Improvement of InGaN–GaN Light-Emitting Diode Performance With a Nano-Roughened p-GaN Surface

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***Abstract*—This investigation describes the development of InGaN–GaN light-emitting diode (LED) with a nano-roughened top p-GaN surface which uses Ni nano-mask and wet etching. The light output of the InGaN–GaN LED with a nano-roughened top p-GaN surface is 1.4 times that of a conventional LED, and wall-plug efficiency is 45% higher. The operating voltage of InGaN–GaN LED was reduced from 3.65 to 3.5 V at 20 mA and the series resistance was reduced by 20%. The light output is increased by the nano-roughening of the top p-GaN surface. The reduction in the series resistance can be attributed to the increase in the contact area of nano-roughened surface.**

***Index Terms*—Gallium nitride (GaN), light-emitting diode (LED), nano-mask, nickel.**

GALLIUM NITRIDE (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 [1]. Recently, as the brightness of GaN-based LEDs has increased, applications such as displays, traffic signals, backlights for cell phones, exterior automotive lighting, and printers have become possible. However, the internal quantum efficiency of GaN-based LEDs is much less than 100% at room temperature because of nonradiative 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. Thus, the critical angle at which light generated in the InGaN-GaN active region can escape is approximately $[\theta_c = \sin^{-1}(n_{\text{air}}/n_{GaN})] \sim 23^\circ$, which limits the external quantum efficiency of conventional GaN-based LEDs to only a few percent [2]. The light from LEDs can be enhanced either through the sample surface or through the side walls of the chip. Research into improving the light extraction efficiency (external quantum efficiency) and brightness in the LEDs [2]–[4] has been intense. Recently, Chang *et al.* reported that cap layers grown at low temperature (800 °C) increased the power output by InGaN-GaN multiple quantum well (MQW) LEDs by 10% [5]. Fujii reported an increase in the extraction efficiency of GaN-based light-emitting diodes by surface roughening [6]. These processes all allow the photons generated within the LEDs to find the escape cone by multiply scattering from a rough surface. Huh *et al.* reported that microroughening the top surface of an InGaN–GaN LED using metal clusters as a wet etching mask increased the wall-plug efficiency by 62% [2]. Huh *et al.* showed a large improvement in the light output power, indicating that the use of metal clusters to fabricate a roughened p-GaN surface is an excellent means of making a high-power LED. However, higher treatment temperature of 900 °C is necessary to form Pt clusters. Therefore, higher temperature may increase the Indium segregation probability in the InGaN–GaN quantum well region and reduce the internal quantum efficiency [7], [8]. Pt has a high melting point and chemical stability [9]. Therefore, specific wet chemical etching should be necessary to remove Pt metal clusters by dipping into a boiling aqua-regia solution [2]. This investigation reports on the production of GaN LED with a nano-roughened p-GaN surface using a self-assembled Ni metal cluster as the wet etching mask. The dimensions and density of the self-assembled Ni cluster can be controlled by rapid thermal annealing (RTA) at temperatures from 750 °C to 850 °C, details of which have been recently reported [10]. As a result, the light output efficiency of the 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 an LED with a nano-roughened surface was lower than that of a conventional LED.

The GaN LED samples were grown by metal–organic chemical vapor deposition with a rotating-disk reactor (Emcore D75) on a c-axis sapphire (0001) substrate at a growth pressure of 200 mbar. Trimethylgallium, trimethylaluminum ammonia, CP_2Mg, and Si_2H_6 were used as sources of Ga, Al, N, Mg, and Si. The LED structure includes a 30-nm-thick GaN low-temperature buffer layer, a 4.0-μm-thick highly conductive Si-doped GaN layer (grown at 1050 °C), an active region of undoped MQWs that includes 2/5-nm-thick $In_{0.21}Ga_{0.79}N$–GaN with five periods of MQWs (grown at 750 °C), a 50-nm-thick Mg-doped AlGaN layer (grown at 1050 °C), and finally 0.1-μm-thick Mg-doped GaN grown at 1050 °C. The top surface of LED, which is a p-GaN surface, was roughened by both the formation of an Ni nano-mask on a top p-GaN surface of an LED and by wet etching. The surface roughness of the LED cap layer was measured by tapping mode atomic force microscopy (Veeco).

Nano-roughened LEDs were formed by depositing an Ni thin film with a thickness of 5 nm on a p-GaN surface by electron beam evaporation. RTA was then performed at 850 °C for 1 min to change the Ni layer to the metal Ni nano-mask on the top p-GaN surface. Then, wet etching was performed to produce nano-roughened LEDs, using a boiling 85% phosphoric acid

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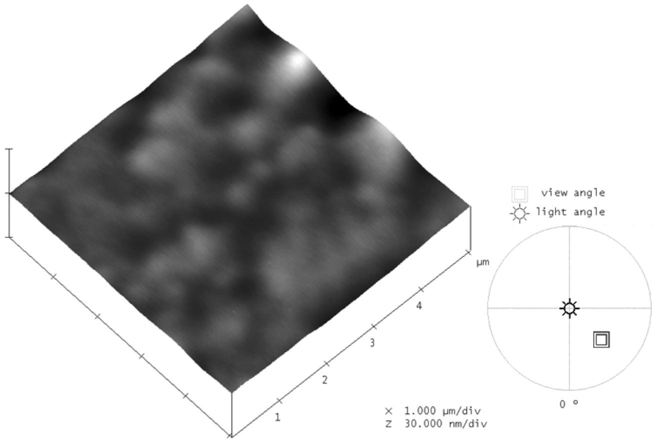
(H_3PO_4) solution for 4-min etching. The etching rate of the p-GaN layer in boiling 85% H_3PO_4 solution was determined to be approximately 15 nm/mim at 200 °C. The nano-roughened LED was dipped into a nitric acid solution (HNO_3) for 5 min to remove the Ni nano-mask from a nano-roughened LED after the wet etching process. Afterwards, the conventional LED and the LED with a nano-roughened surface were fabricated using the standard process (four mask steps) with a mesa area $(300 \times 300\ \mu m^2)$. First, the 0.5-$\mu$m SiO_2 was deposited onto the sample surface by plasma-enhanced chemical vapor deposition. Photolithography was used to define the mesa pattern after wet etching of SiO_2 by a buffer oxide etching solution. The mesa etching was then performed with Cl_2–Ar as the etching gas in an inductively coupled plasma (ICP) reactive ion etching (ICP-RIE) system (SAMCO ICP-RIE 101iPH) which the ICP source power and bias power were operated at 13.56 MHz. The metal contact layers, including transparent contact and pad layers, were patterned by a liftoff procedure and deposited onto samples by electron beam evaporation. Ni–Au (3/5 nm) was used for the transparent electrode and Ti–Al–Ni–Au (20/150/20/200 nm) was used for the n-type electrode. Finally, Ni–Au (20/150 nm) was deposited onto the p-type electrode.

Fig. 1(a)–(c) shows the atomic force microscopy (AFM) images that describe the change of the surface morphology of the p-GaN surface during surface-roughening. Fig. 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. Fig. 1(b) shows a nano-mask AFM image rms roughness of 5.9 nm before wet etching was performed. The self-assembled Ni mask dimension size and density were approximately 250 nm and 2×10^9 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 850 °C for 1 min. Fig. 1(c) displays the AFM image that shows that rms roughness of p-GaN surface increased drastically to 3.6 nm, and the surface depth was approximately 15 nm after wet etching and the removal of the Ni nano-mask.

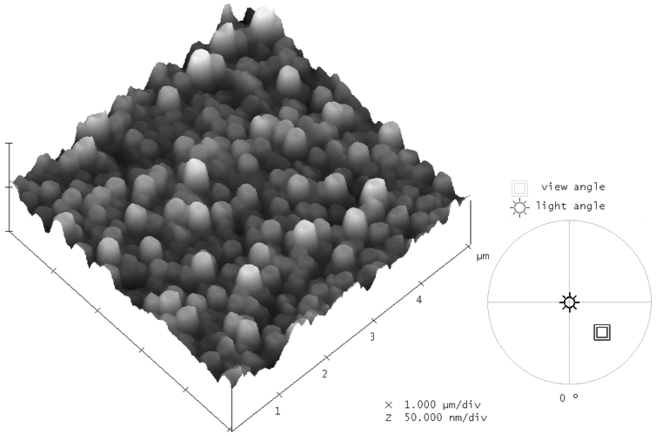
The I–V characteristics of the conventional and nano-roughened LEDs were also measured. Fig. 2 plots the I–V characteristics of conventional and nano-roughened LEDs. The forward voltages of the conventional and nano-roughened LEDs were 3.65 and 3.5 V at a driving current of 20 mA, respectively. Furthermore, the dynamic resistance $(R = dV/dI)$ of the nano-roughened LED (32 Ω) was 20% lower than that of the conventional LED (40 Ω). The reduction in the series resistance of the LED with wet etching on a top nano-roughened LED surface can be attributed to the improvement in the ohmic contact resistance caused by the increase in the contact area [2]. The inset in Fig. 2 shows that the rough surface of the LED nano-roughened using an Ni nano-mask and wet etching did not induce a larger leakage current than that in the conventional LED. Furthermore, two devices, based on conventional and nano-roughened LEDs, in HBM (human body mode) were observed in an electrostatic discharge test at a reverse voltage of >300 V.

Electroluminescence (EL) was measured by injecting a continuous current into a device at room temperature. The light output was detected using a calibrated large-area Si photodiode placed 5 mm from the top of the device. This detecting condition covers α. Fig. 3(a) and (b) plots the spectra and intensity-current $(L$–$I)$ characteristics of conventional and nano-roughened LEDs. The EL intensity of the nano-roughened LED exceeds that observed from the conventional LED [as shown in Fig. 3(a)]. At an injection current of 20 mA, all of the MQW emission peaks of these two were at approximately 450 nm and the



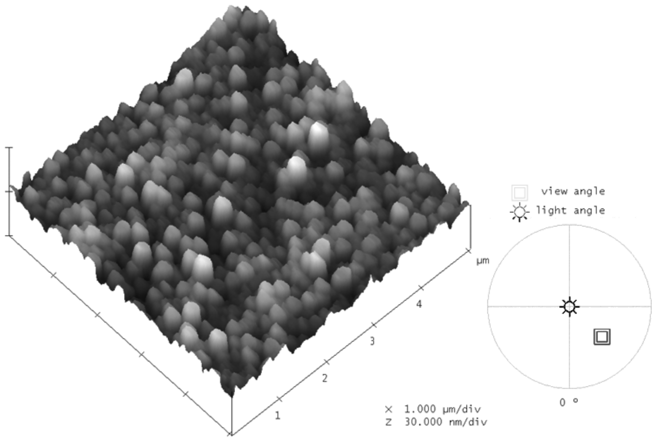
RMS roughness=0.7 nm

(a)



RMS roughness=5.9 nm

(b)



RMS roughness= 3.6 nm

(c)

Fig. 1. AFM images of the top surface morphology of an 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.

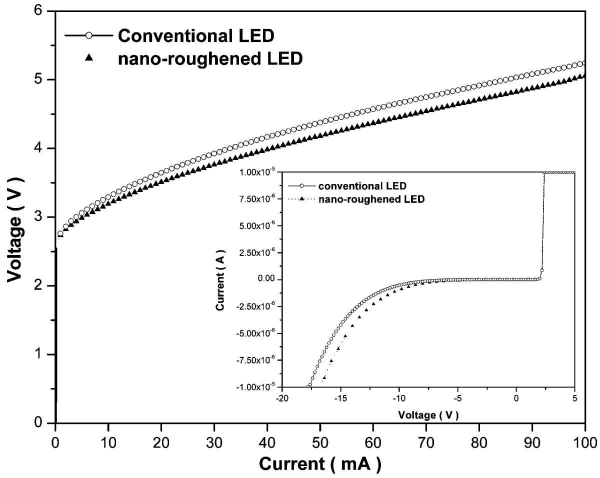
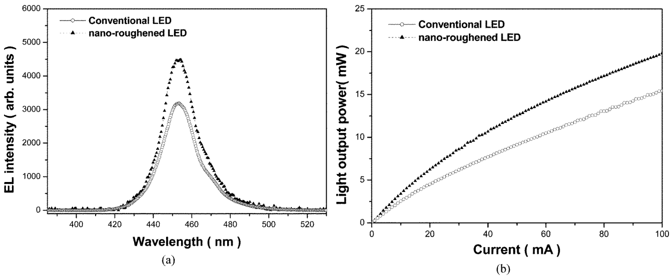


Fig. 2. I–V forward curves of conventional and nano-roughened LEDs fabricated in this investigation. The inset shows reverse curves of the two devices.



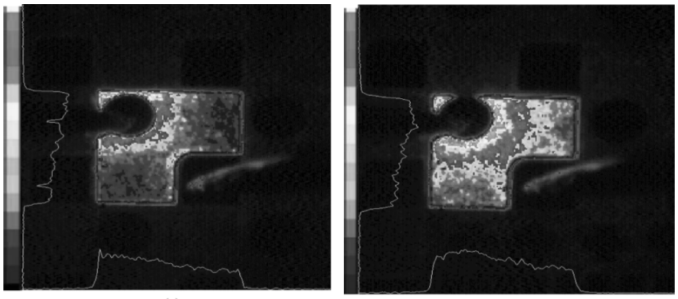
(a) (b)

Fig. 3. (a) Room temperature EL spectrum of conventional and nano-roughened LED at a current of 20 mA. (b) Light output power-current (L–I) characteristics of conventional and nano-roughened LEDs.

light output power of the conventional and nano-roughened LEDs were approximately 4.5 and 6.3 mW, respectively [as shown in Fig. 3(b)]. Restated, nano-roughening the p-GaN surface increased the output power of the InGaN-GaN MQW LEDs by a factor of 1.4, 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 45% 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. 4(a) and (b) shows the photons of conventional and nano-roughened LEDs when a 20-mA dc current is injected into these two devices. Intensity distributions are also shown. The EL intensities observed from the nano-roughened LED clearly exceeded those from the conventional LED at the same injection current, especially on the LED top surface. Such an enhancement could be attributed to the top surface roughness and the fact that photons were more likely to be emitted from the surface-roughed device, resulting in an increase in the light output power of the nano-roughened LED, as shown in Fig. 3.

In summary, this investigation describes the improvement of an InGaN–GaN MQW LED by nano-roughening the p-GaN surface using Ni nano-mask and wet etching. The nano-roughened surface improved the escape probability of photons inside the LED structure, increasing by 40% the light output of InGaN–GaN LED at 20 mA. The operating voltage of the InGaN–GaN LED was reduced from 3.65 to 3.5 V at 20 mA and the series resistance was reduced by 20% by the increase in the contact area of the nano-roughened surface. The wall-plug efficiency of the InGaN–GaN LED was increased by 45% by nano-roughening the top p-GaN surface using the Ni nano-mask and wet etching.



(a) (b)

Fig. 4. Photons of (a) conventional LED and (b) nano-roughened LED at a dc injection current of 20 mA.

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