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Light Output Enhancement of GaN-based Photonic Crystal LED with AlN/GaN DBR

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1. Introduction

Direct wide-bandgap gallium nitride (GaN) and other III-nitride-based semiconductors have attracted much attention for potential applications such as blue, green, and ultraviolet (UV) light-emitting diodes (LEDs). Besides, it can be also applied in flashlights and area lighting to replace the traditional lighting sources. However, due to the applications, the efficiency of the LED such as internal quantum efficiency or external quantum efficiency still need to be improved to replace the conventional fluorescent light source. Besides, it is difficult to control the light emitting direction or enhance specific wavelength by photonic crystal (PC) structures on light emitting devices which are the most important subjects for future applications. According to the simulation of plane wave expansion (PWE) [1-3], it can be utilized PC structures to inhibit emission of guided modes or redirect trapped light into radiated modes. In this research, we fabricated and analyzed the two different PC patterns on the GaN-based LEDs with AlN/GaN bottom distributed Bragg reflector (DBR) of the enhancement of light extraction efficiency.

2. Experiment and Discussion

The GaN-based photonic crystal resonance cavity LED (PC-RCLED) structures were grown by vertical-type metal-organic chemical vapor deposition system. The full epitaxial structure consists of a sapphire substrate, a 35-pairs GaN/AlN bottom DBR, a 560 nm-thick n-type GaN cladding layer, a ten-pair $In_{0.2}Ga_{0.8}N$ multi-quantum well (MQW), and a 200 nm thick p-type GaN cladding layer. The growth details were reported elsewhere [4]. Then, the as-grown sample was deposited with a Si_3N_4 layer of 200 nm followed by a Polymethylmethacrylate (PMMA) layer of 150 nm. Hexagonal PC patterns were fabricated on the PMMA layer by E-beam lithography and the sample was etched down about 150nm deep to the p-type GaN layer by dry etching. The Si_3N_4 and PMMA layers were removed by acetone and buffered oxides etch (BOE) solutions. Finally, the mesa was defined by standard lithograph technology and etched by inductively coupled plasma reactive ion etching (ICP-RIE) with a depth approximately 400nm and a square area of a width about 100μm.

In the research, we promoted two different PC patterns fabricated on the resonance cavity LED (RCLED). The designed structures are shown in Fig 1(a) and 1(b). In Fig 1(a), light would be induced or extracted by the center PC structures labeled as PC-RCLED I. The structure in Fig 1(b) was designed to increase lateral light confinement and to concentrate light on the center region labeled as PC-RCLED II. Both of the two structures are all including the bottom DBR mirror composed of AlN and GaN. The DBR structure has center stop band at 433nm and a width approximately 30nm. Therefore, it can be acted as a mirror to reflect light from the bottom area and played the role as a lower refracted index layer to control the guided modes. Fig 1(c) shows the photonic band diagram of GaN PC-RCLED for hexagonal PC structures with a depth of 150nm and a ratio (r/a) of 0.35. The PC structures also have a frequency of a/λ=0.47.

Figure 2 shows the SEM images of the designed devices with the PC structures. Fig 2(a) is the PC-RCLED II which was fabricated PC structures on the center area showing a square white shape with a width about 80μm. The outside black area is the n-type GaN layer and the gray area without PC structures is the p-type GaN layer. The similar structure is shown in PC-RCLED II, but the PC structures were fabricated on the outside white region with a width about 80μm in Fig 2(b). Fig 2(c) is the SEM image of the PC structures which lattice was 204nm and air hole diameter is 145nm. The etching depth is about 150nm. Both of the two structures have the same etching depth, lattice, and air hole diameter. The result was well agreed with the simulation result in Fig 1(c).

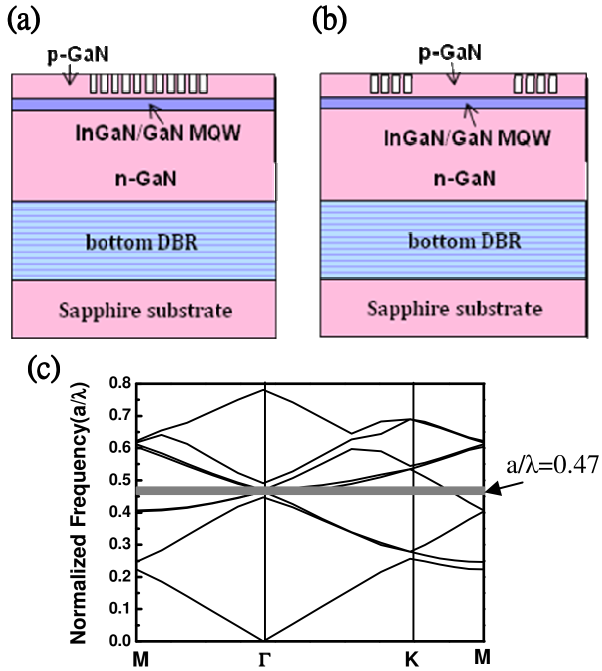

Fig. 1 shows the structure of GaN-based photonic crystal LED with AlN/GaN DBR mirror: (a) photonic crystal fabricated on the center square area (PC-RCLED I); (b) photonic crystal fabricated on the outside of the inner square area (PC-RCLED II); (c) band diagram with r/a=0.35

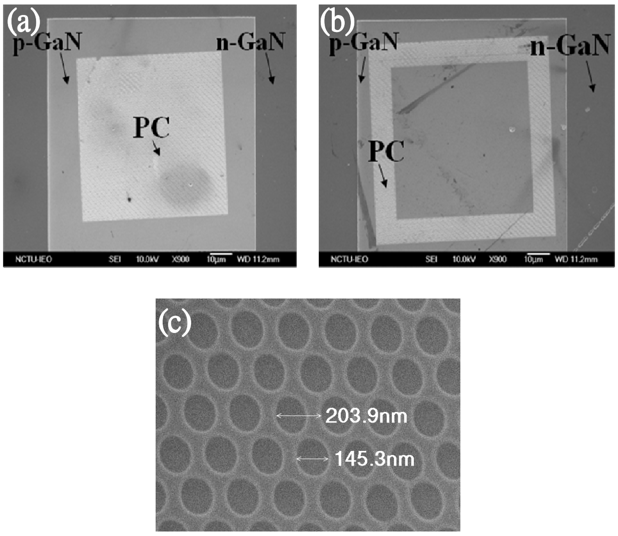

Fig. 2 plane-view SEM images: (a) PC-RCLED I of PC structures on the center white region; (b) PC-RCLED II of PC structures on the outside white region; (c) PC characteristics: a=204m, diameter=145nm.

To realize the enhanced characteristic of the PC-RCLEDs, we used the He-Cd continuous-wave laser at 325nm which has maximal power about 30mW to excite Photoluminescence (PL) spectrum from the two PC-RCLEDs in figure 3. The solid (red), dot (blue), and dash (green) lines represent commercial RCLED without PC structures, PC-RCLED II, and PC-RCLED I. All of them has a dominate peak approximately 430nm.

From the PL spectrum, the enhanced factor of the two PC-RCLEDs compared with commercial RCLED could be calculated as 1.63 and 3.69 of the integrated PL intensity. Even thought compare with two PC-RCLED devices, the PRCLED I also had enhanced factor nearly 2.27-fold. This result also shows that the PL intensity of PC-RCLED I about 2 times than PC-RCLED II. From the enhanced factors, it can be proved that PC-RCLED II can confine the lateral light by the PC structures and enhance 1.63-fold than commercial RCLED, but light cannot extract from the center region without PC structures. On the other hand, PC-RCLED I can successfully extract light from the center region with PC structures and enhance approximately 3.69-fold than commercial RCLED or 2.27-fold than PC-RCLED II. It means that PC-RCLED I can redirect light into radiated modes and emit from the PC structures. However, the enhancement of both two PCLEDs may be attributed by the surface texturing effect rather than the PC structures because the two structures have no photon band gap for blue emission [3], but there are still some probabilities to enhance at the band-edge modes such as band-edge emission [6]. In summary, these results indicated that using the PC-RCLED 1 structure for blue light is very important to high efficiency blue LED.

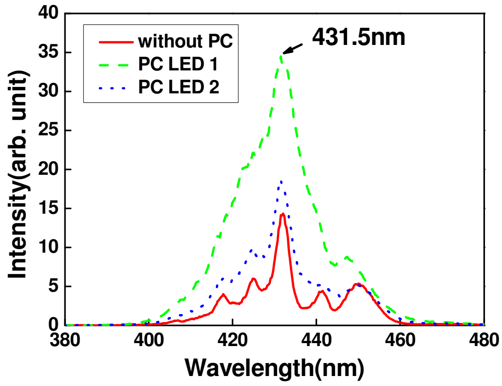

Fig. 3 PL spectrums: Solid (red) line, dot (blue) line, and dash (green) line represent commercial RCLED without PC structure, PC-RCLED I, and PC-RCLED II. The enhancement factors of two structures compared with commercial RCLED are 1.63 and 3.69.

3. Conclusions

We successfully fabricated the GaN-based PC-RCLEDs with two different PC patterns on p-GaN surface labeled as PC-RCLED I and PC-RCLED II. The PC-RCLED I has 3.69 enhancement factor compared with commercial RCLED. Besides, PC-RCLED I has also approximately two-fold enhancement than PC-RCLED II due to the center PC structures. The enhanced efficiency of PC-RCLED I can be attributed by the PC structures and the surface texturing effect of p-type GaN layer. Due to the larger enhancement of the devices, we believe the PCLED with bottom DBR mirror which has the potential to be the electrical injection light emitting devices for the future applications.

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