Photonic Crystal Structure Effect on the Enhancement in the External Quantum Efficiency of a Red LED

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***Abstract*—The enhancement in external quantum efficiency of a red light-emitting diode (LED) from photonic crystal (PhC) hole patterns was investigated. A red LED was chosen because its epitaxial layers are relatively free from defects as compared to GaN-based LEDs. The peak emission wavelength was 642 nm, and a triangular-lattice PhC was designed with a hole diameter to lattice distance ratio of 0.5. The lattice distance to wavelength ratio (a/λ) was varied from 0.2 to 4.6 in order to evaluate the enhancement in the external quantum efficiency. An improvement in efficiency greater than 75% was obtained for a/λ between 0.6 and 2.0. This improvement of the optical characteristics occurred with unchanged electrical properties.**

***Index Terms*—Light-emitting diode (LED), photonic crystal (PhC).**

I. INTRODUCTION

HIGH brightness (HB) light-emitting diodes (LEDs) have been successfully applied to a variety of applications in mobile electronics, flat panel displays, automobiles, traffic signals, large outdoor displays, and general lighting. However, tremendous efforts are still underway to replace conventional incandescent or fluorescent light bulbs with HB LEDs. High efficiency HB LED light sources could provide for a reduction in global energy needs. If HB LEDs with efficiency greater than 150 lm/W can be economically manufactured, it is believed that the energy consumption due to general lighting in the U.S. will be reduced by more than 60% [1].

Despite these promises, the development of high efficiency HB LEDs has been limited because of poor external quantum efficiency, low internal quantum efficiency caused by defects in the epitaxy, and device parasitics [2]–[4]. Among these issues, the external quantum efficiency has been considered to be the most crucial. Because the critical angle of the total internal reflection is low (GaAs $= 18.4^\circ$ and GaN $= 23^\circ$), only a small fraction of light generated in the active region of the LED can escape into the surrounding air [5]. Therefore, the external quantum efficiency would be reduced to a few percent even if the internal quantum efficiency were close to 100%. Among many approaches considered for increasing the external quantum efficiency [6]–[8], surface roughening has been regarded as one of the simpler methods. The largest reported improvement in wall-plug efficiency was 60% using a microroughened top surface, although the roughened surface morphology was irregular and uncontrolled [8]. It has been suggested from a theoretical calculation that the external quantum efficiency of an LED slab could be enhanced by factor of three through the incorporation of a photonic crystal (PhC) pattern due to the existence of a photonic bandgap [9]. Because of this, PhC LEDs are now being actively researched [10]–[14]. In an optical pumping experiment, the external quantum efficiency was improved by factors of 10–15 through a combination of spontaneous emission enhancement from a PhC effect and Bragg scattering [10]. Without a slab-like structure or significant vertical confinement by other means, the use of the photonic bandgap effect to enhance the spontaneous emission may prove difficult to manufacture in high volumes at low cost. It has been argued that Bragg-like scattering due to a surface grating effect by etched holes is responsible for the improved photon extraction in an infrared LED [11]. In previous studies for GaN-based LEDs, a 35% enhancement of wall-plug efficiency from a PhC surface structure could not be isolated because of inconsistent current–voltage (I–V) characteristics [12]–[14]. This phenomenon was attributed to leakage current paths caused by defects in the epitaxial layers.

In this letter, an experiment is designed to measure the enhancement in the external quantum efficiency due to etched PhC holes while ensuring that changes to the electrical properties of the device are minimized. To achieve this, four aspects were considered. First, a red LED based on mature AlGaAs alloys was chosen to avoid epitaxy defect issues. Second, a small LED size (40×40 μm^2) was chosen with a ring pattern electrode to ensure the contact was isolated from the PhC. Third, no transparent electrode was deposited (which could influence current spreading). Finally, the PhC lattice distance (a) to wavelength (λ) ratio—hereafter referred to as the lattice parameter (a/λ)—was varied from 0.2 to 4.6. The PhC hole diameter to lattice distance ratio was fixed at 0.5. Large lattice parameters are of particular interest because if the PhC hole diameters are on the order of a micron, electron-beam lithography would not be necessary, and conventional photolithography, which is compatible with low-cost manufacture, could be applied to define a PhC structure.

II. FABRICATION

A conventional red LED was made following a typical fabrication procedure on a GaAs substrate. The epitaxial

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structure was composed of a 4-μm-thick bottom Te-doped n-$Al_{0.9}Ga_{0.1}As$ current-spreading layer, an InGaP-based active region consisting of 20 quantum wells and lattice-matched to GaAs, a 4-μm-thick top C-doped p-$Al_{0.9}Ga_{0.1}As$ current-spreading layer, and a 4-nm-thick C-doped p-GaAs top contact layer, all grown by metal–organic chemical vapor deposition on a Si-doped n-GaAs substrate. A backside n-GaAs compatible electrode consisting of AuGe–Ni–Au (50 nm/20 nm/200 nm) was deposited by electron beam evaporation. Top ring contacts were then formed by evaporation of Ti–Au (20 nm/200 nm) and a standard lithography liftoff process. After the contacts had been defined, SiO_2 was deposited by plasma-enhanced chemical vapor deposition at 300 °C and used as a mask for defining mesa structures. The mesas, which serve to isolate devices, were etched by inductively coupled plasma reactive ion etching (ICP-RIE) using a $SiCl_4$–Ar gas with an etch rate of 250 nm/min for 20 min.

After removing the mesa mask, SiO_2 was deposited again to serve as a mask for defining the PhC patterns. The triangular-lattice PhCs were patterned by electron-beam lithography. These holes were then etched into the top p-doped $Al_{0.9}Ga_{0.1}As$ layer using ICP-RIE etching for 10 min, corresponding to a nominal etch depth of 2.5 μm. Note that with smaller lattice parameter, a smaller hole diameter is obtained. Due to etching nonuniformity (RIE lag), these smaller diameter holes are etched at a slower rate [15]. The LEDs were tested after removing the PhC mask.

III. RESULTS

Electrical characteristics and emission spectra measurements of the conventional (unetched control) and PhC LEDs were measured at room temperature. A 1-cm^2 Si photodetector with responsivity 0.335 A/W (at $\lambda = 642$ nm) was placed 3 mm from the top of the LED to collect as much light output as possible. Although light from the sides of LEDs was lost, this method was determined to be reproducible and thus accurate enough to compare the light output intensities between the conventional and PhC LEDs.

Fig. 1(a) shows pictures of a red PhC LED. The size of the mesa is 40×40 μm^2, and the actual emission window is 20×20 μm^2. The optical microscope image shows the PhC pattern with a lattice parameter $a/\lambda = 4.6$. The light output is shown in Fig. 1(b) from the PhC (upper) and conventional (lower) red LEDs. As apparent in Fig. 1(b), the total light output of the red PhC LEDs is increased by at least 60% compared to conventional red LEDs. The average measured differential efficiency of the conventional LEDs is 10 $\mu W/mA$, and the measured differential efficiencies of the PhC LEDs range from 13 to 22 $\mu W/mA$. Because emission out the side and bottom of the device is not collected by the photodetector, these measured efficiencies do not reflect the total output of the LED, but are useful for relative comparison.

Previous work has shown that in the case of GaN-based PhC LEDs, there was a ~30% variance in I–V characteristics between PhC and conventional LEDs due to nonradiative carrier leakage paths [14]. However, this is not observed in GaAs-based red PhC LEDs. Fig. 2(a) shows the I–V characteristics both from the PhC and conventional red LEDs. The enlarged portion of Fig. 2(a) for one device is shown in Fig. 2(b). It is difficult to distinguish between I–V characteristics of the PhC red LEDs from conventional LEDs. The inset of Fig. 2(b) illustrates the emission spectra of the PhC and conventional LED. Figs. 1(a) and 2 show that the enhancement in the external quantum efficiency is predominantly caused by the PhC holes and that little effect from nonradiative carrier leakage is apparent.

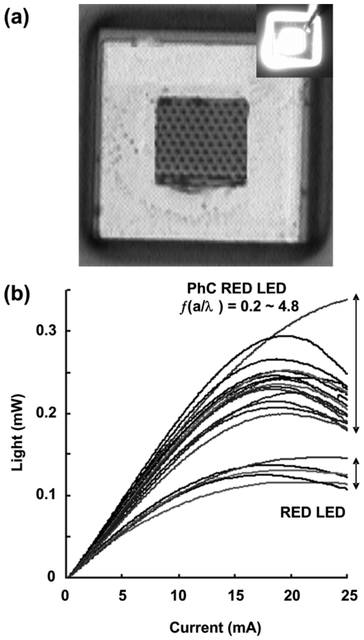

Fig. 1. (a) Optical microscopic image of the PhC LED, with inset showing the same device under operation; (b) light output–current (L–I) characteristics of PhC and conventional red LEDs.

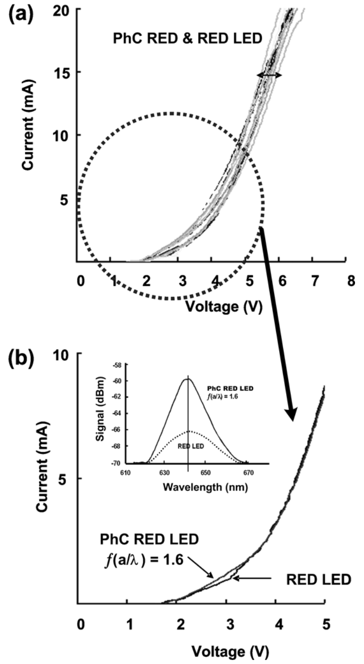

Fig. 2. (a) I–V characteristics of PhC and conventional LEDs. (b) Enlarged portion of (a) and emission spectra of PhC and conventional LED.

The enhancement in the external quantum efficiency of the PhC red LEDs is shown in Fig. 3. This enhancement factor is defined as $(\eta_{\mathrm{PhC}} - \eta_{\mathrm{Ref}})/\eta_{\mathrm{Ref}}$, where η_{PhC} is the differential

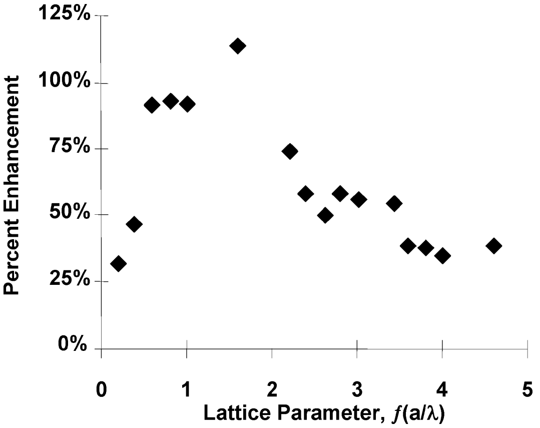

Fig. 3. Behavior of the enhancement in the external quantum efficiency as a function of the lattice parameter.

quantum efficiency (as measured from the origin) of the various PhC red LEDs, and η_{Ref} is the differential quantum efficiency (similarly measured) of the corresponding unetched control LED. Enhancement values between 30% and 120% are observed, with enhancement exceeding 75% for a/λ between 0.6 and 2.0. This improvement is higher than that of a micro-roughened top surface LED. According to a photonic band calculation of the two-dimensional slab [10], a photonic bandgap exists for a/λ between 0.3 and 0.5. When the lattice parameter is $0.2 \sim 2.0$, the behavior of the enhancement is due to the Bragg scattering effect [11]. Enhancement is not expected to reduce to 0% for small lattice parameters until the hole size becomes negligible relative to the wavelength of operation ($a/\lambda \ll 0.1$). Holes this small are difficult to fabricate, and consequently, not fabricated or tested in this study. Enhancement is not expected to reduce to 0% for large lattice parameters either, due to the presence of increased scattering regardless of hole size.

IV. CONCLUSION

Red PhC LEDs with a lattice parameter a/λ from 0.2 to 4.6 were fabricated and an enhancement in the external quantum efficiency was observed. The external quantum efficiency of PhC LEDs was improved by 30% to 120%, with efficiency exceeding 75% for a/λ between 0.6 and 2.0. This improvement in extraction is consistent with Bragg scattering from the PhC. Future work will focus on the hole etch depth dependence on device performance.

REFERENCES

[1] G. Muller, "White light emitting diodes," in *Light Emitting Diodes*, San Diego, CA, Oct. 15–17, 2003, Optical Industry Development Association (OIDA) Tech Roadmaps.

[2] X. Y. Sun, R. Bommerna, D. Burckel, A. Frauenglass, N. Fairchild, S. R. J. Bryeck, G. A. Garrett, M. Wraback, and S. D. Hersee, "Defect reduction mechanisms in the nanoheteroexpitaxy of GaN on SiC," *J. Appl. Phys.*, vol. 95, no. 3, pp. 1450–1454, 2004.

[3] C. Y. Hsu, W. H. Lan, and Y. S. Wu, "Effect of thermal annealing of Ni/Au Ohmic contact on the leakage current of GaN based lighting emitting diodes," *Appl. Phys. Lett.*, vol. 83, no. 12, pp. 2447–2449, 2003.

[4] X. A. Cao, S. J. Pearton, A. P. Zhang, G. T. Dang, F. Ren, R. J. Shul, L. Zhang, R. Hickman, and J. M. Van Hove, "Electrical effects of plasma damage in p-GaN," *Appl. Phys. Lett.*, vol. 75, pp. 2569–2571, 1999.

[5] J. V. Smith*, Geometrical and Structural Crystallography*. New York: Wiley, 1982, p. 449.

[6] S. P. Martin*, Lumileds*. Bellingham, WA: SPIE, 2001.

[7] Press Release by Osram Opto-Semicondutor 2004.

[8] C. Huh, K. S. Lee, E. J. Kang, and S. J. Park, "Improved light-output and electrical performance of InGaN-based lighting-emitting diode by microroughening of p-GaN surface," *J. Appl. Phys.*, vol. 93, no. 11, pp. 9383–9385, 2003.

[9] S. Fan, R. P. Villeneuve, J. D. Joannopoulos, and E. F. Schubert, "High extraction efficiency spontaneous emission from slabs of photonic crystals," *Phys. Rev. Lett.*, vol. 78, no. 17, pp. 3294–3297, 1997.

[10] M. Boroditsky, R. Vrijen, F. T. Krauss, R. Coccioli, R. Bhat, and E. Yablonovitch, "Spontaneous emission extraction and Purcell enhancement from thin-film 2-D photonic crystals," *J. Lightw. Technol.*, vol. 17, no. 11, pp. 2096–2112, Nov. 1999.

[11] H. Ishikawa and T. Baba, "Efficiency enhancement in a light-emitting diode with a two-dimensional surface-grating photonic crystal," *Appl. Phys. Lett.*, vol. 84, no. 4, pp. 457–459, 2004.

[12] T. N. Oder, K. H. Kim, J. Y. Lin, and H. X. Jiang, "III-nitride blue and ultraviolet photonic crystal lighting emitting diode," *Appl. Phys. Lett.*, vol. 84, no. 4, pp. 466–468, 2004.

[13] T. H. Hsueh, J. K. Sheu, H. W. Huang, J. Y. Chu, C. C. Kao, H. C. Kuo, and S. C. Wang, "Enhancement in light output of InGaN-based microhole array light-emitting diodes," *IEEE Photon. Technol. Lett.*, vol. 17, no. 6, pp. 1163–1165, Jun. 2005.

[14] T. S. Kim, A. J. Danner, and K. D. Choquette, "Enhancement in the external quantum efficiency of a blue LED by a photonic crystal surface grating," *Electron. Lett.*, vol. 41, no. 20, pp. 325–326, 2005.

[15] R. A. Gottscho and C. W. Jurgensen, "Microscopic uniformity in plasma etching," *J. Vac. Sci. Technol. B*, vol. 10, no. 5, pp. 2133–2143, 1992.