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# Enhanced light output of an InGaN/GaN light emitting diode with a nano-roughened p-GaN surface

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**Abstract**
This investigation describes the development of an InGaN/GaN light emitting diode (LED) with a nano-roughened top p-GaN surface using an Ni nano-mask and laser etching. The light output of the InGaN/GaN LED with a nano-roughened top p-GaN surface is 1.55 times that of a conventional LED, and the wall-plug efficiency is 68% higher at 20 mA. The series resistance of the InGaN/GaN LED was reduced by 32% by the increase in the contact area of the nano-roughened surface.

(Some figures in this article are in colour only in the electronic version)

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]. 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 about 70% 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 indices 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 ($\theta_c = \sin^{-1}(n_{air}/n_{GaN})$) ~ 23°, which limits the external quantum efficiency of conventional GaN-based LEDs to only a few per cent [5]. 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 [5–11] has been intense. Recently, Chang *et al* reported that cap layers grown at low temperature (800 °C) increased the power output by InGaN–GaN MQW LEDs by 10% [12]. Fujii reported an increase in the extraction efficiency of GaN-based light-emitting diodes by surface roughening [13]. These processes all allow the photons generated within the LEDs to find the escape cone, by multiple scattering from a rough surface. Huh *et al* reported that micro-roughening the top surface of an InGaN/GaN LED using metal clusters as a wet etching mask increased the wall-plug efficiency by 62% [5]. 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. This investigation reports the production of a 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 to 850 °C, details of which have been recently reported [14]. 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 the LED with a nano-roughened surface was lower than that of a conventional LED from the same wafer with standard device processing.

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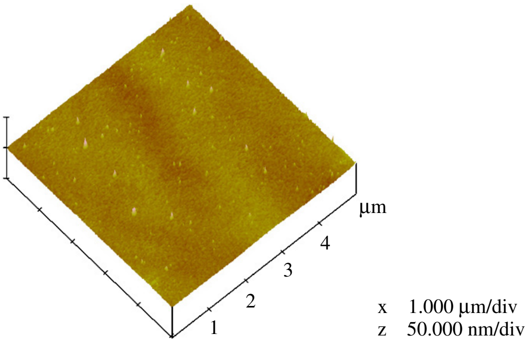
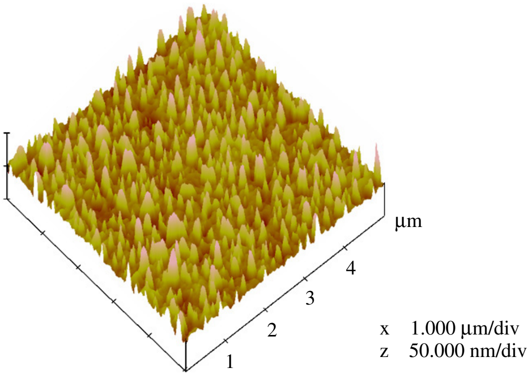
The GaN LED samples were grown by metal–organic chemical vapour deposition (MOCVD) with a rotating-disc reactor (Emcore D75$^{TM}$) on a *c*-axis sapphire (0001) substrate at a growth pressure of 200 mbar. Trimethylgallium (TMG), trimethylaluminium (TMA) ammonia, $CP_2Mg$ and $Si_2H_6$ were used as sources of Ga, Al, N, Mg and Si. The LED structure includes a 30 nm thick GaN low-temperature buffer layer, a 4.0 $\mu$m thick highly conductive Si-doped GaN layer (grown at 1050 °C), an active region of undoped multiple quantum wells (MQWs) that includes 2/5 nm thick $In_{0.21}Ga_{0.79}N$/GaN with five periods of multiple quantum wells (grown at 750 °C), a 50 nm thick Mg-doped AlGaN layer (grown at 1050 °C) and finally 0.1 $\mu$m 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 laser 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 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 1 min 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 300 mJ cm$^{-2}$ was used to etch the p-GaN surface in air. In this process, the beam size 1 mm × 1 mm of the KrF laser was larger than the size of the LEDs. Therefore, the laser irradiation on the surface of p-GaN was uniform. Thus, the etching rate of the p-GaN layer in 300 mJ cm$^{-2}$ was determined to be approximately 10 nm/pulse in air. Then, the nano-roughened LED sample was dipped into HCl solution for 5 min to remove the residual Ga, and Ga oxide on the p-GaN and dipped into a nitric acid solution ($HNO_3$) for 5 min to remove the Ni nano-mask from a nano-roughened LED after the laser 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 × 300 $\mu m^2$). Firstly, the 0.5 $\mu$m $SiO_2$ was deposited onto the sample surface by plasma enhanced chemical vapour deposition (PECVD). Photo-lithography 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 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 lift-off 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.



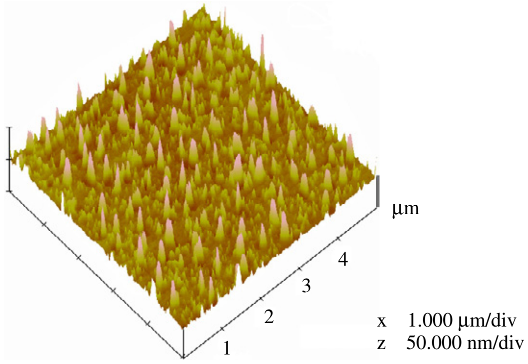
RMS roughness = 0.7 nm

(a)



RMS roughness = 7.4 nm

(b)



RMS roughness = 5.8 nm

(c)

**Figure 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.

Figures 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 3 × 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 750 °C for 1 min. 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.

The $I$–$V$ characteristics of the conventional and nano-roughened LEDs were also measured. Figure 2(a) plots the $I$–$V$ characteristics of conventional and nano-roughened

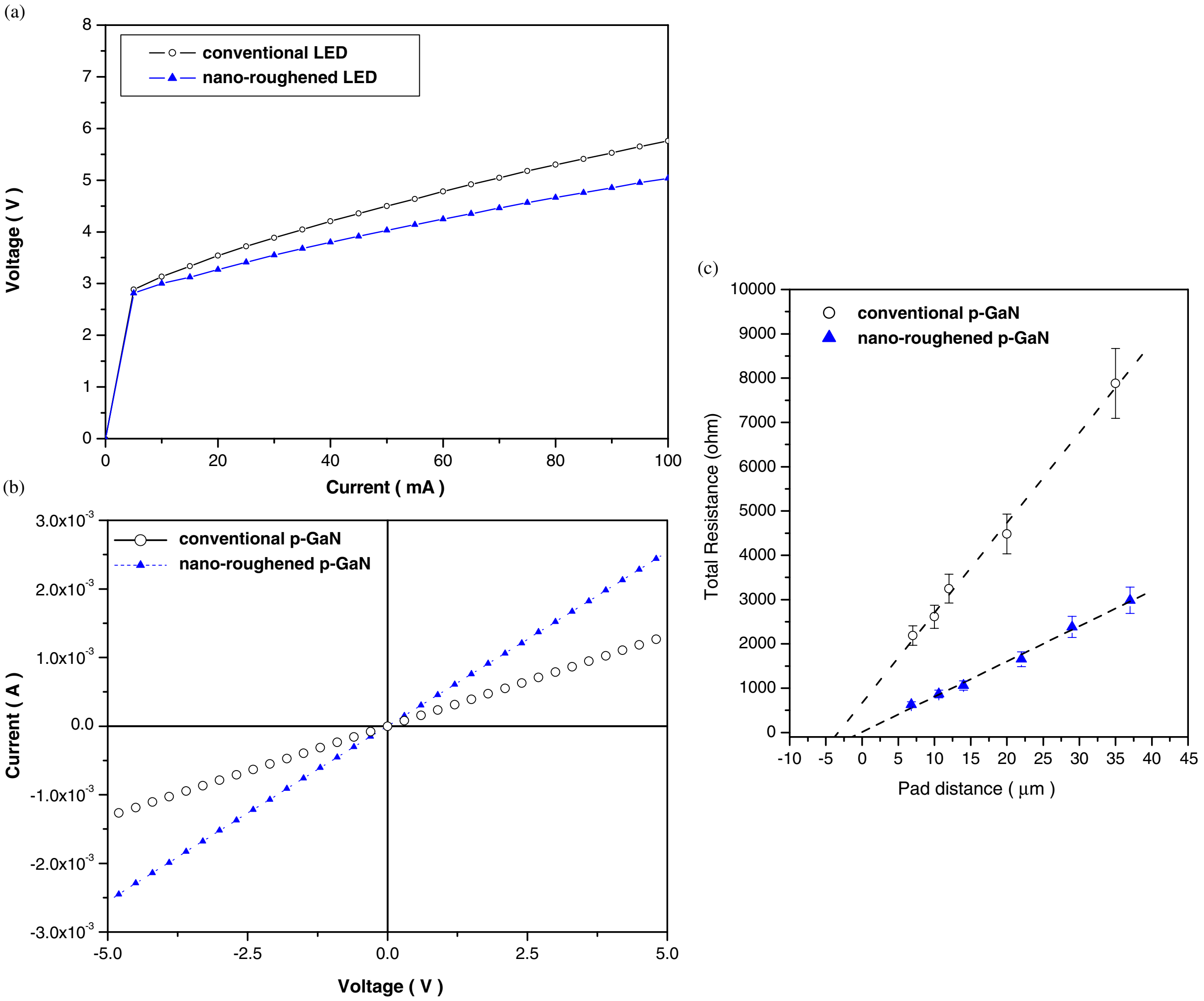


**Figure 2.** (a) $I$–$V$ forward curves of conventional and nano-roughened LEDs fabricated in this investigation. (b) $I$–$V$ characteristics of the nano-roughened and conventional p-GaN measured by the circular transmission line method (CTLM). (c) Total resistance ($Y$) measured by CTLM is linearly related to the pad distance ($X$).

LEDs. The forward voltages of the conventional and nano-roughened LEDs were 3.54 and 3.27 V at a driving current of 20 mA, respectively. Furthermore, the dynamic resistance ($R = \mathrm{d}V/\mathrm{d}I$) of the nano-roughened LED (27 Ω) was 32% lower than that of the conventional LED (40 Ω). A 1 $\mu$m thick p-GaN sample (hole carrier concentration of $5.0 \times 10^{17}$ cm$^{-3}$ and hole mobility of 10.2 cm$^2$ V$^{-1}$ s$^{-1}$) and both nano-roughened and conventional p-GaN samples were deposited with the same metallization of Ni (20 nm)/Au (150 nm) and rapid thermal annealing (RTA) 450 °C for 1 min, to investigate the electric characteristics of the Ohmic contact of nano-roughened and conventional LEDs on the p-GaN layer. Figure 2(b) plots the $I$–$V$ characteristics of the nano-roughened and conventional p-GaN as measured by the circular transmission line method (CTLM). The nano-roughened p-GaN sample has better linearity than the conventional p-GaN sample. The total resistance ($R_\mathrm{T}$) measured by CTLM is linearly related to the pad distance ($X$), as shown in figure 2(c). The specific contact resistance $\rho_\mathrm{c}$ was determined from the linear equation $R_\mathrm{T} = 2R_\mathrm{c} + \rho_\mathrm{s}/2\pi R \times X$, and the relationship between the specific resistance and the sheet resistance was $\rho_\mathrm{c} = \rho_\mathrm{s} \times L_\mathrm{T}^2$, where $R_\mathrm{c}$ is the contact resistance; $\rho_\mathrm{s}$ is the sheet resistance, and $L_\mathrm{T}$ is the transfer length. The data were fitted to obtain a lower specific contact resistance value of $2.5 \times 10^{-4}$ Ω cm$^2$ for the nano-roughened p-GaN than the value $7.2 \times 10^{-3}$ Ω cm$^2$ for the conventional p-GaN sample. The results indicated that nano-roughening facilitates p-type contact, resulting in an Ohmic contact with a low specific resistance.

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 almost all of the power emitted from the LEDs. Figures 3(a) and (b) plot 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 figure 3(a)). At an injection current of 20 mA, all of the MQW emission peaks of these two were

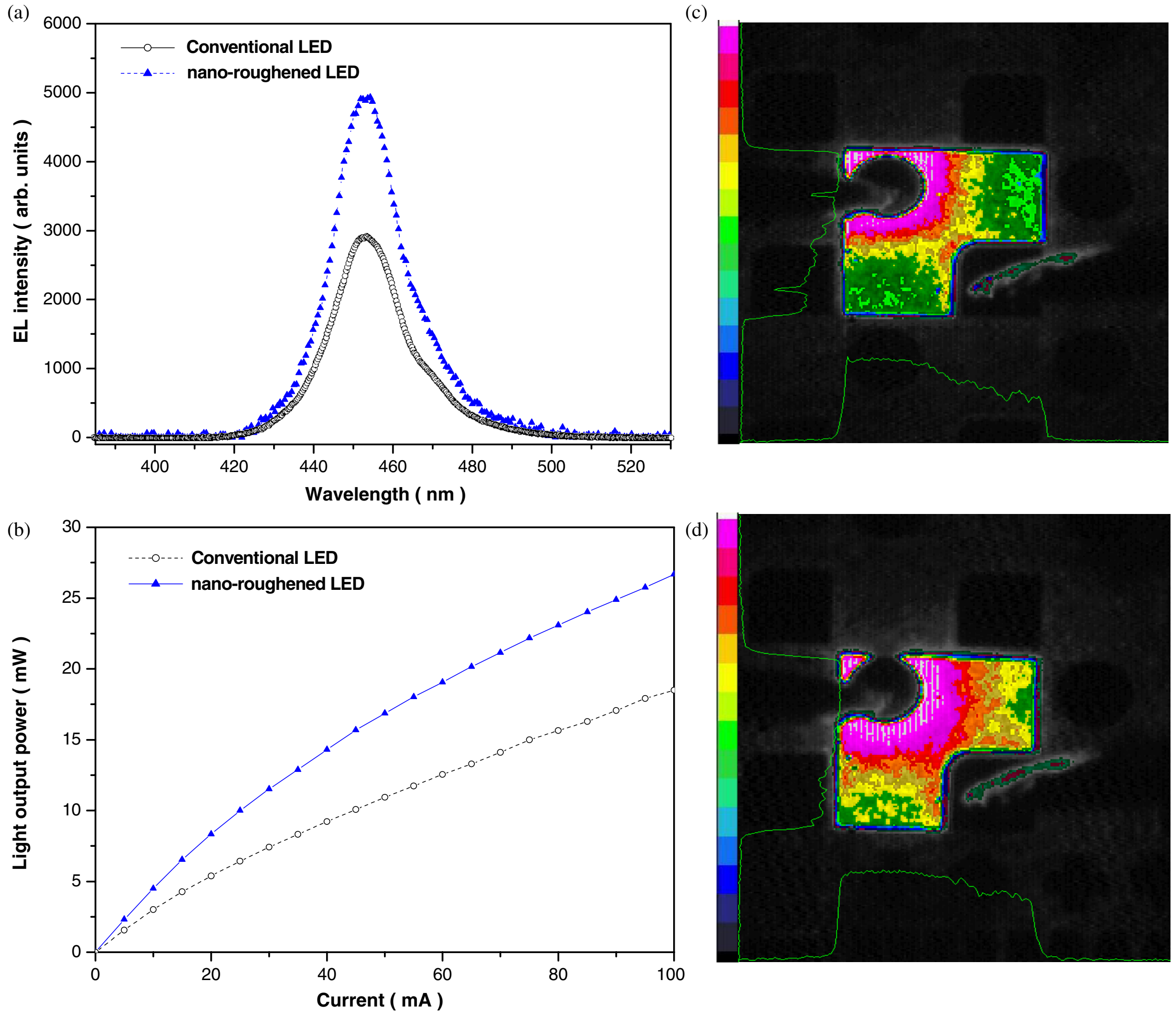


**Figure 3.** (a) Room temperature EL spectrum of conventional and nano-roughened LED at a current of 20 mA. (b) Light output power–current ($L$–$I$) characteristics of conventional and nano-roughened LEDs. (c) Photons of conventional LED and (d) nano-roughened LED at a dc injection current of 20 mA.

at approximately 452 nm and the light output power of the conventional and nano-roughened LEDs were approximately 5.3 and 8.3 mW, respectively (as shown in figure 3(b)). 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: The nano-roughened LEDs (12.6%) was 68% higher than that of the conventional LED (7.5%) 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. Figures 3(c) and (d) show the light output 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.

In summary, 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 light output 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 3.27 V 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 68% by nano-roughening the top p-GaN surface using the Ni nano-mask and laser etching.

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