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# Enhanced Light Output of InGaN/GaN Light Emitting Diode with Excimer Laser Etching on Nano-roughened P-GaN Surface

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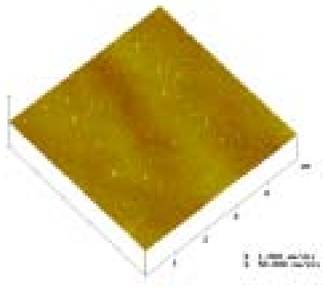
## 1. Introduction

GaN-based materials have attracted considerable interest in relation to their potential use in optoelectronic devices, such as light emitting diodes (LEDs) and laser diodes (LDs) [1]-[4]. The internal quantum efficiency of GaN-based LEDs is much less than 100% at room temperature because of non-radiative defects. Furthermore, the external quantum efficiency of GaN-based LEDs is low because the refractive index of the nitride epitaxial layer differ greatly from that of the air. The refractive indexes of GaN and air are 2.5 and 1.0, respectively. This investigation report the production of GaN LED with a nano-roughened p-GaN surface using a self-assembled Ni metal cluster as the laser etching mask. The dimensions and density of the self-assembled Ni cluster can be controlled by rapid thermal annealing at temperatures from 750°C to 850°C, details of which have been recently reported [5]. As a result, the light output efficiency of LED with a nano-roughened surface was significantly higher than that of a conventional LED without a roughened surface. Additionally, the current-voltage (I-V) measurements demonstrate that the forward voltage of LED with a nano-roughened surface was lower than that of a conventional LED.

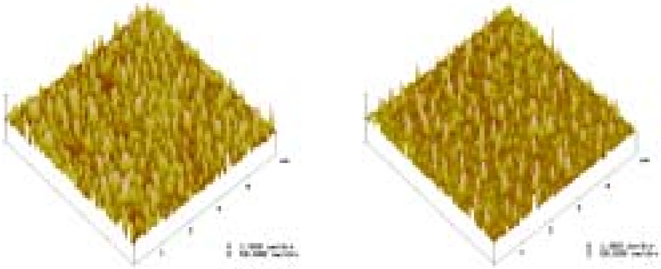
## 2. Experiment

Nano-roughened LEDs were formed by depositing Ni thin film with a thickness of 5 nm on a p-GaN surface by electron beam evaporation. Rapid thermal annealing (RTA) was then performed at 750°C for 1min to change the Ni layer to the metal Ni nano-mask on the top p-GaN surface. Then, a KrF excimer laser at wavelength of 248 nm with pulse width of 25 ns and the incident laser fluence was 300mJ/cm$^2$ was used to etching p-GaN surface in air. In this process, the beam size 1mm × 1mm of KrF laser was larger than that of the size of LEDs.

Figure 1 (a)-(c) show the AFM images that describe the change of the surface morphology of the p-GaN surface during surface-roughening. Figure 1(a) shows that the conventional p-GaN cap has a root mean-square (RMS) roughness of 0.7 nm, and a surface depth of approximately 2 nm. The surface of the conventional LED was smooth. Figure 1(b) shows a nano-mask AFM image RMS roughness of 7.4 nm before laser etching was performed. The self-assembled Ni mask dimension size and density were approximately 250 nm and $3x10^9$ cm$^{-2}$, and the height of the Ni clusters was approximately 30 nm when the original Ni thickness was 50 Å under RTA conditions of 750°C for 1min. Figure 1(c) displays the AFM image that shows that RMS roughness of p-GaN surface increased drastically to 5.8 nm, and the surface depth was approximately 17 nm after laser etching and the removal of the Ni nano-mask.



**(a) RMS roughness=0.7 nm**



**(b) RMS roughness=7.4 nm** **(c) RMS roughness=5.8 nm**

FIG. 1. AFM images of the top surface morphology of a LED sample. (a) Conventional LED p-GaN surface image. (b) Ni nano-mask on p-GaN surface image. (c) Nano-roughened LED top p-GaN surface image.

The I-V characteristics of the conventional and nano-roughened LEDs were also measured. Figure 2 plots the I-V characteristics of conventional and nano-roughened LEDs. The forward voltages of the conventional and nano-roughened LEDs were 3.54V and 3.27V at a driving current of 20 mA, respectively. Furthermore, the dynamic resistance (R=dV/dI) of the nano-roughened LED ( 27Ω) was 32% lower than that of the conventional LED (40 Ω).

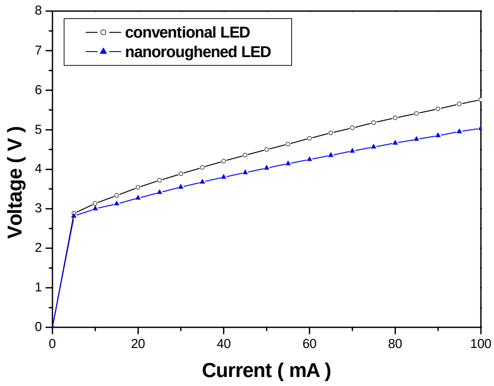


FIG. 2. I-V forward curves of conventional and nano-roughened LEDs fabricated in this investigation.

Figures 3 intensity–current (*L–I* ) characteristics of conventional and nano-roughened LEDs. The light output power of the conventional and nano-roughened LEDs were approximately 5.3 mW and 8.3 mW, respectively. Restated, nano-roughening the p-GaN surface increased the output power of the InGaN–GaN MQW LEDs by a factor of 1.55, indicating that the LED with the nano-roughened surface had larger light extraction efficiency. The wall-plug efficiency (output power/input power) was also calculated: it was 65% higher than that of the conventional LED at an injection current of 20 mA, because of enhanced light output power and a lower forward voltage. The intensity distributions of conventional and nano-roughened LEDs were measured to investigate further the influence of surface roughness on the light output performance of an LED.

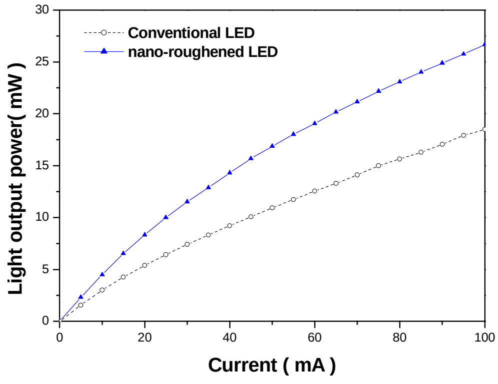


FIG. 3. Light output power-current (L-I) characteristics of conventional and nano-roughened LEDs at a dc injection current of 20 mA.

## 3. Conclusions

This investigation describes the improvement of an InGaN/GaN MQW light emitting diode by nano-roughening the p-GaN surface using Ni nano-mask and laser etching. The nano-roughened surface improved the escape probability of photons inside the LED structure, increasing by 55% the light output of InGaN/GaN LED at 20 mA. The operating voltage of the InGaN/GaN LED was reduced from 3.54 to 3.27V at 20 mA and the series resistance was reduced by 32% by the increase in the contact area of the nano-roughened surface. The wall-plug efficiency of the InGaN/GaN LED was increased by 65% by nano-roughening the top p-GaN surface using the Ni nano-mask and laser etching.

## Acknowledgements

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