Improved Output Power of Nitride-Based Light-Emitting Diodes With Convex-Patterned Sapphire Substrates

Yu-Ting Hsu, Cheng-Chang Yu, Kai-Feng Huang, Wen-How Lan, Jing-En Huang, Jia-Ching Lin, and Wen-Jen Lin

***Abstract*— Nitride-based light-emitting diodes (LEDs) grown on different convex-patterned sapphire substrates are proposed and fabricated. The electrical and optical properties of these LEDs are discussed in detail. It is found that the LED with a ball-shape patterned sapphire substrate has the best crystalline quality and I–V characteristic. On the other hand, on reducing total internal reflection, the LED with hexagonal–shape patterned sapphire substrate (HPSS) has the best performance on output power and external quantum efficiency. In comparison to the LED without patterned substrate, the LED with HPSS has 175% and 165% enhancement on output power and external quantum efficiency, respectively.**

***Index Terms*— External quantum efficiency (EQE), light-emitting diodes (LEDs), patterned sapphire substrate (PSS).**

I. Introduction

Gallium nitride (GaN) based compound light-emitting diodes (LEDs) with a visible spectrum from green to ultraviolet were employed in high brightness and high power applications such as lighting, full color displays and traffic light lamps. One important issue of LEDs is how to increase external quantum efficiency and light output power. The reflective index of GaN-based compound materials around 2.5 is higher than that of air and sapphire. Thus, most of the emitting lights cannot escape from GaN into surrounding air due to total internal reflection. Therefore, several approaches to achieving the high light extraction efficiency in LEDs have been reported, such as textured structure [1]–[3], surface transparent contact layer [4]–[6], sidewall treatment [7]–[9], chip shaped technique [10]–[12] and patterned sapphire substrate (PSS) [13], [14]. Among these approaches, the PSS technique shows a great advantage of both enhancing the light extraction and reducing the threading dislocations for the LEDs.

Recently, several PSS studies had discussed the influences to LEDs with different pattern depths [15], spaces [16], [17] and sizes [18], [19]. Based on different PSS processes, however, the pattern shapes for different researches may not be the same [13]–[15], [17]–[20]. Therefore, the improvement effects for the electrical and optical properties of LEDs are quite different. For example, Lee [21] showed that changing the slanted surface angle of the pattern could improve the light extraction of the LEDs by Monte Carlo ray tracing method. In this letter, we report the GaN-based LEDs fabricated on different pattern sapphire substrates. The electrical and optical properties of the fabricated devices will also be discussed in detail.

The GaN-based multiple quantum wells (MQWs) LED structures were grown on c-oriented non-patterned and patterned sapphire substrates by metal organic chemical vapor deposition (MOCVD). For the preparation of patterned sapphires, an array of circular photo resist (PR) patterns with 3 μm diameter and 3 μm space is fabricated first on c-oriented sapphires by standard photolithography technology. The wafers were then baked out on a hot plate at different temperature as the thermal photo resist reflow method [22]. The inductive coupled plasma (ICP) dry etching process was performed on these convex-patterned sapphire substrates with BCl_3, Cl_2 and Ar gases. During the dry etching process, the ICP power is fixed at 800W. With different reflow temperatures, different pattern shapes can be fabricated on sapphire substrate surface after the ICP etching process. Fig. 1 shows the scanning electron microscope (SEM) images for different convex-patterned sapphire substrates with 1) the non-patterned conventional sapphire substrate (CSS), 2) the ball-shape patterned sapphire substrate (BPSS), 3) the slanted hexagonal–shape patterned sapphire substrate (HPSS) and 4) the cone-shape patterned

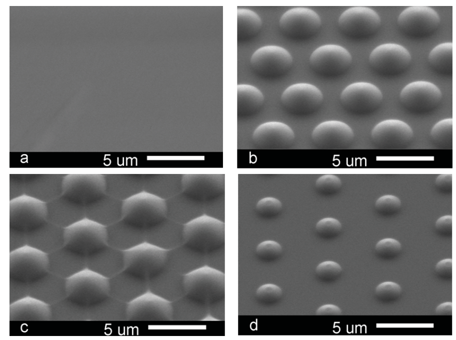

Fig. 1. SEM images of (a) conventional sapphire substrate (CSS), (b) ball-shape patterned sapphire substrate (BPSS), (c) hexagonal-shape patterned sapphire substrate (HPSS), and (d) cone-shape patterned sapphire substrate (CPSS).

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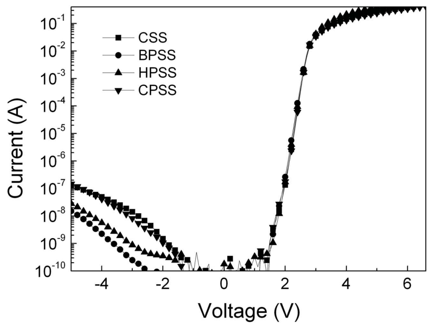

Fig. 2. Current voltage characteristics of the LEDs grown on CSS, BPSS, HPSS, and CPSS.

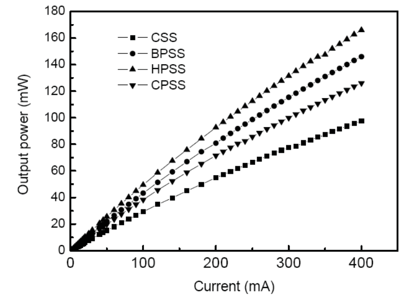

Fig. 3. Light output power-current characteristics of the LEDs grown on CSS, BPSS, HPSS, and CPSS.

sapphire substrate (CPSS). The diameter and spacing of BPSS and HPSS patterns are 3.40 μm and 1.80 μm, respectively, while the diameter and spacing of CPSS patterns are 2.00 μm and 3.20 μm, respectively. These patterned substrates were then cleaned by a wet cleaning process consisting of rinsing in aqua regia for 5 min and deionized water for 5min and drying by nitrogen gas. The InGaN/GaN MQWs LEDs were grown by metal organic chemical vapor deposition (MOCVD) [23] on these patterned and non-patterned sapphire substrates. The LEDs structure consists of a low-temperature GaN nucleation layer, a 2 μm-thick undoped GaN bulk layer, a 2 μm-thick Si-doped n^+-GaN layer, ten periods of InGaN/GaN MQWs, and 0.5-μm-thick Mg doped p^+-GaN layer. GaN LEDs were then fabricated by conventional photolithography and inductively coupled plasma etching. The indium tin oxide (ITO) film was subsequently evaporated on the p-GaN surface and alloyed at 600° in N_2 ambient. On the other hand, Cr-Pt-Au was evaporated onto the n-GaN layer and p-GaN layer as a n-type ohmic contact and p-type bonding pad layer. The wafers were then lapped down to 100 μm. We then used scriber and breaker to fabricate the 1 × 1 cm^2 chips. After these procedures, we used an HP-4155 semiconductor parameter analyzer to measure current-voltage (I–V) characteristics of the fabricated LEDs. The light output power characteristics of these devices were also carried out with a calibrated photo-detector.

Fig. 2 shows the $I-V$ characteristics of the LEDs grown on CSS, BPSS, HPSS and CPSS. The operation voltages of the LEDs with CSS, BPSS, HPSS and CPSS at 20 mA were 2.85, 2.81, 2.83 and 2.83 V, respectively, while their corresponding leakage currents at the reverse bias of 5 V were 1.3×10^{-7}, 1.5×10^{-8}, 2.8×10^{-8} and 1.5×10^{-7} A, respectively. It is obviously that the LED grown on BPSS has the smallest values of operation voltage and leakage current. Usually the excellent crystalline qualities of the devices could result in the superior I–V characteristics of the same devices [19], [24]. For further investigations, the etch pit density (EPD) experiments were performed to identify the crystalline qualities of our LEDs. As we knew that the EPD reveals the amount of threading dislocations propagating from the GaN/sapphire interface to the surface of epitaxial film [19]. It was found that the etch pit densities of the LEDs grown on CSS, BPSS, HPSS and CPSS were 8.7×10^7, 2×10^7, 3×10^7 and 5×10^7 cm^{-2}, respectively. This observation is well consistent with the measurement results of I–V characteristics. We also found that the LEDs with bigger pattern sizes (BPSS and HPSS) have better crystalline qualities and I–V characteristics, which comparing to the results of the LEDs with smaller pattern sizes (CPSS). Furthermore, it should be noted that the ball-shape patterns can suppress more threading dislocations than the hexagonal–shape patterns do under the same pattern size, which lead to the superior I–V characteristics of the LEDs grown on BPSS.

For a LED, the high output power is as important as the good I–V characteristics. That is the main purpose of the LEDs using patterned substrates. Fig. 3 shows the light output powers of the LEDs grown on CSS, BPSS, HPSS and CPSS as function of the injection current. It can be seen that the output powers of the LEDs grown on CSS, BPSS, HPSS and CPSS at a driving current of 400 mA were 96, 144, 168 and 122 mW, respectively. Here, we also define the output-power ratio of high-to-low injection currents as the output power measured at 400 mA divided by the output power measured at 20 mA. It was found that the output-power ratios of the LEDs grown on CSS, BPSS, HPSS and CPSS under this definition are 15.8, 16.4, 16.3 and 15.6, respectively. The higher output-power ratios of the LEDs with BPSS and HPSS can be attributed to the fact that fewer dislocations generated from BPSS and HPSS structures. On the other hand, from the results of I–V characteristics and output-power ratios, the LEDs grown on CSS and CPSS both have similar crystalline qualities. But the output power of LED on CPSS is 1.27 times that of LED on CSS. Moreover, the EPDs of the LEDs grown on BPSS and HPSS are similar. However, the output power of LED on HPSS is much higher than that of LED on BPSS. Thus, the better light extraction should be the dominant factor of the high light output power in the LED with HPSS. In fact, the LED grown on HPSS has the highest output power, which means that the hexagonal–shape patterns are high capable of reducing total internal reflection and increasing emitting angles of lights. In order to prove this assumption, the far-field patterns of these LEDs were measured at injection current of 400 mA and the results are shown in Fig. 4. There is a quite difference in measured far-field patterns between the LEDs on patterned and non-patterned substrates. In contrast with the LEDs grown on non-patterned substrates, the LEDs grown on patterned substrates have a broader view angle. It is worthily noted that the LED grown on HPSS has most emitting lights escaping from GaN into the air in a view angle range of 120 ± 30°. We believe this phenomenon should be attributed to the fact that the hexagonal–shape patterns can reduce the total internal reflections to the least. Under the injection current of 400 mA,

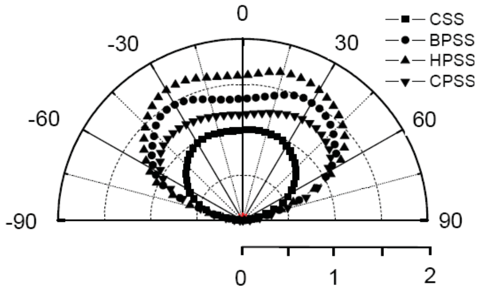

Fig. 4. Far-field pattern of LEDs grown on CSS, BPSS, HPSS, and CPSS with an injection current of 400 mA.

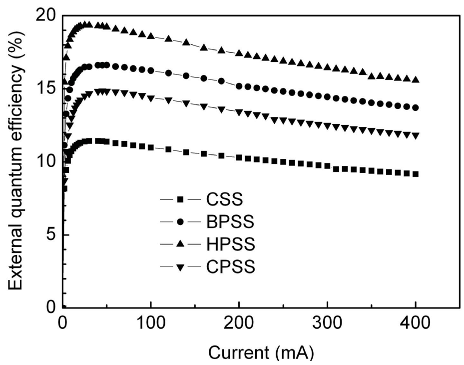

Fig. 5. External quantum efficiencies of LEDs grown on CSS, BPSS, HPSS, and CPSS.

the output power of LED with HPSS can be improved 175% which comparing to that of LED without patterned substrate, as shown in Fig. 3.

Fig. 5 shows the external quantum efficiency of the LEDs grown on CSS, BPSS, HPSS and CPSS at different injection currents. Similarly, the highest external quantum efficiency of LED with HPSS can be expected due to its high output power as mentioned above. It was found that the external quantum efficiency of the LED grown on HPSS can be achieved the highest value of about 20% and still stays as high as 15% even at a injection current of 400 mA. Comparing to the LED without patterned substrate, a 165% improvement on external quantum efficiency has been accomplished for the LED with HPSS in the whole measured current range.

In summary, nitride based LEDs grown on different convex-patterned sapphire substrates were proposed and fabricated. It was found that the LED with ball-shape patterned sapphire substrate has the best crystalline quality and I–V characteristic. On the other hand, for the purpose of reducing total internal reflection, the LED with hexagonal–shape patterned sapphire substrate has the best performance on output power and external quantum efficiency. Comparing to the LED without patterned substrate, the LED with HPSS has 175% and 165% enhancement on output power and external quantum efficiency, respectively.

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