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Near-Ultraviolet InGaN LEDs Grown on Patterned Sapphire Substrates

D. S. Wuu[1], W. K. Wang[1], W. C. Shih[2], J. S. Fang[2], C. E. Lee[1], W. Y. Lin[1] and R. H. Horng[3]

[1] Department of Material Engineering, National Chung Hsing University, Taichung 402, Taiwan R.O.C
Phone: +886-4-22855046 E-mail: dsw@dragon.nchu.edu.tw
[2] Department of Materials Science & Engineering, National Huwei University of Sci. & Technol., Huwei 632, Taiwan R.O.C
[3] Institute of Precision Engineering, National Chung Hsing University, Taichung 402, Taiwan R.O.C

1. Introduction

Recently, UV LEDs are expected to be used as the pump source for developing white LEDs to solve the low color rendering index problem in commercialized white LEDs [1]. It is well known that high density threading dislocations (TDs) are inherent in the epitaxial GaN films on sapphire substrates due to the differences in the lattice constant and thermal expansion coefficient. Epitaxial lateral overgrowth was effective to reducing the number of threading dislocations in the GaN epilayers [2]-[4]. In this work, we propose a new approach for growing a high-quality GaN film using a patterned sapphire substrate (PSS). This technique eliminates the dislocations and increases the emitted light extraction efficiency. The proposed method can reduce the TDs via a single growth process without any interruption and deposition onto the SiO_2 mask. It also eliminates the need for a precise photolithography process to transfer a special pattern axis and prevents induced contamination.

2. Experimental

A cross-sectional diagram of the near-UV LED (λ=408 nm) structure is shown in Fig. 1. The InGaN/GaN MQW LED samples were grown using a low-pressure MOCVD method on (0001)-oriented two-inch PSS and conventional sapphire substrates. PSS was prepared using a periodic hole pattern on the (0001) sapphire with a hole depth of 1.5μm. The hole dimension (diameter: 3 μm; spacing: 3 μm) was fabricated using a standard photolithography process and inductively-coupled-plasma etching. The LED sample had a chip size of 365 μm × 365 μm, fabricated using standard photolithography and dry etch techniques. The Ni-Au and Ti-Al-Ti-Au metal contacts were deposited as p-type and n-type GaN, respectively.

3. Results and discussion

Fig. 2(a) presents the forward and reverse I-V characteristics of near-UV InGaN LEDs with and without PSS at room temperature. It can be seen that the forward voltages LEDs at 20 mA dc current were 3.16 and 3.19 V, respectively. This indicates that the PSS LED has similar I-V characteristics as compared with the conventional LED. The reverse leakage currents of the PSS LED and conventional LED at a reverse voltage of 5 V were around 0.32 and 1.45 nA, respectively. The reverse leakage current of the PSS LED was smaller than that of the conventional LED. The decrease in leakage current could be attributed to the elimination of TDs in the GaN film using the PSS.

Cross-sectional TEM image of the GaN epilayer grown on conventional sapphire and PSS are presented in Fig. 3 (a) and (b), respectively. For the GaN-on-PSS sample, growth was apparently direct laterally from the top of the sapphire substrate and overhangs the trench. Furthermore, the small voids with dimension of ~0.5 μm have been observed on the sidewall of the pattern. The voids are associated with the relaxed morphologies of the side faces of the GaN films and it will usually lead to the threading dislocation bending toward these voids. It is so proved that there are still high dislocation density of the GaN films directly grown on (0001) sapphire substrate and low defect region above the voids by using PSS.

Fig. 4 shows the light output power as a function of injection current between 20 and 100 mA for these LEDs. The output intensity of both LEDs initially increases linearly with the injection current. With a 20 mA forward injection current, the output power (P_o) and external quantum efficiency (η_e) of a lamp-form LED with PSS were estimated at 10.4 mW and 14.1 %, respectively. In contrast, the P_o and η_e of the conventional LED at 20 mA were 8.6 mW and 11.6%, respectively. The external quantum efficiency of the PSS LED reached a maximum value of 27% at 60 mA and then, decreased significantly with further increasing the forward bias current. Nearly the same trend was also obtained for the conventional LED sample except for a lower peak value of external quantum efficiency (20% at 60 mA). Although the PSS LED may still suffer the incomplete step coverage problem at the GaN/PSS interface, the present results indicate that there is no evident difference in thermal dissipation performance between the PSS LED and conventional LED samples.

Referring back to Fig 2, the enhancement of optical output power could be attributed to the effective leakage current suppression using the PSS method to fabricate LEDs. It is well known that the MQW emission efficiency is related to the leakage current through dislocations. Our experimental results indicated that the EPD of the LED with PSS is about 2.8×10^8 cm^{-2}. Hence, the improvement in output power might also be related to the increase in light extraction efficiency through the scattered emitted light from the active nitride and PSS interface.To confirm this point, the light output pattern of the PSS LED (@ 20 mA) was measured and shown in Fig. 5, where the chip was not encapsulated into epoxy. This was compared to the light output pattern of the conventional LED. It is clear from the results that the EL intensities obtained from the PSS LED were larger than those from the conventional LED in the near horizontal directions (i.e., small than ± 45°). The improvement in emitted light extraction efficiency is considered as a consequence of the light scattering by the PSS.

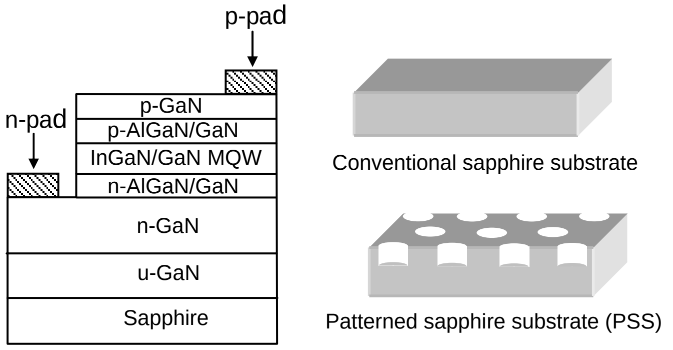

Fig.1 Schematic of InGaN LED structure grown on conventional sapphire substrate and patterned sapphire substrate.

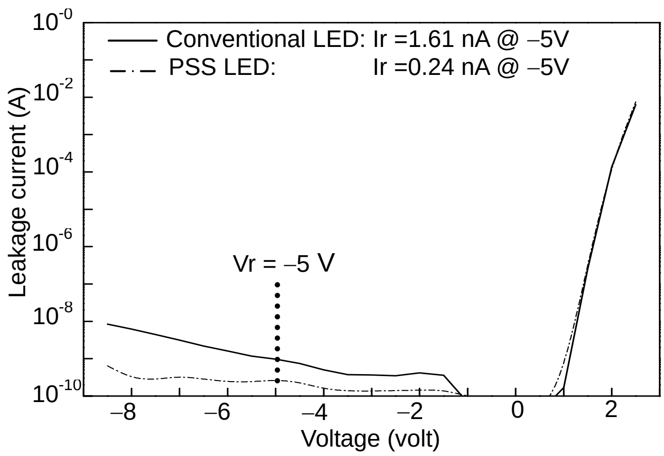

Fig. 2 Reverse I-V characteristic of the GaN LEDs with and without patterned sapphire substrate (PSS)

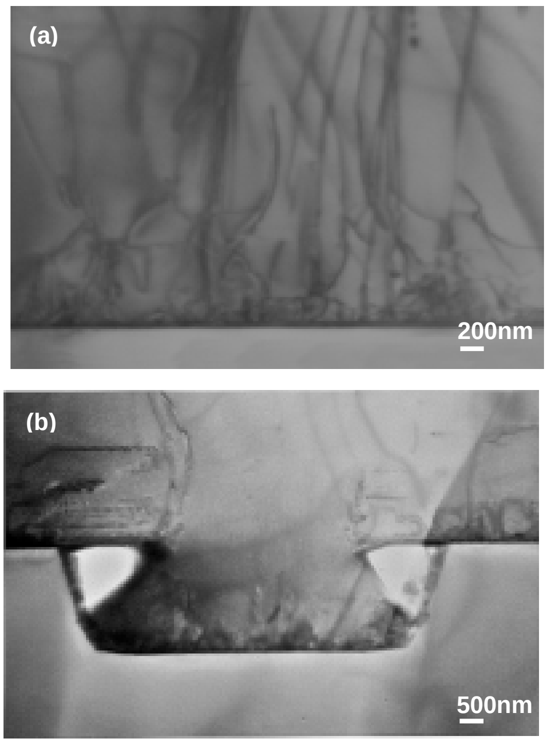

Fig. 3 Cross-sectional TEM image of GaN films with conventional sapphire and patterned sapphire substrates.

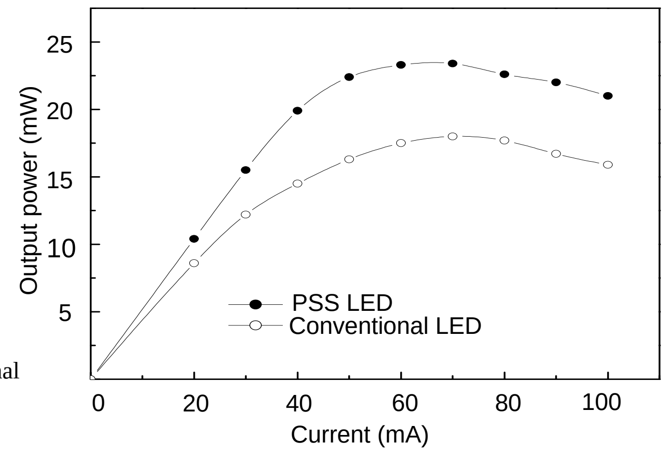

Fig. 4 L-I characteristics of InGaN LEDs with and without PSS.

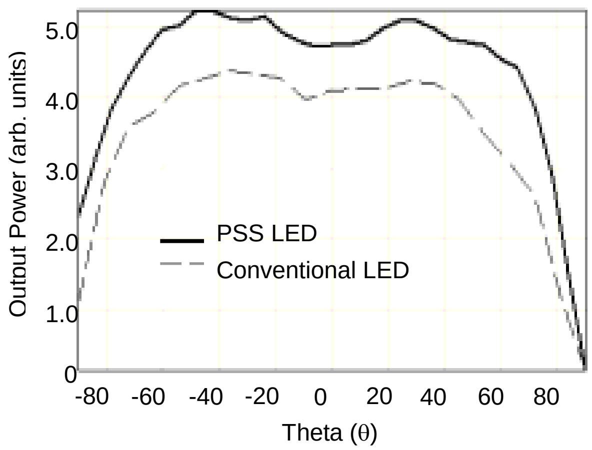

Fig. 5 Light output patterns of the PSS LED and conventional LED.

4. Conclusion

We demonstrated the characteristics of near-UV InGaN-based LEDs with PSS. As much as 63% increased light emission intensity was obtained at 20 mA forward current injection. Moreover, the output power and external quantum efficiency of the PSS LED at 20 mA forward current injection were measured at 10.4 mW and 14.1%, respectively. The output power enhancement could be attributed to the reduction in TD density using PSS. The other factor for enhanced light extraction was the output light scattered at GaN and sapphire interface.

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