Enhanced Output Power of GaN-Based LEDs With Nano-Patterned Sapphire Substrates

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***Abstract*—GaN-based light-emitting diodes (LEDs) with an emitting wavelength of 450 nm were grown on nano-patterned sapphire substrates (NPSS) fabricated by nanosphere lithography. The crystalline quality of the epitaxial film could be improved by using the NPSS technique. The output power of LED grown on NPSS was 1.3 and 1.11 times higher than those of LEDs grown on conventional and patterned sapphire substrates at the injection current of 20 mA, respectively. The enhancement in output power could be contributed to the efficiently scattering by NPSS. But some voids formed at the GaN/NPSS interface cause a thermal dissipation problem of NPSS LED operated at high injection current.**

***Index Terms*—GaN, light-emitting diode (LED), nano-patterned sapphire substrate (NPSS), nanosphere lithography.**

I. Introduction

THE high output power GaN-based light-emitting diodes (LEDs) are extremely in demand for the various applications, such as traffic signals, full-color displays, backlight in liquid crystal displays, and solid-state lighting [1]. However, owing to the large lattice mismatch and thermal expansion between the epitaxial GaN film and sapphire substrate, high threading dislocation densities degrade the internal quantum efficiency of the LED. And the light extraction efficiency of the LED is limited by the critical angle loss which is due to the large difference in refractive index between the GaN film and the surrounding air. In order to enhance the output power of the LED, it is needed to improve the light extraction efficiency as well as the internal quantum efficiency [2].

Using the epitaxial lateral overgrowth technique, threading dislocations can be significantly eliminated [3]–[5], but the two-step growth procedure is time-consuming. In recent years, the single growth technique by introducing patterned sapphire substrates (PSS) has been extensively researched [6]–[13]. The simplified growth method can reduce the threading dislocations and increase the light extraction [9]. The geometrical shape of the sapphire patterns can effectively scatter or redirect the guided-light inside an LED chip to find escape cones, such as the hemispherical shape made by the dry etching technique [10] and the inclined R-plane facet of sapphire made by the wet etching technique [11]. But the geometrical size of the sapphire patterns is focused on the micrometer magnitude. For the same area of sapphire substrate, the reduced geometrical size of sapphire patterns can increase the number of patterns, and then increase the opportunity of light scattering [12], [13]. In this letter, we have reported GaN-based LEDs grown on the nano-patterned sapphire substrates (NPSS), which are fabricated by using nanosphere lithography [14]–[16]. The nanoscale pattern of the sapphire substrate facilitates superior light extraction efficiency. The details of the structural, electrical, and optical properties of LEDs grown on NPSS were discussed.

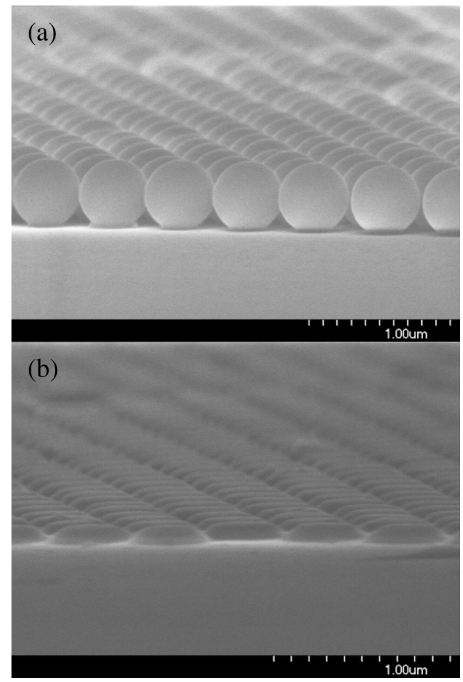

Fig. 1. SEM images of (a) a hexagonal close-packed monolayer of polystyrene spheres with 500-nm diameter on top of the sapphire substrate and (b) NPSS with 450-nm diameter, 50-nm spacing, and 150-nm depth.

II. Experiment

NPSS were fabricated by combining nanosphere lithography and the dry etching technique. The polystyrene spheres with a diameter of 500 nm were spun uniformly onto the surface of the sapphire substrates as shown in Fig. 1(a). The sapphire substrate was then subjected to the inductively coupled-plasma (ICP) etcher using Cl_2–BCl_3 mixture. Finally, the polystyrene spheres were removed to complete the NPSS structure, as shown in Fig. 1(b). The diameter, spacing, and depth of NPSS were

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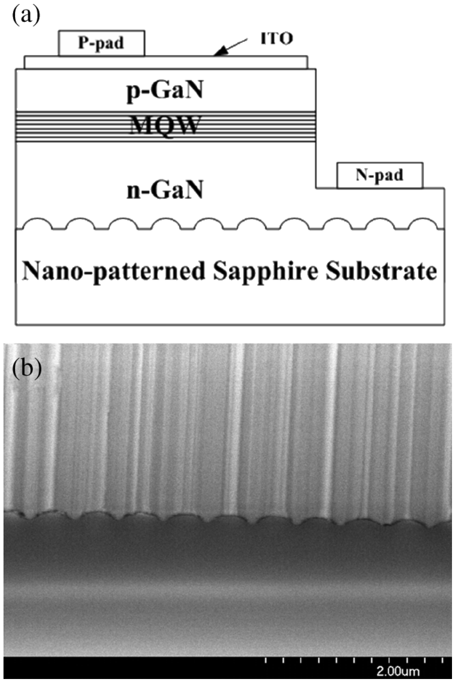

Fig. 2. (a) Schematic diagram of the LED structure grown on NPSS and (b) SEM cross-sectional image of the GaN/NPSS interface of LED grown on NPSS.

450, 50, and 150 nm, respectively. For comparison, conventional sapphire substrates (CSS) and PSS, with 3-μm diameter, 3-μm spacing, and 1.5-μm depth, were also prepared. Then, three kinds of 2-in (0001) sapphire substrates including NPSS, PSS, and CSS were loaded into a metal–organic chemical vapor deposition system. The blue LED structure comprised a 30-nm-thick GaN nucleation layer, a 2-μm-thick undoped GaN layer, a 2-μm-thick Si-doped n-GaN layer, an InGaN–GaN multiple-quantum wells (MQWs) active region of 450-nm emitting wavelength, and a 300-nm-thick Mg-doped p-GaN layer.

For the standard LED process, ICP dry etching was used to etch through the p-GaN layer and MQW active region, until the n-GaN layer was exposed. Indium tin oxide (ITO) was deposited onto the p-GaN layer by e-beam evaporator, and then thermally annealed in oxygen ambient for 10 min. The ITO layer was used as the transparent contact layer. The Cr–Pt–Au metals were deposited as the p- and n-electrodes by e-beam evaporator, respectively. The dimension of the LED dies used here was 350 μm $\times$ 425 μm. The schematic diagram of the final LED structure is shown in Fig. 2(a) and the cross-sectional scanning electron microscopy (SEM) image of the GaN/NPSS interface of LED grown on NPSS is shown in Fig. 2(b). The crystalline quality of epitaxial films was measured by Bede D1 high-resolution X-ray diffraction (HRXRD). The current–voltage (I–V) characteristics of the LEDs were measured by Keithley 2400. The light output power of the LEDs with TO can package was measured by using an integrated sphere with a calibrated power meter.

III. Results and Discussion

Table I shows the structural properties of the GaN films grown on NPSS and CSS. The full-width at half-maximum (FWHM) of the ω-scan rocking curve for the (002) and (102) planes infer the density of screw and edge dislocations, respectively [17]. The FWHMs of (002) and (102) planes were 330 and 380 arcsec for GaN film grown on NPSS, while they were 410 and 560 arcsec for that grown on CSS. The FWHMs of (002) and (102) planes for GaN film grown on NPSS were smaller than those for GaN film grown on CSS. The etch-pit density (EPD) measurement reveals the threading dislocations propagating to the surface of GaN film, which originates from the GaN/sapphire interface. The EPD of GaN film grown on NPSS was 3.5×10^8 cm^{-2}, which was less than that of GaN film grown on CSS (1.2×10^9 cm^{-2}). From HRXRD and EPD results, it clearly indicates that the crystalline quality of epitaxial GaN film could be effectively improved by using the NPSS technique.

TABLE I
Structural Properties of GaN Films Grown on NPSS and CSS

Sample	(002) FWHM of HRXRD (arcsec)	(102) FWHM of HRXRD (arcsec)	Etch pit density (cm^{-2})
NPSS	330	380	3.5×10^8
CSS	410	560	1.2×10^9

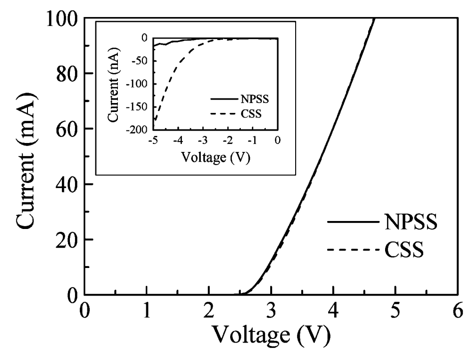

Fig. 3. Forward I–V characteristics of the LEDs grown on NPSS and CSS. The inset is the reverse I–V characteristics of the LEDs grown on NPSS and CSS.

Fig. 3 shows the forward I–V characteristics of the LEDs grown on NPSS and CSS. The forward voltages of the NPSS and CSS LEDs at the forward injection current of 20 mA were 3.13 and 3.15 V, respectively. No significant difference of the I–V curves was found between the two LEDs. The inset of Fig. 3 shows the reverse I–V characteristics of the LEDs grown on NPSS and CSS. The leakage currents of the NPSS and CSS LEDs at the reverse voltage of 5 V were 18 and 192 nA, respectively. The leakage current of the NPSS LED was smaller than that of the CSS LED. It infers threading dislocations of the epitaxial film is eliminated by using the NPSS technique.

Fig. 4 shows the output power of the NPSS, PSS, and CSS LEDs as a function of the injection current. At the injection current of 20 mA, the output power of NPSS, PSS, and CSS LEDs were 10.27, 9.27, and 7.93 mW, respectively. The corresponding external quantum efficiencies were estimated to be 16.39%, 14.97%, and 12.59%. The output power of the NPSS

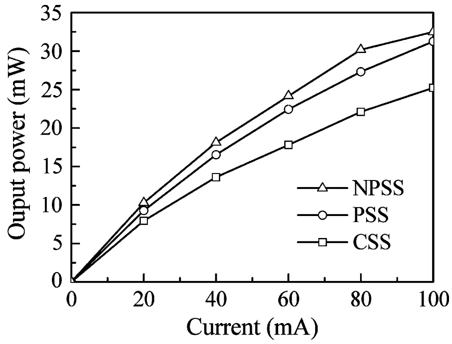

Fig. 4. Output power versus injection current (L–I) curves of the LEDs grown on NPSS, PSS, and CSS.

LED was 1.3 times higher than that of the CSS LED at 20-mA injection current. Moreover, the output power of the NPSS LED was 1.11 times higher than that of the PSS LED at 20-mA injection current. It indicates that the NPSS LED has superior capability for enhancing the light extraction. However, the output power of the NPSS LED saturated at the injection current of 100 mA, while the output powers of the PSS and CSS LEDs still increased linearly with the injection current. Saturation in the light output power of NPSS LED under high injection current was attributed to the blocking voids in the thermal flow path. Some voids were formed at the GaN/NPSS interface when the GaN epilayer grew laterally and coalesced from the top of the NPSS [9]. But no voids were found on PSS and CSS LEDs. Therefore, these voids at the GaN/NPSS interface cause thermal dissipation problem of NPSS LED.

IV. Conclusion

High output power GaN-based LEDs were successfully grown on NPSS fabricated by a combination of nanosphere lithography and the dry etching technique. The measurement results of HRXRD, EPD, and leakage currents infer the crystalline quality of the epitaxial LED film improved by the NPSS technique. The output power was increased by approximately 30% and 11% on the NPSS LED compared with the CSS and PSS ones at the injection current of 20 mA, respectively. The improvement of the external quantum efficiency of NPSS LEDs is attributed not only to the enhancement of the light extraction efficiency via nano-patterns that efficiently scatter the guided light to outside, but also to the reduction of threading dislocations by using the NPSS technique. But some voids formed at the GaN/NPSS interface cause a thermal dissipation problem of the NPSS LED operated at high injection current.

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