Effect Of Photonic Crystal Structure On The Extraction Efficiency Of Blue GaN/InGaN LED On Sapphire Substrate

G. Srivani Padma and Suchandan pal

Council of Scientific and Industrial Research - Central Electronics Engineering Research Institute (CSIR-CEERI), Pilani, Rajasthan

Email address: **sri.vani.padma@gmail.com**, **spal@ceeri.ernet.in**

ABSTRACT: This paper presents the investigation of enhancement in the extraction efficiency of the light emitting diode incorporating Photonic Crystal (PhC) based structure with hole pattern. PhC's were investigated on GaN/InGaN based multiple quantum well (MQW) blue LEDs. Peak emission wavelength of 460nm was considered for the simulations. LEDs with both top and bottom-side PhC's were considered in order to achieve the optimal light extraction efficiency. The design parameters like radius, lattice constant and thickness of the of PhCs are considered along with the distance of PhC from the QW. Results reveal that the increased efficiency is mainly due to scattering through PhC structures.

INTRODUCTION

With the wide spread of blue–white GaN-based light emitting diode (LED) markets, including backlighting and illumination, there arises a strong demand for efficient LEDs. Though the internal quantum efficiency of GaN based LEDs has reached upto 80% due to high quality growth of epitaxial layers, the external quantum efficiency of the device is still lower. This efficiency is limited by low-light extraction efficiency because of total internal reflection (TIR) at LED surfaces, which leads to undesired optical absorption with in the device itself. Light can be extracted only when the incident angle is smaller than the critical value, which is about 23.5^{o} at the interface between GaN and the air [1]. The TIR limits the light extraction efficiency up to approximately 4% per surface in the conventional GaN-based LEDs. Many approaches have been attempted to overcome the poor extraction efficiency of LEDs such as changing the LED chip shape [2], photon recycling [3], coupling to surface plasmon modes [4], or roughening the surface [5]. Recently, an approach using photonic crystals (PhCs) has been adopted to dramatically enhance light extraction efficiency [6]–[8]. The main purpose of this method is to avoid total internal reflection and to prevent the lateral propagation of light–waveguide effect. PhC structure changes the incident angle of propagated light by diffraction, which enhances the light extraction efficiency [9-10].

This paper presents the design optimization and analysis of the GaN blue LED consisting of PhC structures. For this purpose the light propagation and extraction of PhC based LEDs are simulated using the finite-difference time-domain method for various structures using Crystal Wave software tool from the Photon Design, UK.

SIMULATION RESULTS AND DISCUSSION

Simulations are carried out by considering GaN/InGaN based MQW blue LED [11]. Peak emission wavelength of 460 nm with FWHM of 20.4 nm was achieved for this structure. Enhancement in the light extraction efficiency of this LED structure was verified by incorporating PhC with hole type pattern. The hole was considered to be circular in geometry. In this regard, we investigated the enhancement in the extraction efficiency of the device based on several factors like the position of the PhC structure in LED i.e either on top p-GaN or within bottom n-GaN, the effect of thickness (d) of the PhC, effect of lattice constant(a) as well as radius(r) of the PhC. Figs.1(a) and 1(b) show the schematics of the proposed LED structure incorporating (a) top PhC and (b) bottom PhC.

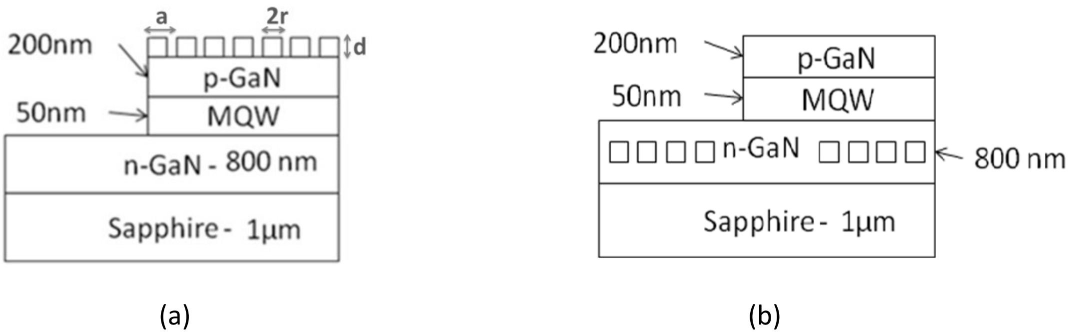


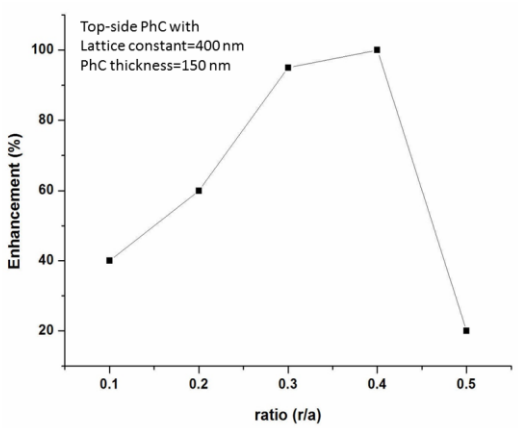
Fig 1: Schematic of GaN LED strcture with (a) top PhC indicating its lattice constant a, thickness d and radius r and (b) bottom-based PhC.

Calculation of the light extraction efficiency of the PhC based LED:

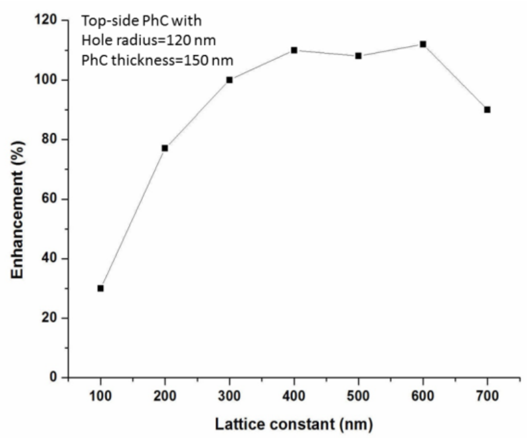
In this section, we calculate the enhancement factor of the LEDs by using various PhC structures with hexagonal lattice consisting of air holes. PhC parameters such as the lattice constant a, the PhC thickness d, the ratio of hole radius to lattice constant r/a, and the position of the PhC were considered. The enhancement factor is calculated as $(E_{PhC} - E_{noPhC})/E_{noPhC}$, where E_{PhC} and E_{noPhC} are the total energies of light escape from the LED with and without the PhC, respectively [9]. In this way, we can find the optimal design of a PhC LED for high enhancement of light extraction and compare the enhancement when using top-side and bottom-side PhCs.

LED structure with top-side PhC:

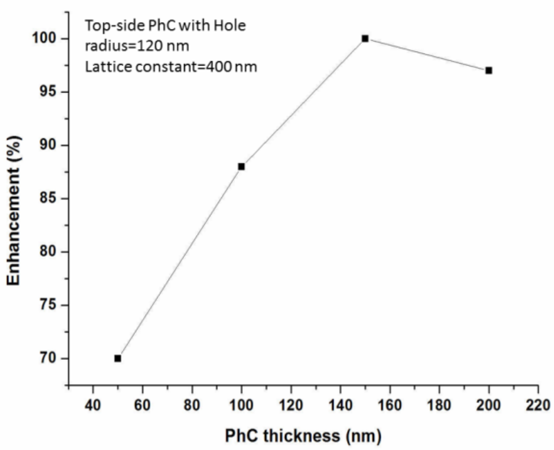
For an LED with a top PhC, the dependence of the enhancement of light extraction is studied based on lattice constant (a), ratio (r/a), Etch depth (d). Each individual PhC parameter was varied in turns, while the other parameters were kept constant, and the enhancement is calculated. In this case, the simulated LED structure consists of a 200-nm-thick p-GaN, an MQW active layer, a 800nm-thick n-GaN, and a 1-µm-thick sapphire substrate with a cross-sectional area of $1\times 1\ mm^2$. During simulation a dipole source is placed in the MQW region to calculate the light extraction. The dependence of the enhancement of light extraction efficiency on the PC parameters is shown in Fig. 2. The lattice constant, PhC thickness, and ratio r/a were varied from 100 to 700 nm, 50 to 200 nm, and 0.1 to 0.5, respectively. From Fig. 2(a), the enhancement factor is low when r/a is too small or too large. A value of r/a = 0.5 is chosen in this simulation in order to avoid having the holes overlap each other. The highest enhancement was obtained at a ratio r/a = 0.3 to r/a = 0.4 in which the lattice constant of 400nm and PhC thickness of 150nm are kept as constant. Fig. 2(b), it is observed that the enhancement factor is increased with the increase in the lattice constant keeping hole radius 120nm and PhC thickness of 150nm as constant. After reaching the maximum value at a lattice constant in the range of 400–600 nm, the light enhancement factor decreased. Fig. 2(c) shows that the enhancement factor almost increased with thickness where the lattice constant a= 400nm and radius 120nm were kept constant. However, after reaching the maximum value at a thickness of 150 nm, the light enhancement factor decreased.



(a)



(b)

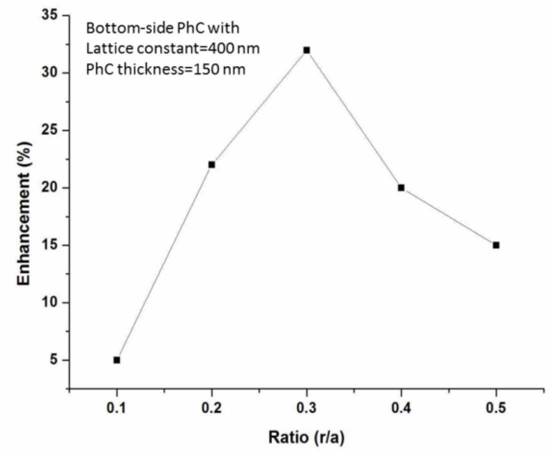


(c)

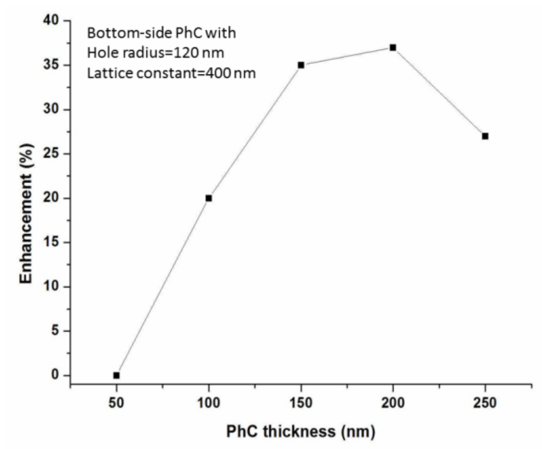
Fig 2: Enhancement of light extraction efficiency as a function of (a) ratio (r/a), (b) lattice constant, and (c) PhC thickness of the top PhC LED.

LED structure with bottom-side PhC:

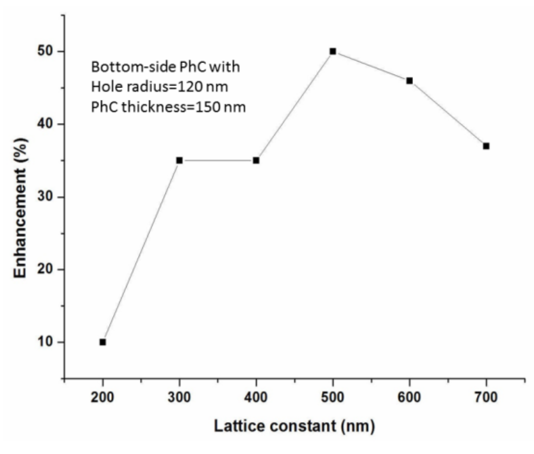
An approach similar to that of the top PhC LED is used to analyze the effect of the bottom-side PhC structure on the enhancement of light extraction efficiency of the LED. A standard bottom-side PhC LED includes a 200- nm-thick p-GaN, an MQW active layer, a 800nm-thick n-GaN, a 1-μm-thick sapphire substrate, and a cross-sectional area of 1×1 mm^2. Intially the PhC was located 50 nm below the MQW in order to find the effect of the PhC parameters like the thickness of PhC, r/a ratio and lattice constant on the enhancement of light extraction efficiency. The enhancement factor was plotted as a function of r/a ratio and PhC thickness in Figs. 3(a) and 3(b). The highest enhancement has been obtained at a ratio r/a of 0.3. Fig. 3(b) shows that the enhancement depends nonlinearly on PhC thickness. The largest enhancement was obtained at a PhC thickness of 150–200 nm. Fig 3(c) shows the effect of lattice constant on the enhancement of extraction efficiency. The highest enhancement in extraction efficiency for bottom-side PhC LED has been obtained at 500nm. The results obtained are quite close to the results of a top-side PhC LED.



(a)



(b)



(c)

Fig. 3: Enhancement of light extraction efficiency as a function of (a) ratio r/a (b) lattice constant (c) PhC thickness for bottom-side PhC LED.

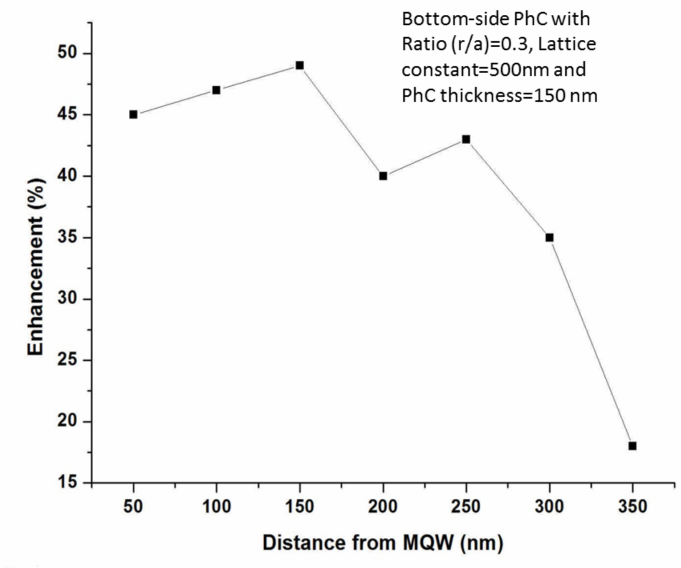


Fig 4: Enhancement of light extraction efficiency as a function of the distance of PhC structure from the bottom of the MQW

Using the optimal parameters obtained for bottom-side PhC, the effect of the distance of the PhC structure from the bottom of the MQW on the enhancement of extraction efficiency is shown in Fig 4. From the Fig. 4 it shows that as the distance of the PhC from bottom side of the MQW is increased, the enhancement factor is decreased. The maximum enhancement in this simulation has been obtained for a distance of 150nm from below the MQW region. Hence when considering a bottom side PhC LED it is essential to determine the distance of the PhC structure from the MQW in order to obtain an optimal enhancement in the extraction efficiency.

Comparison of LED structure with top-side and bottom-side PhC:

To compare the enhancement of the LEDs with a top-side and bottom-side PhC, we used the same PhC parameters with r/a=0.3, a= 400nm and d=150 nm, with PhC placed at a distance of 50 nm from the MQW for both the top-side and bottom-side PhC LED structure. From the Fig 2 and Fig 3 it is clear that the total energy output for the top-side PhC LED increases at faster rate and is more sensitive than that for the bottom-side PhC LED structure. For the top-side PhC LED, PhC pattern diffracts the incoming light, so that some of the light emits outside the escape cone can be extracted to an outer medium, thereby resulting in improved light extraction. Therefore, the light has additional opportunities to escape through the semiconductor and air interface resulting in higher extraction efficiency. However, the LED structure incorporating both top-side and bottom-side PhCs, can lead to further improvement of light extraction efficiency; the results and discussion are beyond the scope of this paper.

CONCLUSION

The light extraction efficiency of an LED with various PhC layers has been calculated using the FDTD method. For the top-side PhC LED, the optimal extraction efficiency is found for a lattice constant of 400–600 nm, PhC thickness of 150nm, and r/a of 0.3–0.4. The optimal design for the bottom-side PhC LED has been obtained with a lattice constant of 500 nm, a PhC thickness of 150 nm, and an r/a of 0.3 at a distance of 150nm from the bottom of the MQW. It is observed that the top PhC is more effective in increasing the light extraction efficiency because of the diffraction of light between the top surface of the LED and the PhC. Hence the design is optimized for 100% enhancement in the extraction efficiency with a lattice constant of 400 nm, a hole radius of 0.4 times *a*, and a PhC thickness of 150 nm for top-side PhC LED.

ACKNOWLEDGEMENT

Authors would like to thank the Director, CSIR-CEERI, for his encouragement and to all members of Opto-electronic Devices Group for their help and cooperation.

REFERENCES

[1]Christopher Wiesmann, Krister Bergenek, Norbert Linder, And Ulrich T. Schwarz, Photonic Crystal LEDs – Designing Light Extraction, Laser & Photon. Rev 3, No. 3, 262–286(2009).

[2] M. R. Krames, M. Ochiai-Holcomb, G. E. Hofler, C. Carter-Coman, E. I. Chen, I. H. Tan, P. Grillot, N. F. Chui, J. W. Huang, S. A. Stockman, F. A. Kish, and M. G. Craford, "High-power truncated-inverted-pyramid (AlxGa1–x)0.5In0.5P/GaP light-emitting diodes exhibiting >50 external quantum efficiency," Appl. Phys. Lett., vol. 75, pp. 2365–2367, 1999.

[3] E.Y. Schnitzer,C.Caneau, andT. J. Gmitter, "Ultrahigh spontaneous emission quantum efficiency, 99.7% internally and 72% externally, from Al- GaAs/GaAs/AlGaAs double heterostructures," Appl. Phys. Lett., vol. 62, pp. 131–133, 1993.

[4] J.Vuckovic, M. Loncar, and A. Scherer, "Surface plasmon enhanced lightemitting diode," IEEE J. Quantum Electron., vol. 36, no. 10, pp. 1131–1144, Oct. 2000.

[5] T. Fujii, Y. Gao, R. Sharma, E. L. Hu, S. P. DenBaars, and S. Nakamura, "Increase in the extraction efficiency of GaN-based light-emitting diodes via surface roughening," Appl. Phys. Lett., vol. 84, pp. 855–857, 2004.

[6] Hung-Wen Huang, Chung-Hsiang Lin, Zhi-Kai Huang, Kang-Yuan Lee, Chang-Chin Yu, and Hao-Chung Kuo "Improved Light Output Power of GaN-Based Light-Emitting Diodes Using Double Photonic Quasi-Crystal Patterns," IEEE Electron Device Letters, Vol. 30, No. 11, November 2009.

[7] Kenji Orita, Yuji Takase, Yasuyuki Fukushima, Manabu Usuda, Tetsuzo Ueda, Shinichi Takigawa, Tsuyoshi Tanaka, Daisuke Ueda, and Takashi Egawa, "Integration of Photonic Crystals on GaN-Based Blue LEDs Using Silicon Mold Substrates", IEEE Journal Of Quantum Electronics, Vol. 44, No. 10, October 2008.

[8] Taesung Kim, Paul O. Leisher, Aaron J. Danner, Ralph Wirth, Klaus Streubel, and Kent D. Choquette, "Photonic Crystal Structure Effect on the Enhancement in the External Quantum Efficiency of a Red LED", IEEE Photonics Technology Letters, Vol. 18, No. 17, September 2006.

[9] Dang Hoang Long, In-Kag Hwang, and Sang-Wan Ryu, "Design Optimization of Photonic Crystal Structure for Improved Light Extraction of GaN LED", IEEE Journal Of Selected Topics In Quantum Electronics, Vol. 15, No. 4, July/August 2009.

[10] Aurelien David, Henri Benisty, and Claude Weisbuch "Optimization of Light-Diffracting Photonic-Crystals for High Extraction Efficiency LEDs" Journal Of Display Technology, Vol. 3, No. 2, June 2007.

[11] K. Singh, M. Mathew, A. chauhan, M. Singh, S. Pal, S.Singh, P. Kumar, B.C. Joshi, S. Das, A.K. Gupta, B.C. Pathak, S. Johri and C. Dhanavantri "Fabrication of InGaN/GaN MQW Blue LEDS on Sapphire Substrate", National conference on Recent Trends and Technological Advances in LED Lighting Systems, Bangalore, Dec. 2010.