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Light extraction enhancement of GaN-based light emitting diodes using crown shaped patterned sapphire substrates

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1. Introduction

High performance 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.

In this paper, we demonstrate the high performance GaN-based light emitting diodes (LEDs) with embedded air void array grown by metal-organic chemical vapor deposition (MOCVD). 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 shows 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.

2. Experiments

To fabricate crown-shaped 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 photo resist pattern was used as the mask with over-exposure in photolithography, and the buffer-oxide etching (BOE) solution was utilized to create the donut-shaped pattern. 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 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 substrate as a reference, denoted as conventional LEDs (C-LEDs).

During 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: 300×300μm^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 donut-shaped air voids (n=1) were formed between the CPSS (n=1.7) and GaN (n=2.5) epilayer on top of the crown shape as shown in Fig.1 (d).

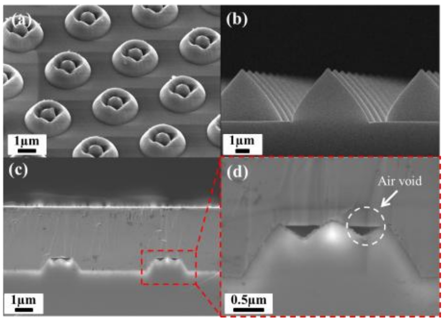

Fig. 1 SEM images for (a) tilted image of CPSS, (b) cross section of HPSS, (c) cross-sectional of CPSS-LEDs. (b) The magnified view of air avoids on top of the crown shape.

3. Results and Discussion

From the sketch of the mechanisms that how the air voids formed by epitaxial lateral overgrowth (ELOG) on top of CPSS was shown as Fig. 2. 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 epilayer eventually 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). We can observed clearly that there were fewer TDDs in the overgrowth region above the crown top. The reduction of TDDs in active region can be attributed to the dislocation bending on the top and sidewall of crown-shaped pattern.

The power-current-voltage (L-I-V) characteristics have been displayed as Fig. 3. From the L-I-V curves, we can observed that the forward voltages are 3.4, 3.39 and 3.38 V, and the output power are 20.2 mW, 24.3 mW and 26.7 mW, for C-LEDs, HPSS-LEDs and CPSS-LEDs at 20 mA, respectively. The light output power of HPSS-LEDs and CPSS-LEDs enhanced by 20% and 32.1% compared with C-LEDs. We believed the enhancement of light output power can be attributed to following factors: First, the TDDs are reduced by the ELOG on the crown tops of PSS. This reduction leads to fewer nonradiative recombination centers and increases photon generation efficiency.[2]

To obtain a better physical understanding of the output power improvement, a Monte Carlo ray-tracing simulation was used to calculate the light extraction efficiency (LEE) of three LEDs samples. From this simulation, we set the light field as lambertian emission pattern, the power is 10 mW and the number of rays are 10000. 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. 4. From the simulation results, the output power are 3.57, 5.41 and 5.69 mW 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. It indicates that more photons escape out into the air easier in CPSS-LEDs than in C-LEDs and HPSS-LEDs.[3]

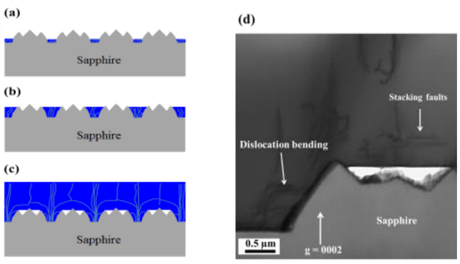

Fig. 2 (a),(b), and (c) Schematic view of the planarization of GaN grown on CPSS; (d) TEM images of GaN grown on CPSS. The diffraction condition is g=0002.

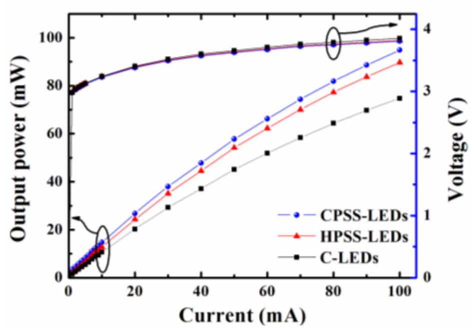

Fig. 3 L-I-V characteristics of CPSS-, HPSS- and C-LEDs

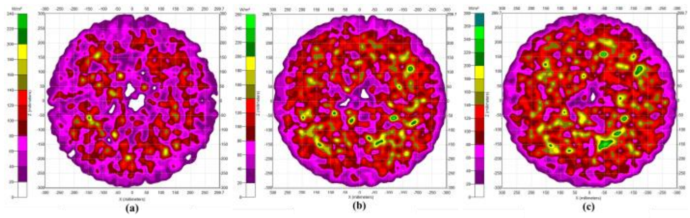

Fig. 4 Trace-Pro simulation of candela map taken from InGaN LEDs grown on (a) C-LEDs, (b) HPSS-LEDs and (c)CPSS-LEDs.

4. Conclusions

In conclusion, we successfully demonstrated LEDs with embedded donut-shaped air voids using CPSS. The TEM shows dislocations-bending behavior by ELOG. 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.

5. Acknowledgment

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