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Enhancement of Nitride-Based Near-Ultraviolet Vertical-Injection Light-Emitting Diodes with Roughened Mesh-Surface by Adopting Pattern Sapphire Substrate

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1. Introduction

Recently, near-ultraviolet (NUV) emitters are of interest for fluorescence based chemical sensing, flame detection, optical storage and a pumping source for exciting phosphor applications [1]. These nitride-based LEDs are also potentially useful for solid state lighting. However, it is still difficult to manufacture high-power NUV LEDs. It can be ascribed to the sensitivity to dislocation and the total internal reflection effect which influence the total external quantum efficiency [2]-[3]. Nowadays, state of the art vertical-injection LEDs (VLEDs) with roughened surface was demonstrated to be one of high potential light-emitting devices to achieve high brightness operation due to its excellent thermal dissipation and light extraction efficiency [4]-[5]. Therefore, how to further reduce the dislocation density and improve the light extraction efficiency are important issues for fabricating high-performance NUV LEDs. In this letter, the pattern sapphire substrate (PSS), wafer bonding, LLO, and chemical wet etching surface treatment processes were implemented to fabricate the roughened mesh-surface NUV-VLEDs for further enhancement of NUV-VLEDs. Both internal quantum efficiency and external quantum efficiency can be improved by the combination of crystal growth on PSS and VLEDs structure techniques. The electrical and optical properties of the roughened mesh-surface VLEDs will be reported.

2. Experiments

The NUV-LED wafers used in this study were grown by low-pressure metal organic chemical vapor deposition onto conventional sapphire substrate and PSS. PSS was fabricated by the standard photolithography and dry etching processes with bump-array patterns of 3 μm diameter, 3 μm spacing and an etching depth of 1 μm. Fig. 1(a) shows the top and cross-sectional side views scanning electron microscope (SEM) images of the pattern sapphire substrate. The NUV-LED structure comprised a 40-nm-thick GaN nucleation layer, a 2.0 um-thick undoped GaN layer, a 2.5 um-thick Si-doped n-type GaN cladding layer, an unintentionally doped active region of 405-nm emitting wavelength with five periods of InGaN–GaN multiple quantum wells, a 0.2 μm -thick Mg-doped p-type GaN cladding layer and a Si-doped n-InGaN-GaN short period superlattice (SPS) structure. Fig. 1(b) shows a cross-sectional SEM micrograph of a GaN-based LED grown on a PSS. The PSS can be buried completely by a GaN epitaxial layer without appearance of void. By performing a detail comparison, both types of NUV-LED wafers with and without PSS were subjected to the VLEDs processes. The fabrication process of VLEDs on Si began with the deposition of highly reflective ohmic contact layer Ni/Ag/Pt and Cr/Au bonding layer on p-GaN. Both types of samples were then bonded onto a Cr/Au-coated p-type conducting Si substrate at 350 ℃ for 1 hr. The wafer bonded samples were then subjected to the LLO process to remove the sapphire substrate. Then the u-GaN was etched away to expose the n-GaN layer and then a square mesa of 750 μm x 750 μm was created by an ICP etcher. In order to further increase the light extraction efficiency of VLEDs, the top n-GaN surfaces surface was treated through a chemical etching using 40 % KOH by weight dissolved in ethylene-glycol solution at 120 ℃ for 120 sec. Finally, a Cr/Pt/Au electrode was deposited as the n-type contact and the VLEDs with and without mesh-surface was obtained.

3. Results and disscussions

The surface morphology of VLEDs was examined by SEM as shown in fig. 2. It is obviously observed that the mesh-surface was naturally formed due to the epi-growth on PSS. The hole-array mesh-surface of 3 μm diameter, 3 μm spacing and 1 μm depth shows a complementary structure from the PSS and was nearly crack-free. It indicates that the epi-layer was not adversely affected to device structure during LLO process. Fig. 2 (b) is a SEM image of the mesh-surface after KOH chemical etching. Such a roughening surface can improve the escape probability of photons for luminance enhancement of VLEDs. Figure 3 shows the room-temperature electroluminescence (EL) spectra of the flat-surface and mesh-surface VLEDs under 20 mA current injection. The EL peak positions of both the LEDs were located at 405 nm. The EL intensity of the mesh-surface LED is higher than that of the flat-surface one. This significant enhancement in EL intensity could be attributed to the increase of the extraction efficiency by scattering the emission light from the mesh-surface. Additionally, it is believed that the improvement in the internal quantum efficiency (IQE) of the PSS LED [6] could also contribute to the higher EL intensity of mesh-surface VLED. Current-voltage (*I-V*) and intensity-current (*L-I*) characteristics of four types VLEDs: conventional flat-surface VLEDs with [LED I] and without [LED II] chemical etching, mesh-surface VLEDs with [LED III] and without [LED IV] chemical etching were shown in fig. 4. It was found that the I-V curves were almost identical and similarity for these devices. According to the corresponding L-I characteristics, four types of VLEDs showed linear characteristics up to 500 mA which indicating a good thermal dissipation management for the VLEDs structure design. It is clearly observed that the light output power of the LED-III was higher than those of LED I. This result could be attributed to the increase of total external quantum efficiency by scattering the emission light from the mesh-surface and dislocation reduction of epi-growth on PSS. Furthermore, it is found that the light output power of meshed and flat surface VLEDs could be significantly raised from 100 mW [LED-III] to 130 mW [LED-IV] and 75 mW [LED-I] to 110 mW [LED-II] under 350 mA current injection respectively after surface roughening process. We note that bare LED-IV (without an epoxy lens encapsulated) exhibit about 20% output power enhancement compared to that of LED-II. Such an enhancement can be ascribed to the increase of surface emission area which improves the probability of photons escaping from semiconductor to air and the reduction of dislocation which increases the internal quantum efficiency by adopting the PSS.

4. Conclusions

In summary, the NUC-VLEDs with rough meshed-surface structure were investigated. The formation rough meshed-surface structure improves not only the surface emission area but the escape probability of photons due to the angular randomization of photos insides the LED structure. In addition, the IQE can be increase by adopting the PSS process. By this novel device design, the output power can be further enhanced up to 20 %.

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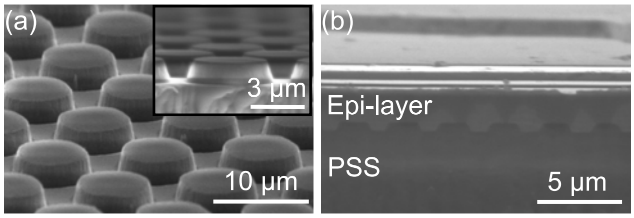

Fig. 1. SEM images of (a) pattern sapphire substrate and (b) a GaN-based LED grown on a PSS.

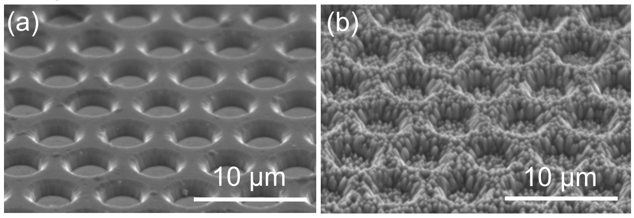

Fig. 2. SEM images of (a) surface morphology of mesh-surface VLEDs after LLO process, (b) mesh-surface VLEDs after chemical etching process.

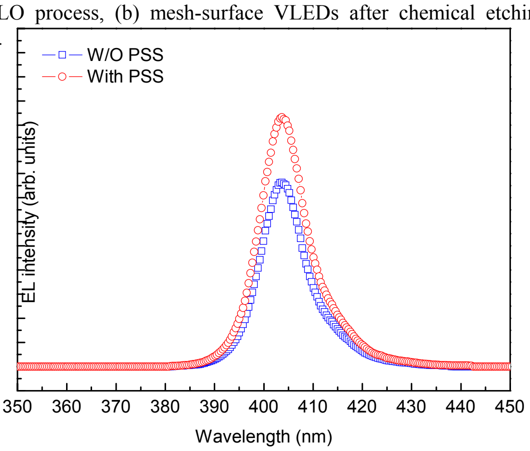

Fig. 3. Room-temperature EL spectra of flat-surface and mesh-surface VLEDs

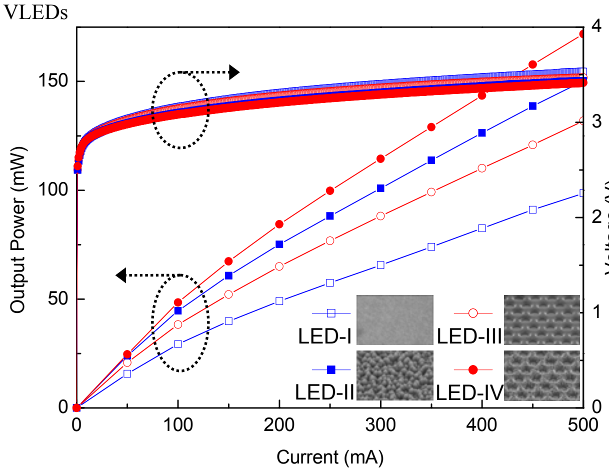

Fig. 4. L-I-V characteristics of flat- and mesh- surface VLEDs with and without chemical wet etching process