Light Extraction Enhancement of GaN-Based Light-Emitting Diodes Using Crown-Shaped Patterned Sapphire Substrates

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***Abstract*—In this letter, we report the high performance GaN-based light-emitting diodes (LEDs) with embedded air void array grown by metal–organic chemical vapor deposition. The donut-shaped air void was formed at the interface between crown-shaped patterned sapphire substrates (CPSS) and the GaN epilayer by conventional photolithography. The transmission electron microscopy images demonstrate that the threading dislocations were significantly suppressed by epitaxial lateral overgrowth (ELOG). The Monte Carlo ray-tracing simulation reveals that the light extraction of the air-voids embedded LED was dramatically increased due to a strong light reflection and redirection by the air voids.**

***Index Terms*—Epitaxial lateral overgrowth, light-emitting diodes, metal–organic chemical vapor deposition.**

I. INTRODUCTION

HIGH-BRIGHTNESS GaN-based light-emitting diodes (LEDs) with luminescence covering photo-emission from infrared to ultraviolet (0.7 to 6.2 eV) have been extensively applied in large full-color displays, short-haul optical communication, traffic and signal lights, backlight for liquid-crystal displays, and regular light fixtures [1]. To fulfill the criteria of next-generation projectors, automobile headlights, and high-end light fixtures, further improvements of the optical power and the external quantum efficiency (EQE) are required.

Typically, the external quantum efficiency (η_{EQE}) of LEDs can be expressed as the product of internal quantum efficiency (η_{IQE}) and light extraction efficiency (η_{LEE}) if the current injection efficiency is assumed to be 100%. Due to the large lattice mismatch and thermal expansion coefficient misfit, the GaN-based epilayer still suffer high threading dislocation densities (TDDs) (approximately 10^8-10^{10} cm^{-2}) which leads to the deterioration of IQE. To improve the crystalline quality of GaN-based epitaxial layer on sapphire substrate, various growth techniques have been proposed, such as epitaxial lateral overgrowth (ELOG), microscaleSiN$_x$or SiO$_x$ patterned mask, and patterned sapphire substrate (PSS). On the other hand, the high refractive index of GaN restricts the escape angle of emitting light, which is only 23°, and results in low light extraction efficiency (LEE). To improve the LEE, several methods have recently been proposed and demonstrated, such as PSS, roughened p-GaN layer, laser lift-off process, and air voids embedded LED structure. In this letter, we report the fabrication of LEDs on crown-shaped patterned sapphire substrates (CPSS). The fabricated LED has donut-shaped air voids between the PSS and GaNepilayer interface, which improves both epitaxial crystal quality and LEE. The detailed analyses of electro-optical properties of LEDs are also provided.

II. EXPERIMENTS

To fabricate CPSS, sapphire substrate with periodic patterns (2 μm diameter and 3 μm spacing) were prepared by standard photolithography. A 200-nm-thick SiO$_2$ film by plasma-enhanced chemical vapor deposition (PECVD) was served as the dry-etching hard mask. The photoresist pattern was used as the mask with over-exposurein photolithography, and the buffer-oxide etching (BOE) solution was utilized to create the donut-shaped pattern. As for the hemisphere-shaped PSS (HPSS), the similar photolithography processes were implemented but without over-exposure. HPSS samples were then etched by reactive ion etching (RIE), and dipped into BOE to remove the SiO$_2$ mask.The scanning electron microscope (SEM) images of the CPSS are show in Fig. 1(a). For comparison, the cross section image of a conventional HPSS is also shown in Fig. 1(b). The diameter and interval of each crown-shaped pattern were 3 and 2 μm, respectively. The height of the cone shape was about 1.17 μm. A standard GaN-based LED structure was then grown on the CPSS and HPSS

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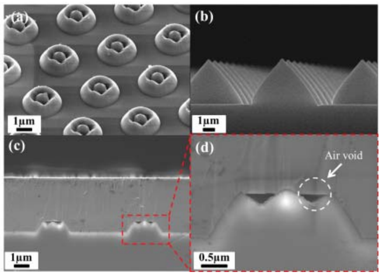

Fig. 1. SEM images for (a) tilted image of CPSS, (b) cross section of HPSS, (c) cross section of CPSS-LEDs, and (d) magnified view of air avoids on top of the crown shape.

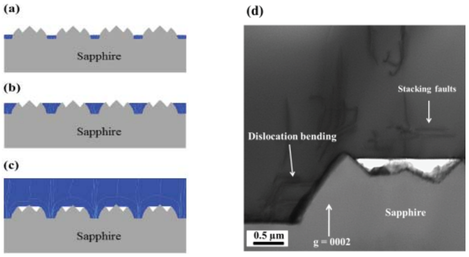

Fig. 2. (a), (b), and (c) Schematic view of the planarization of GaN grown on CPSS. (d) TEM images of GaN grown on CPSS. The diffraction condition is g = 0002.

by a low pressure MOCVD system, denoted as CPSS-LEDs and HPSS-LEDs. The same GaN LED structure was also grown on a flat sapphire substrateas a reference, denoted as conventional LEDs (C-LEDs). In the growth, trimethylgallium (TMGa), trimethylindium (TMIn) and ammonia (NH_3) were used as gallium, indium, and nitrogen sources, respectively. Silane (SiH_4) and biscyclopentadienyl magnesium (CP_2Mg) were used as n-dopant and p-dopant source. The epitaxial structure of the GaN-based LED overgrowth which consists of 3-μm n-doped GaN (n-GaN), 10-pairs of InGaN/GaN multi-quantum wells (MQWs), and 0.2-μm p-doped GaN (p-GaN) cap layer are on all samples universal. The LED wafers were then processed into LED chips (size: 300×300 μm^2) and packaged in epoxy-free metal cans (TO-46). The output power of the LED was measured by an integrated sphere detector at room temperature. Fig. 1(c) shows the cross-sectional SEM image of the CPSS-LEDs. The air voids (n=1) were formed between the CPSS (n=1.7) and GaN (n=2.5) epilayer on top of the crown shape. These embedded donut-shaped air-voids (as shown in Fig. 1(d)) can significantly increase the LEE due to enhanced scattering.

III. Results and Discussion

Fig. 2 shows the mechanisms of air void formation by epitaxial lateral overgrowth (ELOG) on top of CPSS. First, the recrystallized GaN islands were grown on planar part of CPSS as shown in Fig. 2(a). As GaN grew upward, there was also lateral growth toward the peak of crown. The GaN epilaye reventually grew over the crown pattern and coalesced near the summit and formed air voids between the lateral grown GaN and crown top, as shown in Fig. 2(b) and Fig. 2(c). The laterally overgrown GaN has less TDDs due to the bending of defect propagation direction. To analyze the epitaxial layer quality, we took the cross section transmission electron microscopy (TEM) picture, as shown in Fig. 2(d). As we can observed clearly, there are fewer TDDs in the overgrowth region above the crown top. The reduction of TDDs can be attributed to the misfit (mainly perpendicular to the c-axis) and bending dislocation occurred just above and sidewall the crown patterned.

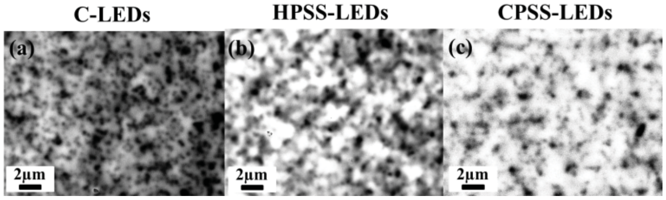

Fig. 3. Top view CL images on samples of energy for (a) C-LEDs, (b) HPSS-LEDs, and (c) CPSS-LEDs.

The reduction of dislocation was also confirmed by performing cathodoluminescence (CL) measurement. Fig. 3 shows the plan-view CL emission images for C-LEDs, HPSS-LEDs, and HPSS-LEDs with a 10kV accelerating voltage at room temperature. The C-LEDs sample shows more black spots than CPSS-LEDs and HPSS-LEDs. These dark areas in the CL images are regions where minority carriers get consumed by dislocations due to high nonradiative recombination velocity [2]. As one can see, the brightness of the images, which is a direct indication of radiative recombination efficiency, significantly incearses from C-LEDs, HPSS-LEDs, to CPSS-LEDs. An important feature to notice is that the emission intensity of CPSS-LEDs is more uniform than that of HPSS-LEDs. This was due to the light scattering effect from the air voids on the crown tops.

Fig. 4 displays the typical power-current-voltage (L-I-V) characteristics of three samples. With an injection current of 20 mA, the forward voltages are 3.4, 3.39 and 3.38 V, and the output powers are 20.2 mW, 24.3 mW and 26.7 mW, for C-LEDs, HPSS-LEDs and CPSS-LEDs, respectively. As compared with C-LEDs, the output power of HPSS-LEDs and CPSS-LEDs were enhanced by 20% and 32.1%, respectively. The light enhancement of L-I-V characteristics can be attributed to the following factors: First, the TDD sare reduced by the ELOG on the crown tops of PSS. This reduction leads to much fewer non-radiative recombination centers and increases photon generation efficiency. The finding is similar to those reported for GaN grown on recess-patterned PSS by D. S. Wuu *et. al.* [4]. Secondly, more lights can be extracted from the LEDs because of the light scattering effect from the air voids on the crown tops. It has been reported that the inclined facets of PSS can redirect photons back to the device surfaces andleads to higher light extraction efficiency. In addition, the LEDs on CPSS exhibited higher output power than on HPSS. This is due to embedded donut-shaped air voids formed between PSS and GaN epilayer. As a result, there is an additional 9.8% output power enhancement for the LEDs grown the CPSS compared to those grown on HPSS.

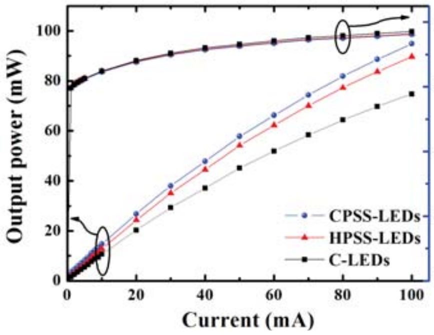

Fig. 4. L-I-V characteristics of the three fabricated LEDs.

To obtain a better physical understanding of the output power improvement, a Monte Carlo ray-tracing simulation was used to calculate the LEE of three LEDs samples. The wavelength used in simulation is 450 nm. For simplicity of the simulations, we do not consider the effects of the electrical pad and current spreading. In these Monte Carlo simulations, the 10 mW power (10000 light rays) were assumed to be generated randomly within the active region, and isotropically emitted and monochromatic unpolarized. For each ray, the trajectory and energy were determined using Snell's law and Fresnel losses, respectively. The simulated illuminance maps of three LED samples are shown in Fig. 5. As it can be seen in the figures, the maximum candelas values in three maps were 3.57, 5.41 and 5.69 mW/sr for C-LEDs, HPSS-LEDs and CPSS-LEDs, respectively. It indicates that more photons escape out into the air easier in CPSS-LEDs than in C-LEDs and HPSS-LEDs. The simulation shows that the patterned substrate's samples do provide better light extraction efficiency consistent with experimental results. So far, we have demonstrated both experimentally and theoretically that CPSS samples outperform other designs. The shape of CPSS, however, is another variable that could influence the outcome of LEE.

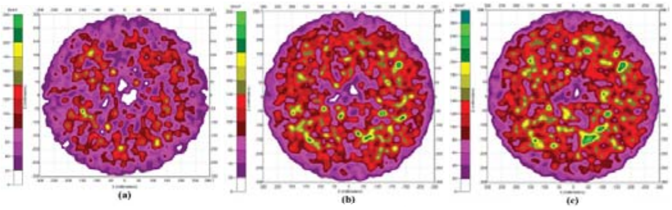

Fig. 5. Trace-Pro simulation of candela map taken from InGaN LEDs grown on (a) C-LEDs, (b) HPSS-LEDs, and (c) CPSS-LEDs.

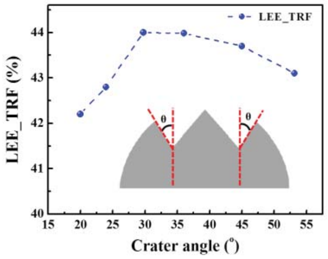

Fig. 6. Optical properties as a function of crater angle for the crown-shaped pattern. The insert shows crater of CPSS.

To probe further, we varied the crater angle (θ) indicated in Fig. 6 and calculated the light extraction efficiency of total radiant flux (LEE_TRF) at different angles, and the results are shown in Fig. 6. LEE_TRF considers the rays that escaped from every surface of the LEDs. In addition, a smaller angle indicates the steep slope with greater depth in the crater, whereas, a larger angle implies a slant slope from the edge of the crater. From the simulation result, the patterned shape in the range of 30 to 35° of crater angle induces the largest LEE. As a result, we can optimize the range of crater angle and predict optical enhancement by the optical ray-tracing method. From previous results [5], we can see the introduction of air voids can be treated as scattering centers due to the difference of refractive indices between the void (n is about 1) and the material (n is about 2). The HPSS, on the other hand, does not have air voids as an extra scattering medium, and thus macroscopically they can not be as effective as the CPSS case. This can be confirmed by our ray-tracing simulation as well. The calculated result is 25.8% vs. over 40% for HPSS and CPSS, respectively. The HPSS sample, on the other hand, does not have air voids as extra scattering media, thus the interfacial non-specular diffraction is not as effective as the CPSS case.

IV. CONCLUSION

In conclusion, we successfully demonstrated LEDs with embedded donut-shaped air voids using CPSS. The light output of CPSS-LEDs is greatly enhanced by 32.1% (at 20mA) compared with C-LEDs. From optical simulation, we confirm the enhancement of LEE in LEDs grown on CPSS in comparison with those made with HPSS and planar sapphire substrate. This novel approach of PSS demonstrated great potentials as the highly efficient sources of the next generation solid state lighting.

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