

## Improvement of InGaN/GaN light emitting diode performance with a nano-roughened p-GaN surface by excimer laser-irradiation

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### Abstract

In this paper, we reported the InGaN/GaN light emitting diode (LED) with a nano-roughened top p-GaN surface which caused by KrF excimer laser-irradiation. Comparing with the conventional LED, the brightness of InGaN/GaN light emitting diode (LED) was raised by a factor of 1.25 at 20 mA after KrF excimer laser-irradiation ( $250 \text{ mJ cm}^{-2}$  at 248 nm for 25 ns). Meanwhile, the operation voltage of InGaN/GaN LED was reduced from 3.55 to 3.3 V at 20 mA with 29% reduction in the series resistance. The causes for the brightness increase can be attributed to laser-irradiation induced nano-roughening of p-GaN surface. The reduction in the series resistance can be attributed to the increased contact area of nano-roughened surface and higher hole concentration after laser-irradiation.

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**Keywords:** Gallium nitride (GaN); Light emitting diode (LED); Excimer laser

GaN-based materials have attracted considerable interest in optoelectronic devices such as light emitting diodes (LEDs) and laser diodes (LDs) [1–4]. Recently, as the brightness of GaN-based LEDs has increased, applications such as displays, traffic signals, backlight for cell phone, exterior automotive lighting, printers, short-haul communication, and optoelectronic computer interconnects have become possible. However, the internal quantum efficiency for GaN-based LEDs is far smaller than 100% at room temperature due to the activation of non-radiative defects. In addition, the external quantum efficiency of the GaN-based LEDs is often low due to the large refractive index difference between the nitride epitaxial layer and the air. It has been reported that the refractive indexes of GaN and the air are 2.5 and 1, respectively. Thus, the critical angle—for the light generated in the InGaN–GaN active region to escape is about  $[\theta_c = \sin^{-1}(n_{\text{air}}/n_{\text{GaN}})] \sim 23^\circ$  which limited the external quantum efficiency of conventional GaN-based LEDs to be only a few percent [5]. Previously, there has been intensive research into the improvement of light extraction efficiency

(external quantum efficiency) and the enhancement of brightness in the LEDs [5–9]. Recently, Huh et al. reported the 62% increase in wall-plug efficiency in the InGaN/GaN LED with a micro-roughened top surface using the metal clusters as a wet etching mask [10]. Chang et al. reported output power enhancement from the InGaN–GaN MQW LEDs with low temperature (800 °C) grown cap layers [11]. All these allow the photons generated within the LEDs to find the escape cone, through multiple scatterings from the rough surface. As a result, the light extraction efficiency and the LED output intensity could both be enhanced. Recently the use of KrF excimer laser-irradiation to activation hole concentration of the Mg-doped GaN layers [12], to improve the metal contacts to n- and p-type GaN were reported [13]. During laser irradiation, the GaN decomposed into metallic Ga and nitrogen gas. The decomposed metallic Ga reacted with oxygen in air to form a Ga oxide layer (e.g.  $\text{Ga}_2\text{O}_3$ ). The amorphous  $\text{Ga}_2\text{O}_3$  can be easily removed by HCl solution. Jang et al. observed the surface roughening with the laser-irradiation in both the n- and p-type GaN samples [13]. In addition, in p-type GaN, the laser-irradiation increased the acceptor concentration and the activation efficiency of Mg dopants (by the factor of  $\sim 2$ ). In this paper, we report on the improved light output and electrical properties of an GaN-based LEDs with a

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nano-roughened surface created by pulsed KrF excimer laser irradiation. The current–voltage ( $I$ – $V$ ) measurement showed that the forward voltage of LED with a nano-roughened surface was lower than that of a conventional LEDs. Furthermore, the light output efficiency of LED with a nano-roughened surface was significantly increased compared to that of the conventional LED without roughened surface.

The GaN LED samples were grown by metal-organic chemical vapor deposition (MOCVD) with a rotating-disk reactor (Emcore D75<sup>TM</sup>) on a  $c$ -axis sapphire (0001) substrate at the growth pressure of 200 mbar. trimethylgallium (TMG), trimethylaluminum (TMA) ammonia,  $\text{CP}_2\text{Mg}$  and  $\text{Si}_2\text{H}_6$  were used as Ga, Al, N, Mg, Si sources, respectively. The LED structure consists of a 30 nm-thick GaN low temperature buffer layer (grown at 560 °C), a 2.0  $\mu\text{m}$ -thick undoped GaN layer, a 1.5  $\mu\text{m}$ -thick highly conductive n-type GaN layer (grown at 1050 °C), a multiple quantum wells (MQW) region consisting of 2/5 nm-thick  $\text{In}_{0.21}\text{Ga}_{0.79}\text{N}/\text{GaN}$  five periods multiple quantum wells (grown at 750 °C), finally a 0.3  $\mu\text{m}$ -thick p-type GaN were grown at 900 °C. The nano-roughened LED using a KrF excimer laser (Lambda Physik LPX210) at wavelength of  $\lambda = 248$  nm with pulse width of 25 ns, repetition rate of 10 Hz in air. The incident laser fluence was  $\sim 250$   $\text{mJ cm}^{-2}$  and laser-irradiation time was 10 min, after dipped into a HCl:DI (1:1) solution for 5 min to remove metallic Ga produced on the surface. Surface roughness of the LED cap layer was measured by tapping mode atomic force microscopy (branded with Veeco) before and after KrF excimer laser-irradiation and HCl treatment.

The conventional LED and LED with nano-roughened surface were fabricated using standard process (four mask steps) with mesa area (300  $\mu\text{m} \times 300 \mu\text{m}$ ). First, the 0.5  $\mu\text{m}$   $\text{SiO}_2$  was deposited onto the sample surface using plasma enhanced chemical vapor deposition (PECVD). By means of photoresist lithography, the mesa pattern was defined after wet etching  $\text{SiO}_2$  by buffer oxide etching solution. The mesa etching was then performed with  $\text{Cl}_2/\text{Ar}$  as the etching gas in an ICP-RIE system (SAMCO ICP-RIE 101iPH) which the ICP source power and bias power operated at 13.56 MHz. Finally, the metal contact layers, included transparent contact and pad layers, were patterned by a lift-off procedure and deposited onto samples using electron beam evaporation. Ni/Au (3/5 nm) was used for transparent and Ti/Al/Ni/Au (20/150/20/200 nm) was used for n-type electrode. Finally, Ni/Au (20/1500 nm) was deposited onto both exposed transparent and n-type contact layers to serve as bonding pads.

Fig. 1(a) and (b) shows the AFM images presenting the change of surface morphology with laser-irradiation on p-GaN surface with and without HCl treatment. The p-GaN cap layer of conventional LED has root mean-square (RMS) roughness of  $\sim 2.7$  nm. It was found that the surface of conventional LED device was rough. Such a rough surface could be attributed to the fact that Ga atoms might not have enough energy to migrate to proper sites at relative low growth temperature (900 °C). The RMS roughness of p-GaN surface increased drastically to the value of 13.2 nm after laser-irradiation and HCl treatment (RMS  $\sim 4.5$  nm after laser-irradiation). Similar results were also observed in Ref. [13].

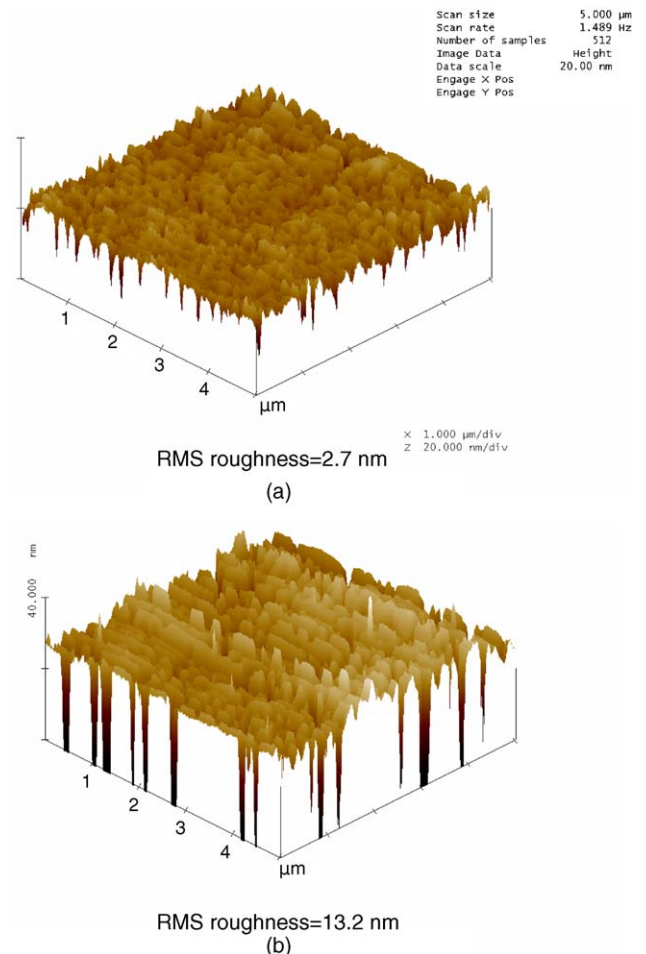


Fig. 1. AFM images presenting the top surface morphology of a LED sample. (a) Conventional LED p-GaN surface image. (b) Nano-roughened LED top p-GaN surface image.

Current–voltage ( $I$ – $V$ ) characteristics of conventional and nano-roughened LEDs were also measured. Fig. 2(a) shows the  $I$ – $V$  characteristics of conventional and nano-roughened LEDs. The operation voltage at 20 mA of conventional and nano-roughened LEDs were 3.55 and 3.3 V, respectively, and it was also found that dynamic resistance ( $R = dV/dI$ ) value 20  $\Omega$  of nano-roughened LED was decrease 29% than conventional LED value 29  $\Omega$ . The reduction in the series resistance for the LED with a laser-irradiation on top nano-roughened LED surface can be attributed to the improved ohmic contact resistance due to an increased contact area [10] and the excimer laser irradiation can be divided into the dissociation of Mg–H complexes by the high photon energy of the excimer laser and the thermal diffusion of the hydrogen out of p-GaN layer by the laser induced temperature rise in the nano-roughened LED [12–15].

In the electroluminescence (EL) measurement, the continuous current was injected into a device at room temperature. The light output was detected by a calibrated large area Si photodiode placed by 5 mm distant from the device top. This detecting condition covers almost all the power emitting from LEDs. Fig. 3 shows the intensity–current ( $I$ – $I$ ) characteristics and spectra of conventional and nano-roughened LEDs. It can be seen that EL intensity of the nano-roughened LED is larger than

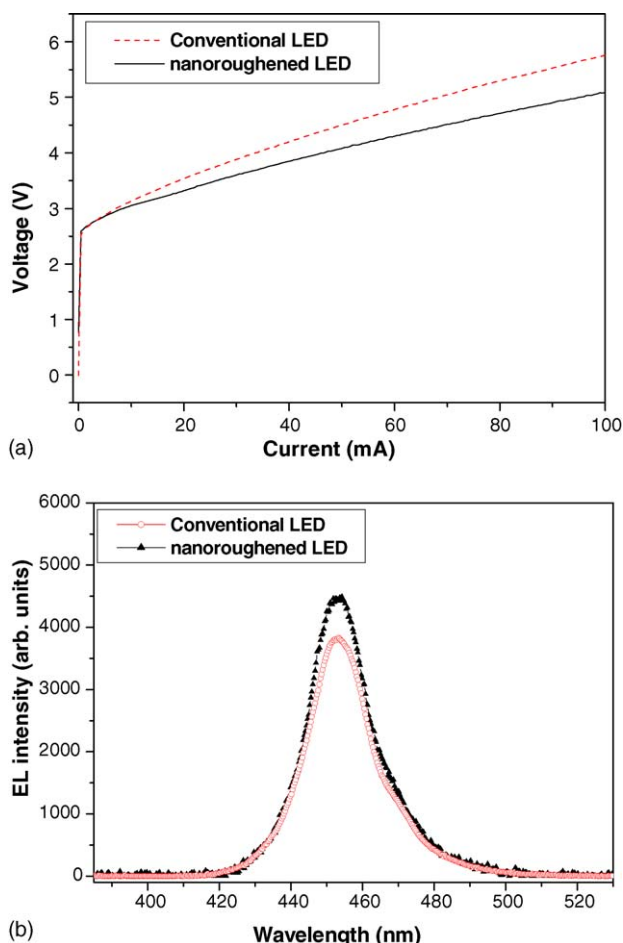


Fig. 2. (a)  $I$ - $V$  curves of conventional and nano-roughened LED fabricated in this study. (b) Room temperature EL spectrum of conventional and nano-roughened LED at a current of 20 mA.

that observed from the conventional LED. At injection current of 20 mA, it could be found that the MQW emission peaks of these two devices were all at about 450 nm and the light output power of conventional and nano-roughened LEDs was about 3 and 3.8 mW, respectively (inset of Fig. 3). This can again be

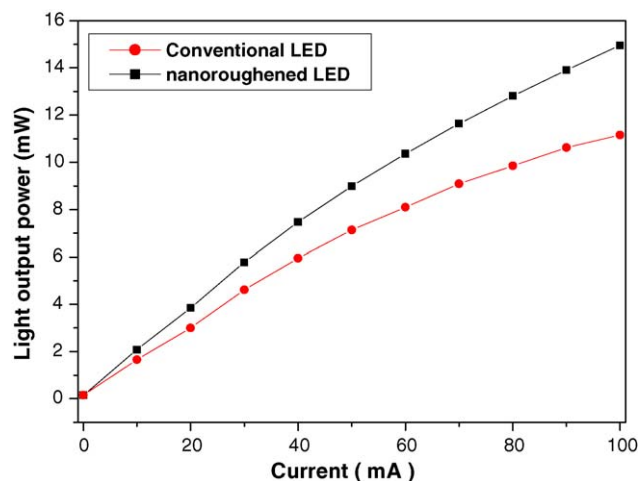


Fig. 3. Optical output powers of conventional and nano-roughened LEDs versus the forward injection current.

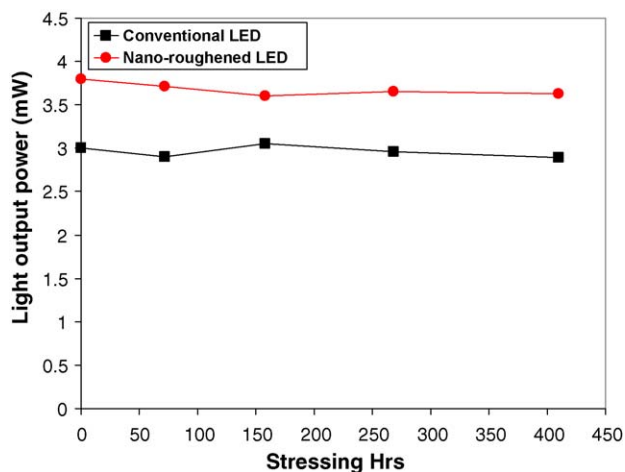


Fig. 4. Life time test of conventional and nano-roughened LEDs at 75 °C/20 mA.

attributed to the larger light extraction efficiency with nano-roughened surface. In other words, we could achieve a factor of 1.25 output power enhancement from the InGaN–GaN MQW LEDs with a nano-roughened p-GaN surface. The light extraction efficiency in the GaN-based LED is limited mainly due to the large difference in the refractive index between the GaN and surrounding air [10].

Fig. 4 shows the life time test of nano-roughened and conventional LEDs. We have accumulated life test data of our LEDs up to 400 h at 75 °C/20 mA with exceptional reliability. The results suggest that the LEDs with nano-roughened have as well as reliable performance.

In summary, we report on the improvement an InGaN/GaN MQW light emitting diode with nano-roughened p-GaN surface using KrF excimer laser-irradiation. The nano-roughened surface structure could improve the escape probability of photons inside the LED structure, resulting in an 25% increase in the light output of InGaN/GaN LED at 20 mA. The operation voltage of InGaN/GaN LED was reduced from 3.55 to 3.3 V at 20 mA with 29% reduction in the series resistance which can be attributed to an increased contact area of nano-roughened surface and higher hole concentration after laser-irradiation.

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