Extended Abstracts of the 2003 International Conference on Solid State Devices and Materials, Tokyo, 2003, pp. 878-879

F-8-3

Enhanced Light Extraction Efficiency of GaN-based Blue LED Using Extended-Pitch Surface Photonic Crystal

Kenji Orita, Satoshi Tamura, Toshiyuki Takizawa, Tetsuzo Ueda, Masaaki Yuri, Shinichi Takigawa, and Daisuke Ueda

Semiconductor Device Research Center, Semiconductor Company, Matsushita Electric Industrial Co., Ltd.,
1-1 Saiwai-cho, Takatsuki, Osaka 569-1193, Japan
Phone: +81-72-682-7530 Fax: +81-72-682-7923 E-mail: orita.kenji@jp.panasonic.com

1. Introduction

Highly efficient GaN-based blue light-emitting diodes (LEDs) with high output power have been required for future solid-state lighting using the white light excited by the LEDs [1]. Even though recent crystal growth technology has been increasing the internal efficiency, the extraction efficiency still remains low value because of the internal reflection at the surface. Integration of photonic crystal (PhC) is one of the potential solutions to attain high extraction efficiency. So far, two-dimensional (2D) surface PhC has enhanced the extraction efficiency in InP-based infrared LEDs [2, 3]. Since the reported PhC LEDs have consisted of periodic structures in the dimension comparable to the emission wavelength, integration of the PhC onto GaN-based LEDs has been believed to have fine structures of which the pitch is less than 0.5 μm. Thus, considering the difficulties to make such fine structures on chemically stable GaN-based materials at low cost, integration of PhC structure on the blue LEDs has never been examined.

In this report, we calculate in detail the enhancement of the extraction efficiency by 2D surface PhC structures on GaN-based blue LEDs. The results show that the PhC pitch of even larger than 1 μm enhances the extraction efficiency for the emitted blue light. Such a pitch is much larger than the emission wavelength, so we call it "extended-pitch". Upon this calculation, we fabricate extended-pitch 2D surface PhCs onto GaN-based LEDs together with a unique current-injection structure. The enhancement of the extraction efficiency by surface PhC has been realized in blue LEDs for the first time.

2. Device Design and Fabrication

Schematic cross-section of the 2D surface PhC GaN-based blue LED is shown in Fig. 1. PhC infrared LEDs reported so far spread the injected current through the layers beneath the surface PhC, such as the contact and current diffusion layers [3]. Employing this type of current flow to a p-GaN cladding layer would limit the luminescent area because of its inherent highly resistive nature. Thus, PhC blue LEDs in this study flows the injected current into the entire area of the active region through a transparent electrode on PhC as shown in Fig. 1, which would result in uniform emission and high output power operation.

We calculate the extraction efficiency enhancement in blue LEDs with PhC structures using finite difference time domain method (FDTD). The 2D model having surface rectangular corrugation PhC with 50% duty is used to make the calculation simpler [3]. The used refractive index for GaN is 2.48 [4] and the emission wavelength is assumed as 0.45 μm.

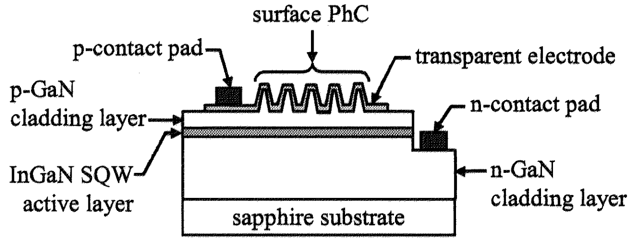

Fig. 1 Schematic cross-section of surface PhC GaN-based LED.

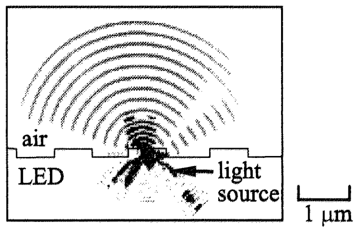

Fig. 2 Simulated light extraction with extended-pitch surface PhC. Its pitch is 1.5 μm. The light is p-polarized and each line indicates the electric-field peak position of propagating light.

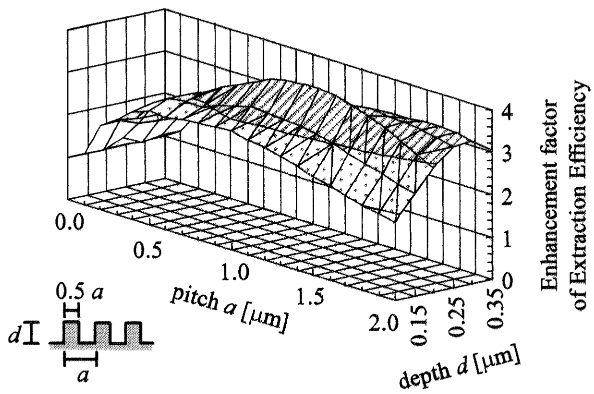

Fig. 3 Calculated enhancement factor of light extraction efficiency using parameters of GaN-based LED.

Fig. 2 shows an example of simulated light propagation with an extended-pitch surface PhC. Its pitch is 1.5 μm. The incident angel of the emitted light from the light source is set to be 45°. The extended-pitch surface PhC extracts much amount of the light inside LED, while light with the same incident angle is reflected totally at the surface in case of the LED without PhC (non-PhC LED). The calculated enhancement factor of the extraction efficiency is plotted as functions of pitch a and depth d in Fig. 3. The extraction efficiency is normalized by that of the non-PhC LED. The enhancement factor reaches its maximum value around pitch of 1.5 μm, extended-pitch, for each depth. The highest enhancement factor in the calculation is 3.6 at a = 1.5 μm and d = 0.25 μm.

The LED structure is grown on a c-plane sapphire substrate by metal-organic chemical vapor deposition. The LED consists of a single quantum well (SQW) of undoped InGaN and exhibits 0.45 μm peak in photoluminescence spectra. Triangular-lattice columns, which form 2D PhC, are patterned on the surface of the p-GaN cladding layer by electron-beam (EB) lithography and reactive ion etching (RIE). Typical height and pitch of the PhC columns are 0.25 μm and 1.5 μm, respectively. Then an ITO-based transparent electrode is deposited directly on the surface PhC, followed by the formation of contact pads both on the transparent electrode and n-GaN cladding layer. Non-PhC LEDs are also fabricated on the same wafer.

Fig. 4 shows the cross section of the PhC LED by scanning electron microscopy (SEM), in which the transparent electrode covers the whole surface of the PhC.

3. Measurements and Results

Fig. 5 shows the light output characteristics of a PhC GaN-based blue LED compared with that of a non-PhC LED. The output of the PhC LED was about 1.5 times higher than that of the non-PhC LED, which indicates that the enhancement factor is 1.5 in the PhC LED. The inserted photo in Fig. 5 shows the top view of the emitting PhC LED observed through optical microscopy. The emitted light is uniform, suggesting that the current is injected to the PhC uniformly owing to the transparent electrode.

The obtained results are promising for future solid state lighting applications, but still the enhancement factor is lower than the theoretical value in Fig. 3. One possible explanation for it is the RIE-induced processing damage [5] in the p-GaN cladding or InGaN active layer which is located between the PhC columns. Provided that the RIE-etched area (about 50% of the active area) is not damaged, the enhancement factor of the light extraction could be reached to about 3, which is very close to the theoretical prediction. Therefore our experimental result will support the light extraction enhancement design using the extended-pitch surface PhC. In this structure, we speculate that resonance effect inside PhC columns could enhance light extraction for the extended-pitch surface PhC. Further investigation on the physics for the enhancement is necessary to make the reason clear.

4. Conclusions

We have demonstrated GaN-based blue LEDs with 2D extended-pitch surface PhC to enhance the light extraction efficiency. The detailed theoretical calculation using FDTD method reveals that the PhC enhances the extraction

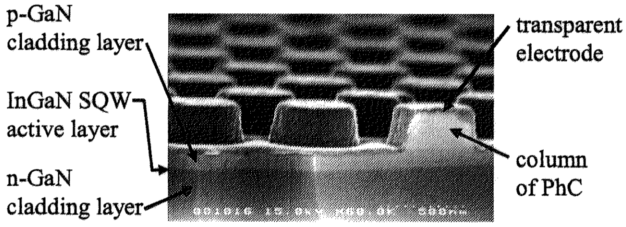

Fig. 4 Cross-sectional SEM image of the 2D surface PhC in GaN-based blue LED.

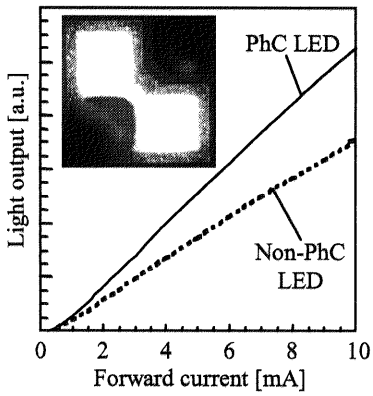

Fig. 5 Light output characteristics of PhC and non-PhC LEDs. Inset is the top view of the emitting PhC LED.

efficiency by 3.6 times higher than that of LED without PhC. While such enhancement has been believed to appear in the range of emission wavelength, our calculation indicates that the enhancement can be obtained even at larger pitch than the wavelength. Blue LEDs with extended-pitch PhC are fabricated and 1.5-fold increase in the light output is observed. Note that the transparent electrode over the PhC enables uniform light emission from the whole area of PhC. The demonstrated device with the high extraction efficiency and uniform emission is applicable for future highly efficient and high power solid-state lighting.

Acknowledgements

The authors thank Mr. N. Ikedo for the growth of nitride semiconductors, Mr. H. Nakayama, Dr. Y. Fujimoto, Mr. T. Matsuno and Dr. M. Kito for help in the PhC LED fabrication, and Prof. Y. Miyamoto (Tokyo Inst. Tech.) in Nanotechnology Support Project by MEXT for technical advice on EB lithography.

References

[1] D. A. Steigerwald, J. C. Bhat, D. Collins, R. M. Fletcher, M. O. Holcomb, M. J. Ludowise, P. S. Martin, and S. L. Rudaz, IEEE Sel. Top. Quantum Electron. **8**, 310 (2002).

[2] A. A. Erchak, D. J. Ripin, S. FaN, P. Rakich, J. D. Joannopoulos, E. P. Ippen, G. S. Petrich and L. A. Kolodziejski, Appl. Phys. Lett. **78**, 563 (2001).

[3] H. Ichikawa and T. Baba, Integrated Photon. Res. Conf., IFF3, 2002.

[4] G. Yu, G. Wang, H. Ishikawa, M. Umeno, T. Soga, T. Egawa, J. Watanabe and T. Jimbo, Appl. Phys. Lett. **70**, 3209 (1997).

[5] S. J. Pearton, R. J. Shul, and F. Ren, MRS Interet J. Nitride Semicond. Res., **5**, 11 (2000).