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Enhanced Light Output of Vertical-Structured GaN-Based LEDs with Surface Roughening using KrF Laser and ZnO Nanorods

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1. Introduction

GaN-based semiconductors have attracted considerable interest in relation to their potential use in optoelectronic devices, such as light emitting diodes (LEDs) and laser diodes (LDs) [1-2]. Nevertheless, severe current-crowding effect and heat-conducting problem usually encounter in conventional lateral conducting GaN-based LEDs, which is mainly due to the use of insulating sapphire substrate. Recently, vertical-structured GaN-based LEDs based on the transfer of sapphire substrate to a metal or semiconductor substrate have been shown being very promising in enhancing the light output, efficiency, and power capability of the GaN-based LEDs [3]. However, the light exterinal efficiency from a GaN flat surface is only ~4%. Due to the narrow escape cone (~23.6°), the parasitic nonradiative losses during photon recycling degrade the external quantum efficiency. Extensive efforts have been made to improve the light extraction from GaN LEDs, such as surface roughening [4] and forming photonic crystals on the top layer.

In this study, to further improve the optoelectronic properties of Vertical-Metallic-substrate GaN-based light emitting-diodes (VM-LEDs, surface roughening of n-GaN using KrF laser and chemical etching followed by the hydrothermal growth of vertically-aligned ZnO nanorods on the roughened n-GaN surface were investigated and discussed.

2. Experiments

Figure 1 illustrates the key fabrication processes of the proposed VM-LEDs. Samples used in this work were grown by metal organic chemical vapor deposition (MOCVD). For device isolation, an inductively coupled plasma (ICP) dry-etching was conducted to etch the wafer all the way down to the surface of the sapphire substrate with photoresist mask. It was followed by the removal of the photoresist mask and the deposition of a passivation layer (SiO_2) in the cutting-way. Note that the device size and cutting-way width are 1300 μm×1300 μm (suitable to tune the KrF laser beam energy density exactly) and 25 μm, respectively. A highly reflective Ni(1 nm)/Ag(150 nm)/Ni(100 nm) metal system was deposited and patterned on the p-GaN layer by E-beam evaporator, which was subjected to an thermal annealing at 500°C in N_2 ambient to realize good ohmic behaviors. Prior to nickel electroplating, an adhesive and seed layer comprising of a Cr(100 nm)/Ti(100 nm)/Au(100 nm) metal system was deposited by E-beam evaporator. Subsequently, an 80-μm-thick nickel substrate was formed by electroplating under a constant current of 0.6 A for 90 min (Fig. 1(a)). Through the use of metal mask to define both size and shape of KrF excimer laser beam (25 ns pulse width at 248 nm) and the LLO process was performed at a reactive energy of 800 mJ/cm^2 (Fig. 1(b)). After the removal of the sapphire substrate, the exposed buffer layer (u-GaN) was removed by ICP (Fig. 1(c)), and then n-GaN was irradiated in air by the same KrF laser with 120 pulses at an energy density of 750 mJ/cm^2 (Fig. 1(d)). It was followed by the dipping into a HCl:DI (1:1) to remove metallic Ga and surface roughening with 6-mol KOH solution at 60°C to improve light extraction (Fig. 1(e)). Prior to the formation of Cr/Al/Cr/Au metal pad to the exposed n-GaN layer, device mesa (300 μm×300 μm) was defined by ICP and surface cleaning with HF/diluted HCl solutions was performed to improve ohmic properties, respectively. Finally, metal pad was protected with photoresist and ZnO nanorods were synthesized vertically on n-GaN surface by hydrothermal method (Fig. 1(f)). Note that VM-LEDs without surface roughening by KrF laser and without ZnO nanorods (abbreviated as regular VM-LEDs), and VM-LEDs with surface roughening by KrF laser but without ZnO nanorods were also fabricated for comparison.

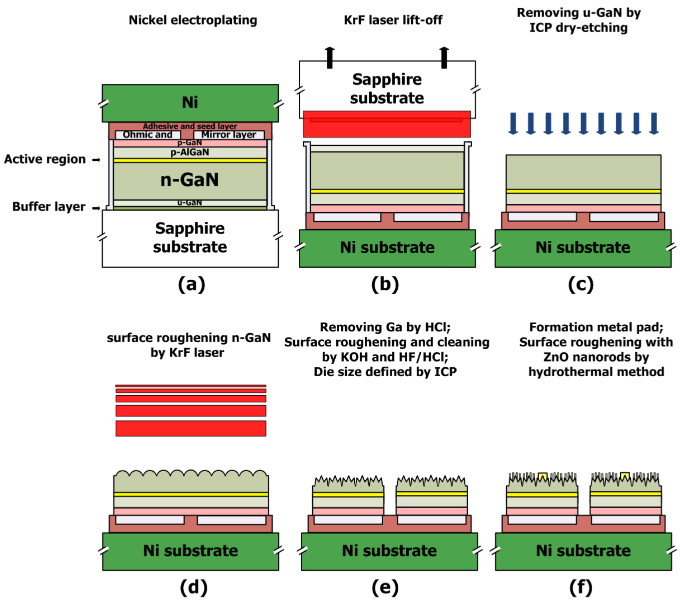

Fig. 1 The fabrication process of VM-LEDs employing n-GaN surface roughness by KrF laser, KOH wet etching and vertically-aligned ZnO nanorods.

3. Results and Discussion

The scanning electron micrographs of the n-GaN surface roughening for various process stages were shown in Fig. 2. Note that the use of KrF excimer laser to roughen n-GaN produced simultaneously curved protrusions on the exposed n-

GaN layer. Moreover, diluted KOH wet etching followed by the growth of ZnO nanorods also made a textured surface, which would further increase the light extraction efficiency. Figure 3 shows the comparison of L-I characteristics of regular VM-LEDs and prepared VM-LEDs with various roughening schemes onto the n-GaN top-layer. Based on experimental results, VM-LEDs with the n-GaN surface roughened by KrF laser and covered with vertically-aligned ZnO nanorods, as compared to regular VM-LEDs, reveal an enhancement in light output power (i.e., ΔLop/Lop) by 29% and 41% under an injection current of 20 mA and 100 mA, respectively.

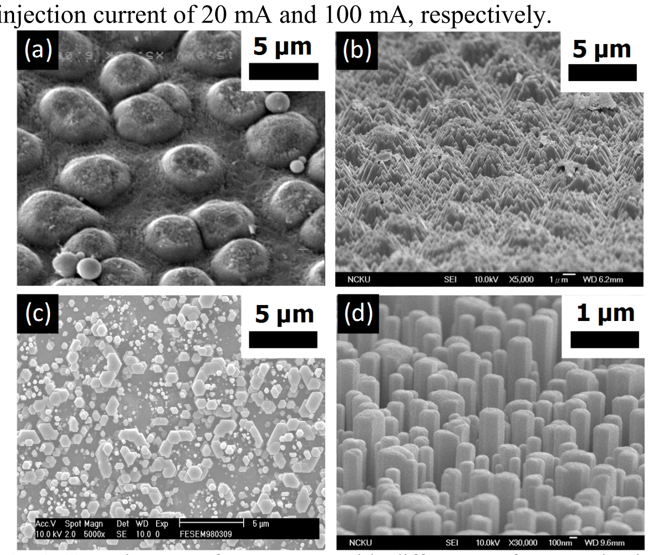

Fig. 2 SEM images of VM-LEDs with different surface roughening schemes: (a) surface roughening by KrF laser with 120 pluses at energy density of 750 mJ/cm^2; (b) surface roughening by KrF laser and diluted KOH wet etching. (c) top- and (c) side-view (d) of sample with surface roughened by KrF laser, diluted KOH, and covered with vertically-aligned ZnO nanorods by hydrothermal method, respectively.

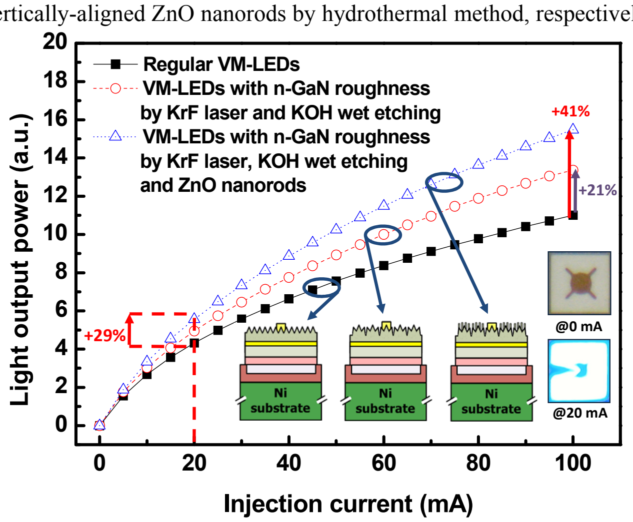

Fig. 3 Comparison of Lop-I characteristics of regular VM-LEDs and VM-LEDs prepared in this work. The inset shows the device diagram and photos of light emission at 20 mA from the fabricated VM-LEDs with n-GaN roughened by KrF laser, KOH wet etching, and covered with vertically-aligned ZnO nanorods.

Moreover, even as compared to the regular VM-LEDs, VM-LEDs with surface roughening by only the KrF laser etching, it still gains about 21% increment in Lop at 100 mA, indicating surface roughening via KrF laser irradiation would be beneficial for photons escape from device.

Figure 4(a) shows the room-temperature electro-luminescence (EL) spectra of VM-LEDs with various surface roughening schemes under an current injection of 20 mA. It is seen that the EL peak of regular VM-LEDs and VM-LEDs prepared in this work located at 451 nm. The comparison of I-V characteristics of various VM-LEDs is shown in Fig. 4(b). Compared to regular VM-LEDs, VM-LEDs with n-GaN surface roughening by KrF laser show a decrease in forward voltage drop (Vf) from 3.22 (3.9) V down to 3.09 (3.69) V under an injection current of 20 (100) mA. Note that the I-V characteristics of the VM-LEDs exhibits good electrical properties even if after growing ZnO nanorods on top layer.

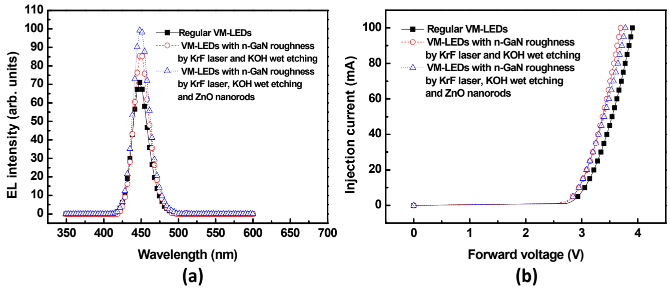

Fig. 4. Comparison of (a) EL spectra at 20 mA and (b) I-V characteristics of regular VM-LEDs and VM-LEDs with various surface roughening schemes onto the n-GaN top-layer.

The improvements in Lop and Vf of the prepared VM-LEDs could be attributed the scattering of photons from the curved protrusions and ZnO nanorods (refractive index= 2.1-2.5) [5], and good electrical contact between metal pad and laser-irradiated n-GaN surface [6].

4. Conclusion

In summary, the fabrication of vertical-structured GaN-based LEDs with surface roughening by KrF laser and growing ZnO nanorods process has been demonstrated and investigated. Compared to regular VM-LEDs, the VM-LEDs prepared in this work have been shown having an enhancement in Lop by 29% and 41% at 20 mA and 100 mA, respectively. It is expected that the use of proposed KrF excimer laser surface roughening process in conjunction with the growth of ZnO nanorods would be a potential roughening technology for the further improving light extraction efficiency of GaN-based LEDs for solid-state lighting in the near future.

Acknowledgements

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