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Output power enhancements of nitride-based light-emitting diodes with inverted pyramid sidewalls structure

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ABSTRACT

This study presents nitride-based light-emitting diodes (LEDs) with inverted pyramid sidewalls by chemical wet etching nitride epitaxial layers and investigates the chemical wet etching mechanism of inverted pyramid sidewalls. It is well known that chemical etching solutions such as KOH, H_2SO_4 and H_3PO_4, to selectively etch the N-face GaN but not the Ga-face GaN. In this study, the N-face GaN was exposed around the chip by laser scribing at the GaN/sapphire interface. These channels provided paths for the chemical etchant to flow and allow the etching solution to further contact with and etch the exposed bottom N-face GaN. Chemical etching of the chip sidewalls formed the inverted hexagonal pyramid shape with $\{10\,-1\,-1\}$ facets. Findings show that inverted pyramid sidewalls enhance 20 mA LED output power by 27% for LEDs, with chemical etching of the chip sidewalls for 4 min, compared to the conventional LED. The larger LED output power is attributed to increased light extraction efficiency by inverted pyramid sidewalls.

1. Introduction

Researchers have recently developed high-performance optical devices, such as light-emitting diodes (LEDs) and laser diodes (LDs), using GaN-based materials grown on sapphire substrates [1,2]. For example, GaN-based blue and green LEDs have already been extensively used in full-color displays and high-efficiency light sources for traffic light lamps. UV emitters may have potential for fluorescence-based chemical sensing, flame detection, and possibly optical storage. These nitride-based LEDs are also potentially useful for solid-state lighting. To realize solid-state lighting, however, one needs to further improve the output efficiency of these LEDs.

Light extraction efficiency of the GaN-based LED is limited mainly by the large difference in refractive index between GaN film and the surrounding air. Snell's law determines the critical angle for photons to escape from the GaN film. This angle is crucially important for light extraction efficiency of LEDs. Since the refractive indices of GaN and air are 2.5 and 1, respectively, external quantum efficiency is limited to only a few percentages for conventional GaN-based LEDs. Several methods improve the output efficiency of nitride-based LEDs, such as textured surface [3–5], a highly transparent p-contact layer [6], proper substrate design [7], and flip-chip packaging [8]. Findings have shown enhancing light output by the light scattering layer (e.g., roughening the p-GaN or n-GaN surface, patterned substrate, etc.). With a light scattering layer, photons generated in the active layer will have multiple opportunities to find the escape cone [3–8]. Scattering from the roughened top surface of the LED or/and patterned substrate thus achieves angular randomizing of photons. A similar concept applied to the chip sidewalls could also enhance LED output intensity by the textured chip sidewalls of LEDs. Previously, using an inductively coupled plasma (ICP) etcher or photo electrochemical (PEC) etching process [9,10] could texture LED sidewalls. This research reports a more detailed study on the wet etching mechanism of inverted pyramid sidewalls and describes the characteristic of nitride-based LEDs with textured inverted pyramid sidewalls.

2. Experimental procedure

The blue InGaN/GaN MQW LEDs used in this study were all grown on c-face (0 0 0 1) 2-inch sapphire (Al_2O_3) substrates by a metalorganic chemical vapor deposition (MOCVD) system. The emission wavelength was 454 nm. Details of the growth procedures can be found elsewhere [11,12]. The samples consisted of a 30-nm-thick GaN nucleation layer, a 2-μm-thick undoped GaN (u-GaN) layer, a 2-μm-thick Si-doped GaN layer, an $In_{0.17}Ga_{0.83}N$/GaN multiple quantum well (MQW) active region, a 0.25-μm-thick

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planar Mg-doped GaN layer and a Si-doped n^+-InGaN/GaN (5 Å/5 Å) short-period superlattice (SPS) tunnel contact structure. The MQW active region consisted of six periods of 3-nm-thick $In_{0.17}Ga_{0.83}N$ well layers and 15-nm-thick GaN barrier layers. After growth, we first partially etched the surface of the samples to expose the n-type GaN layer. We then deposited a 250-nm-thick ITO film onto the LED surfaces by e-beam evaporation to serve as the p-contacts and subsequently deposited Cr/Au onto the exposed n-type GaN layer to serve as the n-type electrode. After the chip process, the experiment sequentially fabricated LEDs with inverted pyramid sidewalls. Fig. 1 schematically illustrates the proposed wet etching process of the inverted hexagonal pyramid sidewalls. A 2-μm-thick SiO_2 layer was deposited on top of the samples by a plasma-enhanced chemical vapor deposition (PECVD). The 2-μm-thick SiO_2 layer was used for protecting LED chip surface while etching the sidewalls of the LED chip by chemical etching. Laser scribing was subsequently performed to define the dimension of chip size and expose the GaN/sapphire interface, as shown in Fig. 1b. The deep valley between the two chips, formed by laser scribing, provided paths for the chemical etching etchant to flow and allow the etchant to further contact with and etch the exposed bottom N-face GaN (i.e., the GaN/sapphire interface). The samples were then placed into a H_2SO_4:H_3PO_4 = 3:2 solution to form inverted pyramid sidewalls and the temperature of solution was 250 °C. The LEDs with the wet etching process for 2 min, 3 min and 4 min, respectively, were labeled as LEDII, LEDIII and LEDIV. With increasing etching time, the inverted pyramid sidewalls became more obvious, as schematically illustrated in Fig. 1c–e. For comparison, a conventional LED without the wet etching process was also prepared. The conventional LED was labeled as LED I.

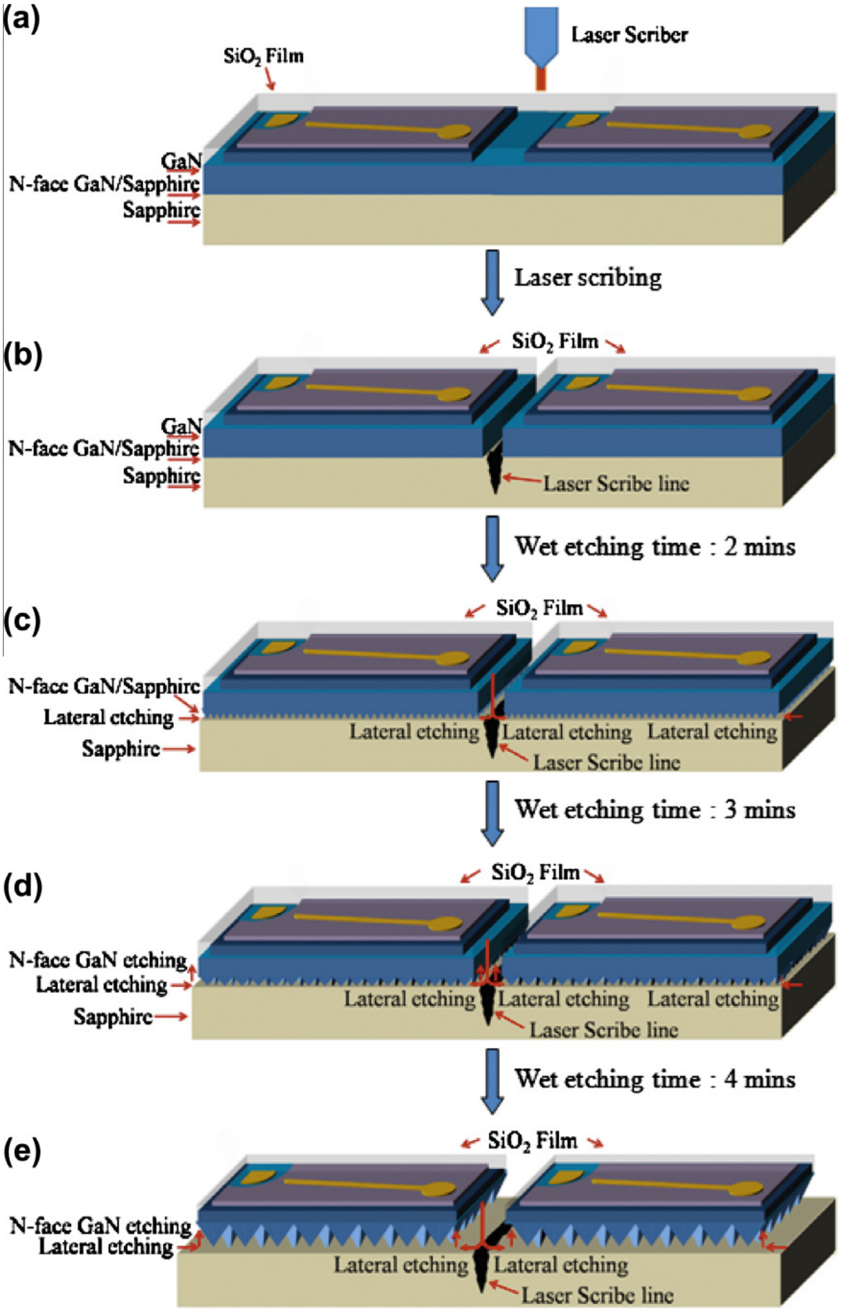


Fig. 1. Schematic diagram of fabrication of the inverted hexagonal pyramid sidewalls LED.

After wet etching, the remaining SiO_2 mask was removed by a buffer oxide-etching solution. The epitaxial wafers were then lapped down to about 90 μm thick. We then used a scriber to complete the fabrication of 23 mil × 10 mil blue InGaN/GaN LED chips. Fig. 1e shows a schematic diagram of the fabricated inverted pyramid sidewalls LEDs after wet etching for 4 min. We then packaged the LED chips into LED lamps and measured their room-temperature current–voltage (*I*–*V*) characteristics by an HP4156 semiconductor parameter analyzer. Intensity–current (*L*–*I*) characteristics of the fabricated LEDs were also measured using molded LEDs with an integrating sphere detector.

3. Results and discussion

To demonstrate the mechanism for forming inverted pyramid sidewalls through anisotropic chemical etching, after removing SiO_2 layer, the chip was cleaved into two and measured by SEM. Fig. 2a–c show the cross-sectional SEM micrographs of cleaved LEDII, LEDIII and LEDIV with different etching times, respectively. Observations clearly show that the undercut increased with increased wet etching times from 2 min to 4 min. The lateral etching depth was 4.9, 9.4 and 13.5 μm for LEDII, LEDIII and LEDIV, respectively. The vertical etching depth was 1.0, 2.1 and 2.8 μm for LEDII, LEDIII and LEDIV, respectively. The height of the inverted hexagonal pyramids was the largest in the chip sidewall and the height of the inverted hexagonal pyramids decreased from the chip sidewall toward the un-etched part, due to varying exposure time to the etchant. Fig. 2d–f shows the cross-sectional inverted hexagonal pyramids of SEM micrographs of LEDII, LEDIII and LEDIV, respectively. The height of the inverted hexagonal pyramid observed from LEDIV was larger than that observed from LEDII and LEDIII. This indicates that the wet etching process occurred at the chip edge, which is the exposed GaN/sapphire interface formed by laser scribing, schematically illustrated in Fig. 1b. A previous study reported chemical etching solutions such as KOH, H_2SO_4 and PEC, to selectively etch the N-face GaN but not the Ga-face GaN [9,13,14]. The hexagonal pyramid shape was observed with the chemical etching solution of N-face GaN. In this study, the N-face GaN was exposed around the chip by laser scribing at the GaN/sapphire interface, as schematically illustrated in Fig. 1b. These channels provided paths for the chemical etchant to flow and allow the etching solution to further contact with and etch the exposed bottom N-face GaN (i.e., the GaN/sapphire interface). The (0 0 0 −1) N-face GaN (i.e., lattice plan) has higher chemical activity than the (0 0 0 1) Ga-face GaN [13]. Therefore, the etching process began at the bottom of the N-face GaN (i.e., the GaN/sapphire interface) and the etching direction was vertical along the [0 0 0 1] bottom to top surface, as schematically illustrated in Fig. 1e. As reported in Ref. [13], {10 −1 −1} the face had lower surface energy than (0 0 0 −1) the N-face GaN. In other words, during wet etching, the GaN began at the bottom (0 0 0 −1) of the N-face GaN, and the bottom-up etching GaN process stopped at the {10 −1 −1} face because the {10 −1 −1} face was exposed to achieve the lowest surface energy. Thus, inverted hexagonal pyramid structures formed at the edge of the chip. Fig. 2f shows the inverted hexagonal pyramid structure. The etching process ended at the six {10 −1 −1} faces of the GaN layer. The measured angle between

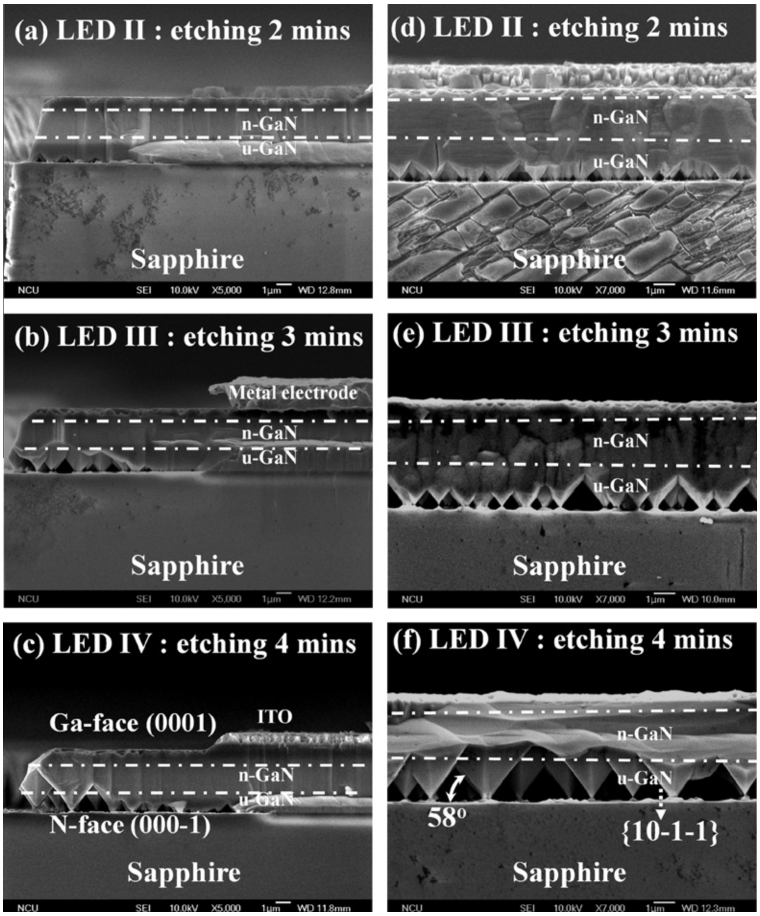


Fig. 2. Cross-sectional SEM micrographs after cleaved chip of: (a) LEDII, (b) LEDIII and (c) LEDIV. Cross-sectional inverted hexagonal pyramids SEM micrographs of: (d) LEDII, (e) LEDIII and (f) LEDIV.

the inverted hexagonal pyramid sidewalls and the sapphire evidenced the {10 −1 −1} face. The measured angle was around 58°. The result agrees well with that reported by Ng et al. [13]. As a result, we observed inverted hexagonal pyramid sidewalls from the LED by a wet etching process. The lateral etching rate notably increased with increasing solution temperature and etching time. Fig. 2c clearly shows that the lateral etching process from the chip sidewalls stopped at the u-GaN layer under the edge of the ITO transparent contact (TCL) layer with a 4 min etching time. Increasing etching time will damage the n-GaN and the active region of the MQW under the ITO TCL layer. Reducing the MQW area will reduce the emitting area. Therefore, we suggest that optimizing the etching time and temperature of the etching solution to form inverted pyramid sidewalls, obtained the maximum emitting area in the LED.

Fig. 3 shows *V–I* and *L–I* characteristics of the fabricated LEDs. The forward voltages, which operated with 20 mA current injection, were 3.69, 3.72, 3.69 and 3.75 V for LEDI, LEDII, LEDIII and LEDIV, respectively. Electrical properties of the inverted pyramid sidewall LEDs were almost the same as the conventional LED, indicating that inverted pyramid sidewalls LEDs are still electrically useable. This could be attributed to the fact that the n-GaN under the ITO layer was un-damaged during the wet etching process with an etching time from 2 to 4 min. Fig. 3 also shows *L–I* characteristics of the fabricated devices. The output powers of these four LEDs increased with injection current. The output power of the inverted pyramid sidewalls LEDs was always larger than that of the conventional LED. With 20 mA injection current, the output powers were 7.07, 7.71, 8.38 and 8.95 mW for LEDI, LEDII, LEDIII and LEDIV, respectively. The output power increased as the wet etching time increased from 2 to 4 min, due to the increased dimensions of the inverted hexagonal pyramid sidewalls with a longer etching time.

Fig. 4 shows the light-emitting patterns observed from the conventional LED and inverted pyramid sidewalls LEDs, respectively, photographed at 20 mA current injection. The light-emitting patterns in Fig. 4b–d, shows that the LEDs with inverted pyramid sidewalls were larger than those observed from the conventional LED around the sidewalls. The high efficiency may be ascribed to two reasons: 1. The photon generated from MQW was redirected toward the top surface because of the increased refractive index difference by air, efficiently reflecting the GaN inverted pyramid sidewalls. 2. The surface of the LED sidewalls with inverted pyramid sidewalls, were rougher than the conventional LED. Due to the change of geometrical shape, the photon had more chances to escape from the sidewall of the inverted pyramid sidewalls LEDs, compared to the conventional LED. Recently, Kim et al. showed that output power is higher with triangular LEDs than with quadrangular LEDs [15]. They also showed that light extraction of the triangular LEDs is higher than conventional quadrangular LEDs. A similar phenomenon should also occur for inverted hexagonal pyramid sidewalls with LEDs. Therefore, such an enhancement could be attributed to the inverted pyramid sidewalls that increase the probability of emitting photons from the device.

Fig. 5 shows reliability test of relative luminous intensity measured from these four LEDs, normalized to their respective initial

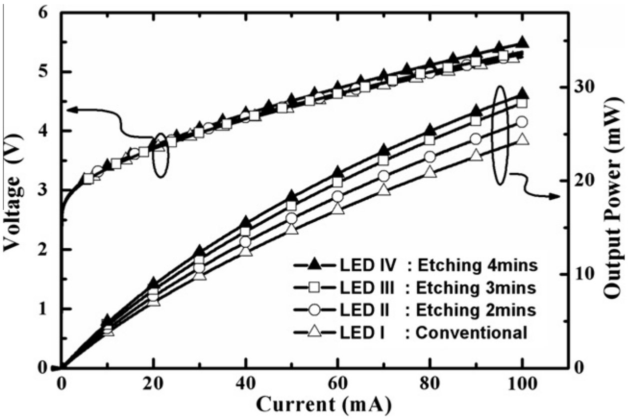


Fig. 3. *L–I–V* characteristics of the fabricated LEDs.

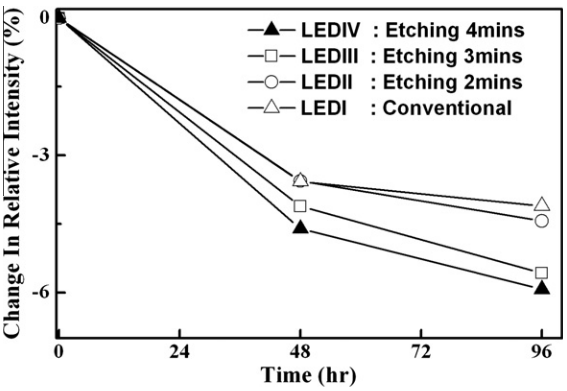
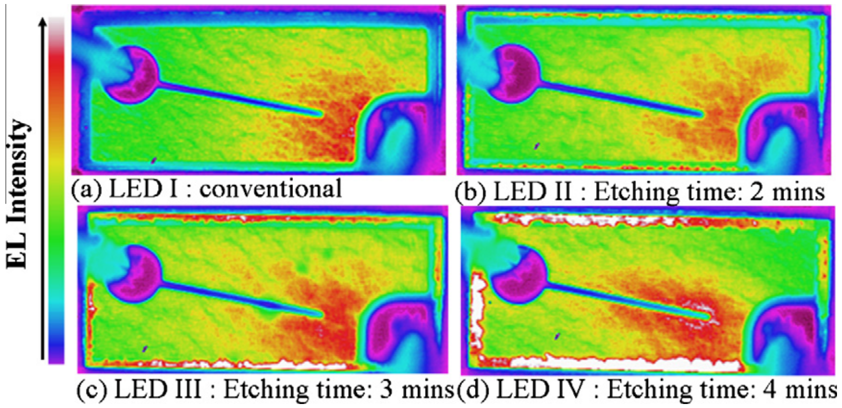


Fig. 5. Life test of relative luminous intensity of the fabricated LEDs, driven by a 50 mA current injection and the temperature was controlled at 30 °C.



(a) LED I : conventional
(b) LED II : Etching time: 2 mins
(c) LED III : Etching time: 3 mins
(d) LED IV : Etching time: 4 mins

Fig. 4. Light-emitting patterns of the: (a) LEDI (b) LEDII (c) LEDIII (d) LEDIV, photographed at 20 mA current injection.

readings. During life test, all four LEDs were driven by a 50 mA current injection and the temperature was controlled at 30 °C. It was found that the luminous intensity decreased by 4.1%, 4.4%, 5.5% and 5.9% after 96 h for LEDI, LEDII, LEDIII and LEDIV, respectively. Generally, if the luminous intensity was decreased less than 10% after reliability test, LED would be pass test. In other words, inverted pyramid sidewalls LEDs were still useable and reliable.

4. Conclusions

In summary, this study proposes and fabricates nitride-based inverted pyramid sidewalls with LEDs. The wet etching process is an inexpensive and simple method and is useful to those who work in the LED industry. Such inverted pyramid sidewalls could mainly enhance light output. Compared with conventional LEDs, the 20 mA LED output power enhances by 27% from inverted pyramid sidewalls LEDs. The enhancement is attributed to much larger light extraction efficiency.

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