Enhancement of Flip-Chip Light-Emitting Diodes With Omni-Directional Reflector and Textured Micropillar Arrays

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***Abstract*—The flip-chip light-emitting diodes (FC-LEDs) with a conductive omni-directional reflector and textured micropillar arrays were investigated. The micropillar arrays structure was formed on the bottom side of sapphire substrate by dry etching process to increase the light-extraction efficiency. The light output power of the FC-LED was increased by 65% for a 3.2-μm textured micropillar on the bottom side of the sapphire substrate. Our work offers promising potential for enhancing output powers of commercial light-emitting devices.**

***Index Terms*—Dry etching, flip-chip light-emitting diodes (FC-LEDs), micropillar-array, omni-directional reflectors (ODRs).**

I. Introduction

WIDE bandgap light-emitting diodes (LEDs) that are III–nitride, ranging from ultraviolet to the short-wavelength part of the visible spectrum have been intensely developed in the past ten years [1], [2]. Recently, as the brightness of GaN-based LEDs has increased, applications such as traffic signals, backlight for cell phones, and LCD-TVs have become possible [3]. However, as for the replacement of the conventional fluorescent lighting source with solid-state lighting, it still needs a great effort for improving the light extraction efficiency as well as internal quantum efficiency of LEDs. The conventional LEDs are inherently inefficient because photons are generated through a spontaneous emission process and emitted in all directions. A large fraction of light emitted downward toward the substrate does not contribute to useable light output. In addition, there is an inherent problem associated with conventional nitride LEDs, i.e., the poor thermal conductivity of the sapphire substrate. It has been shown that the flip-chip (FC) techniques are an effective way to further enhance light extraction and heat dissipation [4]. Therefore, the FC-LEDs were always used in high-current and high-power operation to alleviate the thermal budget problem. The FC-LEDs configuration has high extraction efficiency compared to conventional LEDs due to the thicker light extraction windows layer and lower refraction index contrast between sapphire substrate ($n = 1.76$) and air ($n = 1$). This leads the critical angle of light output to become larger and let total internal reflection reduce. Furthermore, metal contact including n- and p-metal of FC-LEDs would not baffle light output and can be served as a reflective mirror to reflect the light and extract through transparent sapphire substrate [5], [6]. However, FC-LEDs still have a total internal reflection effect between the sapphire substrate and air, reducing the extraction efficiency of transparent windows layer. The surface roughness technique is an approach for light output enhancement has been proven due to the scattering of photons from the textured semiconductor surface and the probability of photons escaping from the semiconductor can be increased [7]–[9]. In this work, the combinations of conductive omni-directional reflectors (ODRs) [10] and micropillar-array sapphire surface were developed. The conductive ODR was not only served as an ohmic contact layer but also high reflective mirror. The use of highly reflective omnidirectional reflectors allows radiated light with any incident angle to be reflected to the top surface of the device [11], [12]. The formation of micropillar arrays on the bottom side of sapphire surface can be a better way to improve the probability of photons escape through the textured sapphire surface. The comparisons of FC-LEDs performance versus different micropillar depth and shape will be discussed.

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II. Experiments

The GaN LED structure with dominant wavelength at 460 nm used in this study was grown by metal–organic chemical vapor deposition on c-plane sapphire substrates. The LED structure consists of a 2-μm-thick undoped GaN layer, a 2-μm-thick highly conductive n-type GaN layer, a 0.2-μm-thick InGaN–GaN MQW, a 0.2-μm-thick p-type GaN layer, and n-InGaN–GaN short period superlattice tunneling contact layers for indium–tin–oxide (ITO). Top-emitting LEDs with a size of 1000 μm$\times$ 1000 μm were fabricated using standard photolithography and BCl_3/Cl_2 inductively coupled plasma etching for current isolation purposes. The p-GaN and active layers were partially etched by an ICP etcher to expose an n-GaN layer for electrode formation. After subsequent depositions of a 200-nm-thick ITO ($n \sim 1.7$ at 465 nm) low-refractive-index layer and a 500-nm-thick Ag mirror layer on top of LEDs, the p-side surface of sample A could be served as specular ODRs (flat type GaN–ITO–Ag). The design is similar to our recent publication [12]. The Cr–Pt–Au metals were deposited for the p- and n-contact pads. After completing the conventional face-up LED structure, the Ni (500 nm) metal

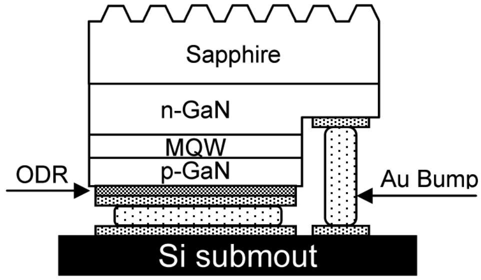

Fig. 1. Schematic diagram of FC-LEDs structure with micropillar arrays surface.

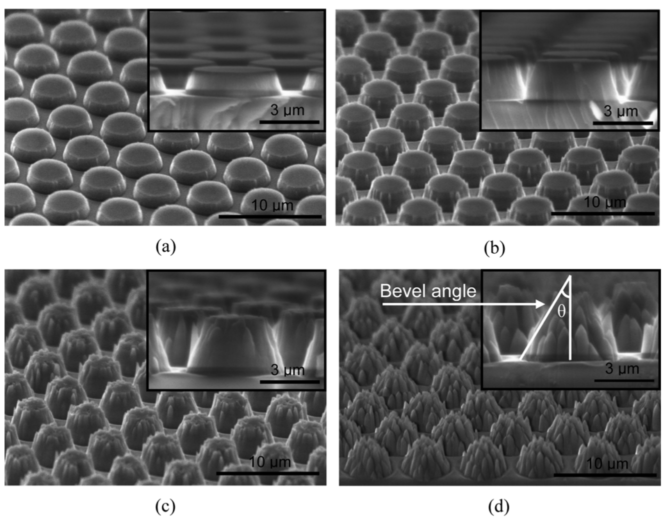

Fig. 2. Scanning electron micrographs of micropillar-array surface of sapphire backside with various depth and bevel angle. (a) 1.1-μm MPA, (b) 1.8-μm MPA, (c) 2.7-μm MPA, and (d) 3.2-μm MPA.

was deposited onto the bottom side of sapphire substrate as the mask layer. The sample was then subjected to the ICP process using Cl_2/BCl_3 (10 sccm/30 sccm) plasma with an ICP power of 850 W and RF power of 400 W to form the disk-array for light extraction purpose. The ICP etch rate for the sapphire was approximately 800 Å/min. A schematic diagram of the GaN FC-LEDs structure with ODR and micropillar arrays was obtained and shown in Fig. 1. Finally, the chips were flip-chip bonded on silicon submount using Panasonic ultra sonic flip chip bonder for electrical and optical measurement.

III. Results and Discussion

The surface morphology of an FC-LED with micropillar array sapphire surface was examined by scanning electron microscope as shown in Fig. 2. The periodic distance for pillar-array was about 5.5 μm with the depth of the pillar between $\sim$1.1 and $\sim$3.2 μm. In attempt to verify the effect of micropillar array surface on light extraction efficiency, the various depths and bevel angle of pillar was formed for further comparison. Fig. 2(a) and (b) shows the rather smooth top surface and side wall. With the increase of the dry etching time, the surface of the micropillar becomes rougher and the bigger bevel angle was obtained as shown in Fig. 2(c). Even the pineapple like textured pillar surface was obtained as shown in Fig. 2(d). The results could be ascribed to the uniformity of Ni hard mask, which results in partial over etching and

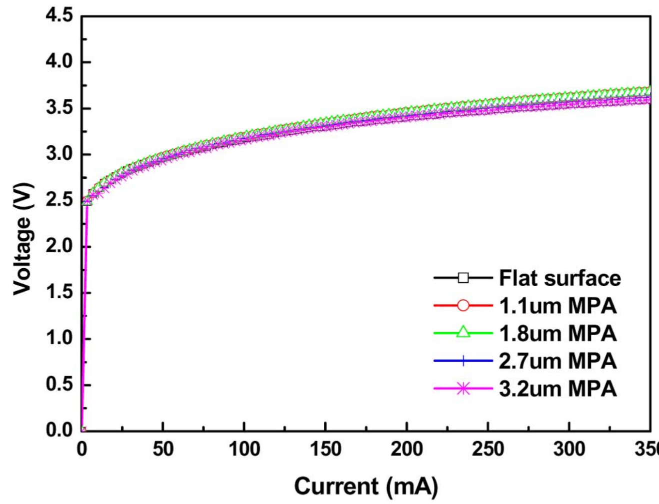

Fig. 3. I–V characteristics of flat surface FC-LEDs and MPAFC-LEDs.

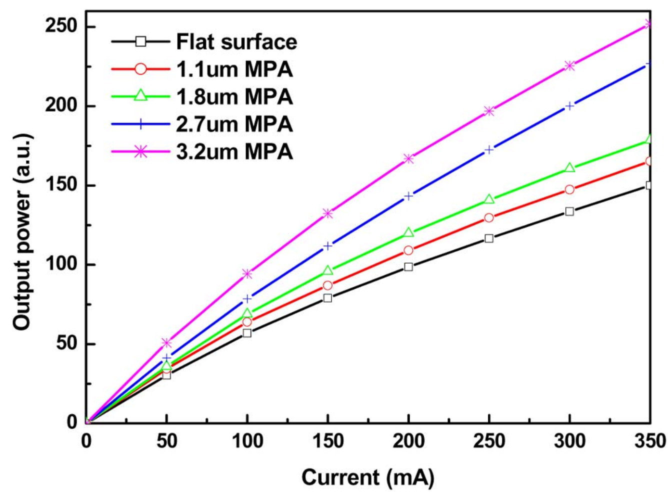

Fig. 4. L–I curves of flat surface FC-LEDs and MPA FC-LEDs.

the uneven pillar surface. The corresponding current–voltage (I–V) characteristics of flat surface FC-LEDs and micropillar array FC-LEDs (MPAFC-LEDs) were also measured, respectively, as shown in Fig. 3. It was found that the I–V curve of MPAFC-LEDs presents a normal p-n diode behavior with a forward voltage (at 350 mA) of 3.4 V, indicating that there is no heating and charging damages for the fabrication process of micropillar array during ICP etching process. The light output power-current (L–I) characteristics of the flat FC-LEDs and MPAFC-LEDs are shown in Fig. 4. We clearly observed that the output powers of the MPAFC-LEDs were larger than those of the flat FC-LEDs. At an injection current of 350 mA, it is found that the MQW emission peaks of those devices are located at about 460 nm, and the light output powers of the flat FC-LEDs and MPAFC-LEDs are about 151, 165, 179, 227, and 252 mW, respectively. Fig. 5 shows the light extraction efficiency enhancement of MPAFC-LEDs with various depth of pillar was 10%–68% at 350-mA current injection compared to a conventional flat surface FC-LED. It is indicated that the textured sapphire surface reduces the total internal reflection and improves the probability of photons escaping from semiconductor to air. Furthermore, with the increase of pillar depth

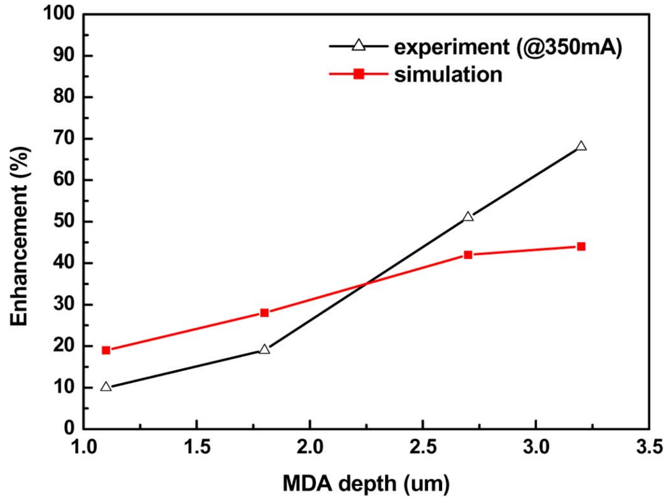

Fig. 5. Light extraction enhancement comparison of experimental and simulation results versus different depth of MPA.

(1.1–3.2 μm) and bevel angle (8°–35°), the light output power of 3.2-μm MPAFC-LED in Fig. 2(d) was increased by 55% compared to the 1.1-μm MPAFC-LED Fig. 2(a) under 350-mA current injection. These results can be attributed to the increase of the effective surface areas by increasing the depth and bevel angle of microdisk. The improved light extraction efficiency can be further supported by the simulation data as shown in Fig. 5 (open dots). The Trace-Pro software was used to simulate the MPAFC-LED structures as illustrated in Fig. 2(a)–(d) and the output power versus different depths of micropillar array could be obtained from the irradiance maps. The enhancement efficiency could be calculated and it was found that the efficiency was increased by larger heights of micropillar array. The simulated results were similar to experiment performance except 3.2-μm point because the simulated model did not consider the further enhancement due to nano roughness of microarray sidewalls. Obviously, the results indicate that the sapphire substrate with micropillar array surface reduces the internal light reflection and increases the light extraction efficiency. The probability of light escaping form the sapphire to air increases due to the increase of escape cone by pillar array structure [13].

IV. Conclusion

In summary, the FC-LEDs with highly reflective ODR and micropillar array structure were investigated. Luminescence improved with increasing of the depth and bevel angle of the micropillar-array on the sapphire substrate of GaN FC-LEDs. The formation of 3.2-μm depth textured micropillar arrays on the bottom side of the sapphire surface increased the light output power up to 65%. The micropillar arrays structure could improve the escape probability of photons due to the angular randomization of photons inside the LED structure, resulting in an increase in the light extraction efficiency of FC-LEDs.

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