

Characteristic enhancement of InGaN-based light emitting diodes grown on pattern sapphire substrates

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Abstract. Blue light-emitting diodes (LEDs) with an InGaN multi-quantum well (MQW) structure were fabricated on cone-shaped patterned sapphire substrate (PSS) using a single growth process of metal organic chemical vapor deposition (MOCVD). The PSS was proved to be an efficient method to decrease the threading dislocation (TD) density in GaN epilayer with the lateral growth mode on PSS. The LED designed on PSS increased the electroluminescence (EL) intensity. The internal quantum efficiency is increased by reducing the dislocation density, and light extraction efficiency is also enhanced owing to PSS.

1. Introduction

GaN and related compound semiconductors have been attracting great attention in optoelectronic device applications, for example light-emitting diodes (LEDs), laser diodes (LDs), and high-power and high-temperature electronics [1-3]. It is well known that high-density threading dislocations are inherent in epitaxial GaN films on sapphire substrates, due to the large difference in lattice constant and thermal expansion coefficient between the epitaxial layer and sapphire substrate. High dislocation density will affect the device properties, for instance device lifetime, electron mobility, and the quantum efficiency of radiative recombination. Thus, further more decreasing the dislocation density is an important problem for manufacturing high-performance InGaN LEDs. To enhance the crystalline quality for GaN-based epitaxial layers on sapphire substrate, different epitaxy methods have been recommended, for example extension lateral overgrowth (ELO) [4], cantilever extension (CE) [5], deflection selected passivation [6], micro-scale SiN_x or SiO_x patterned mask [7], plastic stress relaxation via buried AlGaIn crazing [8], and patterned sapphire substrate (PSS) [9]. The maskless, growth uninterrupted and single-step overgrowth technique is commendatory, which can decrease the TDs and add entire internal reflection of light owing to geometrical action [10, 11]. The various PSS were designed [12-15] which could be effectively enhance the external efficiency in InGaN-based LEDs grown on PSS through the effect of the optical reflection from the side edge of the etched



sapphire.

In this paper, the manufacture, optical and electrical properties of InGaN LEDs are discussed. The performance advance of the LED grown on PSS by contrasting LED on conventional planar sapphire substrates (CSS) is described here. Moreover, the microcosmic structures of LEDs on PSS were researched through a transmission electron microscopy (TEM).

2. Experiment

The samples were all grown over 2-in (0001) sapphire substrates with MOCVD system. Before the MOCVD growth, the PSS is prepared using dry etching to form a cone-shaped patterned array. The sapphire substrate was etched employing BCl_3/Cl_2 in an inductively coupled-plasma etcher. After that, the scanning electron microscopy (SEM) is used for inspecting the PSS, and inspecting micrograph is shown in figure 1. The diameter and height of each cone were about $2.5 \mu\text{m}$ and $1.5 \mu\text{m}$, and interval is $0.5 \mu\text{m}$. During the MOCVD growth, the Trimethylgallium, trimethylindium, and ammonia were used as precursors for Ga, In, and N, respectively. Biscyclopentadienyl magnesium and Si_2H_6 were used as p- and n-type dopants. H_2 and N_2 were used as carrier gases. The reactor pressure was maintained at 100 Torr. The LED structure is as following: a 25 nm thick GaN nucleation layer, a $2.5 \mu\text{m}$ thick un-doped GaN layer, a $2 \mu\text{m}$ thick highly doped n-type GaN layer, fifteen pairs of InGaN (2.5 nm)/GaN (12.5 nm) MQWs, a 25nm thick p-type AlGaIn electron blocking layer, and a 100 nm thick Mg-doped GaN layer. In order to obtain better coalescence on PSS, the u-GaN growth temperature was risen up 1120°C . LEDs with $300 \times 300 \mu\text{m}^2$ sizes were achieved via a normative photoetching technics until the n-GaN was exposed. Both p- and n-contacts were located on the epitaxial surface. The indium tin oxide (ITO) layer was deposited to form a p-side transparent contact layer and a current spreading layer, then the Cr/Au layer was deposited on the ITO layer to form the p-side and the n-side electrodes.

These samples were characterized by transmission electron microscopy (TEM) to reveal microstructure. TEM samples were processed with standard mechanical polishing and Ar ion-milling techniques to achieve electron transparency. The EL intensity of the LED lamp was observed utilizing an integrated sphere detector and the observed deviation was about 5%.

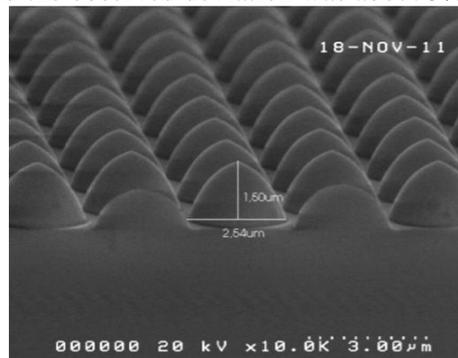


Figure 1. Plan-view SEM images of PSS.

3. Results and Discussion

To clarify the relation between the dislocation and microstructure, cross-sectional TEM observation for GaN on PSS was achieved. figure 2 shows cross-sectional TEM images of GaN on PSS. The GaN was assorted into three parts: (A) a GaN region (in circle 1 in figure 2(b)) with a high dislocation density where many dislocations begin from the interface owing to the lattice mismatch between GaN and sapphire, as usually observed when GaN is grown on a flat sapphire substrate, (B) a GaN region (in circle 2 in figure 2(b)) with few dislocation, where there is no vertical disseminate of dislocations because dislocations engendered anear the cone border bent as progressing GaN epitaxial growth, and (C) a GaN region (in circle 3 in figure 2(b)) with high dislocation density on the top of the cone area, this result is attributed to full coalescence by the lateral overgrowth of the GaN film on the trench region. It should take notice that the bent dislocations and presence of voids as indicated by arrows in figure 2(a) can effectively reduce the TDs by ELO. Thus, the ELO caused by the cone shaped pattern

is responsible to the specific way of defect reduction and for the strain relaxation in GaN epilayers on PSS. In addition, a recrystallized GaN initiation layer (as indicated by arrows in figure 2(b)) is also observed as it grew into three-dimensional islands on the bulging patterns. Contrasting difference in the two-beam bright field images, we inferred that this initiation islands had a different crystallographic orientation relationship with the later GaN layer.

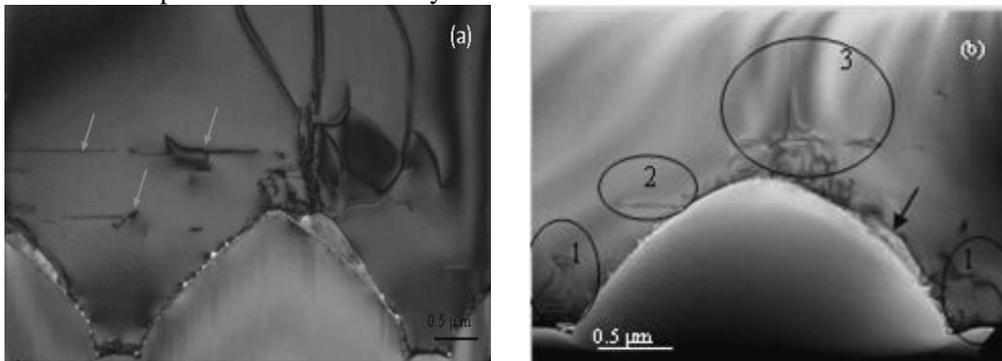


Figure 2. Cross-sectional TEM images of GaN on PSS.

Figure 3 shows the different luminescence ability for different injection currents. The luminous intensity of the LEDs on PSS and CSS at 40 mA injection current were 320.6 and 198.4 mcd. The luminescence ability of LED on PSS was 1.62 times higher than that of LED on CSS at the applied current of 40 mA. Through restraining the total internal reflection at cone-shaped interface and enhancing crystal quality owing to decrease of TDs via PSS, the light extraction efficiency is increased, which results in larger luminous intensity for LED grown on PSS. The main cause of enhancement of luminous intensity is that the photons obtain a large number of opportunities to seek out the escape cone. The PSS can induce photons that were initially radiated out the escape return to the escape cone on LED surfaces. The chance of photons escaping from the LED on PSS is enhanced, thus light extraction is more effective. When reaching 78 mA for LED on PSS and 72 mA for LED on CSS, the luminous intensities begin to reduce although the injection current rises. The decline of luminous intensity relates to the thermal dissipation. Because when carriers recombine in defects and/or dislocations, this recombination is non-radiative, yet non-radiative recombination will generate heat. The energized carriers that get the heat are more likely to escape from the InGaN/GaN MQW active layer. Due to the thermal action at high temperature, the effective radiation recombination rate will decrease. Because the PSS can effectively reduce the dislocation density, the heat dissipation effect for LED on PSS is superior to LED on CSS. Therefore, the maximum luminous intensity for LED on PSS is also above LED on CSS at a bigger injection current.

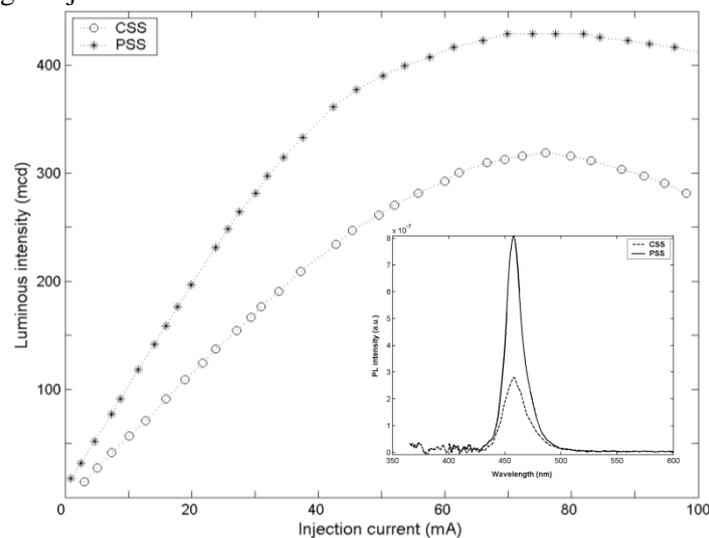


Figure 3. Luminous intensity of LEDs grown on PSS and CSS, the inset shows the room temperature EL spectra for LED on PSS and CSS.

The inset in figure 3 presents room temperature EL spectras of LED on PSS and on CSS at a forward current of 20 mA. A little blue shift of approximate 4 nm was viewed for the LED on PSS. This alteration can be relate to the band filling effect and screening effect in a piezoelectric field quantum well. The larger piezoelectric field is caused by the larger lattice mismatch in InGaN-based multiple quantum wells. The EL intensity of the LED on PSS is higher about 48% than that of LED on CSS as an injection current 20 mA. Moreover, the full width at half maximum for LED on PSS and on CSS is 22 nm and 34 nm respectively. It is well known that dislocations are non radiative recombination centers, while nonradiative recombination directly affects luminous efficiency. Therefore, the key improvement in EL intensity is mainly traceable to the reduction of TDs for LED on PSS. The another reason for the improvement of light extraction efficiency is effect of optical back scattering, because PSS can raise the chance of optical back scattering for LED on PSS.

4. Conclusion

We studied the strong association between the structure and optical characters of InGaN-based blue LEDs on PSS. The LED on PSS exhibit improved performance compared to the LED on CSS. The ELO caused via the cone shaped pattern is responsible for the specific way of defect reduction and for the strain relaxation in GaN epilayers on PSS. The enhancement of EL intensity of LED on PSS depends on upgrading of the quality of GaN epitaxial layer and high light extraction efficiency by PSS. Owing to the effect of facets of PSS, the light can be effectively induced to the top escape-cone of the LED surface.

Acknowledgments

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References

- [1] Nakamura S, Senoh M, Iwasa N, Nagahama S, Yamada T and Kukai T 1998 *Jpn. J. Appl. Phys.* **37** L479
- [2] Tadatomo K, Okagawa H, Ohuchi Y, Tsunekawa T, Jyouichi T 2001 *Physica Status Solidi*. **188** 121
- [3] Jeon H C, Rark C J, Cho H Y, Kang TW, Kim T W, Oh J E and Na J H 2005 *J. Korean Phys. Soc.* **47** S489
- [4] Zheleva T S, Nam O H, Bremser M D and Davis R F 1997 *Appl. Phys. Lett.* **71** 2472
- [5] Follstaedt D M, Provencio P P, Missert N A, Mitchell C C, Koleske D D, Allerman A A and Ashby C I H 2002 *Appl. Phys. Lett.* **81** 2758
- [6] Lo M H, Tu P M, Wang C H, Cheng Y J, Hung C W, Hsu S C, Kuo H C, Zan H W, Wang S C, Chang C Y and Liu C M 2009 *Appl. Phys. Lett.* **95** 211103
- [7] Sakai A, Sunakawa H, and Usui A 1997 *Appl. Phys. Lett.* **71** 2259
- [8] Bethoux J M, Vennegues P, Natali F, Feltin E, Tottereau O, Nataf G, Mierry P De and Semond F 2003 *J. Appl. Phys.* **94** 6499
- [9] Lee Y J, Hwang J M, Hsu T C, Hsieh M H, Lee B J, Lu T C, Kuo H C and Wang S C 2006 *IEEE Photon. Technol. Lett.* **18** 1152
- [10] Yamada M, Mitani T, Narukawa Y, Shioji S, Niki I, Sonobe S, Deguchi K, Sano M and Mukai T 2002 *Jpn J Appl Phys.* **41** L1431
- [11] Hsu Y P, Chang S J, Su Y K 2004 *J Cryst. Growth* **261** 466
- [12] Lee J H, Oh J T, Park J S, Kim J W and Kim Y C, Lee J W and Cho H K 2006 *Phys. Status Solidi (c)* **3** 2169
- [13] Lee J H, Oh J T, Choi I S and Kim Y C 2007 *J. Korean Phys. Soc.* **51** S249
- [14] Song J C, Lee S H, Lee I H, Seol K W and Lee C R 2007 *Journal of Crystal Growth* **308** 321
- [15] Jeonga S M, Kissinger S, Kim D W, Lee S J, Kim J S, Ahn H K and Lee C R 2010 *Journal of Crystal Growth* **312** 258