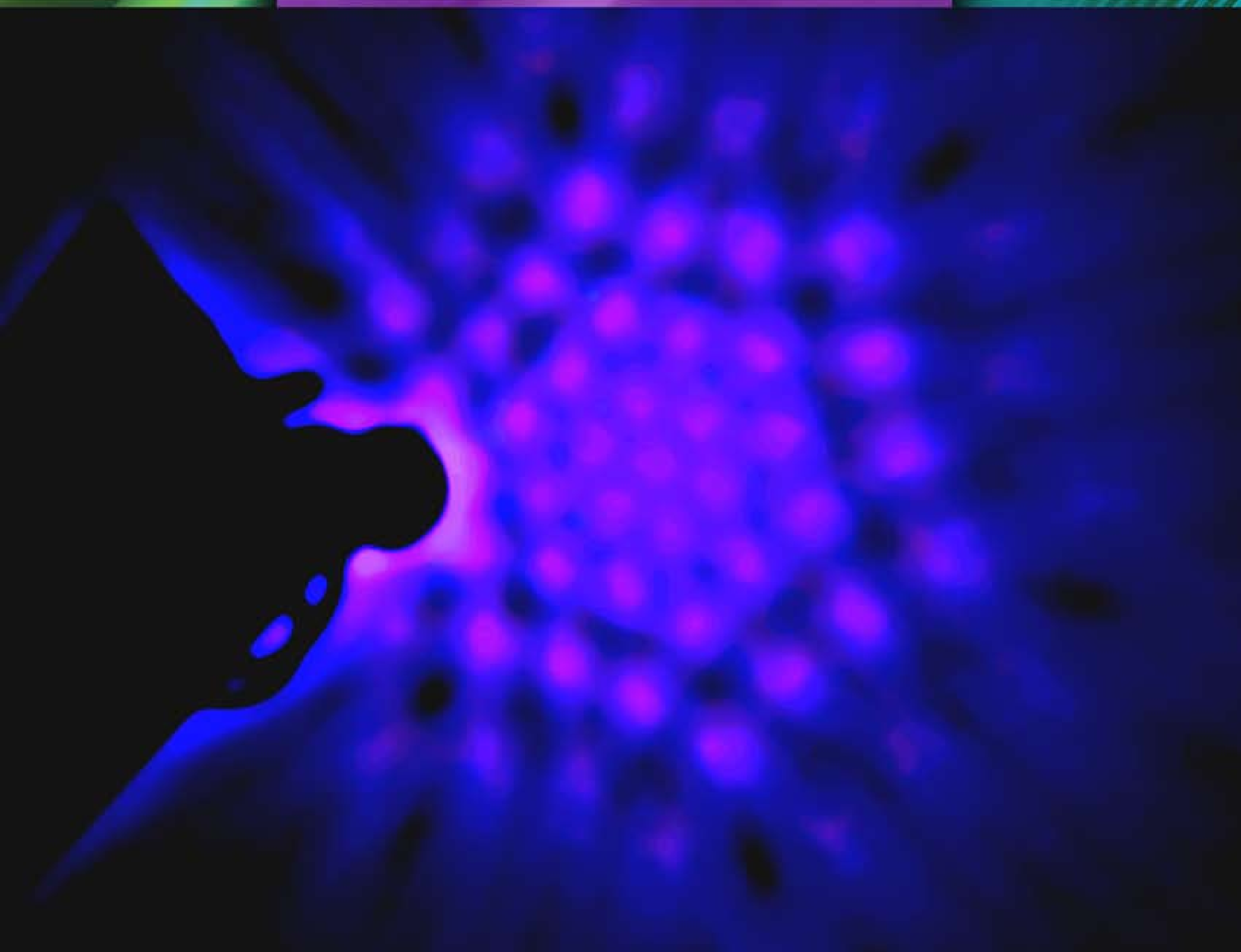
2008 R&D 100 Award Entry Form

SAND2008-1805P

Blue and Green Photonic Crystal Light-Emitting Diodes (LEDs): Advanced Devices for Energy Efficient Lighting



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AFFIRMATION: I affirm that all information submitted as a part of, or supplemental to, this entry is a fair and accurate representation of this product.

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Joint Entry

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Product Name

Blue and Green Photonic Crystal Light Emitting Diodes (LEDs): Advanced Devices for Energy Efficient Lighting

Brief Description

Blue and green LEDs are key components used to create high-efficiency, semiconductor-based white-light sources for solid-state lighting. Photonic crystals can be incorporated into the surface of the LEDs to dramatically enhance both the efficiency and the directionality of these visible LEDs.

When was this product first marketed or available for order?

Two new patents were granted in October and November 2007 that secure our intellectual property position so that this technology is now ready for licensing or for incorporation into advanced semiconductor-based light sources. Our final joint project on high-efficiency photonic crystal light emitters concluded in January 2007.

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Product Price

Product prices rapidly change in the semiconductor field; these are estimated prices based on proposed lamps at the time of this application:

- $5–$15 for 1 mm x 1 mm 1 Watt LED
- $8–$24 for 2 mm x 2 mm 5 Watt LED
- $15–$45 for a 15 Watt high lumen lamp

Patents

"Photonic Crystal Light Emitting Device," US 7,294,862 granted to Jonathan J. Wierer, Jr., et al. on November 13, 2007.

"LED Including Photonic Crystal Structure," US 7,279,718 granted to Michael R. Krames, et al. on October 9, 2007.

"Photonic Crystal Light Emitting Device," US 7,012,279 granted to Jonathan J. Wierer, Jr. et al, on March 14, 2006.

(See Appendix)

Description of Product

Semiconductor-based lighting, also called solid-state lighting, is an emerging new technology which promises to revolutionize the lighting industry with very long lifetimes (> 100,000 hours) and very high efficiencies that are 10 times greater than incandescent bulbs and two times greater than fluorescent tubes[1]. In order to realize the promise that this new technology holds, the efficiency of light emitting diodes (LEDs)[2] must improve, and the manufacturing costs must come down. Photonic crystal LEDs are an exciting new technology that solves many of the problems associated with the efficiency and functionality of standard photonic crystal LEDs.

A photonic crystal is a periodic modulation of the index of refraction of a dielectric material in one or more dimensions[3] that dramatically alters the optical properties of the material. One of the phenomena produced by photonic crystals is a modulation of the photonic density of states, including in some cases the complete absence of allowed photon states at certain wavelengths – the so-called photonic band gap.

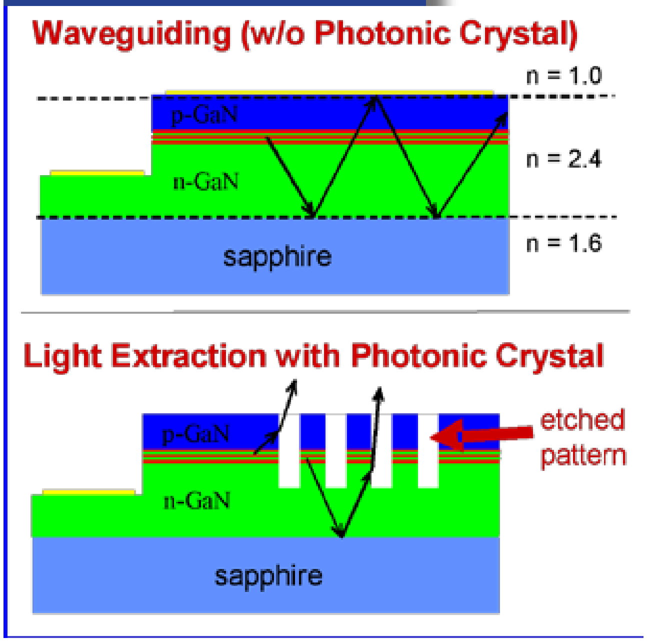

Figure 1. Schematic diagram of an LED with poor efficiency without a photonic crystal (top) and an LED with a photonic crystal with enhanced efficiency due to improved light extraction (bottom).

Photonic crystals can enhance the efficiency of LEDs in three basic ways. The first approach involves placing the light emitters inside, or at the edge, of the photonic band gap of the photonic crystal. This can enhance the radiative emission rate. In this case, the fundamental rate of photon emission can be enhanced, thereby improving the overall device efficiency.

A second method of enhancing LED efficiency using photonic crystals is by improving light extraction. One fundamental limitation of semiconductor-based lighting is that light is generated inside of a material with a high index of refraction. This light tends to bounce around inside the semiconductor due to total internal reflection so that very little light can escape the LED unless special steps are taken to address this problem. The same mechanism that causes light to be efficiently waveguided inside of an optical fiber causes light to be trapped inside of an LED and is detrimental to its energy efficiency. Figure 1 shows a schematic diagram of the light extraction problem in a gallium nitride-based (GaN-based) LED. The top LED shows an LED without a photonic crystal where the light is trapped due to total internal reflection, while the bottom LED has a photonic crystal pattern etched into the semiconductor which allows the light to escape from the device improving the efficiency.

A third mechanism of improving LED efficiency with a photonic crystal is to add directionality to the light emission pattern, thereby increasing the source brightness and providing light to a specific desirable location. As will be shown later in this section, the emission direction of light can be extremely well controlled using a photonic crystal LED.

For solid-state lighting applications, the most promising material system is GaN[4], where LEDs have been demonstrated at wavelengths across the entire visible spectrum[5]. Thus, a large majority of our work focused on demonstrating photonic crystal LEDs in the visible spectrum using GaN and alloys with Indium (In) GaN is a very chemically robust material that is difficult to etch using wet-etching techniques; the only practical approach is to use a dry-etching method such as reactive ion etching. A significant amount of time was devoted to developing the appropriate dry-etch processing to allow us to etch sub-micron features in GaN. The results of our etch process development are shown in Figure 2 where a cross-sectional scanning electron microscope (SEM) image shows 380 nm deep holes etched in GaN with a diameter of 110 nm and a lattice constant of 205 nm. The ability to etch these high-aspect ratio features in GaN was a key enabling process that allowed us to demonstrate efficiency enhancements using photonic crystal LEDs.

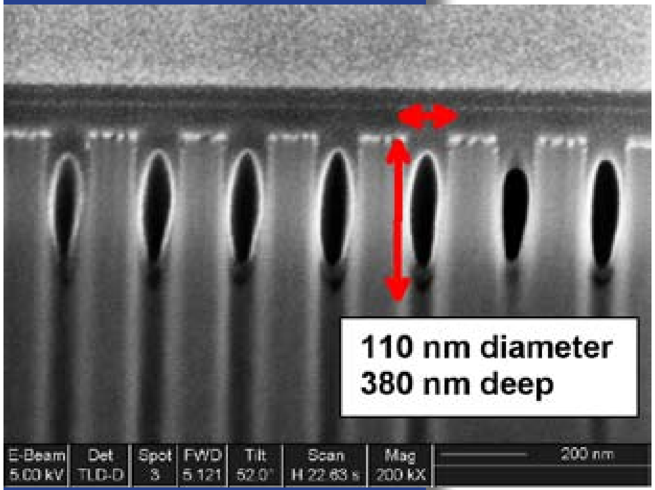

Figure 2. Cross-sectional SEM image showing high-aspect ratio holes etching in GaN forming a photonic crystal.

Our goal was to demonstrate efficiency enhancements in an electrically injected InGaN LED. The left side of Figure 3 shows a schematic diagram of one of our small-area photonic crystal LEDs. The epitaxial material for these LEDs is grown by metalorganic chemical vapor deposition on sapphire substrates. After the nucleation and buffer layers are grown, n-type GaN is deposited. Next is a multiple quantum well active region consisting of $In_xGa_{1-x}N$ wells and GaN barriers emitting at ~460 nm. Then ~1500 Å of *p*-type layers and an InGaN tunnel junction[6] are grown. The structure is completed by ~1900 Å of *n*-GaN. The total epitaxial thickness is~4 μm.

The center image in Figure 3 shows an electroluminescence image of a 170 μm x 170 μm square LED taken using an optical microscope. The photonic crystal is patterned in the mesa area and is recessed ~10 μm from the mesa edge and the center top contact. This electroluminescence image shows that the area containing the photonic crystal is brighter than the non-patterned edge and center. The right side of Figure 3 shows an atomic force microscope image of the two-dimensional triangular lattice of holes etched in the GaN surface to form

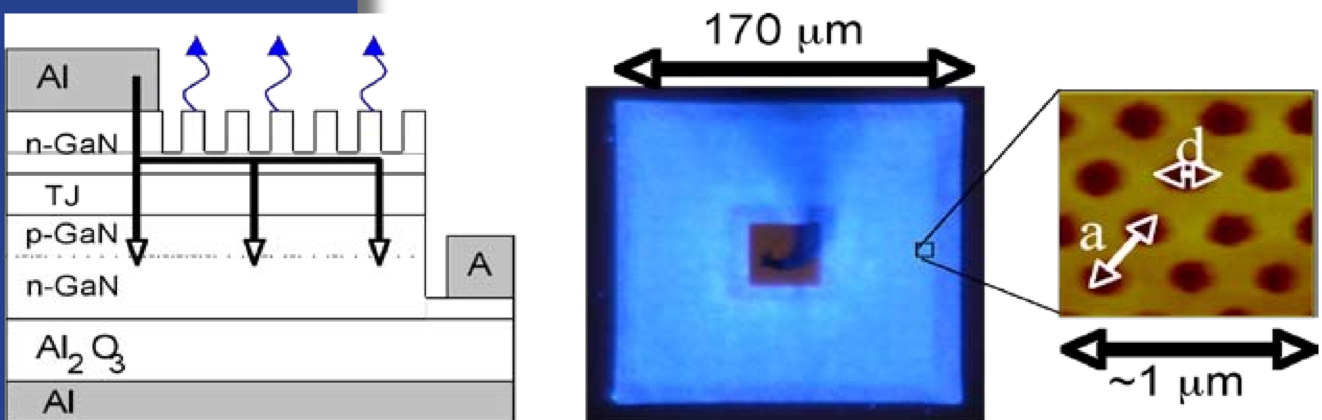

Figure 3. Schematic diagram of a photonic crystal LED (left) showing holes etched into GaN to form a photonic crystal. An electroluminescence image is also shown (middle) with enhanced emission due to photonic lattice patterning. An atomic force microscope image shows the two-dimensional array of sub-micron holes (right).

the photonic crystal. These LEDs demonstrated a 1.75 times increase in LED brightness measured in a central cone of +/- 40 degrees and a total increased intensity of 1.5 times when the intensity is integrated over all emission angles. This work resulted in the first electrically injected photonic crystal InGaN LED[7].

Many of the small area photonic crystal LEDs were fabricated using electron beam (e-beam) lithography to pattern the sub-micron photonic crystal features. Electron beam lithography is a very flexible direct write technique that is well suited to photonic crystal research. The main drawback to e-beam lithography is that it is a very slow process that cannot easily be scaled up for manufacturing large numbers of photonic crystal LEDs. To address this issue, we have investigated large-area patterning methods such as interferometric lithography[8].

Patterning two-dimensional photonic crystals using interferometric lithography is accomplished by exposing resist on the surface of the sample using the interference pattern of two or more laser beams. The left side of Figure 4 shows a two-dimensional sub-micron pattern created using interferometric lithography. The right side of Figure 4 contains an image of the entire 3-inch wafer where the center 22 mm x 22 mm square region was patterned in less than a minute using a two-beam double exposure technique to generate the 2D pattern. This large region contains a two-dimensional, triangular array of approximately 4 x 10^9 sub-micron posts. This process can easily be scaled up to pattern full 2-inch or 3-inch nitride wafers, making this a process suitable to large-scale manufacturing. As a demonstration of this process, we fabricated

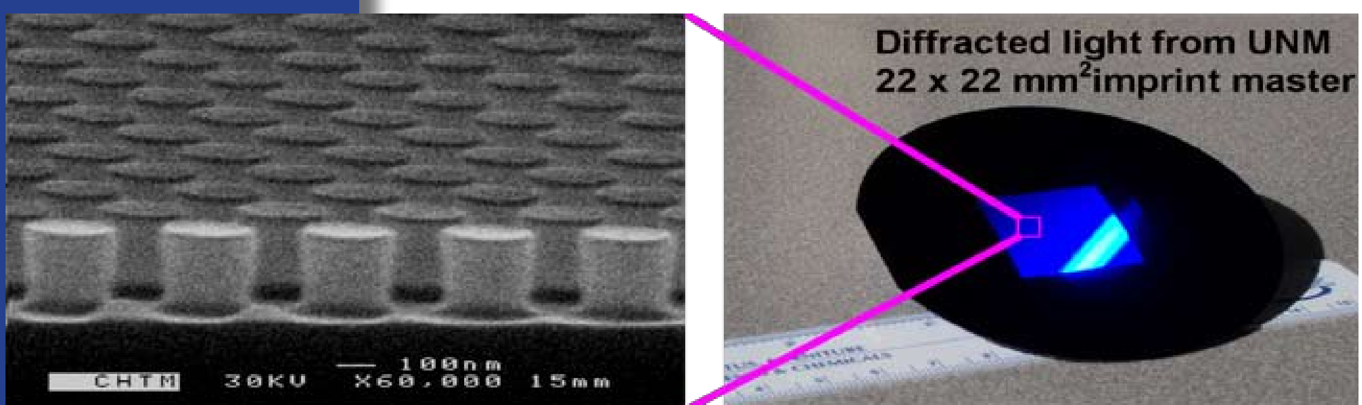

Figure 4. Scanning electron microscope image (left) of a two-dimensional array of posts that were patterned using interferometric lithography. Image of diffracted light (right) from the center region of a 3-inch wafer showing that larger areas (22 x 22 mm²) can be rapidly patterned.

large-area, 1 mm x 1 mm InGaN photonic crystal LEDs. This was the first large-area photonic crystal LED ever demonstrated that clearly shows that the sub-micron patterning required for photonic crystal LEDs is not an impediment to volume manufacturing.

For our more recent work on InGaN LEDs, we have moved away from the tunnel junction design shown in Figure 2 and have focused on more standard devices with a single *n*-type and *p*-type region. The photonic crystal patterns were fabricated using the same method of etching into the GaN material to form a two-dimensional photonic crystal. For this work, the LEDs were patterned using e-beam lithography so that a variety of different photonic crystal patterns could be rapidly investigated. We investigated photonic crystal patterns with hole sizes ranging from about 110 nm to 220 nm in diameter and with pitches ranging from 205 nm to 315 nm. This range of photonic crystal feature sizes is expected to cover the whole range of wavelengths of interest for blue and green InGaN emitters.

A variety of different two-dimensional geometric patterns also were investigated. For this work, LEDs were epoxied into device packages and wire bonded to make electrical connections. This packaging allowed for easy optical testing in an integrating sphere. The use of an integrating sphere allows us to measure the total LED intensity emitted in all directions such that the total external quantum efficiency (EQE) of our devices could be measured and compared to 'control LEDs', which were not patterned with a photonic crystal. Figure 5 shows the EQE plotted as a function of current density for a representative photonic crystal LED (red curve) compared to a control LED (black curve). This graph shows that control LEDs without a photonic crystal have an EQE of ~12% which can be improved to ~18% by incorporating the appropriate photonic crystal into the device structure for a 1.5 times enhancement in device efficiency.

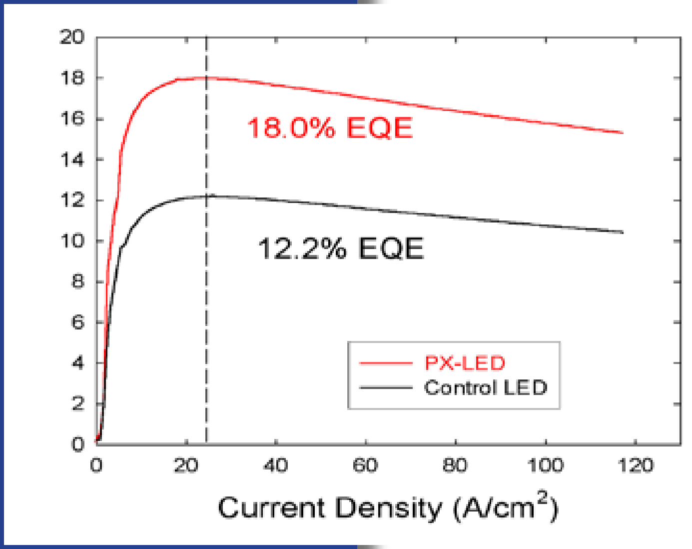

Figure 5. External quantum efficiency (EQE) plotted as a function of current density for a photonic crystal LED (red curve) compared to a control LED (black curve).

It is important to note that, for the LED data presented in Figure 5, these devices were all left unencapsulated. One method of improving light extraction in LEDs is to encapsulate LEDs with a high-index material. However, encapsulating LEDs can be problematic since most encapsulants degrade with prolonged exposure to blue and ultraviolet light. This degradation causes them to become opaque, reducing the emitted light.

The high-temperature operation of power LEDs also causes the encapsulant to degrade. Although the higher efficiency of semiconductor-based lighting can somewhat mitigate thermal problems in solid-state white-light sources, even a 5 watt, 50% efficient

Description of Product

LED will generate 2.5 watts of thermal load that must be dissipated in a heat sink. This excess heat causes device temperatures in excess of 100°C, which can cause the LED encapsulation to degrade over time.

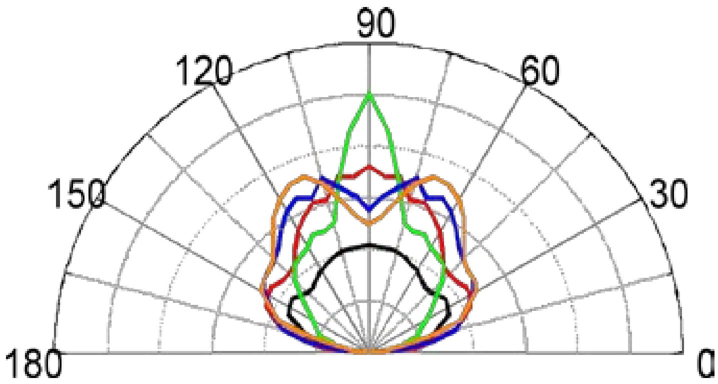

Figure 6. Far-field radiation patterns for photonic crystal LEDs (colored curves) plotted on a polar plot together with a control LED (black curve).

Our photonic crystal LEDs provide a method of improving light extraction without relying on encapsulation, and thus completely avoids these issues of encapsulant degradation. Photonic crystal LEDs can operate at higher temperatures without suffering premature device failure. Our most recent work on photonic crystal LEDs has culminated in the demonstration of devices with greater than 65% extraction efficiency without the use of any encapsulation material whatsoever.

Photonic crystal LEDs can also be used to control the emission direction of LED sources. For certain lighting applications, such as spot lights and vehicle head lights, it is desirable to direct the light in a particular direction. By choosing the appropriate photonic crystal pattern, the far-field radiation pattern for a photonic crystal LED can be dramatically different from that of a conventional LED. Figure 6 shows the emission pattern for several photonic crystal LEDs with different patterns (colored curves) plotted on a polar plot, together with an unpatterned LED (black curve).

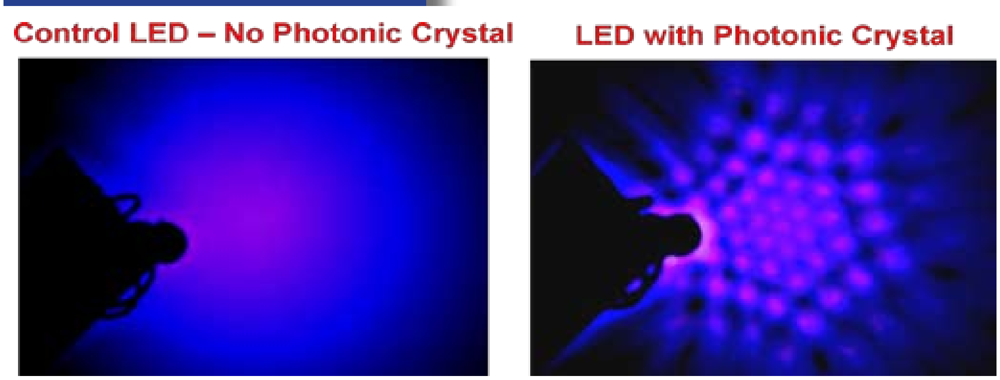

Figure 7. Emission pattern from a control LED (left) compared to a photonic crystal LED (right) projected onto a white background. Note that the emission pattern for the photonic crystal LED shows a triangular pattern similar to the sub-micron pattern etched into its surface.

The unpatterned LED emits light uniformly in all directions with a smoothly varying light pattern as a function of emission angle. In contrast, the photonic crystal LED has significantly modified far- field emission patterns. For example, the LED represented by the green curve shows significantly more emission in the forward direction, which is useful for a variety of lighting applications. Similarly, the orange curve emits in two prominent side-lobes near 60° and 120°, which would be useful for broad area illumination such as in street-lights. (We note that while some directionality can be achieved using lens and/or reflecting surfaces, these add to the complexity and cost of the system, as well as reducing overall luminaire efficiency because such additional optical components also absorb some of the emitted light, and typically operate at only 80-90% efficiency.) Thus, in addition to improving efficiency, photonic crystal LEDs can improve the source brightness by directing light into a certain desired direction.

Figure 7 shows a comparison of the emission pattern for a photonic crystal LED to that of a control LED. For these images, the LED emission in each case was projected onto a white background and a picture was taken with a digital camera. Notice that the photonic crystal LED has a modified far-field radiation pattern indicative of the triangular pattern etched in the LED, while the unpatterned LED has a smoothly varying intensity profile.

In summary, we have shown that photonic crystal LEDs can be used to improve the overall efficiency of InGaN LEDs without the use of an encapsulant. This allows photonic crystal LEDs to operate at higher powers and higher temperatures without any issue of encapsulant degradation. We have investigated large-area patterning techniques and have demonstrated the first large area 1mm x 1mm photonic crystal LED. Finally, we have demonstrated that the far- field pattern for photonic crystal LEDs can be dramatically altered using a photonic crystal. Photonic crystals can, therefore, improve efficiency, durability, and functionality of InGaN LEDs, making photonic crystal LEDs very valuable as sources for solid-state white-light emitters.

Competing Products and Technologies

Photonic crystal LEDs can be used for a variety of applications including back-lighting for displays, LED traffic lights, task lighting, automotive lighting, as well as general illumination for homes and offices. A very large number of manufacturers produce and sell LEDs both in the US and overseas for a variety of applications. Accurate comparison of different manufacturers' products for efficiency, price, and lifetime is extremely difficult in this rapidly changing high-technology field. The following list shows several of the major manufacturers together with competing LED products:

1.) Luminous – PhlatLight products
2.) Phillips Lumileds Lighting – Luxeon based emitters (models I, II, III, V, K2 and rebel)
3.) CREE–x-lamp line (XR, XR-C, XR-E)
4.) Nichia Corporation (power LED series and Top View series)
5.) Osram Opto Semiconductors (OSTAR, TOPLED, and Dragon)
6.) Samsung (Mobile Top View, Mobile Side View, and High Power)
7.) SemiLEDs – Metal Vertical Photon Light Emitting Diode

Although all of these companies sell LEDs, only one company (Luminous) uses photonic crystals to enhance the properties of their product and the Luminous product is currently limited to the back-lighting market where this product is in use in Samsung HDTVs. Due to the proprietary nature of their product, very little is known about their product with regard to efficiency, light extraction, the use of an encapsulant, or luminous efficacy.

Comparison Matrix

Equal and fair comparisons between LEDs from different manufacturers are extremely difficult. Therefore, the comparisons made here will compare only key features of each product. Particularly, no comparison will be made for price since the price of LEDs changes depending on volume, and the prices change very rapidly. Prices for photonic crystal LEDs are expected to compare favorably to other LEDs incorporating advanced light extraction methods.

Key features →	Use of encapsulant	Can improve internal quantum efficiency	Use of photonic crystal	Ability to control emission pattern	Estimated extraction efficiency	High-power LED operation
Photonic crystal LED	Not required	YES	YES	YES	~65%	YES
Luminous	unknown	unknown	YES	YES	unknown	YES
Phillips	YES	NO	NO	NO	~80%	YES
CREE	YES	NO	NO	NO	~70%	YES
Nichia	YES	NO	NO	NO	unknown	NO
Osram	YES	NO	NO	NO	unknown	YES
Samsung	YES	NO	NO	NO	unknown	Some products
SemiLEDs	YES	NO	YES	NO	unknown	YES

Improvements to LED Technology using Photonic Crystals

Photonic crystals offer a new and unprecedented ability to control and modify the emission of light from LEDs. There are several different ways that photonic crystals can improve LEDs. The first method is by improving light extraction. Theoretical studies have shown that light extraction efficiencies of 80% or better are possible for photonic crystal LEDs[9]. This enhanced light extraction can also be accomplished without the use of encapsulants, which can degrade under high-power LED operation conditions. Enhancements to light extraction efficiency are only the tip of the iceberg in possible enhancements to light emitters using photonic crystals.

A second and potentially very powerful method of utilizing photonic crystals in LEDs is through changes to the radiative recombination rate. All materials in use for LEDs emit light at a rate that is characteristic for that material. This was once thought to be an immutable material property that could never be changed. As early at 1946, it was discovered that this fundamental light emission rate could be enhanced by placing the material inside of an optical cavity[10]. A photonic crystal represents the ultimate optical cavity and is therefore an ideal way to realize enhanced emission rates for LEDs. However, this method of enhancement has never been realized for a practical LED. The photonic crystal LED fabrication methods demonstrated here represent a practical approach to demonstrating an enhanced light emission rate from InGaN blue and green emitters. This method of enhancement is particularly exciting because it can potentially address the problems associated with the low efficiencies of green and yellow, emitters which are limited to 10% or less.

Photonic crystals can also be used to control the emission direction of the light coming from an LED. This is particularly important for applications such as automobile headlights and projected displays. One common method of creating a more directional light source is to place the LED inside of a reflector cup to point the light in a particular direction. The reflector cup clearly must be larger than the LED which means that the source extent is larger making a light source that is more difficult for light engineers to utilize in the final lighting application. By using a photonic crystal for light extraction, all of the light can be extracted from the top of the chip and sent in a useful direction. This provides for a brighter, more versatile light source which can accurately place the light where it is needed for a certain application.

The use of photonic crystals in LEDs allows us to improve the light emission rate, enhance the light extraction efficiency without the use of encapsulants, and tailor the emission direction to make a high-efficiency light source that is extremely versatile and can be tailored for a use in a wide variety of applications.

Principal Applications

The most promising application for photonic crystal LEDs is solid-state lighting[1]. Solid-state lighting refers to the use of semiconductor-based light-emitting diodes (LEDs) for general illumination purposes. While lighting consumes more than 20% of all electricity consumption, conventional lighting technologies are remarkably low in efficiency: fluorescent lamps are only 25% efficient and incandescent lamps are only 5% efficient. This means that 95% of the electrical energy put into an incandescent bulb goes to heat and only 5% goes to useful illumination. LED technology is at the beginning of its development curve and is rapidly progressing such that 50% efficient lighting will be possible in 5 to 10 years. This would dramatically reduce national electricity use, perhaps by ~10%, saving $35B/year.
At the same time, this would result in a reduction by up to 100 million tons of carbon dioxide emissions, in the US alone, significantly reducing our impact on the environment.

In addition to improved efficiency, LED-based white-light sources have a number of other advantages. Although fluorescent bulbs with an efficiency of about 25% have been around for many, many years, people continue to use incandescent bulbs in their homes since the quality of the white light is perceived to be much higher. Using LEDs, it is possible to create a white-light source that can be varied in both intensity and color over a very wide range, making a highly adaptable light source that could be utilized in a wide variety of lighting applications. Finally, LED-based lighting will have much longer lifetimes than traditional light sources. While an incandescent bulb lasts about 1,000 hours or so, LED-based sources will have lifetimes of 100,000 hours or longer. This equates to 20 to 30 years of service life for LED-based sources. This allows LEDs to be used in a variety of new ways, such as being permanently built into walls and ceilings. Maintenance costs associated with changing bulbs will also be dramatically reduced. Solid-state lighting will revolutionize the way we light our homes and workspaces.

Other Applications

Photonic crystal LEDs can be used in any applications where light emission is required. One important area which is gaining momentum is the use of LEDs in automotive applications. The low-voltage, direct current requirements and long lifetimes of LEDs make them suitable for use in automobiles for interior lighting, indicators, brake lights and turn signals, and even headlights. Traffic lights around the world are being replaced with high-efficiency LED-based replacement fixtures, since their greater energy efficiencies allow them to pay for themselves in less than a year, and thereafter save electricity usage at a rate of $1,000 per intersection per year. LEDs can also be used as back-lights for flat panel computer monitors and televisions as well as other display technologies such as projectors. LEDs are currently used for the flash on cell phone cameras. Large outdoor displays, such as those at stadiums, use LED technology since it provides for high-efficiency, sunlight-visible displays.

The rapid switching speed of LEDs also makes them useful for short-range fiber-based local area networks. Photonic crystal LEDs in particular could be used as an efficient means of coupling light into a fiber for short haul communications applications. One particularly interesting idea is to use solid-state light sources in homes and offices as an in-building local area network to transmit data. The actual white light would be modulated at a frequency much higher than humans can see, yet data could easily be transmitted throughout the whole building or complex.

The list of applications for LED-based light sources is almost endless. We expect that high efficiency photonic crystal LEDs will help to enable a widespread adoption of this technology, which will reduce energy usage and our impact on the environment, as well as enhance our lives.

Summary

Photonic crystal light emitting diodes (LEDs) represent the merging of two exciting new technologies into a product that is more efficient and more versatile. Photonic crystals are periodic modulations of a transparent material that have a unique ability to control and modify the properties of light. LEDs are semiconductor-based light sources that have the potential to replace inefficient incandescent bulbs and fluorescent tubes.

By combining photonic crystal technology with LEDs, we have created a superior light source that will find use in a wide variety of applications, including high-brightness displays, automotive lighting, and general illumination. The primary advantages of photonic crystal LEDs are higher-efficiency operation, elimination of the need for encapsulation, and modification and adaptation of the light emission pattern to suit a wide variety of applications. Photonic crystal LEDs will help to bring about a revolution in the lighting industry where inefficient bulbs and tubes are replaced by extremely efficient, long-lifetime semiconductor-based lighting, thereby reducing our fossil fuel consumption and our impact on the environment.

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Appendix 1: References

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Appendix 2: Copies of Patents

US007294862B2

(12) **United States Patent**
Wierer, Jr. et al.

(10) **Patent No.: US 7,294,862 B2**
(45) **Date of Patent: Nov. 13, 2007**

(54) **PHOTONIC CRYSTAL LIGHT EMITTING DEVICE**

(75) Inventors: **Jonathan J. Wierer, Jr.**, Fremont, CA (US); **Michael R. Krames**, Mountain View, CA (US); **Mihail M. Sigalas**, Santa Clara, CA (US)

(73) Assignees: **Philips Lumileds Lighting Company, LLC**, San Jose, CA (US); **Avago Technologies General IP Pte. Ltd.**, Singapore (SG)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **11/373,639**

(22) Filed: **Mar. 9, 2006**

(65) **Prior Publication Data**

US 2006/0151794 A1 Jul. 13, 2006

Related U.S. Application Data

(63) Continuation of application No. 10/691,026, filed on Oct. 21, 2003, now Pat. No. 7,012,279.

(51) **Int. Cl.**
H01L 29/22 (2006.01)

(52) **U.S. Cl.** **257/94**; 257/96; 257/98

(58) **Field of Classification Search** 257/94, 257/96, 432, 98, 99
See application file for complete search history.

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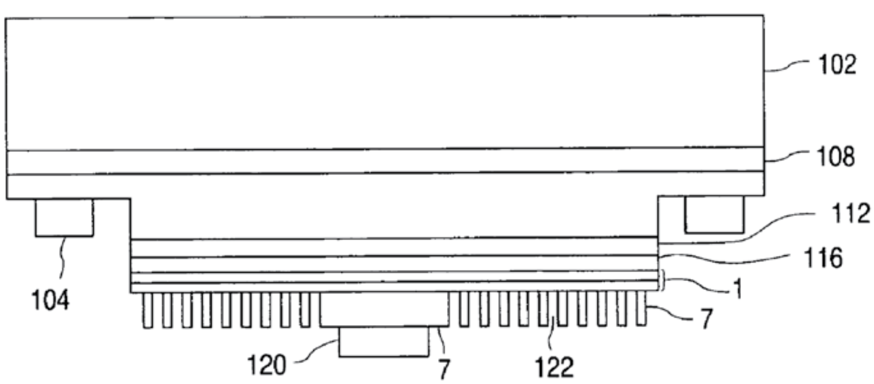
Primary Examiner—Sara Crane
(74) *Attorney, Agent, or Firm*—Patent Law Group LLP; Rachel V. Leiterman

(57) **ABSTRACT**

A photonic crystal structure is formed in an n-type layer of a III-nitride light emitting device. In some embodiments, the photonic crystal n-type layer is formed on a tunnel junction. The device includes a first layer of first conductivity type, a first layer of second conductivity type, and an active region separating the first layer of first conductivity type from the first layer of second conductivity type. The tunnel junction includes a second layer of first conductivity type and a second layer of second conductivity type and separates the first layer of first conductivity type from a third layer of first conductivity type. A photonic crystal structure is formed in the third layer of first conductivity type.

13 Claims, 10 Drawing Sheets



Appendix 2: Copies of Patents

US007279718B2

(12) **United States Patent**
Krames et al.

(10) **Patent No.: US 7,279,718 B2**
(45) **Date of Patent: Oct. 9, 2007**

(54) **LED INCLUDING PHOTONIC CRYSTAL STRUCTURE**

(75) Inventors: **Michael R. Krames**, Los Altos, CA (US); **Mihail M. Sigalas**, Santa Clara, CA (US); **Jonathan J. Wierer, Jr.**, Pleasanton, CA (US)

(73) Assignees: **Philips Lumileds Lighting Company, LLC**, San Jose, CA (US); **Avago Technologies General IP Pte. Ltd.**, Singapore (SG)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **10/059,588**

(22) Filed: **Jan. 28, 2002**

(65) **Prior Publication Data**

US 2003/0141507 A1 Jul. 31, 2003

(51) **Int. Cl.**
H01L 33/00 (2006.01)
H01L 33/001 (2006.01)
H01L 33/054 (2006.01)
H01L 33/077 (2006.01)

(52) **U.S. Cl.** **257/98**; 257/79; 257/94; 257/99

(58) **Field of Classification Search** 257/79
See application file for complete search history.

(56) **References Cited**

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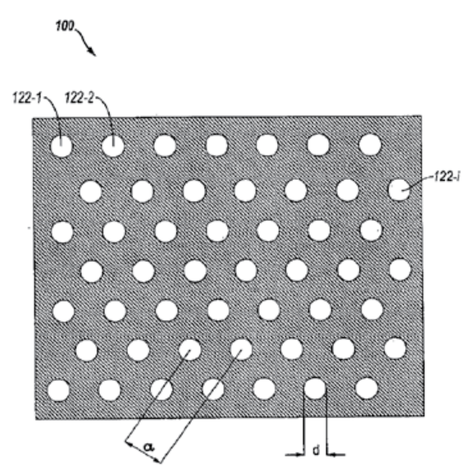
Primary Examiner—Wai-Sing Louie
(74) *Attorney, Agent, or Firm*—Patent Law Group LLP

(57) **ABSTRACT**

A photonic crystal light emitting diode ("PXLED") is provided. The PXLED includes a periodic structure, such as a lattice of holes, formed in the semiconductor layers of an LED. The parameters of the periodic structure are such that the energy of the photons, emitted by the PXLED, lies close to a band edge of the band structure of the periodic structure. Metal electrode layers have a strong influence on the efficiency of the PXLEDs. Also, PXLEDs formed from GaN have a low surface recombination velocity and hence a high efficiency. The PXLEDs are formed with novel fabrication techniques, such as the epitaxial lateral overgrowth technique over a patterned masking layer, yielding semiconductor layers with low defect density. Inverting the PXLED to expose the pattern of the masking layer or using the Talbot effect to create an aligned second patterned masking layer allows the formation of PXLEDs with low defect density.

56 Claims, 14 Drawing Sheets



Photonic Crystal LEDs

Appendix 2: Copies of Patents

US007012279B2

(12) **United States Patent**
Wierer Jr. et al.

(10) **Patent No.: US 7,012,279 B2**
(45) **Date of Patent: Mar. 14, 2006**

(54) **PHOTONIC CRYSTAL LIGHT EMITTING DEVICE**

(75) Inventors: **Jonathan J. Wierer Jr.**, Fremont, CA (US); **Michael R. Krames**, Mountain View, CA (US); **Mihail M. Sigalas**, Santa Clara, CA (US)

(73) Assignees: **Lumileds Lighting U.S., LLC**, San Jose, CA (US); **Agilent Technologies, Inc.**, Palo Alto, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 125 days.

(21) Appl. No.: **10/691,026**

(22) Filed: **Oct. 21, 2003**

(65) **Prior Publication Data**

US 2005/0082545 A1 Apr. 21, 2005

(51) **Int. Cl.**
H01L 29/22 (2006.01)

(52) **U.S. Cl.** **257/94**; 257/98; 438/32
(58) **Field of Classification Search** 257/94, 257/98, 432; 438/32, 47
See application file for complete search history.

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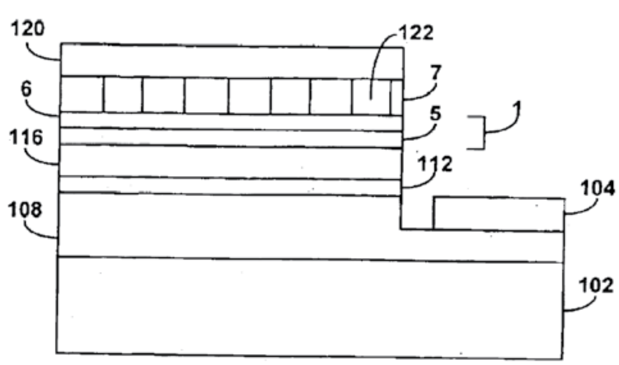
Primary Examiner—Sara Crane
(74) *Attorney, Agent, or Firm*—Patent Law Group LLP; Rachel V. Leiterman

(57) **ABSTRACT**

A photonic crystal structure is formed in an n-type layer of a III-nitride light emitting device. In some embodiments, the photonic crystal n-type layer is formed on a tunnel junction. The device includes a first layer of first conductivity type, a first layer of second conductivity type, and an active region separating the first layer of first conductivity type from the first layer of second conductivity type. The tunnel junction includes a second layer of first conductivity type and a second layer of second conductivity type and separates the first layer of first conductivity type from a third layer of first conductivity type. A photonic crystal structure is formed in the third layer of first conductivity type.

38 Claims, 10 Drawing Sheets



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