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Extraction Enhancement and Collimation From a Thin-Film InGaN/GaN Photonic Crystal Light-Emitting Diodes

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1. Introduction

Recently, high-brightness Gallium nitride (GaN) based light-emitting diodes (LEDs) have become a strong candidate for applications such as flat-panel displays and many other display technologies [1]. To address the next generation of applications of light-emitting diodes (LEDs) on projectors and automobile headlight, further improvements of optical power and light extraction efficiency are required. Improved light extraction from GaN LEDs using photonic crystals (PhCs) has attracted much attention recently [2-3]. PhC structure fabricated on LEDs can offer efficient extraction the guided light into the escaping cone to circumvent the deleterious effects due to total internal reflection (TIR) which traps the majority of the emitted light in LED chips [2]. In addition, PhC can control the collimating and polarization properties of these escaped lights to offer new possibilities to enhance the performance and to simplify the design of the optical system using LED light sources [3]. The thin-film LED structure is a recent development and shall be a good candidate for enhancing the light extraction efficiency of GaN-based LEDs [4]. In this paper, we combine the thin-film GaN LEDs with PhC assisted light extraction and collimation. LEDs with thin thickness are characterized by angle-resolved electroluminescence (EL). As a result, the light output efficiency of thin-film GaN LED with PhCs was significantly higher than that of a thin-film GaN LED without PhCs (thin-film GaN standard LED). Additionally, the angular distribution radiation pattern measurements demonstrate that a thin-film GaN LED with PhCs has a narrow far-field angle than that of a thin-film GaN standard LED.

2. Experiment

The schematic diagram for the structure of thin-film GaN LED with PhC is shown in Fig. 1(a) and (b). The prepared GaN-based green LED wafer consists of a 30-nm-thick GaN nucleation layer, a 4 μm thick un-doped GaN buffer layer, a 3 μm thick Si-doped n-GaN layer, a 100 nm InGaN/GaN multiple quantum well (MQW) active region, a 50-nm-thick Mg-doped p-AlGaN electron blocking layer, a 0.4 μm thick Mg-doped p-GaN contact layer. Firstly, the fabrication process of the thin-film GaN LEDs on Si began with the deposition of transparent contact Ni/Au layer (3/5 nm), silver mirror (200 nm), and Cr/Pt/Au (50/50/2400 nm) bonding metal layer on p-GaN. The LED samples were then bonded onto a Cr/Pt/Au (50/50/2400 nm) coated p-type conducting Si substrate by commercial SUSS SB6e wafer bonder. Secondly, the wafer bonded samples were taken to undergo the LLO (Laser Lift-Off) process to remove the sapphire substrate. In this process, the beam size of KrF laser was larger than our desired size (1 mm × 1 mm) of LEDs. Therefore, the laser irradiation on the interface of sapphire and GaN was uniform. Thirdly, after the sapphire substrate was removed by the excimer laser, the sapphire-removed samples were dipped into HCl solution to remove the residual Ga on the un-GaN. Fourthly, the resulting structure is then thinned down by chemical-mechanical polishing to obtain the $4\lambda/n$ (T~865 nm) GaN cavity thickness, where n=2.5 is the GaN effective refractive index. Fifthly, the associated mesas were etched further down to the bonding metal interface using SiO_2 etching mask by inductively coupled plasma (ICP) dry etching to single chip isolation and then used a buffer oxidation etchant (BOE) to remove the residual SiO_2 layer. Sixthly, in order to fabricate PhC on the n-GaN surface, we first deposited a 200-nm-thick layer of SiN to serve as a hard mask on the n-GaN by plasma-enhanced chemical vapour deposition (PECVD). The PhC with a square lattice of circular holes was then defined by holography lithography on the hard mask. Holes were then etched into the top n-GaN surface using ICP dry etching to a depth t=70 nm. The lattice constant and holes diameter of PhC were to be 300 and 200 nm, respectively. The top view of the scanning electron microscopy (SEM) image of the PhC is shown in Fig. 1(c). Finally, a patterned Cr/Pt/Au (20/30/1400 nm) electrode were deposited on n-GaN as the n-type contact layer and Cr/Au (50/1400 nm) metal was deposited on Si substrate backside.

We performed EL measurement by injecting a continuous current into the thin-film GaN LEDs at room temperature. Figure 2 compares the angle-resolved spectra of a thin-film GaN PhC LED and a thin-film GaN standard LED, for which light was collected in TE polarization along the ΓX direction of the square lattice [5]. The broad variation in emission was observed with thin-film fringes typical of emission from an InGaN QW in a thin GaN structure. The additional sharp emission lines observed for the thin-film GaN PhC LED resulted from the coupling of guided modes to PhC modes above the light line of air. Numerous guided modes were supported in the GaN layer due to its thickness, and their diffraction angle varies with wavelength. The PhC extraction of guided modes as a result of the presence of the PhC was clearly observed as shown in Fig. 2(a).

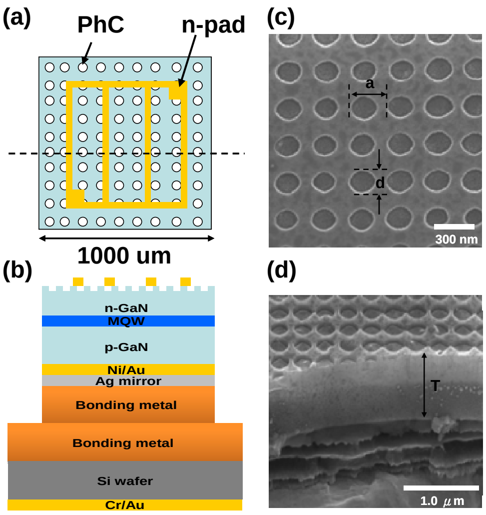

Fig. 1 (a) Sketch of the top view devices. (b) Schematic diagram of thin-film GaN PhC LED structures. (c) Top-view SEM image of PhC with the lattice constant a =300 nm and the diameter of air holes d =200 nm. (d) The GaN cavity thickness is about T=865 nm.

We also measured the angular distribution radiation patterns of the light output from a thin-film GaN PhC LEDs and a thin-film GaN standard LEDs at a driving current of 350 mA, as shown in Fig. 3. At 50% intensity, it can be seen that the thin-film GaN PhC LEDs show higher extraction efficiency with a collimation angle about 104.9° compared to the thin-film GaN standard LEDs with an angle about 125.4°. The detailed radiation patterns also show a stronger enhancement around the vertical direction. Additionally, the intensity-current characteristics the thin-film GaN PhC LEDs shows output power enhancement by 177% at a driving current of 350 mA, when compared to the thin-film GaN standard LEDs.

3. Conclusions

In summary, a GaN-based thin-film PhC LEDs were fabricated and studied. Angle-resolved measurement revealed a strong PhC effect in the thin-film GaN LEDs, and could lead to much stronger extraction enhancement and collimation. This could lead to promising LEDs, offering high efficiency and brightness together with unusual directionality properties.

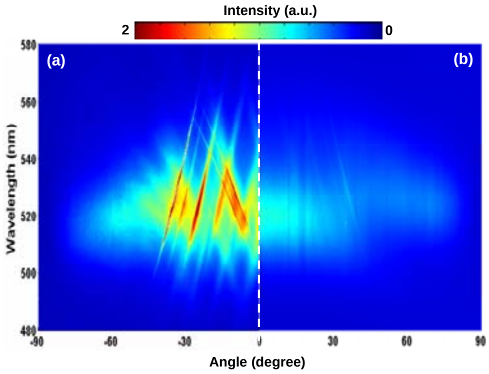

Fig. 2 Angle-resolved EL measurements of (a) a thin-film GaN PhC LED and (b) a thin-film GaN standard LED.

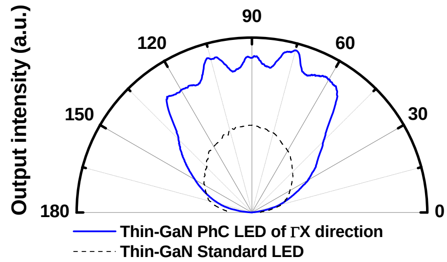

Fig. 3 Radiation patterns of a thin-film GaN PhC LED and thin-film GaN standard LED. The device without PhC has a near Lambertian radiation pattern while that of thin-film GaN PhC LEDs is heavily modified.

Acknowledgements

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