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Power Enhancement of GaN-Based Flip-Chip Light-Emitting Diodes with Triple Roughened Surfaces

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The flip-chip light emitting diodes (FC-LEDs) with triple roughened surfaces were fabricated comprising top surface sapphire textured layer, interface patterned sapphire layer, and bottom naturally textured p-GaN layer. Light extraction efficiency was enhanced by such triple textured layers. The light output power of FC-LEDs was increased 60% (at 350 mA current injection) compared to that of conventional FC-LEDs by implementing the triple roughened surfaces. The enhancement efficiency can be simulated and the simulated results showed the same trend as the results of experiment.

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1. 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] Recently, as the brightness of GaN-based LEDs has increased, applications such as traffic signals, backlight for cell phone, and liquid-crystal display television (LCD-TV) have become possible.[2] It has many advantages, such as energy-saving, long lifetime, environment friendly and stable. So it has a promising future to become a next generation light source. However, the external quantum efficiency of a GaN-based LED still requires improvement. This comes from the fact that the refractive index of the GaN ($n_{GaN} = 2.45$) differs greatly from that of the air ($n_{air} = 1$). The critical angle at the GaN–air interface determined by Snell's law is about 24° [$\theta_c = \sin^{-1}(n_{air}/n_{GaN})$], which limits the light output efficiency to 8.7% [decided by $(1 - \cos\theta_c)$].[3] A large fraction of light generated in the active region of the LED is absorbed by the GaN material and the metal pad at the GaN surface. Some efforts have been made to increase the light extraction efficiency of an LED by making the GaN surface rough.[4–7] All these methods have one thing in common, which is that photons generated within the LEDs can experience multiple opportunities to find the escape cone. As a result, the light extraction efficiency and the LED output intensity could both be enhanced significantly.

In this letter, GaN-based flip-chip LEDs (FC-LEDs) with triple roughened surfaces were fabricated by a combination of epi-growth naturally textured surface,[8] epi-growth on patterned sapphire substrate (PSS), and micro-pillar array sapphire surface techniques. The detail of device fabrications and characteristics will be discussed. The ray-tracing simulation of FC-LEDs with textured surfaces were discussed in order to investigate the fundamental of light output enhancement.

2. Experiment

The LED samples were grown on a *c*-plane PSS by means of a metal-organic chemical vapor deposition (MOCVD) with a rotating-disc reactor (Emcore D75TM). The detail patterned sapphire substrate process could be described elsewhere.[9] The fabrication flowchart of GaN-based FC-LEDs with triple roughened surfaces was shown in Fig. 1. The LED

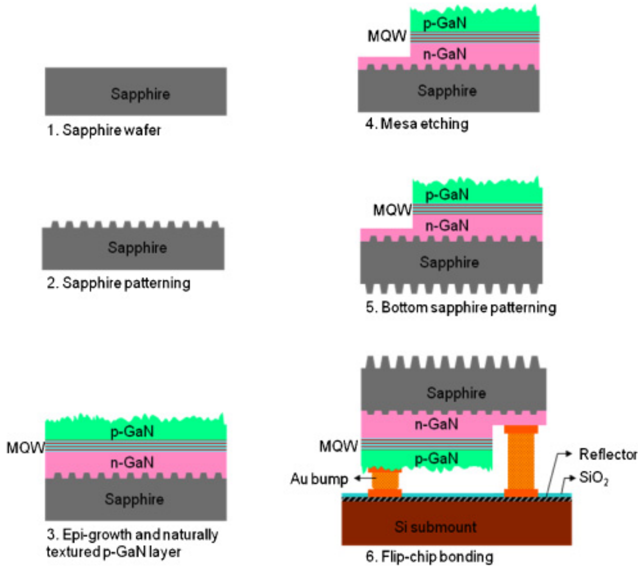

Fig. 1. (Color online) The fabrication flowchart of GaN-based FC-LEDs with triple roughened surfaces.

structure with a size of $1000 \times 1000\,\mu m^2$ consisted of a 30-nm-thick GaN nucleation layer on patterned sapphire, a 4-μm-thick Si-doped n-GaN layer, a 0.2-μm-thick InGaN/GaN multiple quantum well (MQW) active layers, a 50-nm-thick Mg-doped p-AlGaN electron blocking layer, a 0.2-μm-thick Mg-doped p-GaN cladding layer, and n- InGaN/GaN short period super-lattice (SPS) tunneling contact layers for indium–tin-oxide (ITO). The p-GaN and active layers were partially etched by an inductively coupled plasma (ICP) etcher to expose an n-GaN layer for electrode formation. An ITO film (250 nm) was deposited on p-GaN layer as the transparent conductive layer. The Cr/Pt/Au (50 nm/50 nm/2500 nm) metals were deposited for the p- and n-contact pads. After completing the conventional face-up LED structure, the Ni (500 nm) metal was deposited onto the bottom side of sapphire substrate as the mask layer and then the sample was subjected to the ICP process to form the pineapple like pillar-array surface for light extraction purpose.[9] The processed LED wafer was then subjected to the laser scribe and broken into $1000 \times 1000\,\mu m^2$ chips. Finally, the LED chips were flip-chip bonded on reflector coated silicon sub-mount using Panasonic ultra sonic flip chip bonder for electrical and optical measurement.

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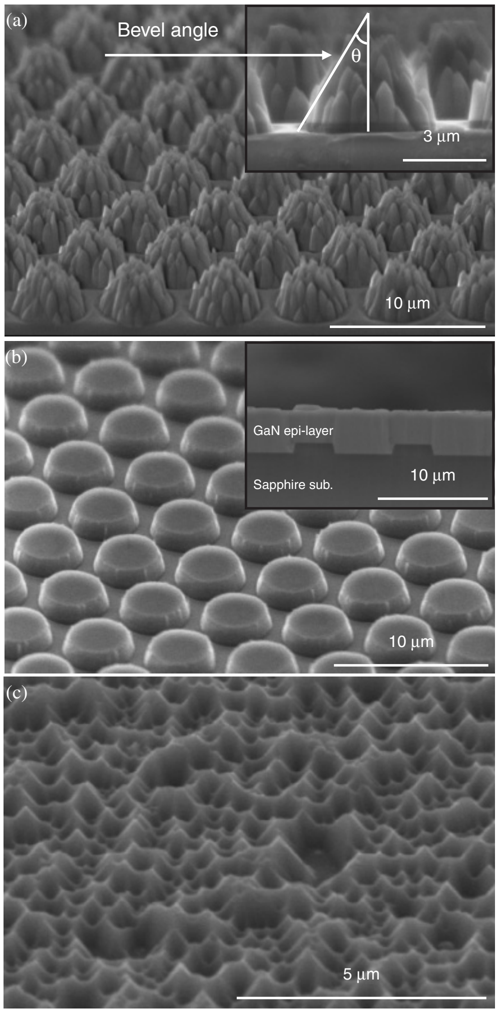

Fig. 2. SEM image of surface morphology of (a) top surface sapphire textured layer, (b) interface pattern sapphire layer, and (c) bottom naturally textured p-GaN layer.

A schematic drawing of the GaN-based FC-LED with triple roughened surfaces including top pineapple like pillar-arrays surface layer, interface pattern sapphire layer, and bottom naturally textured p-GaN layer was shown in Fig. 1(6). Four types of FC-LEDs were fabricated for detail comparison: conventional FC-LEDs, FC-LEDs with bottom side naturally textured p-GaN surface (LED-I), FC-LEDs with bottom side naturally textured p-GaN surface and interface PSS layer (LED-II), and FC-LEDs with triple roughened surfaces (LED-III).

3. Results and Discussion

The scanning electron microscopy (SEM) images of triple light scattering layers were shown in Fig. 2. Figure 2(a) shows the top textured sapphire surface with 1 μm space distance and 3.2 μm etching depth of pillar-array surface. Such a pineapple like textured pillar surface could be ascribed to the uniformity of Ni hard mask, which results in partial over etching and the uneven pillar surface. Figure 2(b) shows the patterned sapphire substrate before and after epi-growth (inserted image). In this study, the patterns with 3 μm diameter, 1 μm space distance, and 1 μm etching depth were form on the sapphire substrate for epi-growth. According to the inserted images, the PSS can be buried completely by GaN epitaxial layer without appearance of void. Shown in Fig. 2(c) was the naturally textured surface grown by MOCVD, the honeycombed surface can be formed onto the p-GaN surface.

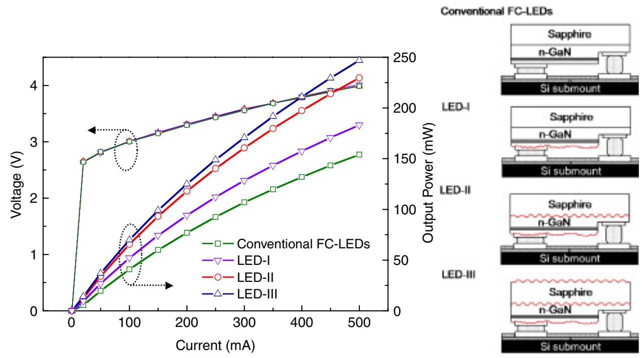

Fig. 3. (Color online) The corresponding *I*–*V* and *L*–*I* characteristics of the four types FC-LEDs.

The corresponding current–voltage (*I*–*V*) and intensity–current (*L*–*I*) characteristics of the four types FC-LEDs were shown in Fig. 3. It was found that the *I*–*V* curves were almost identical for these devices. The forward voltage (at 350 mA) was all about 3.55 V for these four devices. The similarity of electrical property indicates that the implementing of triple roughened surfaces would not result in any degradation in the electrical properties of GaN-based FC-LEDs. According to the *L*–*I* curves, it could be seen that electroluminescence (EL) intensity of LED-I, -II, and -III were all larger than that of conventional FC-LEDs. Compared with that of conventional FC-LED at 350 mA current injection, it can be found that the LED-I, -II, and -III present 20, 50, and 60% enhancement in output power, respectively. This result of 60% enhancement can be attributed to the implemented of triple roughened surfaces.

In order to investigate the fundamental of enhancement in light output with different FC-LED structures, we used the commercial ray-tracing software employing the Monte-Carlo algorithm to obtain trajectory of ray-tracing, efficiency enhancement and spatial intensity distributions of radiometric and photometric data. Four types model of FC-LEDs in this study were built. It was difficult to simulate the roughened surface of p-GaN, so we used a diffuse layer with 20% enhancement to replace the p-GaN layer as LED-I. The detector model was built in the shape of integrating sphere and recorded the emission flux from the LED models. The wavelength and temperature in this simulation were 460 nm and 300 K, respectively. The simulation results as shown in Fig. 4 were the intensity distribution from the detector models indicated LED-II [Fig. 4(c)] and LED-III [Fig. 4(d)] with great enhancement compared to the conventional FC-LED [Fig. 4(a)]. Therefore, the enhancement efficiency can be calculated and the simulated enhancement of LED-II and LED-III were 50.4 and 68.4%, respectively. The simulated results are similar to experiment performance except LED-III because the simulated model did not consider the further loss due to not uniform absorption of the material. However, the simulated results showed the same trend as the results of experiment.

Furthermore, in order to further investigate the influence of PSS and micro-pillar array sapphire surfaces in light

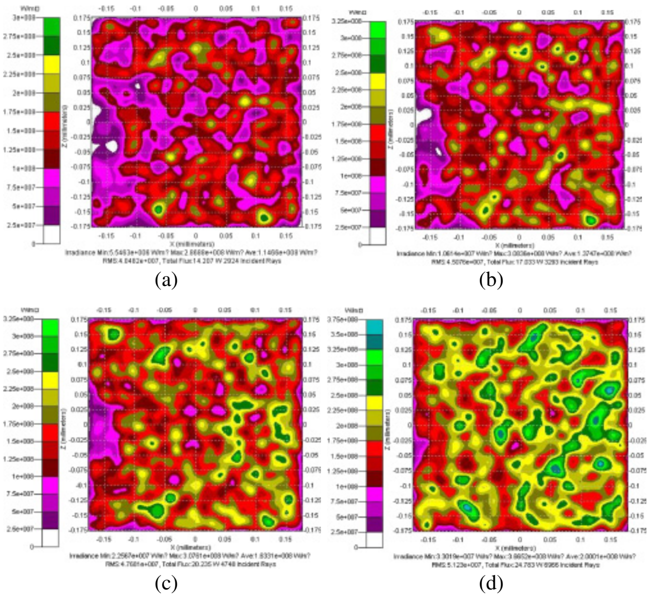

Fig. 4. (Color online) The irradiance maps of simulations: (a) conventional FC-LED, (b) LED-I, (c) LED-II, and (d) LED-III.

extraction efficiency. The models of FC-LEDs with PSS and FC-LEDs with micro-pillar array sapphire surfaces were built by varying the ratios of etching depth and space distance from 0.1 to 3.5. The conventional LED model was built for comparison. The relations between the light output enhancement and the ratio (depth/space) of FC-LEDs with PSS and FC-LEDs with micro-pillar array sapphire surfaces were shown in Fig. 5. It was obviously found that the light output enhancement was saturated over the ratio of 2.5. The ratio of the PSS and micro-pillar array sapphire surfaces on FC-LEDs we fabricated was 1 and 3.2, respectively. In order to consider the quality of epi-growth on PSS, the ratio of FC-LEDs with PSS was controlled on 1 for a non-void epilayer. The ratio of FC-LEDs with micro-pillar array sapphire surfaces was greater than that of saturation value for roughened surfaces; therefore the pattern design of micro-pillar array sapphire surfaces was an optimized parameter in this study.

4. Conclusions

In summary, the FC-LEDs with triple roughened surfaces were investigated. The formation of FC-LEDs structure

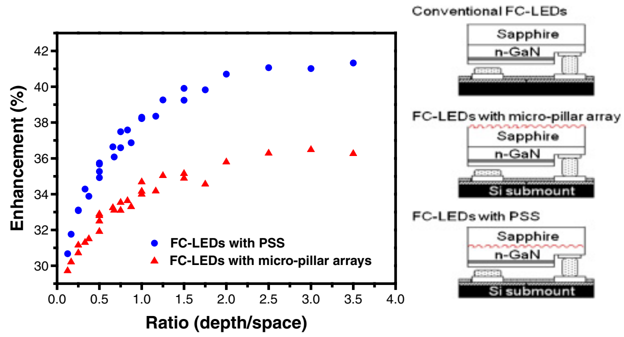

Fig. 5. (Color online) Relationship between the light output enhancement and the ratio (depth/space).

increased the light output power up to 60%. The improved light extraction efficiency can be further supported by simulation data. The novel FC-LEDs structure could not only reduce the TIR effect but efficiently facilitate light emission from the top pineapple-like pillar arrays surface and bottom honeycombed textured p-GaN surface.

Acknowledgments

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