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III-Nitride Light Emitting Diodes with GaN Micro-Pillars around Mesa and Patterned Substrate

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Nitride-based materials have recently emerged as important semiconductor materials, leading to the realization of high performance light emitters from ultraviolet (UV) to blue and green spectral regions [1, 2]. High efficiency nitride-based LEDs are also potentially useful for solid-state lighting. To approach solid-state lighting, however, one needed to be improved further is light output of the LEDs. There are several parameters considerably related to the light output of the LEDs, such as light extraction efficiency, internal quantum efficiency, and current distribution of the LEDs. It has been demonstrated that the light output of the GaN-based LEDs can been significantly enhanced by extracting the light traveled within the LEDs [3-7]. In this work, GaN-based blue LEDs grown on patterned sapphire substrates with textured sidewalls, microsize pillars (μ-pillars) around the mesa region were fabricated and their optoelectronic characteristics of these fabricated LEDs are also discussed.

Samples used in this work were all grown on 2-inch (0001) patterned/un-patterned sapphire substrates by metal-organic chemical vapor deposition. Periodic cylinders were fabricated by dry etching on the sapphire substrates (PSS). The depth, diameter and spacing for each cylinder are 0.7, 3 and 3 μm, respectively. Detail layer structures and growth procedures have been described in the previous report [5]. A 200-nm-thick indium-tin-oxide (ITO) film and a 2-nm-thick SiO_2 film were subsequently evaporated onto the LED wafers, serving as transparent contact layers (TCL) and hard masks for texturing mesa sidewalls and etching of micro-pillars, respectively. Depth of the mesa with texture sidewalls and the μ-pillars is about 1.1μm. Cr/Au (50/200nm) metal contact was deposited on the ITO TCL and the exposed n^+-GaN layers to form p-type electrode (anode) and n-type electrode (cathode), respectively. In this study, the LEDs grown on un-patterned substrates without or with sidewall-textured mesa and μ-pillars were also fabricated for comparison and labeled as LED I and LED II, respectively. Meanwhile, the LEDs grown on patterned substrates without or with sidewall-textured mesa and μ-pillar were labeled as LED III and LED IV, respectively. All fabricated LEDs have a dominant emission wavelength of 465 nm.

Figure 1(a) and (b) show a scanning electron microscopy (SEM) image of the fabricated device and an enlarged image at the mesa edge of the LED with a textured sidewall and μ-pillars. As shown in Fig. 1(a), the device is in a size of 250×575 μm^2. As shown in Fig. 1(b), the diameter of the textured sidewall and μ-pillars, as well as the spacing between two neighboring pillars, was 3μm. The light output power and injection current vs. forward voltage (L-I-V) of the fabricated LEDs are shown in Fig.2. The forward voltage (V_f) at 20mA is approximately 3.2 V for all LEDs in this work indicating that the electrical properties of LEDs are not deteriorated by textured sidewalls, μ-pillars and PSS processes. The light output powers are 3.73, 4.71, 4.77, and 5.96 mW for LED I, LED II, LEDIII, and LED VI, respectively, driving at 20mA. As shown in Fig. 2, the 20mA-output-power of LED IV was improved by 60% in magnitude compared with LED I by combining the sidewall-textured mesa, GaN μ-pillars around mesa and patterned substrate. Usually the light emitted from the active layer could partially be trapped in the whole LED region because of the Fresnel loss and total reflection angle limit. Comparing our LED III and LED I, an output power enhancement of about 28% in magnitude by introducing the PSS. Normally the surface of the exposed n^+-GaN is optical flat may resulting in small critical angle and total reflection of the light traveling under the exposed n^+-GaN region. From the results shown in Fig. 2, the μ-pillars around the mesa can increase the light output power significantly. Beside the μ-pillars around the mesa, the sidewall-textured mesa sidewall would also help the light to get out of the LEDs emitting region because of scattering effects.

In order to understand the fraction of light emitted around the device, the light emission intensity distribution of LEDs has been measured with a charge-coupled device (CCD) camera. Figure 3 shows the light intensity profiles crossed the LEDs and measured at a current of 20mA for all LED samples. The light intensity image of the whole LED with or without μ-pillars and sidewall-textured mesa are shown in the inset of Fig. 3. The white color indicates the highest emission intensity. Compared with LED I (conventional LEDs, see the inset (b) in Fig. 3), the LEDs with sidewall-textured mesa and μ-pillars (LED II, insert (a) in Fig. 3) clearly shows more light escaping from the exposed n^+-GaN around the mesa region. The quantification of light intensity in the exposed n^+-GaN region of all LEDs is indicated in Fig. 3. We found that the light intensity of the exposed n^+-GaN for the LEDs with a sidewall-textured mesa and μ-pillars (LED II and IV) were stronger than that for the LEDs without the design structures (LED I. III). On the other hand, the LEDs with PSS (LED III) showed stronger light intensity than the LEDs without PSS (LED I), which may result from more light scattering at the GaN/patterned Sapphire interface. However, light intensity at the exposed n^+-GaN region of LED III was less than that of LED IV indicating more light could escape out more efficiently form the exposed n^+-GaN region through these micro structures. Additionally, the decrease in light intensity was observed from the light intensity profile in Fig. 3 in all LEDs. The decrease behavior in light intensity a can be fitted by a function proportional to $(1/r) \times \exp(-r/r_0)$ where r_0 is the light decay length. The values of decay length for LED II, III and IV can be obtained from the fitting results in Fig. 3 are 17 μm, 32 μm, and 12 μm respectively, indicating that light emitting from the active region can travel in less path to escape out of the device with sidewall-textured mesa and μ-pillars on the n^+-GaN surface. In addition to the enhancement in the external efficiency, this also leads to a faster radial decay of emission.

In summary, we have demonstrated an enhancement in output power about 60% of LEDs with sidewall-textured mesa, μ-pillars around mesa and patterned substrate. From the light intensity profile of the LEDs with sidewall-textured mesa and μ-pillars, we found that the light intensity over the exposed n^+-GaN of LEDs was stronger than that of LEDs without sidewall-textured mesa and μ-pillars. In conclusion, this kind of device structure has demonstrated a significant improvement on extraction of light in the GaN-based LEDs and an advantage of no additional steps to the conventional device process, which can be considerably useful and costless to the high-brightness /high performance GaN-based LEDs.

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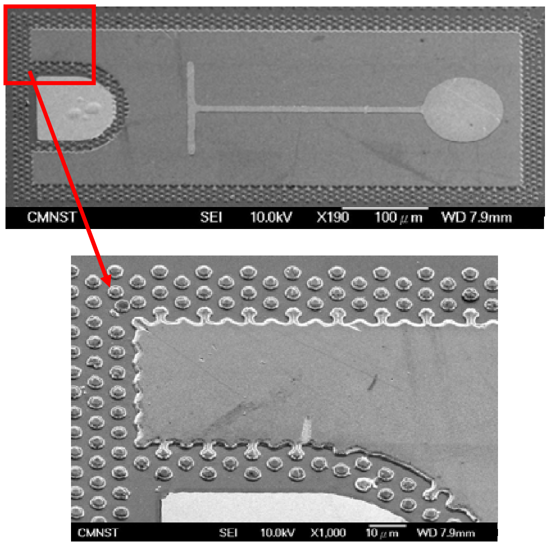

(a) (b)

Fig. 1 SEM images of (a) full view and (b) enlarge view of the LED IV with textured side wall and μ-pillars..

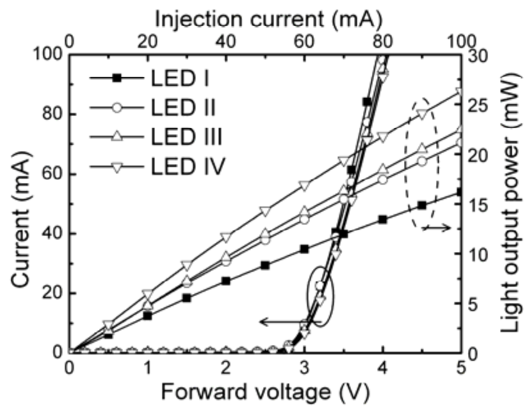

Fig. 2 L-I-V characteristics of the fabricated LEDs.

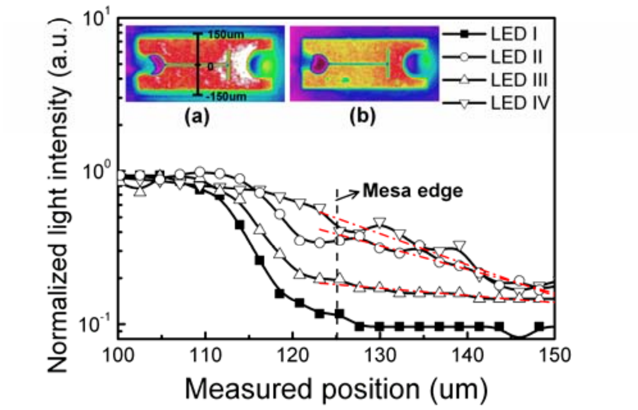

Fig. 3 The light intensity profiles crossed the LEDs at 20mA of all LED samples. Insets show the light intensity image of (a) LED II and (b) LED I.