Theoretical analysis of polarization characteristics of InGaN/GaN LEDs with photonic crystals

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***Abstract*— We investigated theoretically the polarization characteristics of GaN-based green (525 nm) light-emitting diodes (LEDs) with photonic crystals (PCs) using a three-dimensional finite difference time domain method. The light extraction efficiency depends strongly on the photonic bandgap (PBG) position relative to a frequency (a/λ) and the depth of air hole for transverse electric (TE) and transverse magnetic (TM) polarizations. The maximum extraction efficiency was achieved when the frequency of a/λ was matched within PBG region, leading to about 29% (22%) higher than the conventional LED without photonic crystals for TE (TM) polarization. It is found that the polarization of light can be controlled by the a/λ in PC structure.**

***Keywords*— Light-emitting diodes, photonic crystals, photonic bandgap, finite difference time domain (FDTD), polarizations**

I. Introduction

As the technology in light-emitting diodes (LEDs) has developed, it has possible for the device to be used for various applications such as lighting, optical communications, full-colour displays, and exterior automotive lights. The LED has many advantages of long lifetime, energy saving and environment friendly, thus a next generation light source. However, the improvement of external light efficiency of LED still remains main challenge. The external quantum efficiency is mainly limited by total internal reflection (TIR) due to the significant difference in the refractive index between the semiconductor and air. Especially, the light efficiency of InGaN based green LEDs is lower than that of red and blue LEDs. Some efforts have been attempted to overcome the poor light extraction of LED [1,2]. On the other hand, the ability to better control the polarization of the light in LEDs is important for some applications.

Recently, photonic crystals (PCs) have attracted much attention in LEDs due to the enhanced light extraction. The periodic PCs can generate a photonic bandgap (PBG) and the propagation of light is disallowed in the PBG. The light generated in the PBG cannot be confined, so that the periodic PCs are employed to minimize the TIR. The PBG can also control light propagation in a desired way. Several groups have studied 2D PC structures on LED surface to improve experimentally light extraction efficiency [3-5]. However, theoretical studies were carried out not much in details. In this presentation, we report the optimization and analysis of polarization and light extraction characteristics for the InGaN/GaN green LED with PCs using 3D finite difference time domain (FDTD) method.

II. Results and Discussions

The PC structures were designed and analysed using a commercial software of RSoft based on the plane-wave expansion method using a conjugate-gradient minimization [6]. The PC structure with periodic 11×7 square lattice air hole patterns was formed in the *p*-layer as shown in the schematic diagram in Fig. 1 (a). We assumed that PC structure was surrounded by a perfectly matched layer. Fig. 1 (b) and (c) shows the band diagram of the optimized green InGaN/GaN LEDs with a circle square lattice PC structure of r/a=0.31 and r/a= 0.34 and a depth of 105 nm (including indium tin oxide (ITO) ~ 5 nm) for transverse electric (TE) mode and transverse magnetic (TM) modes, respectively. The energy bands are distributed below the light line and the PBG can be observed in this region. Three PC structures were studied in the photonic band diagram in order to investigate the light extraction on the PC structure from green LEDs.

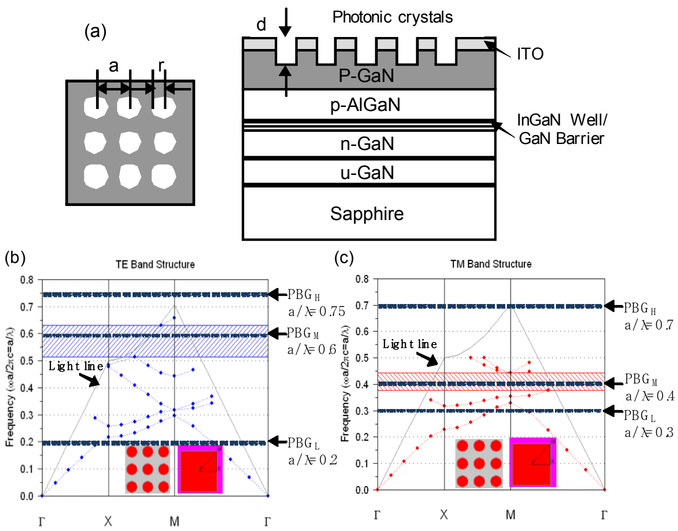

Fig. 1 (a) Schematic diagram of green InGaN/GaN LED PC structure with a circle square lattice hole pattern. (b) Band diagram of the optimized green InGaN/GaN LED at r/a of 0.31 and a depth of 105 nm for TE mode. (c) Band diagram of the optimized green InGaN/GaN LEDs at r/a of 0.34 and a depth of 105 nm for TM mode.

As shown in Fig. 1(b) and (c), one PC structure is located in the PBG (PBG_M), another PC structure is located in the any higher frequency rather than PBG (PBG_H). And then the other PC structure is located in the any lower frequency rather than PBG (PBG_L).

Fig. 2 shows the relative extraction efficiency of the optimized green InGaN/GaN PC LEDs with PBG_M, PBG_H, PBG_L and without PC patterning for (a) TE and (b) TM modes. The extraction efficiency of the peak point in green PC LED was calculated by 3D FDTD in the position of frequency with the PBG_M. As shown in Fig. 2(a), the maximum light extraction with the PBG_M frequency was about 29% higher than that without PC patterning for TE mode. Fig. 2(b) shows the maximum light extraction for TM mode with the PBG_M frequency was about 22% higher than that without PC patterning. The relative light extraction with the PBG_H, PBG_L frequency was also improved slightly compared to the device without PC patterning. Consequently, the relative extraction efficiency at the PBG_M is maximum value due to the effect of the PBG. The relatively low extraction efficiency in green PC LED with PBG_H and PBG_L is shown in Fig. 2. For PBG_H and PBG_L, the improvement in extraction efficiency may be not attributed to the PC effect but the surface texturing effect. The blueshift of maximum value of PC LEDs with PBG_M, PBG_H and PBG_L was observed compared to that without PC patterning. A laser beam through the air holes to the MQW is easy access. Thus, the carrier concentration increases in the MQW due to the band filling effect.

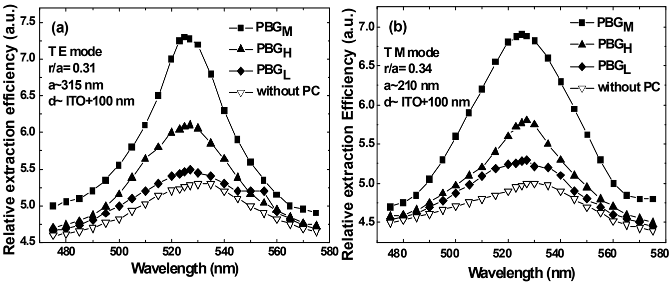

Fig. 2. Relative extraction efficiency of the optimized green InGaN/GaN PC LEDs with PBG_M, PBG_H, PBG_L and without PC patterning for (a) TE and (b) TM modes.

The PC structure is significantly sensitive to the light polarization, the PC LED can perform equally well for both TE and TM polarizations like a polarization beam splitter. The main reason is the occurrence of strong in-plane-light diffraction and out-of-plane scattering at PC interface for air hole. Fig. 3 shows the relative extraction efficiency of the TE and TM polarizations of the optimized green InGaN/GaN PC LEDs at the PBG_M position as a function of frequency (a/ λ) for (a) TE and (b) TM modes, respectively. The use of two coupled light propagations with different coupling frequencies of a/λ for TE and TM polarized lights allows for a light propagation with only desired polarization. When the green InGaN/GaN PC LED was optimized for TE mode, the TE polarized light strongly emitted in PBG region. The dominant TE and TM polarizations based on the PBG occur at different frequencies (a/ λ). Therefore, the polarization of light can be controlled by the a/λ in PC structure. It is possible to design the polarization independent LEDs with PC structure.

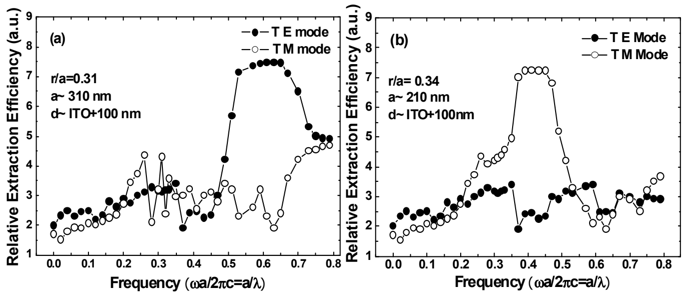

Fig. 2 Relative extraction efficiency of the TE and TM polarizations of the optimized green InGaN/GaN PC LEDs at the PBG_M position as a function of frequency (a/ λ) for (a) TE and (b) TM modes, respectively.

III. Conclusions

We have optimized theoretically the radius of air hole and depth of air holes using the circle square lattice air hole patterns for green PC LEDs. The effect of PBG relative to different frequency and polarization was investigated using a 3D FDTD. For the optimized green PC LED with relative different frequencies of a/λ for TE and TM modes, the maximum light extraction efficiency is obtained with matched the PBG region. The maximum extraction efficiency was obtained for the frequencies of a/λ matched within PBG region, leading to the improvement by ~ 29% and 22% compared to the conventional LED without photonic crystals for TE and TM polarizations, respectively. The polarization of light can be controlled by the a/λ in PC structure.

Acknowledgment

This work was supported by the IT R&D program of MKE/IITA [2007-F-045-02, Development of the projection input/output optical platform for realistic portable devices].

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