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Improvement in light-output efficiency of near-ultraviolet InGaN–GaN LEDs fabricated on stripe patterned sapphire substrates

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Abstract

InGaN/GaN multi-quantum wells near ultraviolet light-emitting diodes (LEDs) were fabricated on a patterned sapphire substrate (PSS) with parallel stripe along the $\langle 1\,\bar{1}\,0\,0\rangle_{\mathrm{sapphire}}$ direction by using low-pressure metal-organic chemical vapor deposition (MOCVD). The forward- and reverse-bias electrical characteristics of the stripe PSS LEDs are, respectively, similar and better than those of conventional LEDs on sapphire substrate. The output power of the epoxy package of stripe PSS LED was 20% higher than that of the conventional LEDs. The enhancement of output power is due not only to the reduction of dislocation density but also to the release of the guided light in LEDs by the geometric shape of the stripe PSS, according to the ray-tracing analysis.

Keywords: GaN; InGaN; Patterned sapphire substrate (PSS)

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1. Introduction

GaN-based wide band-gap semiconductors have attracted considerable interest, in terms of applications for optoelectronic devices, which operate in the blue, green, and ultraviolet UV wavelength regions, as well as for electronic devices operating at high-temperature/high-power conditions [1,2]. The blue and green light-emitting diodes (LEDs) are used in various applications, such as traffic signals, outdoor displays, and back lighting in liquid-crystal displays [3]. The UV LEDs can be used as a pumping source for the white-light LEDs that are the most promising solid-state lighting source to replace the conventional incandescent and fluorescent lamps [4]. Therefore, the nitride-based near UV LEDs with high output power is crucial in the development of white LEDs. However, due to the large differences in lattice constant and thermal expansion coefficient between the GaN epitaxial layers and the underneath sapphire substrate, the threading dislocation density are very high in the range of 10^9–$10^{10}\,\mathrm{cm}^{-2}$ that can degrade the light emitting efficiency [5]. In particular for UV LEDs, the emission efficiency is more sensitive to the dislocation density than the green and blue LEDs. Hence, in order to increase the output power of the UV LED, the reduction of the dislocation density is desirable. There are many techniques such as epitaxial lateral overgrowth (ELOG) [6], pendeo epitaxy [7], and patterned sapphire substrates (PSS) [8–11] to reduce the dislocation density. Among there, the PSS technique has recently attracted much attention for its high production yield due to the single growth process without any interruption. In this study, we describe the fabrication and characteristics of InGaN-based near UV stripe PSS LEDs and demonstrate the enhancement of light output power of stripe PSS LEDs over the conventional LEDs on non-pattern sapphire substrate.

2. Device fabrication

Epitaxial layers of near UV LED device were grown on a c-face (0 0 0 1) PSS in a low-pressure vertical metal-organic chemical vapor deposition (MOCVD) system. For

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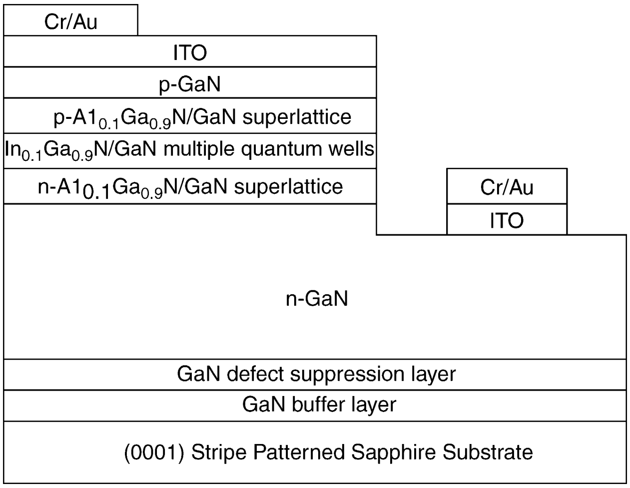
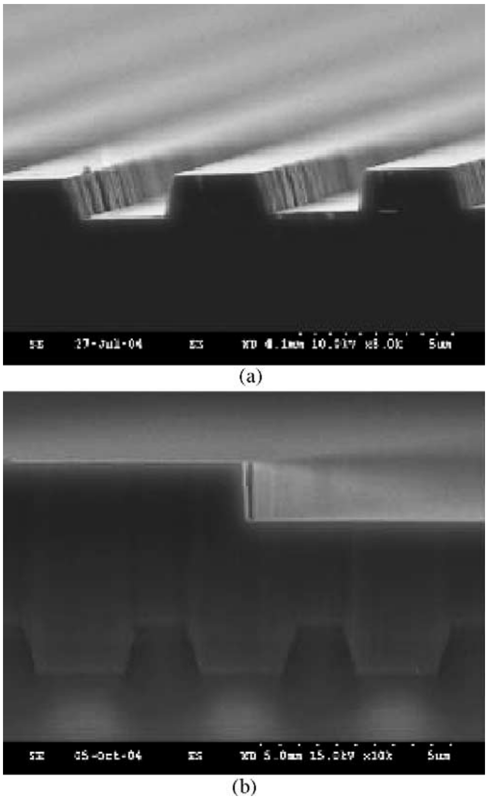


Fig. 1. The schematic drawing of epitaxial layers and device structure.

comparison, the same epitaxial structure was also grown on a conventional sapphire substrate at the same time. The PSS was defined by the standard photolithography and etched by inductively coupled plasma (ICP). The PSS has the stripe parallel along the $\langle 1\bar{1}00\rangle_{\mathrm{sapphire}}$ direction with following dimensions: the widths of the ridges and grooves and the depth of grooves and the slope of sidewall were 3 μm, 3 μm, 1.5 μm, and 75°, respectively. Epitaxial layer consists of a 25-nm-thick GaN buffer layer grown at 500 °C, a 500-nm-thick GaN defect suppression layer grown at 800 °C, a 4-μm-thick Si-doped n-GaN layer grown at 1050 °C, a 40-nm-thick Si-doped $Al_{0.1}Ga_{0.9}N$/GaN superlattice layer grown at 1050 °C, seven pairs of MQW consisting of 2 nm $In_{0.1}Ga_{0.9}N$ well layer and 10 nm GaN barrier layer grown at 770 °C, a 20-nm-thick Mg-doped $Al_{0.1}Ga_{0.9}N$/GaN superlattice layer grown at 1050 °C, and a 200-nm-thick Mg-doped GaN contact layer grown at 1000 °C. The details of the epitaxial structure are described elsewhere [12]. Device process of light emitting diodes is as following: The grown wafer was partially etched until the exposure of n-GaN to define the emitting area and n-electrode; ITO was deposited as the transparent conductive layer and Cr/Au were deposited as n and p electrodes, respectively. The sapphire was lapped and polished down to about 90 μm. The wafer was then cut into 350 μm × 350 μm chips and packaged into TO-18 without epoxy resin for the subsequent measurement. The conventional LED sample was also prepared with exactly the same process for comparison. Fig. 1 shows the schematic drawing of epitaxial layers and device structure. The typical current–voltage (*I*–*V*) measurements were performed using a high current measure unit (KEITHLEY 240). The light output power of the LEDs was measured using an integrated sphere with a calibrated power meter.

3. Results and discussion

The cross-sectional SEM micrographs of stripe PSS after ICP dry etching and subsequent epitaxy of LED full structure aligned along the $\langle 1\bar{1}00\rangle_{\mathrm{sapphire}}$ direction are presented in Fig. 2(a) and (b), respectively. As the previous report, the groove aligned along the $\langle 1\bar{1}00\rangle_{\mathrm{sapphire}}$ direction can be buried by the GaN layer completely [8]. Fig. 3 shows the (a) current–voltage (*I*–*V*) characteristics and (b) the leakage currents of the stripe PSS and conventional LEDs measured on TO-18 without epoxy resin at room temperature. From this figure, the *I*–*V* characteristics are very similar for both structures and with respective 3.57 and 3.58 voltage for stripe PSS and conventional LEDs at a driving current of 20 mA. In Fig. 3(b), the smaller leakage current at a reverse-bias voltage of 5 V of about 3 nA for the stripe PSS LED compared to that of about 15 nA for the conventional LED could be attributed to elimination of threading dislocation density in the GaN film by using stripe PSS [8]. Fig. 4(a) shows the output power of stripe PSS and conventional LEDs as a function of driving current. About a 20% enhancement of stripe PSS LED with 6.5 mW compared to that of conventional LED with 5.4 mW at a driving current of 20 mA. The corresponding electroluminescence (EL) spectra with an about 409 nm emitting wavelength at a forward-biased current of 20 mA for both LEDs are also shown in the inset of Fig. 4(a).



(a)

(b)

Fig. 2. (a) The cross-sectional SEM micrographs of stripe PSS after ICP dry etching and (b) the subsequent epitaxial layers of LED full structure.

Many reports indicate that the enhancement of optical output power could be attributed to the effective suppression of leakage current using the PSS method [8,10,11]. But among these studies, the reduction of threading dislocation density of PSS LEDs is less than one order of magnitude compared

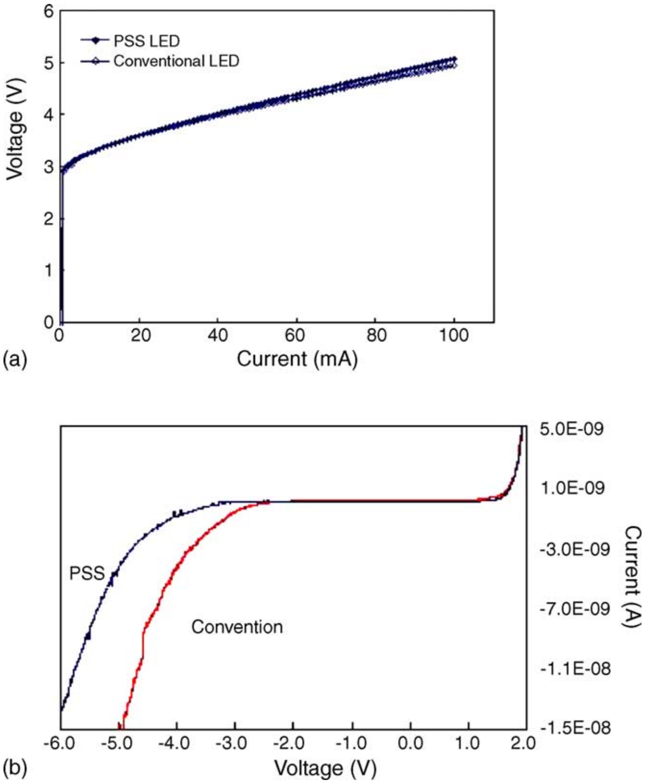


Fig. 3. (a) Curves of current–voltage (*I–V*) of stripe PSS and conventional LEDs and (b) reverse *I–V* characteristics of stripe PSS and conventional LEDs.

to that of conventional LEDs; thus, besides the elimination of threading dislocations due to the lateral growth of GaN on top of stripe patterned sapphire substrate, we believe that there must exist other mechanisms for improving the light extraction. It is well known that the large difference of refractive index between semiconductor and air will limit the escape of light and results in large percentage of light emitting from multi-quantum wells with the emitting angle larger than the critical angle to be trapped or confined in the LED, thus intensive researches for extracting the guided light from the LED by the shape of geometric consideration had been reported [13–15]. In our study, the enhancement of light extraction of stripe PSS LED was also simulated by the ray-tracing method (TracePro) with exactly the same epitaxial structure and dimensions. A 13% improvement of light extraction of stripe PSS LED was calculated based on our simulation model, ∼80% of the total output power improvement was in axial direction and ∼20% of the output power improvement was in lateral direction. The simulation results showed that the stripe PSS LED can increase the escape probability of guided light by the multi-reflection at interface between the patterned sapphire and GaN film and eventually lead the guided light toward the axial direction with an emitting angle less than the critical angle. The improvement of light output efficiency of our PSS LED is about 20%, which is higher than our simulation results. The additional improvement of light output efficiency could be attributed to the elimination of threading dislocations with better epitaxial quality.

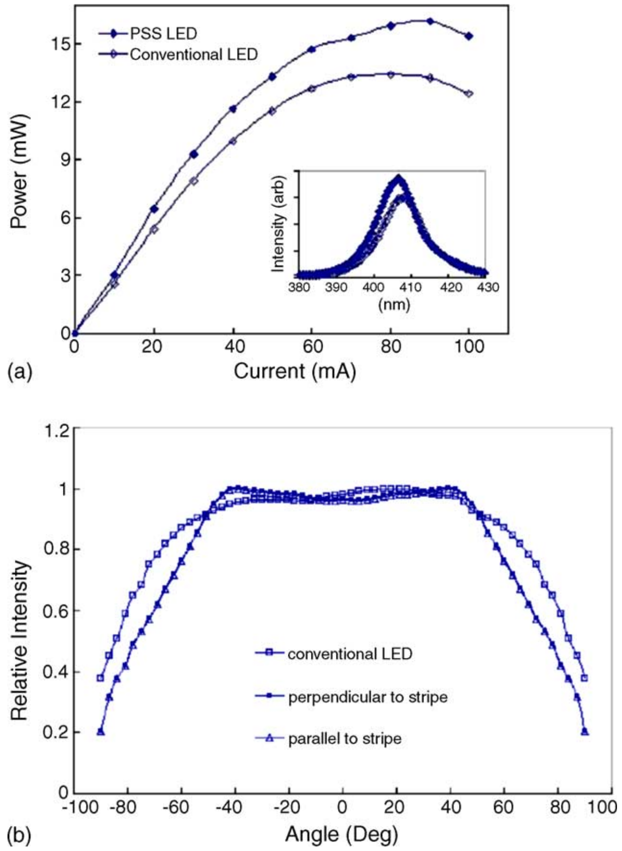


Fig. 4. (a) The output power of stripe PSS and conventional LEDs as a function of driving current. The insert is the room temperature EL spectra for both LED structures under a driving current of 20 mA and (b) the far field patterns of PSS LEDs of parallel and perpendicular to the stripe directions and of conventional LEDs.

The far field patterns of the stripe PSS and conventional LEDs measured at 20 mA are shown in Fig. 4(b). The far field patterns of stripe PSS LED with two different measuring directions: parallel and perpendicular to the stripe were also shown in this figure, and with no significant difference between them. From Fig. 4(b), the far field angle of stripe PSS LED is less than that of conventional LED. This agrees with the simulation results indicating the stripe PSS LED can increase the escape probability of the light with an emitting angle lager than critical angle, which was supposed to be trapped in the LED.

Fig. 5 plots the reliability test results of stripe PSS and conventional LEDs under the stress condition of 55 °C and 50 mA. The decline of output power of these two samples have no significant difference during all the burning time. The reliability of LEDs often directly links to the dislocation density of epitaxial wafer with the same subsequent process condition [16]. In Fig. 5, the same trend of the declination of the output power might indicate that the treading dislocation density is similar for the stripe PSS and conventional LEDs. Thus, the improvement of output power is dominated by the

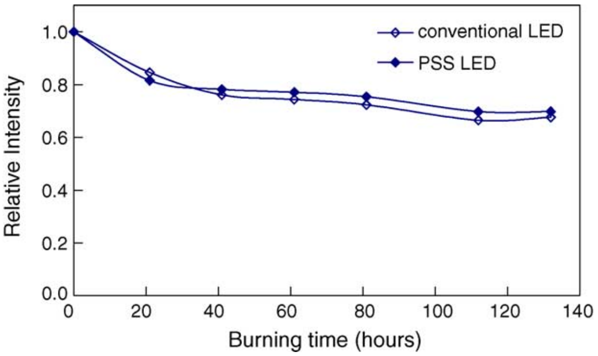


Fig. 5. Reliability result of stripe PSS and conventional LEDs under the stress-condition of 55 °C and 50 mA.

geometric effect in stripe PSS LED in good agreement with our simulation result.

4. Conclusion

The improvement of light extraction had been demonstrated on the stripe PSS LEDs grown by MOCVD. Their characteristics were measured and compared with those of conventional LEDs. The light output power of the stripe PSS LEDs was about 20% higher compared to that of conventional LEDs. Based on the result of ray-tracing simulation, measurement data of far field pattern and reliability, this improvement of the output power is mainly attributed to the geometric effect of stripe PSS adding the escape probability of the guided light.

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