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Implementation of light extraction improvements of GaN-based light-emitting diodes with specific textured sidewalls

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Textured-sidewall GaN-based light-emitting diodes (LEDs) with various sidewall angles (15–90°) and convex or concave sidewalls prepared using an inductively-coupled-plasma approach are comprehensively fabricated and studied. The device with 45° sidewalls (Device F) and that with convex sidewalls (Device B) show significant improvements in optical properties. Experiments show that, at an injection current of 350 mA, the light output power, external quantum efficiency, wall-plug efficiency, and luminous flux of Device F (Device B) are greatly improved by 18.3% (18.2%), 18.2% (18.2%), 17.3% (19.8%), and 16.6% (18.4%), respectively, compared to those of a conventional LED with flat sidewalls. In addition, negligible degradation in electrical properties is found. The enhanced optical performance is mainly attributed to increased light extraction in the horizontal direction due to a significant reduction in total internal reflection at the textured sidewalls. Therefore, the reported specific textured-sidewall structures (Devices B and F) are promising for high-power GaN-based LED applications.

1. Introduction

Highly efficient GaN-based light-emitting diodes (LEDs) are widely applied in color displays, traffic lights, and solid-state lighting due to their direct and wide band gap and excellent electrical, optical, and thermal performance [1–6]. However, the external quantum efficiency (EQE) of GaN-based LEDs is too low for high-performance solid-state lighting. GaN LEDs have a very small critical angle (~23.6°) due to the difference in the refractive index between GaN (n = 2.5) and the surrounding air (n = 1), total internal reflection (TIR) results in a significant reduction in light extraction efficiency (LEE) according to Snell's law [7–9]. In order to alleviate this problem, numerous structures, e.g., patterned sapphire substrates [10,11], an anti-reflection layer [12], flip-chip packaging [13], chip-shaping [14], and textured surfaces [15,16], have been proposed for enhancing the LEE of GaN LEDs. LEE can be improved by texturing the top [15] and bottom [16,17] surfaces of LEDs. As compared to LEDs with flat sidewalls, a similar concept by etching sidewalls has also been reported to allow photons to escape from LEDs [18,19]. Lv et al. reported that a wavy sidewall structure exhibited a light output improvement of 11% compared to that of a flat sidewall one [20]. In our previous work, we reported that GaN-based LEDs with 45° and convex sidewalls and nanohemispherical backside reflector could effectively increase light extraction in all directions due to a significant reduction in the TIR [21]. However, there is lack of studies on the light extraction of LEDs with various sidewall angles and convex/concave sidewalls. The present work demonstrates detailed studies on the improved LEEs of GaN-based LEDs with convex or concave sidewalls and various sidewall angles fabricated using standard photolithography and inductively coupled plasma (ICP) dry etching. Significant improvements in light output power (LOP) of 18.2% and 18.3% at an injection current of 350 mA were obtained for LEDs with convex sidewalls and a sidewall angle of 45°, respectively.

2. Experiments

The studied device structure was grown on a c-plane sapphire substrate by a metal organic chemical vapor deposition. The epitaxial structure consisted of a 2-μm-thick undoped GaN layer, a 2-μm-thick Si-doped n-GaN layer ($n = 1 \times 10^{18}$ cm^{-3}), 15-period InGaN/GaN multiple quantum wells (MQWs) as active layers, and a 0.3-μm-thick Mg-doped p-GaN layer ($p = 4 \times 10^{17}$ cm^{-3}). After epitaxial growth and a wafer cleaning process, an ICP dry etching process was utilized to define mesa regions and fabricate sidewall structures. During the mesa fabrication process, a photoresist layer was

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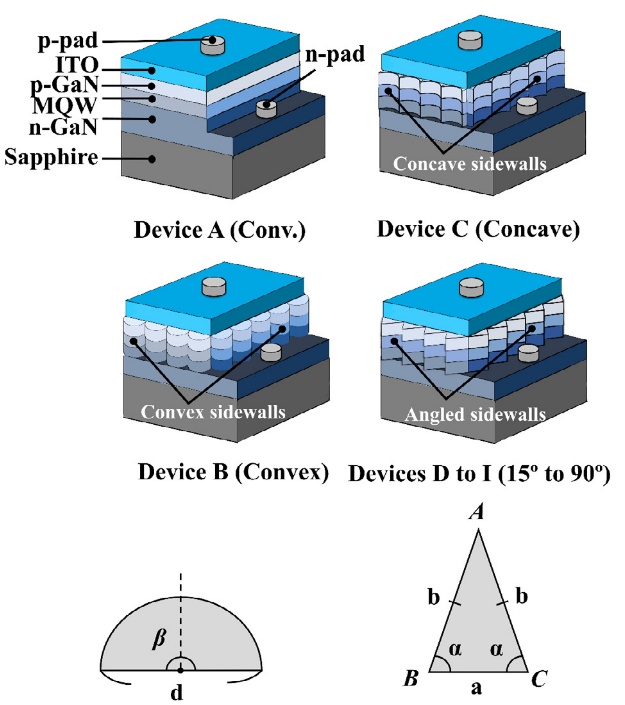
deposited on the top surface of the LED wafer and photolithography was subsequently used to form sidewalls with convex/concave patterns and various angles (15°–90°). The pattern depth was 1.2 μm. The textured sidewalls were then transferred to the LED using Cl_2/Ar plasma etching. A 220-nm-thick ITO current-spreading layer was subsequently deposited on the p-GaN layer via RF sputtering. Cr/Pt/Au (25/50/2000 nm) metal layers were sequentially deposited via thermal evaporation as n- and p-electrode pads. Then, the n-p pads were activated in a nitrogen atmosphere to improve the metal-semiconductor contact characteristics. Devices B and C had convex and concave sidewall patterns, respectively. GaN-based LEDs with sidewall structure base angles of α = 15°, 30°, 45°, 60°, 75°, and 90° were denoted as Devices D, E, F, G, H, and I, respectively. For comparison, a conventional GaN-based LED with flat sidewalls was included in this study (denoted as Device A). A schematic illustration and corresponding geometric designs of Devices A, B, C, D, E, F, F, H, and I are shown in Fig. 1. A diameter of d = 10 μm was used for the wavy patterns of Devices B and C. A side length of a = 10 μm was used for the isosceles-triangle-like patterns of Devices D to I. To limit process deviation, all studied devices were fabricated from the same uniform LED wafer. All samples were diced into individual chips with dimensions of 650 × 750 μm^2. Finally, these chips were attached and bonded to TO-3 submounts for electrical and optical tests by a semiconductor parameter analyzer (HP-4155C) and an integrated sphere.



	Central angle, β (º)	Diameter, d (μm)
Device B	180	10
Device C	180	10

	Base angle, α (º)	Side length, a (μm)
Device D	15	10
Device E	30	10
Device F	45	10
Device G	60	10
Device H	75	10
Device I	90	10

Fig. 1. Schematic cross sections and geometric designs of textured sidewalls of studied devices.

3. Results and discussion

Fig. 2(a)–(c) show schematic diagrams of possible light paths at the surface between the sidewalls and the surrounding air in the horizontal direction. According to Snell's law, the critical angle for escape can be calculated using $\theta_C = \sin^{-1}(n_2/n_1)$, where n_1 is the refractive index of GaN and n_2 is the refractive index of air. It is very important to give photons more opportunities for find escape cones at the critical angle between GaN and air [22]. Textured sidewalls have advantage over flat ones in increasing the number of photon scattering events [22]. As shown in Fig. 2(a), due to the significant influence of TIR, fewer photons could find the escape cone with flat sidewalls. As shown in Fig. 2(b) and (c), more photons, emitted from the MQW active region, travel into the escape cone when textured sidewalls are used. This improves the LEE of high-power GaN-based LEDs [14,20]. Fig. 3(a) shows the top-view scanning electron microscopy (SEM) images of Device A (flat sidewalls). Fig. 3(b)–(i) show the tilt-view SEM images of the etched sidewalls of Devices B to I (convex, concave patterns, and sidewall angles of 15°–90°). The side length of these sidewalls is 10 μm. The images show that the devices have uniform and smooth textured sidewalls.

The current-voltage (*I-V*) characteristics of the studied devices are shown in Fig. 4. The corresponding reverse-biased *I-V* characteristics are shown in inset. The devices have similar *I-V* curves. The forward voltages of the studied devices are all around 2.9 V (4.9 V) at 20 mA (350 mA). Since all studied devices were made from the same uniform GaN-based LED wafer, these results confirm that the formation of textured sidewalls via an ICP dry etching process does not degrade the electrical properties. Under a reverse bias of 5 V, a leakage current of around 15 nA was obtained for all devices. The ICP dry etching process of textured sidewalls did not induce a large reverse leakage current.

Based on the measured *I-V* characteristics, the series resistance (R_S) can be estimated as [23]:

$$I(dV/dI) = IR_s + \eta KT/q \qquad (1)$$

where η and K are the ideality factor and Boltzmann constant, respectively, T is the absolute temperature in degrees Kelvin, and q is the electronic charge. $I(dV/dI)$ and dynamic resistance (R_D) as a function of operating current I are shown in Fig. 5. From the slopes of $I(dV/dI)$-I relations, the R_S values of the studied devices are around 5.5 Ω. In addition, the R_D values, under an injection current of 350 mA, are around 14 Ω for the studied devices. Thus, the fabrication process of the sidewall structures did not degrade the electrical properties of the high-power LEDs. Because the employed textured sidewalls are not located on the current pathway, the electrical properties are preserved.

The LOP versus injection current of the studied LEDs are shown in Fig. 6. Under an injection current of 350 mA, the LOP values of Devices A, B, C, D, E, F, G, H, and I are 139.1, 164.4, 163.2, 151.2, 159.4, 164.5, 156.4, 157.7, and 158.7 mW, respectively. Compared to the conventional GaN LED (Device A), all studied LEDs show enhanced light output characteristics. In particular, the LOP values of Devices B (convex sidewalls) and F (45° sidewalls) exhibit 18.2% and 18.3% improvements, respectively, on account of the substantial TIR reduction. These results are superior to that of the wavy sidewall structure reported by Lv et al. [20]. The relationship between EQE values and injection current is also shown in Fig. 6. At an injection current of 350 mA, the EQE values of Devices A to I are 14.8%, 17.5%, 17.3%, 16.1%, 16.9%, 17.5%, 16.6%, 16.6%, and 16.9%, respectively. Compared to Device A, Devices B and F both exhibit a 18.2% improvement. The LOP and EQE values of Devices B and F are much higher than those of Device A. This significant improvement in LOP is mainly attributed to the use of appropriate