Luminance Enhancement of Flip-Chip Light-Emitting Diodes by Geometric Sapphire Shaping Structure

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***Abstract*—The flip-chip light-emitting diodes (FC-LEDs) with geometric sapphire shaping structure were investigated. The sapphire shaping structure was formed on the bottom side of the sapphire substrate by a chemical wet etching technique for light extraction purpose. The crystallography-etched facets were (1010) M-plane, (1102) R-plane, and (1120) A-plane against the (0001) c-axis with the angles range between 29°$\sim$60°. These large slope oblique sidewalls are useful for light extraction efficiency enhancement. The light–output power of sapphire shaping FC-LEDs was increased 55% (at 350-mA current injection) compared to that of conventional FC-LEDs.**

***Index Terms*—Flip-chip light-emitting diodes (FC-LEDs), geometric sapphire shaping, oblique sidewall, sapphire wet etching.**

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 phones, and LCD-TV have become possible [2]. However, as for the replacement of 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 techniques are an effective way to further enhance light extraction and heat dissipation [3]. The flip-chip LED (FC-LED) configuration has high extraction efficiency compared to that of conventional LEDs due to the lower refraction index contrast between sapphire substrate ($n = 1.76$) and air ($n = 1$). This leads 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 lights and extract through transparent sapphire substrate [4]. However, FC-LEDs still have total internal reflection effect between the sapphire substrate and air, reducing the extraction efficiency of transparent windows layer. Previously, there has been intensive research into the improvement of light extraction efficiency and the enhancement of brightness in the LEDs. The geometric chip structure effect on light extraction efficiency enhancement was discussed in many papers [5]–[8]. Krames *et al.* reported the extraction efficiency enhancement from truncated-inverted-pyramid AlGaInP-based LEDs [5]. Eisert *et al.* reported the experimental and simulated results for enhancing light extraction efficiency from GaN-based LEDs chip with undercut SiC substrate [6]. Chang *et al.* reported 10% output power enhancement from the InGaN–GaN multiple quantum-well (MQW) LEDs by the introduction of the wavelike textured sidewalls [7]. Kao *et al.* reported light-output enhancement in a nitride-based LED with 22 undercut sidewalls [8]. 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. It is said that a simple method to fabricate oblique sidewall will be beneficial to raise the brightness of the nitride-based LEDs. In this letter, nitride-based FC-LEDs with a geometric sapphire shaping structure were fabricated. The oblique sidewalls were achieved by a chemical wet etching technique. The electrical and optical properties of the sapphire shaping FC-LEDs (SSFC-LEDs) are reported.

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 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). First, the SiO_2 film with size of 1000 μm $\times$ 1000 μm was deposited onto the backside of sapphire substrate by plasma-enhanced chemical vapor deposition and defined using standard photolithography to serve as the wet etching hard mask. In order to prevent the damage of front epi-layer during the high-temperature sapphire wet etching. The front epi-side was covered by a 3-μm-thick SiO_2 film for

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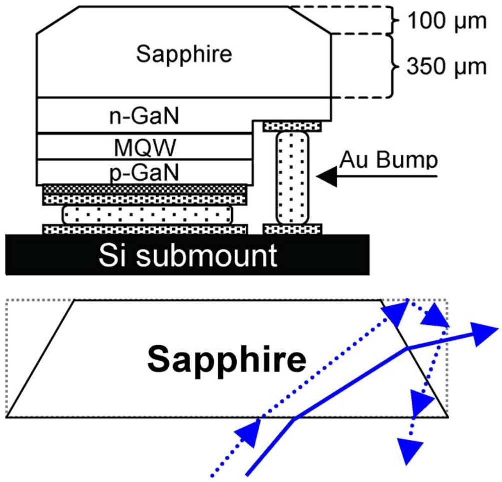


Fig. 1. Schematic drawing of the GaN SSFC-LEDs, illustrating the means by which light may be extracted from the oblique sapphire sidewall.

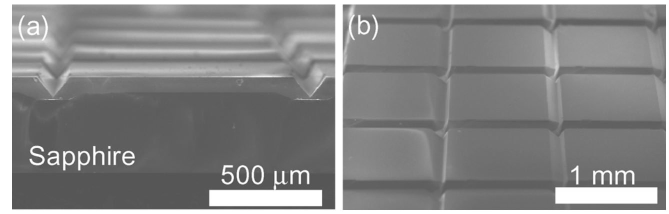


Fig. 2. Scanning electron micrographs of sapphire shaping structure (a) cross section and (b) top views.

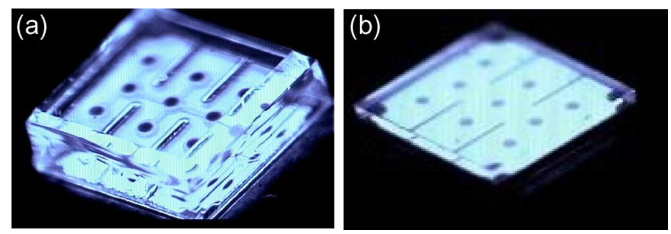


Fig. 3. Photomicrographs of (a) SSFC-LED and (b) CFC-LED chips (40 × 40 mil) operating at 20 mA (dc) with an emission wavelength of $\lambda_p \sim 460$ nm.

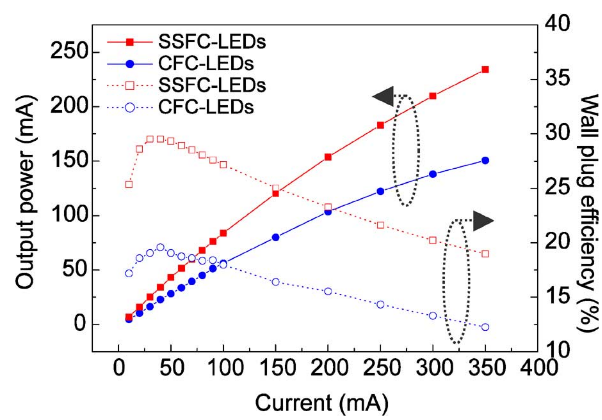


Fig. 4. Light–output power and wall plug efficiency as a function of injection current for $\lambda_p \sim 460$ nm devices of SSFC-LEDs and CFC-LEDs.

passivation purpose. The sapphire substrate was then immersed into a $H_2SO_4 : H_3PO_4$ (3 : 1) solution at an etching temperature of 330° for 70 min. The wet etching rate of sapphire substrate is about 1.4 μm/min in this study and can be related to the H_3PO_4 composition and the etching temperature. After finishing the sapphire shaping process, top-emitting LEDs with a size of 1000 μm × 1000 μm were fabricated using standard photolithography process which were aligned with the backside sapphire shaping pattern and were partially etched using an inductively coupled plasma 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 samples were then annealed at 500 °C for 10 min in air. The Cr–Pt–Au (50 nm/50 nm/2500 nm) metals were deposited for the p- and n-contact pads. After conventional LED processes, the processed LED wafer was subjected to the laser scribed and broken into 1000 × 1000 μm^2 chips. Finally, the LED chips with oblique sapphire shaping sidewall were flip-chip bonded on silicon submount using Panasonic ultrasonic flip chip bonder for electrical and optical measurement. A schematic drawing of the GaN SSFC-LEDs, illustrating the means by which light may be extracted from the oblique sapphire sidewall, as shown in Fig. 1.

The crystallography facets were (1102) R-plane, (1010) M-plane, and (1120) A-plane against the (0001) c-axis and their angles against the (0001) c-axis are about 60°, 50°, and 29°, respectively. In this study, the sapphire substrate was etched for 70 min via the 1.4-μm/min etching rate and the etching depth was about 100 μm. Fig. 2 shows the scanning electron micrographs of sapphire shaping structure (a) cross section and (b) top views. The oblique sidewall with 100-μm etching depth could be obviously observed. Furthermore, the etching structures are all V-grooves. The V-sharp structure can be used to form a cleaving line to break the thick (∼450 μm) sapphire substrate. Fig. 3 shows the photomicrographys of (a) SSFC-LED and (b) conventional FC-LED (CFC-LED) chips under 20-mA current injection. The sapphire shaping area and thick sapphire substrate were obviously observed on the SSFC-LED structure compared with the conventional FC-LED structure. Fig. 4 shows the light–output power and wall plug efficiency as a function of injection current for $\lambda_p \sim 460$ nm devices of SSFC-LEDs and CFC-LEDs. It is clearly observed that the light–output powers of the SSFC-LEDs were larger than those of the CFC-LEDs. Under 350-mA current injections, it is found that the enhancement of light–output powers of the SSFC-LEDs and CFC-LEDs could be significantly raised from 150 to 234 mW and the wall plug efficiency could be increase from 12.26% to 18.98%. We note that bare SSFC-LEDs (without an epoxy lens encapsulated) exhibit 55% light extraction efficiency enhancement at 350-mA current injection compared to the CFC-LEDs. Such an enhancement could be ascribed to the geometric sapphire shaping structure which reduces the totally internally reflected photons from the oblique sidewall interface and improves the probability of photons escaping from semiconductor to air. It notes that the SSFC-ELDs offer a significant advantage over CFC-LEDs by facilitating light emission from the oblique sidewalls of the chip. Fig. 5 shows light–output pattern of the SSFC-LED and CFC-LED under 20-mA current injection, respectively. For detail comparison, the light–output patterns via two directions

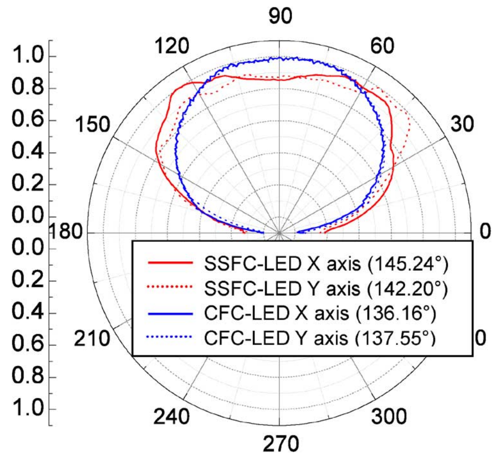
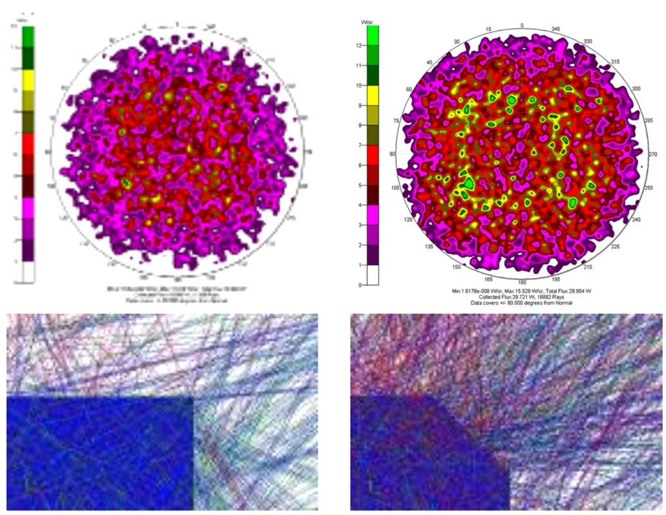


Fig. 5. Light–output pattern of the SSFC-LED and CFC-LED versus two directions (M-plane to M-plane, x-axis; A-plane to R-plane, Y-axis), respectively.



(a) (b)

Fig. 6. The simulated candela maps and ray-tracing images of (a) CFC-LEDs and (b) SSFC-LEDs, respectively.

(M-plane to M-plane, x-axis; A-plane to R-plane, Y-axis) were measured and the measurement data had been normalized. It can be observed that the electroluminescence (EL) intensities of SSFC-LEDs were smaller than that of CFC-LED in the near-vertical directions (i.e., in between 70 and 110), since the top side area was reduced to oblique sapphire sidewall. In contrast, EL intensities observed from the SSFC-LED were larger than those observed from CFC-LED in the near-horizontal directions (i.e., smaller than 60 or larger than 120). Such an enhancement could be attributed to the oblique sidewall hat photons could have a larger probability to be emitted from the device in the near horizontal directions. The improved light extraction efficiency can be further supported by the simulation result using ray-tracing method. Fig. 6(a) and (b) shows the simulated candela maps and ray-tracing images of CFC-LEDs and SSFC-LEDs, respectively. The intensity of SSFC-LEDs obviously exceeds that of CFC-LEDs. The corresponding ray-tracing images of oblique sidewall indicate that a large number of lights can be extracted from the oblique sidewall due to the reduction of total internal reflection and the probability improvement of photos escaping from semiconductor to air.

In summary, the FC-LEDs with geometrical sapphire shape structure and thick sapphire windows layer were investigated. The formation of SSFC-LED structure increased the light–output power up to 55%. The novel FC-LED structure could not only reduce the totally internal reflection effect but facilitate light emission from the edges of the thicker sapphire windows layer. From ray-tracing simulation results, the geometrical sapphire shape structure was confirmed to provide more probability of escaping photons from the sapphire–air interface, making an increase in the light extraction efficiency.

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