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Investigation of GaN-based light-emitting diodes using double photonic crystal patterns

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ABSTRACT

GaN-based LEDs with photonic crystal (PhC) patterns on an n- and a p-GaN layer by nano-imprint lithography (NIL) are fabricated and investigated. At a driving current of 20 mA on Transistor Outline (TO)-can package, the light output power of the GaN-based LED with PhC patterns on an n- and a p-GaN layer is enhanced by a factor of 1.30, and the wall-plug efficiency is increased by 24%. In addition, the higher output power of the LED with PhC patterns on the n- and p-GaN layer is due to better crystal quality on n-GaN and higher scattering effect on p-GaN surface using PhC pattern structure.

1. Introduction

Recent developments of high performance GaN-based light-emitting diodes (LEDs) are dominated by both material techniques, such as metal organic chemical vapor deposition (MOCVD) epitaxial growth, and device fabrication techniques. Thus, high brightness LEDs have been used in various applications, including backlight of large and small size flat-panel displays, traffic signal light and illumination lighting by white light LEDs [1,2]. In order to get higher brightness of LEDs, extensive research has been conducted. In epitaxial growth method, a number of attempts have been made to reduce the dislocation effect using such strategies as the insertion of a micro-scale epitaxial lateral overgrowth (ELOG) layer over a SiO_2 or Si_xN_y pattern on the GaN thin film [3,4], as well as the use of micro-scale patterned sapphire substrate (PSS) [5,6]. Moreover, high-quality GaN-based LEDs have been demonstrated on a micro-scale PSS by wet or dry etching [5,6], where the micro-scale patterns serve as a template for the ELOG of GaN and scattering centers for the guided light in GaN-based LEDs structure. Both the epitaxial crystal quality and the light extraction efficiency were improved by utilizing a micro-scale PSS. Recently, MOCVD growth of GaN-based LEDs on PSSs with micro-scale and nano-scale pyramidal patterns has been reported and compared [7,8]. The LEDs grown on the nano-scale PSS showed more enhancements in EQE than those grown on micro-scale PSS. Furthermore, photonic crystal (PhC) is a promising technique due to the great improvement of light extraction efficiency [9–11]. However, PhC patterns were often performed by electron beam lithography, which takes a lot of time to accomplish the pattern on a device. Another high throughput and economic technique, nano-imprint lithography (NIL), was recommended to manufacture light-emitting devices with PhC or photonic quasi-crystal (PQC) structures [12]. In this letter, we report the nano-imprinting and epitaxial overgrowth techniques to fabricate GaN-based LEDs using PhC nano-patterns on an n- and a p-GaN layer for 2-in. mass production. As a result, the intensity-current (*L-I*) measurements demonstrate that the light output power of a LED with PhC patterns on an n- and a p-GaN layer was higher than that of a conventional LED at 20 mA with standard device processing. In addition, the reliability test of normalized output power of LED with PhC patterns on an n- and a p-GaN layer only decreased by 5%. This results offer promising potential technique to enhance the light output power of commercial light-emitting devices using the technique of nano-imprint lithography.

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2. Experiments

All GaN-based LED samples are grown by MOCVD with a rotating-disk reactor (Veeco) on a *c*-axis sapphire (0 0 0 1) substrate at a growth pressure of 200 mbar. The LED structure with a 100 nm-thick SiO_2 PhC rod pattern on an n-GaN layer structure was fabricated with a sapphire substrate consists of a 50 nm-thick GaN nucleation layer grown at 500 °C, a 2 μm un-doped GaN buffer, a 1.0 μm-thick Si-doped GaN buffer layer grown at 1050 °C. The detail of the nano-imprint process is described in Ref. [12]. Then, the LED structures with a SiO_2 PhC rod pattern overgrowth on an n-GaN layer were designed and re-grown on a 2 in. wafer. The re-grown LED structures consists of a 1.2 μm-thick n-type Si-doped GaN layer grown at 1050 °C, an unintentionally doped InGaN/GaN multiple quantum well (MQW) active region grown at 770 °C, a 50 nm-thick Mg-doped p-AlGaN electron blocking layer grown at 1050 °C, and a 220 nm-thick Mg-doped p-GaN contact layer grown at 1050 °C. The MQW active region consists of five periods of 3 nm/7 nm-thick $In_{0.18}Ga_{0.82}N$/GaN quantum well layers and barrier layers. Then, the LED with a SiO_2 PhC rod pattern on an n-GaN layer were performed PhC hole pattern on the p-GaN surface by NIL process. Fig. 1 shows the schematic structure of the LED with double PhC patterns. The conventional LED structure consists of a 50 nm-thick GaN nucleation layer grown at 500 °C, a 2 μm un-doped GaN buffer, a 2 μm-thick Si-doped GaN buffer layer grown at 1050 °C, and afterward the same epitaxial structure as LEDs with PhC patterns on an n- and a p-GaN layer.

All LED samples, including the LED with double PhC patterns and the conventional LED, are fabricated using the standard LED processes with a mesa area of 265 μm × 265 μm (LED chip area of 300 μm × 300 μm). Fig. 2 shows a scanning electron microscope (SEM) top-view image of a PhC pattern on the p-GaN surface based on triangular lattice. Additionally, in this study, the PhC nano-rod and hole diameters (*D*) and lattice constant (*a*) we used were approximately 370 nm and 550 nm, respectively. The ratio D/a is fixed to 0.67. The height of SiO_2 PhC pattern is 200 nm and the PhC hole depth on the p-GaN is 100 nm.

3. Results and discussion

Fig. 3a plots the typical current–voltage (*I–V*) characteristics of a conventional LED, an LED with a PhC pattern on the n-GaN layer, and an LED with PhC patterns on the n- and p-GaN layer. It is found that the measured forward voltages under injection current 20 mA at room temperature for a conventional LED, an LED with a PhC pattern on the n-GaN layer, and an LED with PhC patterns on the n- and p-GaN layer are 3.11, 3.08, and 3.14 V, respectively. Therefore, there is no influence on this type of devices by incorporating PhC structures into the LED. The light output is detected by calibrating an integrating sphere with an Si photodiode on package device, so that light emitted in all directions from the LED can be collected. The intensity-current (*L-I*) characteristics of the LEDs with and without PhC structures are shown in Fig. 3b. At an injection current of 20 mA and peak wavelength of 460 nm for Transistor Outline (TO)-can package, the light output powers of a conventional LED, an LED with a PhC pattern on the n-GaN layer, and an LED with PhC patterns on the n- and p-GaN layer on TO-can are given as 11.6, 13.5, and 15.1 mW, respectively. Hence, compared to the conventional LED, the enhancement percentages of the LED with a PhC pattern on the n-GaN layer, and the LED with PhC patterns on the n- and p-GaN layer are 16%, and 30%, respectively. The higher enhancement on the LED with a PhC pattern on the n-GaN layer may be owing to the scattering light from PhC layer onto the top direction and higher epitaxial crystal quality [13,14] to increase more light output power. In addition, the corresponding wall-plug efficiencies (WPE) of a conventional LED, an LED with a PhC pattern on the n-GaN layer, and an LED with PhC patterns on the n- and p-GaN layer are 19%, 22%, and 24%, respectively, which addresses a substantial improvement by the PhC patterns on an n- and a p-GaN layer as well at a driving current of 20 mA.

Fig. 4 shows that temperature dependent photoluminescence (PL) used to determine the internal quantum efficiency (IQE) of

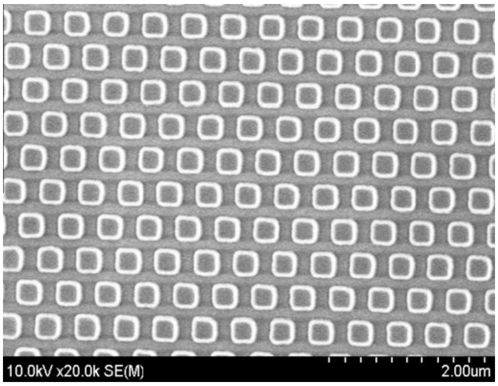

Fig. 2. Top-view SEM image of a PhC pattern on a p-GaN layer.

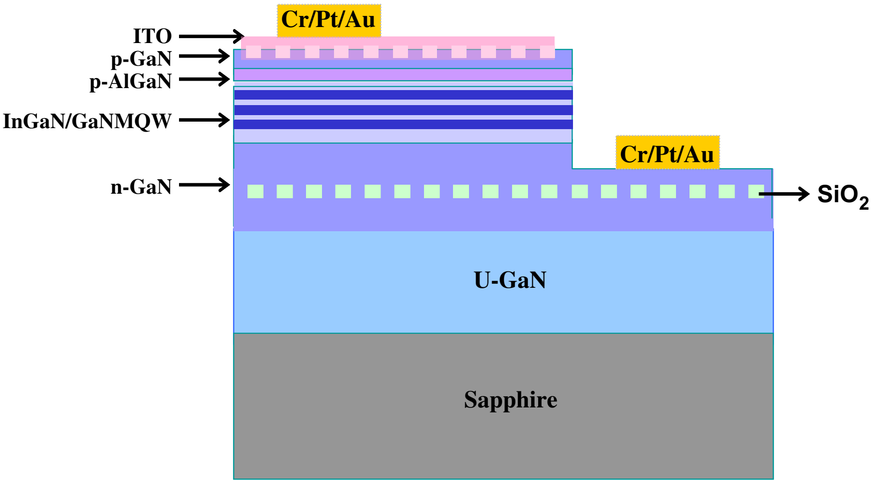

Fig. 1. Schematic diagram of GaN-based LEDs with a PhC pattern on an n- and p-GaN layer.

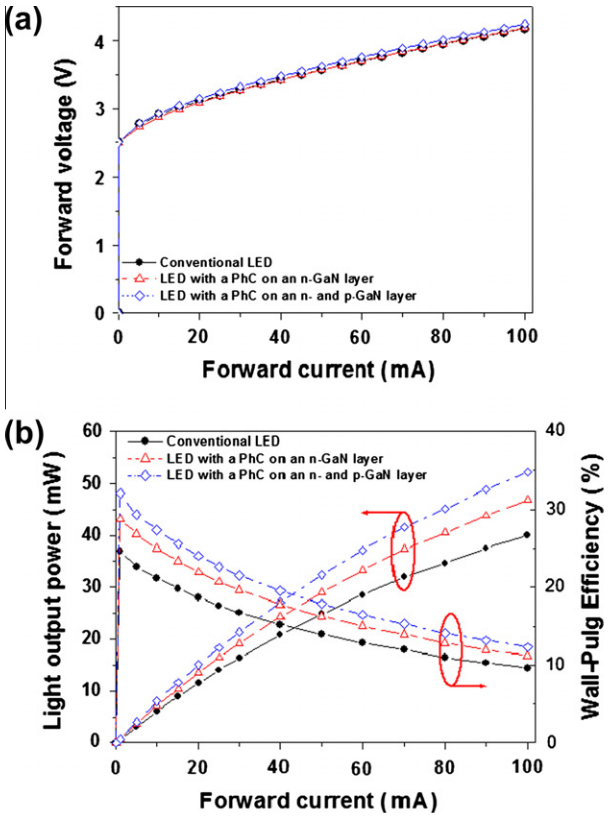

Fig. 3. (a) The current–voltage (*I*–*V*) characteristics, and (b) the light output power–current (*L*–*I*) and wall-plug efficiency (WPE) characteristics of a conventional LED, an LED with a PhC pattern on the n-GaN layer, and an LED with PhC patterns on the n- and p-GaN layer.

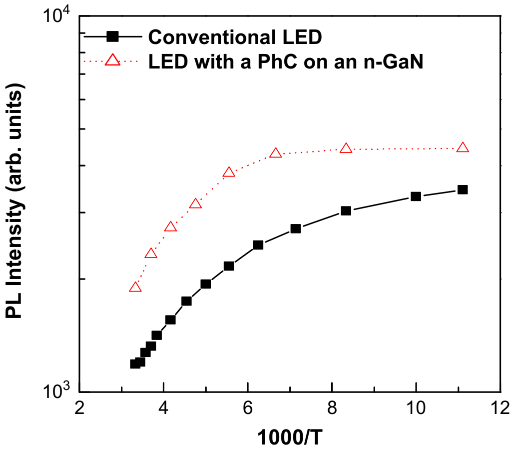

Fig. 4. Arrhenius plots of integrated PL intensities for GaN-based LED with/without a PhC structure on an n-GaN layer.

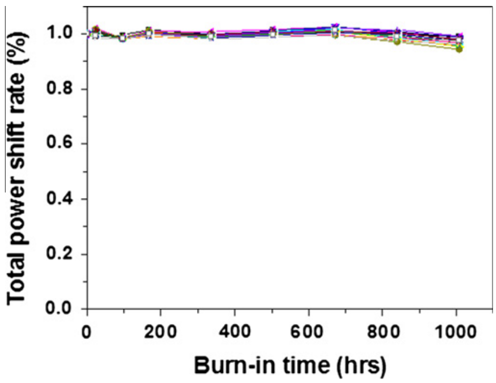

Fig. 5. The lifetime test results of the LEDs with the PhC structures on an n- and a p-GaN layer under the driving condition of 50 mA/55 °C.

the InGaN/GaN MQW structures. The IQE of LED samples with and without a PhC pattern on an n-GaN layer calculated from $\mathrm{IQE} = \mathrm{PL}_{300\mathrm{K}}/\mathrm{PL}_{90\mathrm{K}}$, where $\mathrm{PL}_{300\mathrm{K}}$ is the PL intensity at room temperature and $\mathrm{PL}_{90\mathrm{K}}$ is the PL intensity at the 90 K which is the lowest temperature in our system. Assuming that the internal quantum efficiency equals unity at 90 K, we obtain an internal quantum efficiency of LED with PhC pattern on an n-GaN layer to be 42%, which is higher than that of the conventional LED (IQE = 34%) at room temperature [15]. The integrated intensity of the PL peak at 460 nm of MQW with a PhC pattern on an n-GaN layer was increased by 55%, compared to that MQW without a PhC pattern on an n-GaN layer at room temperature. The increase in IQE of MQW with a PhC pattern on an n-GaN layer can be attributed to reduction of defects, for example, screw and edge-type threading dislocation in the n-GaN and MQW layer. Based on the observed increases of 55% for EQE and 24% for IQE, the increase in light extraction efficiency was estimated to be 25% for LED with a PhC pattern on an n-GaN layer. The increase of 25% is attributed to the enhancement of light extraction from LED by the PhC patterned inside an n-GaN layer which scatters light onto the top surface [14].

During lifetime test, twenty chips of GaN-based LED were encapsulated and driven by 50 mA injection current at 55 °C of ambient temperature. As shown in Fig. 5, it was found that forward voltage and normalized output power of LED with PhC structures on an n- and a p-GaN layer only decreased by 5% after continuity driving of 1000 h. The result indicates that using the PhC structures on an n- and a p-GaN performed by NIL technique is a reliable and promising method for device production.

4. Conclusion

GaN-based LEDs with PhC patterns on an n- and a p-GaN layer by nano-imprint lithography are fabricated and investigated. At a driving current of 20 mA on TO-can package, the light output power of a LED with a PhC pattern on n-GaN, a LED with PhC patterns on the n- and p-GaN layer are enhanced by 16% and 30%, respectively, compared with the conventional LED. After lifetime test of 1000 h (55 °C/50 mA), normalized output power of the LED with PhC patterns on an n- and a p-GaN layer only decreased by 5%.

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