Efficiency Improvement of GaN-Based LEDs with SiO₂ Nanorod Array and Nano-Scale Patterned Sapphire Substrate

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1.Introduction

The high brightness Gallium-nitride (GaN)-based light-emitting diodes (LEDs) have made possible their use in traffic signals, backlight in liquid crystal displays, and solid state lighting [1-2]. However, there is still a great need to improve the internal and external quantum efficiency (EOE) in order to increase the light output performance, and thus reduce the total cost of LED modules. The further improvement in the EQE of a GaN-based LED on a patterned sapphire substrate (PSS) is required. In addition, high qualities GaN-based LEDs are affixed onto a micro-scale PSS [3-4]. The micro-scale patterns serve as a template for the epitaxial lateral overgrowth (ELOG) of GaN and the scattering centers for the guided light. Both the epitaxial crystal quality and the light extraction efficiency are improved by utilizing a micro-scale PSS. 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 ELOG layer of SiO_2 or a Si_xN_y pattern on the GaN thin film [5-7]. However, they are typically fabricated by photolithography or self-assembly. To fabricate them more easily, one candidate method is nano-imprint lithography (NIL).

In this paper, we utilize a nano-imprinting technique to fabricate a nano-scale patterned sapphire substrate (NPSS) and a SiO₂ photonic quasi-crystal (PQC) on an n-GaN layer to be used for mass production. As a result, the light output power of LED with a NPSS and a SiO₂ PQC pattern on an n-GaN layer is significantly greater than that of a conventional LED.



Fig. 1. Schematic diagrams of LED with NHPSS and SiO_2 PQC structure.

Figure 1 shows the schematic diagram of GaN-based LED with a NPSS and a SiO_2 PQC structure on an n-GaN layer. In our study, three types are fabricated in order to investigate the influence the NPSS and a SiO_2 PQC on an n-GaN layer has on the LED light output power and beam

profile performance. In Fig. 1, the LED structure consists of a Cr/Pt/Au p-electrode, a 240nm-thick ITO transparent layer, a 50 nm-thick GaN nucleation layer grown at 500 °C, a 3 µm-thick un-doped GaN buffer layer grown at 1050 °C, a 2 µm-thick Si-doped GaN layer grown at 1050 °C, an unintentionally doped InGaN/GaN multiple quantum well (MOW) active region grown at 770 °C, a 50 nm-thick Mg-doped p-AlGaN electron blocking layer grown at 1050 °C, and a 120 nm-thick Mg-doped p-GaN contact layer grown at 1050 °C. The MQW active region consists of five periods of 3nm/20nm-thick In_{0.18}Ga_{0.82}N/GaN quantum well layers and barrier layers and a Cr/Pt/Au n-electrode on NPSS structure. Further, the LED epitaxial structure has inset a 100nm-thick SiO₂ PQC pattern on an n-GaN layer by NIL.

The transmission electron microscopy (TEM) images were employed to investigate the crystalline quality of GaN layers epitaxial grown on a flat sapphire substrate and a NPSS. As shown in Fig. 4(a)-(b), Clear, in Fig. 4(b) the threading dislocation density (TDD) of GaN was the crystalline quality of GaN epi-layer on a NPSS and a SiO₂ PQC structure was drastically improved from that grown on a NPSS compared with flat sapphire substrate (as shown in Fig. 4(a)). We found that a number of stacking faults often occurred above the nano-lens patterns, where visible threading dislocations (TDs) were rarely observed in the vicinities. It is believed that the presence of stacking faults could block the propagation of TDs [7]. Moreover, the TDs of the GaN layer on a NPSS and a SiO₂ PQC structure mainly originated from exposed sapphire surface, which could be bent due to the lateral growth of GaN.



Fig. 2 The TEM images of GaN/sapphire interface for the GaN epi-layer grown on a (a) flat sapphire substrate and (b) a NPSS and a SiO₂ PQC structure on an n-GaN layer.

Fig. 3 show a top-view image of an atomic force microscopy (AFM) with 12-fold PQC pattern based on a square-triangular lattice. The lattice constant (*a*) of NPSS

structure and SiO₂ PQC is 750 nm and the diameter *d* (455 nm) is fixed to ratio d/a=0.61. In addition, the etching depth of NPSS is approximately 182 nm.





Fig. 3 shows the top-view AFM image of an n-GaN surface with a SiO_2 PQC.

Fig. 4 shows the characteristics of a typical current-voltage (I-V) and intensity-current (L-I)characteristics of conventional LED, LED with a SiO₂ PQC, LED with a NPSS, and LED with a NPSS and a SiO₂ PQC structure. It is found that the measured forward voltages under injection current 20 mA at room temperature for conventional LED, LED with a SiO₂ POC, LED with a NPSS, and LED with a NPSS and a SiO₂ PQC structure are 3.16, 3.15, 3.15 and 3.23 V, respectively. At an injection current of 20 mA and peak wavelength of 460 nm for TO-can package, the light output powers of conventional LED, LED with a SiO₂ PQC, LED with a NPSS, and LED with a NPSS and a SiO₂ POC structure on TO-can are 12.8, 15.4, 17.3, and 18.9 mW, respectively. Hence, the enhancement percentages of LED with a SiO₂ PQC, LED with a PSS, and LED with a NPSS and a SiO₂ PQC structure are 20 %, 35 %, and 48 %, respectively,





Fig. 4(a) Current-voltage (*I-V*) characteristics of conventional LED, LED with a PSS, and LED with a NPSS and a SiO₂ PQC structure.
(b) Intensity-current (*L-I*) characteristics of conventional LED, LED with a NPSS, and LED with a NPSS and a SiO₂ PQC structure.

3.Conclusion

GaN-based LEDs with a NPSS and a SiO₂ PQC structure are fabricated and demonstrated by NIL system. At a driving current of 20 mA on TO-can package, the light output power of LEDs with a NPSS and a SiO₂ PQC structure is enhanced by a factor of 1.48. The higher output power of the LED with a NPSS and a SiO₂ PQC structure is due to higher reflectance on NPSS and higher epitaxial quality on n-GaN layer using a SiO₂ 12-fold PQC pattern. This work offers promising potential to

increase output powers of commercial light emitting devices.

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Appendix

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