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High Performance Angled Light-Emitting Diodes by Laser Micromachining

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1. Introduction

With an increasing brightness, GaN-based light-emitting diode (LED) has found widespread applications, including traffic signals, LED lighting and backlight for LCD monitors, which have been continuously emerging in the market [1]. However, due to the large refractive index difference between nitride material (n_{GaN} = 2.5) and air (n_{air} = 1), total internal reflection inherent in nitride-based LEDs is a major cause for low external quantum efficiency. As a result, light generated from InGaN/GaN active layer will be reflected when it hits the LED-air interface with incident angle larger than the critical angle of approximately 23 degree [2], and this implies a large portion of light being trapped. There are several schemes proposed to deal with such problem so as to enhance light extraction efficiency of LEDs, for instance, texturing of surfaces [2], photonic crystal [3], flip-chip packaging [4], and a direct engineering of LED structure such as chip-shaping [5]. The first two schemes still have room to improve considering the part of light lost in the sapphire substrate as waveguide propagation mode in lateral direction. In the cases of flip-chip packaging and chip-shaping, expensive cost associated with fabrication limits the application of such schemes. Moreover, most reports of GaN-based LEDs chip- shaping by altering geometric structure so far only demonstrate an enhancement of light extraction efficiency in downward direction, which is less useful for general high brightness illumination application. Therefore, a simple and cost-effective approach to perform chip-shaping and redirect photons propagating laterally inside the sapphire substrate to upward direction is promising.

In this paper, a geometric chip-shaping of GaN-LEDs utilizing laser micromachining to fabricate mirror-coated angled LED (ALED) is introduced. Compared to conventional wafer sawing and polishing method [5], the main advantage is mechanical-loss-free as replacement of sawing blades is unnecessary during fabrication. Also, the minimum cutting width of dicing can be controlled down to 4 µm, thus the packing density of devices on the wafer can be further increased. This approach involves only a focused UV laser beam, tilted at an oblique angle, to produce chips with angled sidewalls. Additionally, sidewalls of ALED can further be coated with silver material, and this redirects laterally-propagating photons to upward direction.

2. Experimental Details

The set-up for laser micromachining consists of a UV laser source, beam focusing optics and an x-y motorized translation stage. Figure 1 is a schematic diagram illustrating the tilting of laser beam. The laser source is a third harmonic ND:YLF diode-pumped solid state (DPSS) laser manufactured by Spectra Physics. Details of experimental set-up are reported in the reference [6]. The LEDs were fabricated using standard photolithography, dry etching and electron beam metal evaporation. The emissive active area of individual LED chips is 500 µm x 500 µm. Oblique angle cutting was performed with a UV beam of 1 kHz repetition rate and 86 µJ pulse energy. Devices of ALED geometry were fabricated by applying four successive oblique cuttings onto the four sides of planar LED. SEM image of the fabricated ALED is shown in Figure 2. Before depositing Silver (Ag) metal on oblique sidewalls of green and blue LED chips, the sapphire surface was coated with a layer of photoresist (PR) prior to the shaping into angled structure by laser micromachining.

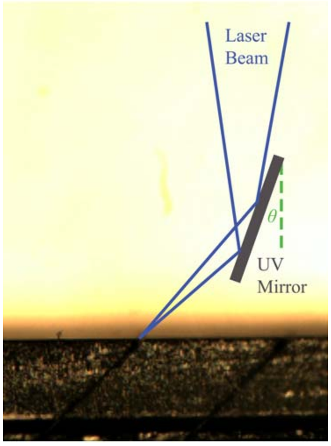

Fig. 1 Schematic diagram illustrating a reflected laser beam, superimposed on an optical image showing laser micro-machined oblique cutting

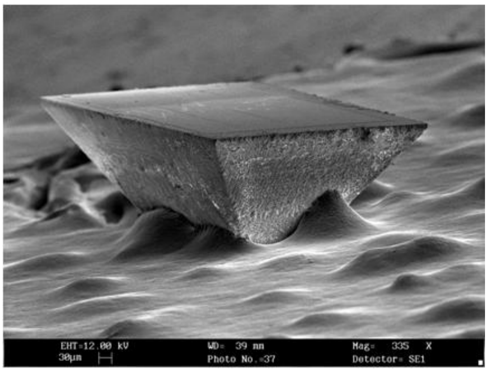

Fig. 2 SEM image of truncated pyramidal geometry of an InGaN LED die.

3. Results and Discussion

To evaluate the effect of mirror-coated inclined sidewall on LED performance, EL intensity with respect to driving current was investigated. The degree of inclination is defined as the interior angle between the surface and sidewall of the LED. The devices were mounted onto a rotational stage for angular intensity measurement in the range of -90 to 90 degrees, in steps of 2 degrees. Light signals were collected via an optical fiber and channeled into an optical spectrometer (Ocean Optics HR2000) for analysis.

Operation images of a cuboid LED and a mirror-coated ALED are shown in Figure 3(a) and (b) respectively, while their L-I characteristics are plotted in Figure 4. At 30 mA, the total output powers (measured with an integrating sphere) of the ALED and cuboid LED are 16 mW and 9.5 mW respectively, corresponding to an enhancement factor of 68%. Such significant improvement to light extraction efficiency highlights the effectiveness of geometrical chip-shaping, particularly with our approach based on laser micromachining. It is noted that the light output of the ALED begins saturating at I > 50mA; shaping the chip into pyramids leaves behind a reduced contact area with the package, diminishing thermal exchange. This is easily overcome by extending the coverage of the die-bonding epoxy to the inclined sidewalls.

Figure 4 demonstrates how electroluminescence (EL) intensity of ALED varies with current, and notes the intensity enhancement over planar LED. The significant improvement in the light extraction efficiency of ALED with mirror coating is attributed to an effective alternation of propagation direction of photons, which are originally propagating laterally inside sapphire substrate, to upward direction of the chip. Thus, more photons are extracted and emitted from the top surface of ALED. Therefore, this approach can effectively modify the Lambertian emission pattern of a planar LED, and help to confine emission intensity in upward direction.

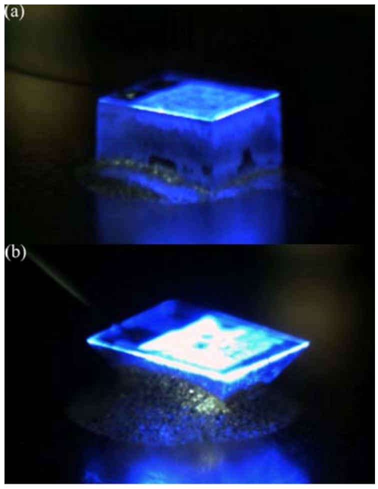

Fig. 3 Optical image of (a) cuboid LED and (b) mirror-coated ALED biased at 20 mA.

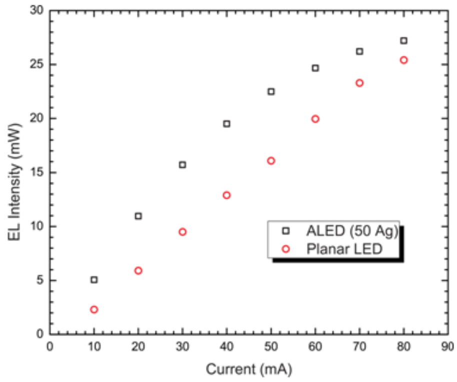

Fig. 4 L-I curve comparing the performance of mirror-coated ALED and cuboid LED.

Conclusions

ALED with mirror-coated inclined sidewall was fabricated by laser micromachining. Experimental results indicate that an enhanced improvement in the light extraction efficiency of ALED with inclined sidewall structure compared to planar LED. The enhancement of light extraction efficiency is attributed to the mirror-coated inclined sidewalls of ALED which redirect photons propagating in lateral direction of the sapphire substrate to upward direction.

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