Enhanced Cathode-Luminescence in a $In_xGa_{1-x}N$/ $In_yGa_{1-y}N$ Green Light Emitting Diode Structure Using Two-Dimensional Photonic Crystals

Eui Sub Choi* and Jae Jin Lee†

Abstract – We report on the enhancement of cathode-luminescence in an $In_xGa_{1-x}N/In_yGa_{1-y}N$ green light emitting diode structure using two-dimensional photonic crystals. The square lattice arrays of photonic crystals with diameter/periodicity of 200/500 nm were fabricated by electron beam lithography. Inductively coupled plasma dry etching was used to etch and define photonic crystals. Three samples with different etch depths, i.e., 170, 95, and 65 nm, were constructed. Field emission scanning electron microscope analysis shows that air holes of photonic crystal structure with inverted-cone shapes were fabricated after dry etching. Cathode-luminescence measurement indicated that up to 30-fold enhancement of cathode-luminescence intensity has been achieved.

Keywords: Light Emitting Diode, Photonic Crystal

1. Introduction

LEDs inherit important advantages including lifetimes measured in tens of thousands of hours, ruggedness, environmental friendliness (no mercury), compact size, low operating voltages, and cool operation. The blue and green light emitting diodes (LEDs) with high efficiency are currently in great demand for various applications such as back light units for the flat panel display, signage, and general lighting. Especially, white LEDs are indispensable in order for LEDs to get into the general lighting market. To fabricate high power white LEDs, a combination of RGB LEDs are the preferred choice due to superior color reproducibility and color purity. However, most of the light is lost in GaN semiconductor materials. One of its loss mechanisms is due to that fact that the external quantum efficiency of blue and green LEDs are much lower than that of the internal quantum efficiency due to the total internal reflection at the interface of GaN material and outer space. Roughly $1/(4n^2)$, where n is the index of refraction, of the light emitted from the active layer radiates through the top and bottom of the LED [1]. Improving the external efficiency of LEDs is challenging work, especially in the case of the Ⅲ-nitride material system for blue and green LEDs. Various efforts such as truncated-inverted-pyramid (TIP) chip geometry, photonic crystal (PC), transparent substrate, and laser lift-off techniques [2-7] have been made to improve the efficiency of the LED. Recently, many researches have been focused on improving quantum efficiency using PCs in blue LEDs, however, only a few studies concerning the green LEDs have been carried out.

In this paper we report on the cathode-luminescence (CL) study of the PC green LED. PC structures were fabricated by electron beam lithography and the inductively coupled plasma (ICP) dry etching process. Compared to the as-grown sample without PC structures, up to 30-fold enhancement of CL intensity was obtained from samples having a PC structure.

2. Sample Fabrication

The green LED wafer has been grown by low pressure metal organic chemical vapor deposition (LP-MOCVD) on sapphire substrates. Trimethylgallium (TMGa), trimethylindium (TMIn), trimethylaluminum (TMAl), and ammonia (NH_3) were used for Ga, In, Al, and N sources, respectively. Bicyclopentadienyl magnesium (CP_2Mg) and disilane (Si_2H_6) were utilized for p-type and n-type dopants, respectively. The wafer was composed of a GaN-based double heterostructure with a total thickness of 5.232 μm, which included, from the bottom, an undoped GaN buffer layer of 3 μm, Si-doped n-GaN layer of 2 μm, 6 $In_{0.25}Ga_{0.75}N/In_{0.015}Ga_{0.985}N$ Multiple Quamtum Wells (MQWs), Mg-doped p-AlGaN layer of 0.03 μm, and Mg-doped p-GaN layer of 0.1 μm. Optical characterization was done by photoluminescence (PL) (RPM 2000, Accent) using λ=266 nm laser on an as-grown green LED structure,

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crystal quality was examined by high resolution x-ray diffractometer (HRXRD) (D8 DISCOVER, Bruker), and non contact sheet resistant measurement (LEI 1500, Lehighton) was also carried out. The green LED structure was coated with 200-nm-thick electron beam resist. Square lattice two-dimensional PC patterns with circular air holes were created by electron beam lithography (JBX 9300FS, JEOL). Diameter/periodicity of 200/500 nm PC patterns were then etched using an inductively coupled plasma (ICP) dry etcher (MULTIPLEX INDUCTIVELY COUPLED PLASMA (ICP) DRY ETCHING, STS). Three samples were fabricated with the same PC configuration but with different etch depths. FE-SEM (S4200, Hitachi) and CL (MONO CL3, GATAN) studies were performed to analyze the etching and CL intensity profile at room temperature.

3. Result and discussion

From the cross section FE-SEM analysis, it was found that etch depths of the three samples were 175 (sample A), 95 (sample B), and 63 nm (sample C). Three samples were fabricated sequentially. Unlike the original pattern, i.e., cylindrical air holes, on electron beam resist, most of the actually etched hole has an inverted-cone shape and a little has a partially truncated-inverted-cone shape. AFM line profiles of the studied three samples are given in Fig. 1.

One possibility of this etch profile is the positive e-beam resist used during PC pattern definition. Areas of the positive resist that are exposed to electrons become more soluble in the developer solution, thus inducing resist swelling which can distort the PC pattern. It was also found that this inverted-cone shape is related to the electron beam resist thickness, if etched under the same etching condition.

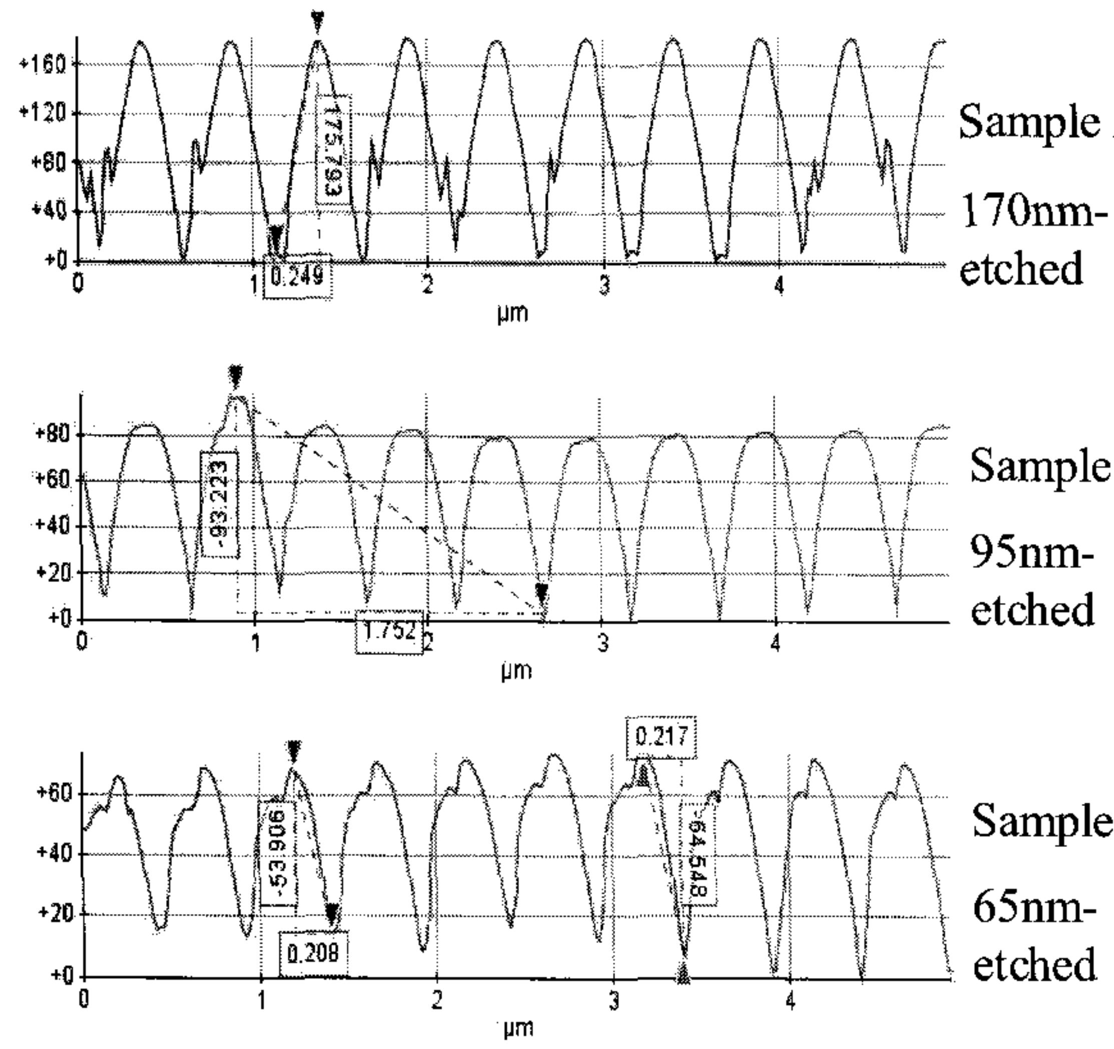

Fig. 1. AFM line profiles of samples with different etching depths: Inverted-cone-shaped holes have been created.

CL analysis was carried out on the fabricated three samples. For sample A, almost no light was emitted from the PC patterned region compared to the unpatterned region. The green light emission (λ ~ 535 nm) was so weak that the CL intensity from the PC patterned region was comparable to the light emission from GaN layer (λ ~ 370 nm) (data not shown). Considering our wafer structure, we etched the PC pattern through into the active layer, or quantum wells. One possible reason for this behavior is that the surface-to-volume ratio in the active layers has increased and thus surface recombination has also been increased in the active layer. To minimize surface recombination in the active layer, the active light generating region should be physically separated from the PC region [8]. The etch depth of sample B was tuned to about 95 nm so the air holes that compose the PC patterns could be separated from the quantum wells. The CL spectra comparison result indicated that about 16-fold light enhancement was achieved. We could confirm that inverted-cone shaped holes have been etched from Fig. 1. We could conclude from sample A and sample B that the shallower the etched hole depth, the greater the number of photons can be extracted from the sample. So we tuned the etch depth of sample C to be about 65 nm. The observed CL image of sample C is shown in the left half of Fig. 2(a).

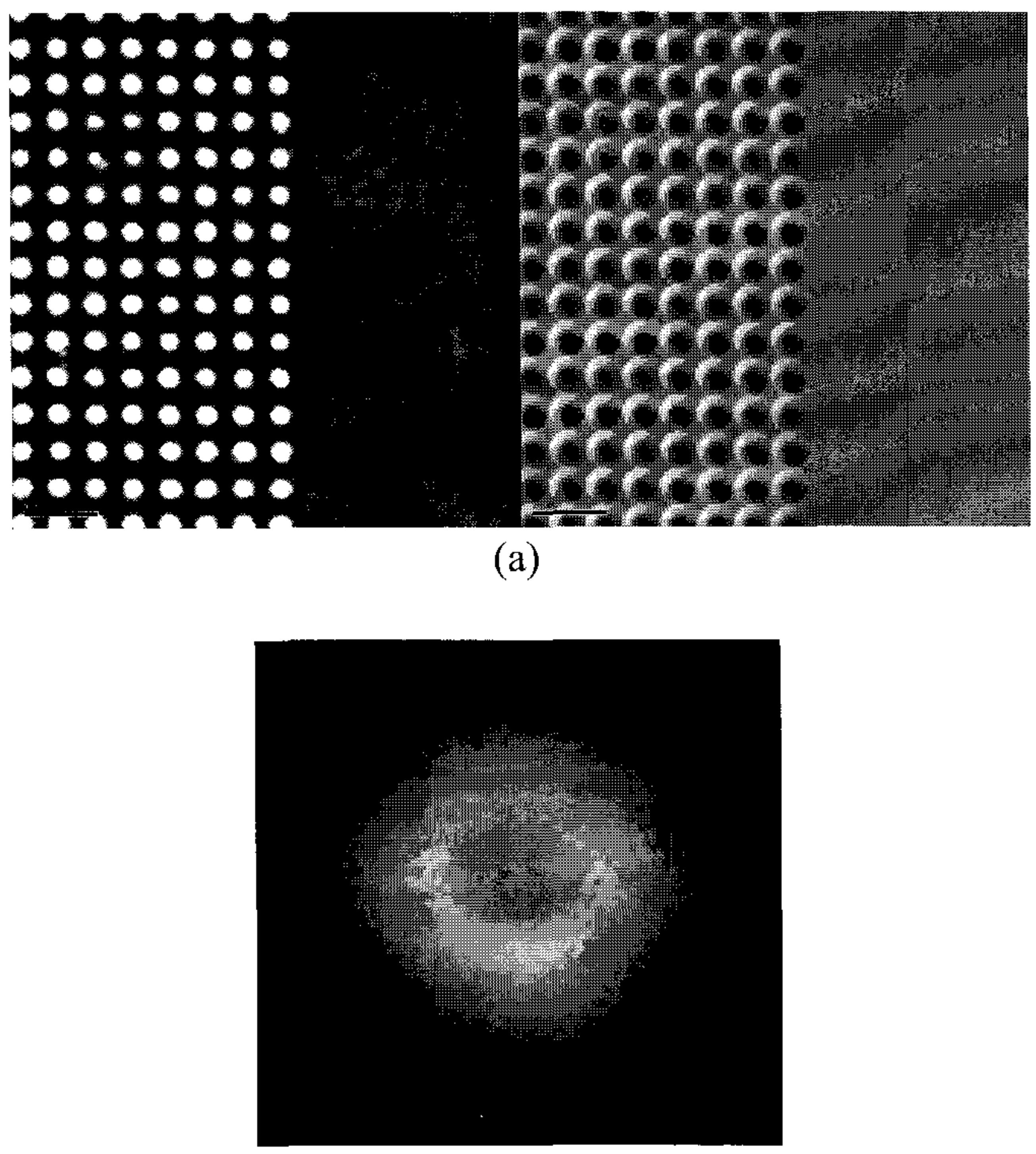

Fig. 2. FE-SEM and CL images of sample C: (a) FE-SEM image (right) and CL image (left) and (b) Enlarged CL image of the single hole shows that most of the light emission takes places from the inclined-inner-surface of the inverted cone shaped hole.

CL measurement, which records luminescence after creating electron-hole pairs by electron bombardment with the above bandgap energy on the specimen, provides higher spatial resolution than PL. Thus, we could pinpoint the light emitting spot of our samples; most of the green light (λ ~ 535 nm) was emitted from the inclined-inner-surface of each inverted-cone shaped hole and very little from the center of each hole. From sample C, about 30-fold enhancement of CL intensity was obtained, which suggests that the lattice dimensions of PCs might be correctly tuned. Photonic band gap can be created by this PC structure where photons with frequencies within the gap are not allowed to propagate laterally, thus resulting in an enhancement in the extraction of light in the vertical direction of the LED. And the refractive index of the PC can be reduced to the mean value between the dielectric material and the air, so that the pathway of light propagation could be smoothly established to enhance the light extraction onto the surface [9]. The measured CL spectra comparison of sample C, sample B, and as-grown region are shown in Fig. 3.

It is shown not only in Fig. 2 that the light emitting spot from unpatterned regions is not uniform, but from other samples as well. This is mainly due to the large atomic size of In, which is needed in fabricating InGaN quantum wells that emit green light. However, we could observe that the light emitted from PC patterned regions is more uniform than the light from unpatterned regions of the studied three samples. This is due to the redirect effect of light from a laterally guided mode to a vertically radiated mode in LEDs with PC.

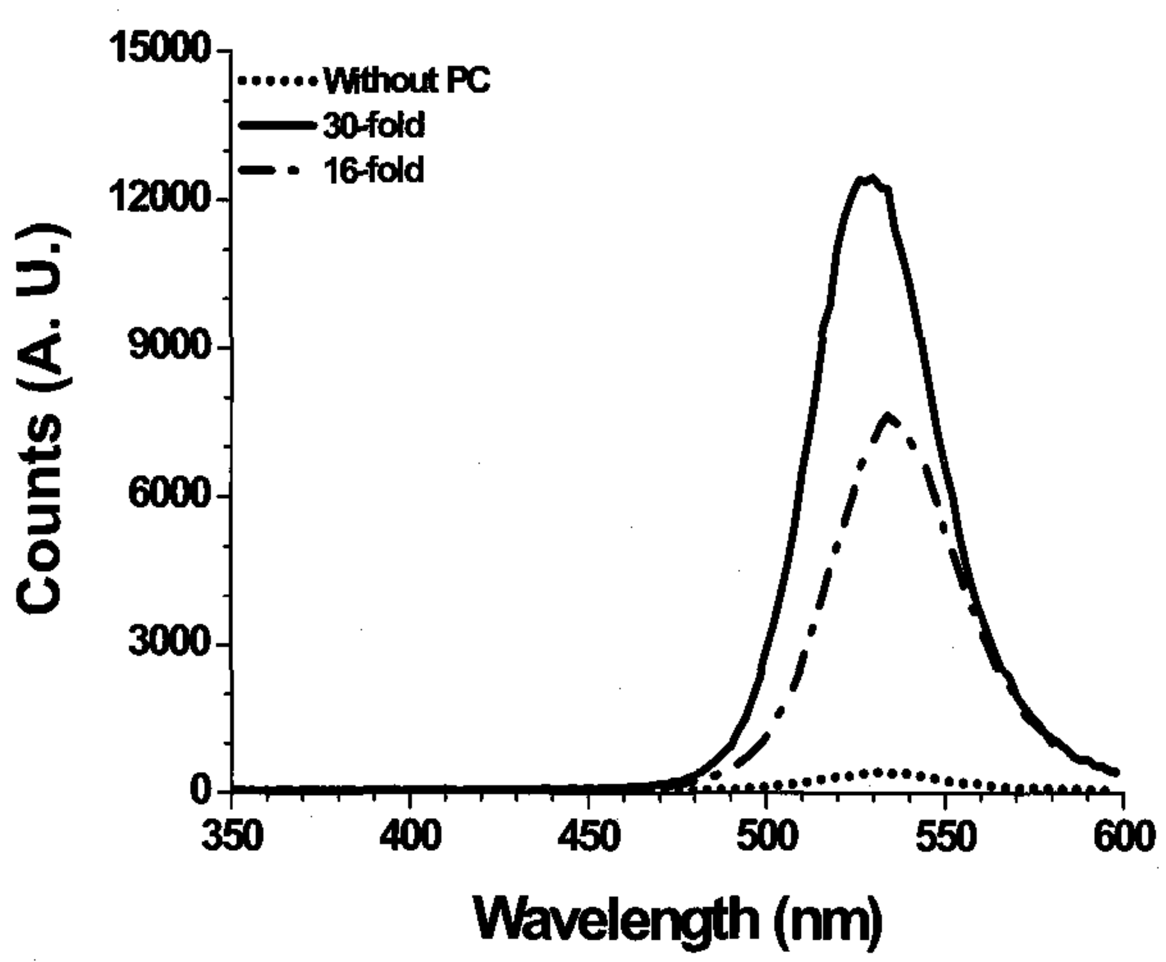

Fig. 3. CL intensity comparison between PC patterned region (sample C and sample B) and as-grown region. Up to 17 and 30-fold enhancement was achieved.

4. Conclusion

Two-dimensional photonic crystal structures were fabricated on Mg-doped p-GaN layer of green LEDs that have active regions of $In_xGa_{1-x}N/In_yGa_{1-y}N$ multiple quantum wells. Compared to the as-grown regions, about 30-fold enhancement in CL intensity from the PC patterned regions was achieved. Spatial-resolution of the luminescence around single holes which compose photonic crystal structure was obtained by CL measurements. This study provides the possibility of fabricating high power PC green LEDs that can be adapted for various applications.

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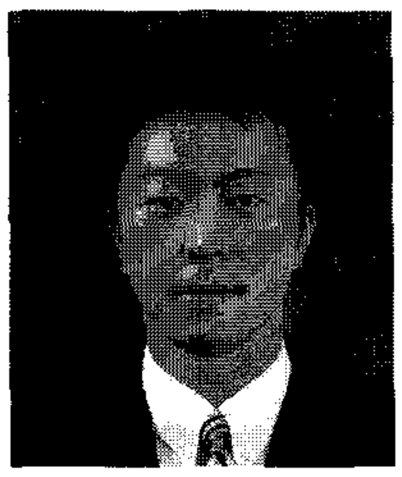

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