

Investigation of InGaN/GaN light emitting diodes with nano-roughened surface by excimer laser etching method

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Abstract

The InGaN/GaN light emitting diodes (LEDs) with a nano-roughened top p-GaN surface fabricated by using Ni nano-masks and laser etching methods were demonstrated and analyzed. The experiment results observed the maximum light output power of the InGaN/GaN LED with a nano-roughened top p-GaN surface etched with the laser energy of 300 mJ/cm² was 1.55 times higher than that of a conventional LED, and the wall-plug efficiency was enhanced 68% at 20 mA. The series resistance of InGaN/GaN LED was reduced by 32% by the increase in the contact area of the nano-roughened surface.

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GaN-based materials have attracted considerable interest due 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 much less than 100% at room temperature because of the presence of non-radiative defects. Furthermore, because the refractive index of the nitride epitaxial layer differs greatly from that of the air, for which the refractive indexes of GaN and air are 2.5 and 1.0, respectively, the critical angle at which light generated in the InGaN–GaN active region can escape, is approximately $[\theta_c = \sin^{-1}(n_{\text{air}}/n_{\text{GaN}})] \sim 23^\circ$, which limits the external quantum efficiency of conventional GaN-based LEDs to only a few percent [5,6]. The light from LEDs can be enhanced either through the device surface or through the side walls of the device. Research on improving the light extraction efficiency (external quantum efficiency) and brightness in the LEDs [5–12]

has been intense. Recently, Chang et al. reported that cap layers grown at low temperature (800 °C) increased the power output in the InGaN–GaN MQW LEDs by 10% [13]. Fujii reported an increased extraction efficiency in the GaN-based LEDs by surface roughening [12]. These processes all allow the photons generated within the LEDs to find the escape cone, by multiple scattering from a rough surface. We had reported that nano-roughened top surface of an InGaN/GaN LED using Ni clusters as a wet etching mask increased the wall-plug efficiency by 45% [5]. The large improvement in the light output power we have shown indicated that the use of metal clusters to fabricate a roughened p-GaN surface is an excellent means of making a high-power LED. In comparison to the wet etching, the excimer laser etching for p-GaN surfaces have advantages of the easy control and high etching rate. This investigation reported the fabrication of GaN LEDs with nano-roughened p-GaN surfaces using a KrF laser etching and self-assembled Ni metal clusters as the laser etching masks. The dimensions and density of the self-assembled Ni clusters can be controlled by the rapid thermal annealing (RTA) at temperatures from 750 to 900 °C. Details of Ni cluster formation have been recently reported [14]. Fig. 1 depicts a schematic diagram of the LED with nano-roughened surface. The light output efficiency of LED with a

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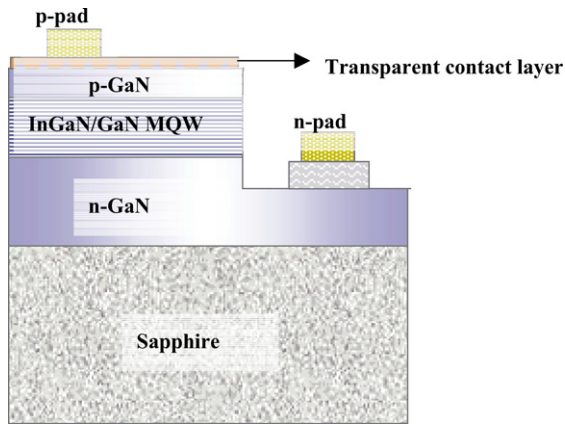


Fig. 1. Schematic diagram of the nano-roughed LED structure.

nano-roughened surface fabricated by the laser etching through the nano-masks was significantly higher than that of a conventional LED without a roughened surface. Additionally, the current–voltage (I – V) measurements showed that the forward voltage of the LED with a nano-roughened surface was lower than that of a conventional LED.

We simulated light propagation and reflection using the ray tracing method provided by Advanced System Analysis Program (ASAP). For simplicity, we employed a two-dimensional model which is similar on GaN-based LED structures. The top mesa area is $300\ \mu\text{m} \times 300\ \mu\text{m}$ and depth is $1\ \mu\text{m}$ with and without rough top surface. Fig. 2 shows light extraction efficiency of conventional and rough top surface LED structures as a function of absorption coefficient of the p-GaN layer. The light extraction efficiency here was defined as the ratio of the collected power outside the LED structure and the total power generated from the active region. The result clearly shows that by adding a rough top surface, the extraction efficiency can be greatly enhanced. The extraction efficiency can be enhanced about a factor of 1.29–1.67 times compared with conventional and rough top surface LED structures considering the absorption coefficient of p-GaN layer changed from $10,000$ to $100\ \text{cm}^{-1}$.

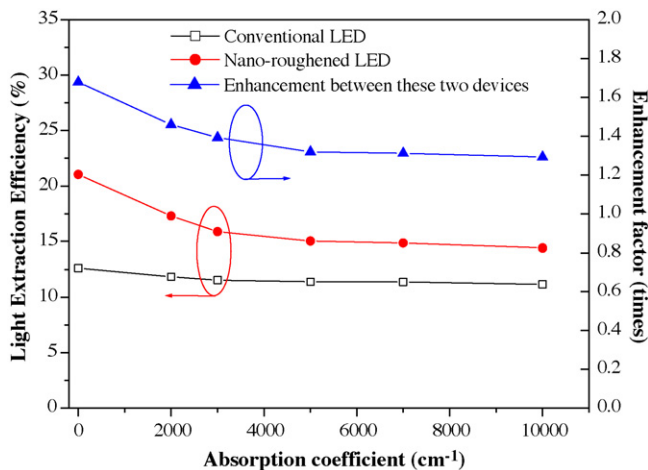


Fig. 2. Simulation describes the light extraction efficiency of LEDs with and without rough top surface as a function of absorption coefficient of the p-GaN.

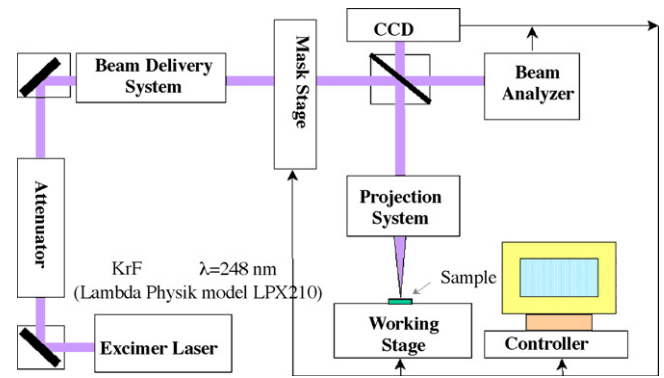


Fig. 3. The schematic diagram of laser etching process setup.

Fig. 3 shows the schematic diagram of the setup for conducting the laser etching experiment. A KrF excimer laser (Lambda Physik LPX210) operated at wavelength of $\lambda = 248\ \text{nm}$ with a pulse width of $25\ \text{ns}$ was used for laser etching technique. The laser output energy can be varied from 10 to $25\ \text{mJ}$. The laser beam was reshaped and homogenized using a special optical system to form a highly uniform ($\pm 5\%$ RMS) beam profile of $12\ \text{mm} \times 12\ \text{mm}$ after the mask plane. A beam splitter then splits the laser beam into a laser etching beam and a monitor beam. The laser etching beam passed through a projection system of $10\times$ magnification with a 0.2 numerical aperture, and then focused on the LED sample with a squared spot size of $1.0\ \text{mm} \times 1.0\ \text{mm}$. The monitor beam was incident on a beam analyzer for real-time monitoring of the laser beam quality. The LED samples were placed on the top of a working station which can be moved $1.0\ \text{mm}$ step by step to scan a typical sample size of $2\ \text{cm} \times 2\ \text{cm}$ by using the computer controlled stepper motor. The CCD camera was used to in situ monitor the laser etching process.

The GaN LED samples were grown by metal-organic chemical vapor deposition (MOCVD) with a rotating-disk reactor (Emcore D75TM) on a c -axis sapphire (0001) substrate at a growth pressure of $200\ \text{mbar}$. 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 $30\ \text{nm}$ -thick GaN low-temperature buffer layer, a $4.0\ \mu\text{m}$ -thick highly conductive Si-doped GaN layer (grown at $1050\ ^\circ\text{C}$), an active region of undoped multiple quantum wells (MQW) that includes five periods of $2/5\ \text{nm}$ -thick $\text{In}_{0.21}\text{Ga}_{0.79}\text{N}/\text{GaN}$ (grown at $750\ ^\circ\text{C}$), a $50\ \text{nm}$ -thick Mg-doped AlGaIn layer (grown at $1050\ ^\circ\text{C}$) and finally a $0.1\ \mu\text{m}$ -thick Mg-doped GaN layer (grown at $1050\ ^\circ\text{C}$). The top surface of LED, which is a p-GaN surface, was roughened by the laser etching after the formation of Ni nano-mask on the top surface. The surface roughness of the LED cap layer was measured by the tapping mode atomic force microscopy (Veeco).

The nano-masks were formed by depositing a Ni thin film with a thickness of $5\ \text{nm}$ on a p-GaN surface by electron beam evaporation. RTA was then performed at $750\ ^\circ\text{C}$ for $1\ \text{min}$ to change the Ni layer to the metal Ni nano-masks on the top p-GaN surface. Then, a KrF excimer laser at wavelength of $248\ \text{nm}$ with a pulse width of $25\ \text{ns}$ and the incident laser flu-

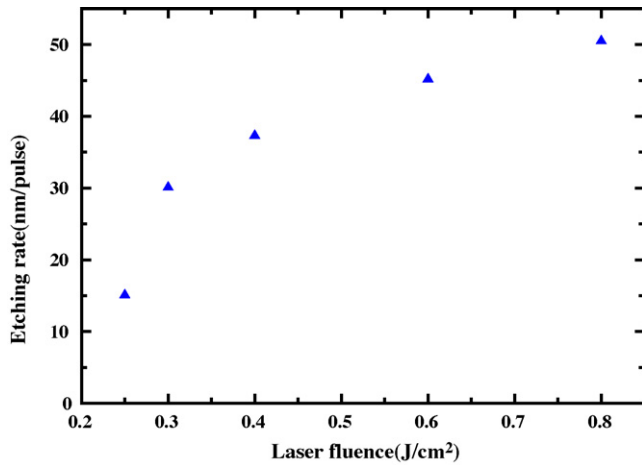
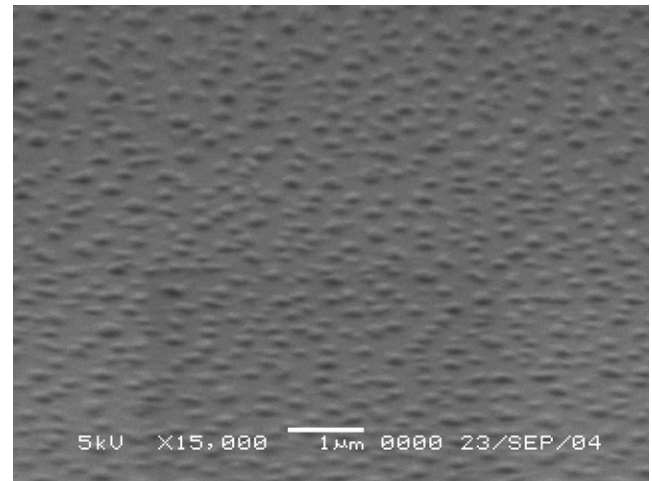
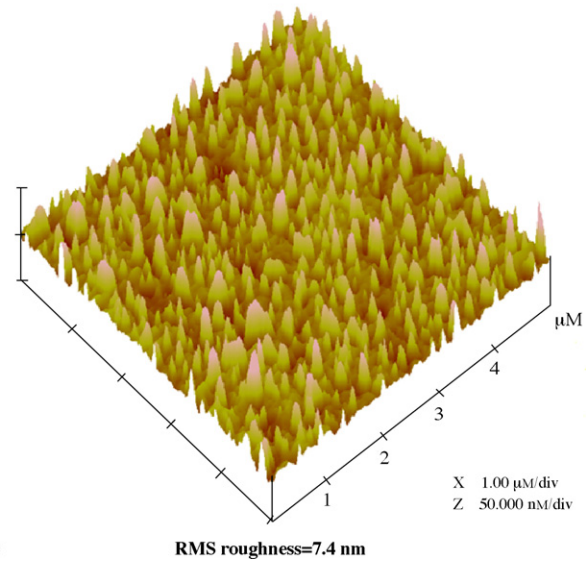


Fig. 4. The etching rate as a function of laser fluence.



(a)



(b)

Fig. 5. (a) SEM and (b) AFM images of the Ni nano-mask on p-GaN surface morphology of a nano-roughened LED sample.

Fig. 6(a and b) show the AFM images depicting the change of the surface morphology of the p-GaN surface during the surface roughening. Fig. 6(a) shows that the conventional p-GaN cap has a RMS roughness of 0.7 nm, and a surface depth of approximately 2 nm, demonstrating a rather smooth p-GaN surface in the conventional LED. Fig. 6(b–d) show the AFM images of the p-GaN surface roughened by the laser etching energy of 300, 400 and 800 mJ/cm², respectively. The RMS roughness of p-GaN surface increased drastically to 8.7 nm as the energy of excimer laser increased from 300 to 800 mJ/cm². The maximum depth of the surface etched by the laser energy of 800 mJ/cm² was approximately 37 nm after the removal of the Ni nano-masks.

The *I*–*V* characteristics of the conventional and nano-roughened LEDs were also measured. Fig. 7 plots the *I*–*V* characteristics of conventional and nano-roughened LEDs. The forward voltages of the conventional and nano-roughened LEDs etched by the laser energy of 300 mJ/cm² were 3.54 and 3.27 V at a driving current of 20 mA, respectively. Furthermore, the dynamic resistance ($R = dV/dI$) of the nano-roughened LED (27 Ω) was 32% lower than that of the conventional LED (40 Ω).

ence were from 250 to 800 mJ/cm² was used to etch the p-GaN surface in the air atmosphere. In this process, the beam size of KrF laser (1 mm × 1 mm) was larger than the size of LEDs (300 µm × 300 µm) to avoid non-uniformity of the laser irradiation on the surface of p-GaN. Fig. 4 shows the etching rate of the p-GaN layer as a function of laser fluence in the air atmosphere. The etching rate increased with the increasing laser fluence. The etching rate of the p-GaN layer from 250 to 800 mJ/cm² were determined to be approximately 15 to 50 nm/pulse. After the laser etching process, the nano-roughened LED samples were dipped into HCl solution for 5 min to remove the residual Ga and Ga oxide on the p-GaN and then dipped into a nitric acid solution (HNO₃) for 5 min to remove the Ni nano-mask from a nano-roughened LED. Afterwards, the conventional LED and the LED with a nano-roughened surface were fabricated using the standard process (four mask steps) having a mesa area of 300 µm × 300 µm. First, the 0.5 µm SiO₂ was deposited onto the sample surface by plasma enhanced chemical vapor deposition. Photo-lithography was used to define the mesa pattern after wet etching of SiO₂ by a buffer oxide etching solution. The mesa etching was then performed with Cl₂/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 the frequency of 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.

Fig. 5 show the (a) SEM and (b) AFM images of the Ni nano-mask on p-GaN surface morphology of a nano-roughened LED sample. The SEM image in Fig. 5(a) shows that the dimension and density of the self-assembled Ni masks under RTA conditions of 750 °C for 1 min were approximately 250 nm and 3 × 10⁹ cm⁻², and the height of the Ni clusters was approximately 30 nm when the original Ni thickness was 50 Å. The AFM image in Fig. 5(b) shows a Ni nano-mask with a root mean-square (RMS) roughness of 7.4 nm before the laser etching was performed.

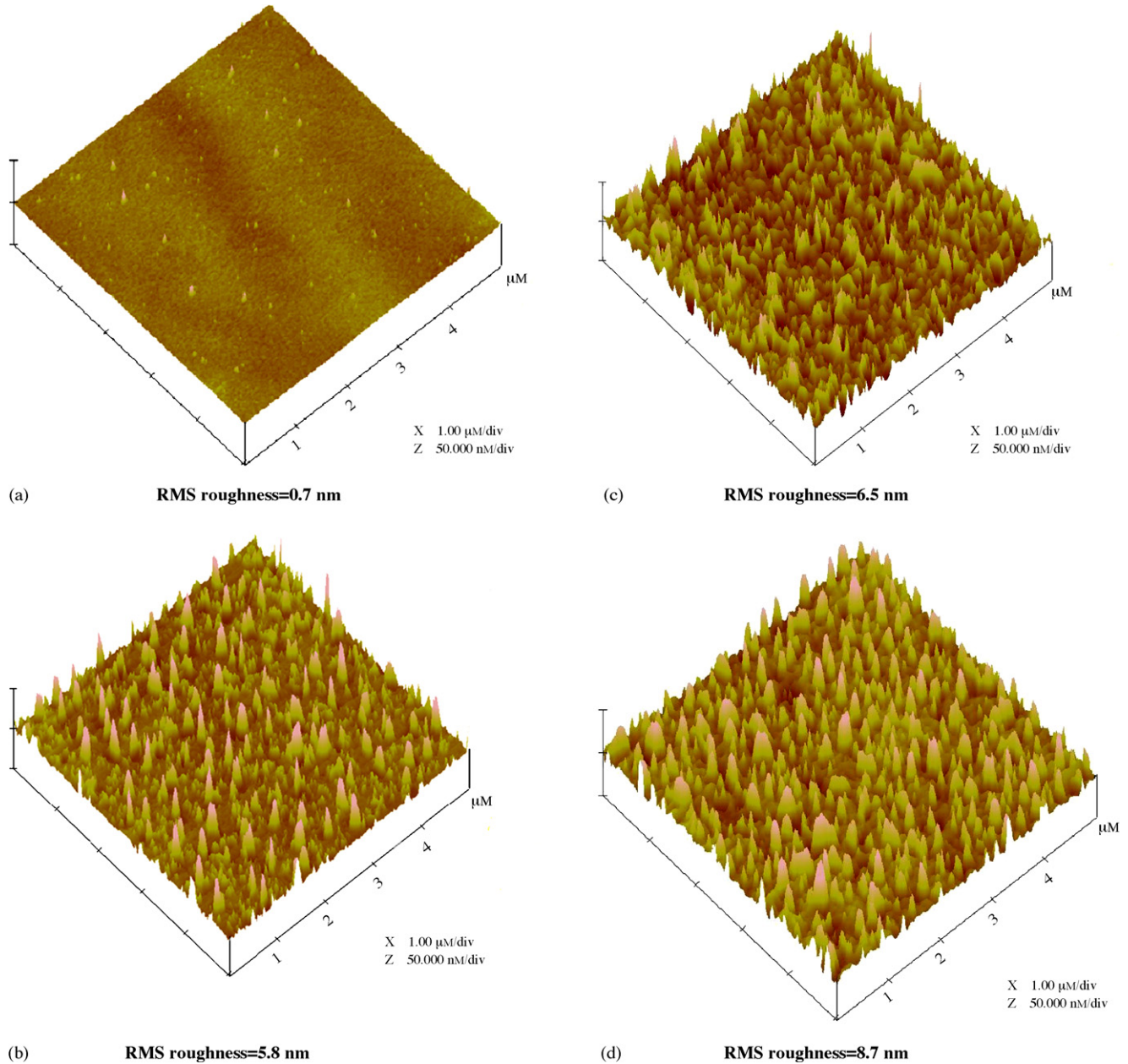


Fig. 6. AFM images of the top surface morphology of a LED sample. (a) Conventional LED p-GaN surface image. Nano-roughened LED top p-GaN surface applied laser etching energy of: (b) 300 mJ/cm², (c) 400 mJ/cm² and (d) 800 mJ/cm².

The results indicated that the nano-roughening surfaces could facilitate the p-type contact to form an Ohmic contact with a low specific resistance when the energy of laser etching ranged from 250 to 400 mJ/cm². However, the energy of laser etching over 600 mJ/cm² could result in a Schottky contact with a high specific resistance, which might be due to that the surface morphology was too rough to form good contacts on the top p-GaN surface.

Electroluminescence (EL) was measured by injecting a continuous current into a chip 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 top

of the LEDs. Fig. 8(a) shows the spectra of the conventional and nano-roughened LEDs. Fig. 8(b) plots the intensity–current ($L-I$) characteristics versus the RMS roughness of the surfaces in nano-roughened LEDs. As shown in Fig. 8(a), the EL intensity of the nano-roughened LED exceeds the conventional LED. At an injection current of 20 mA, the MQW emission peak was at approximately 452 nm and the light output power of the conventional and nano-roughened LEDs etched by laser energy of 300 mJ/cm² were approximately 5.3 and 8.3 mW, respectively (as shown in Fig. 8(b)). Nano-roughening the p-GaN surface with the laser etching energy of 300 mJ/cm² increased the output power of the conventional InGaN–GaN MQW LEDs by a factor of 1.55. The enhancement of the wall-plug efficiency

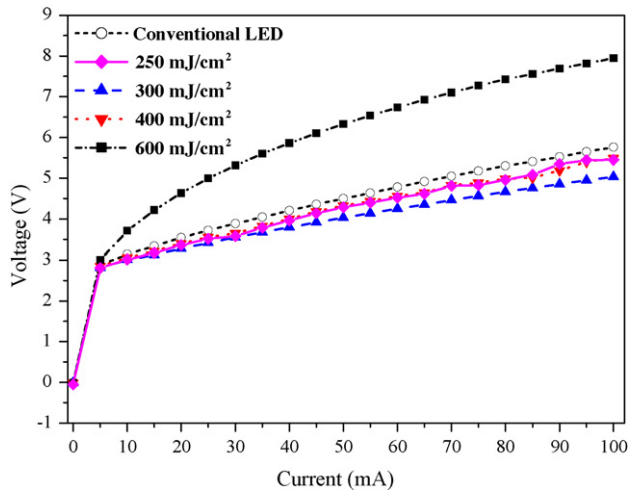


Fig. 7. Forward I - V curves of conventional and nano-roughened LEDs.

of the nano-roughened LEDs over the conventional LED was 68% at 20 mA. The nano-roughened LEDs with energy of laser etching over 600 mJ/cm^2 shows slightly lower light output than the conventional LED. This could be due to a Schottky contact

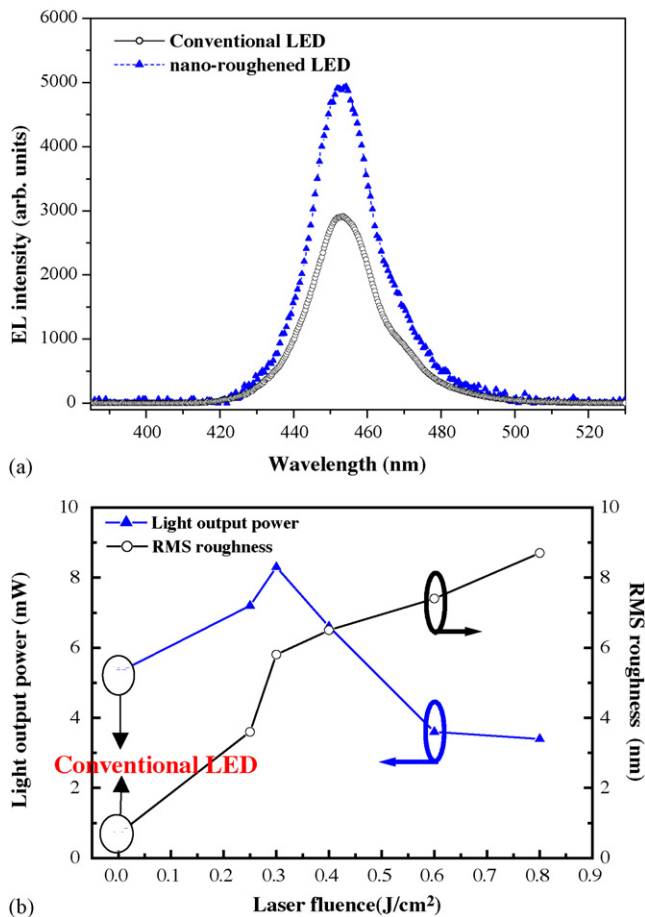


Fig. 8. (a) Room temperature EL spectra of conventional and nano-roughened LEDs with laser etching energy of 300 mJ/cm^2 at a current of 20 mA and (b) light output power-current (L - I) and RMS surface roughness characteristics of conventional and nano-roughened LEDs.

with a high specific resistance (shown in Fig. 7) and generation of non-radiative defects and slight deterioration in the InGaN/GaN MQW active regions during the high energy laser etching [15,16]. The laser etched surface morphology was also obtained by AFM measurement with a scan area of $5 \mu\text{m}^2$. The RMS roughness of the nano-roughened surface morphology were increased from 0.7 to 8.7 nm as the laser fluence increased from 0 to 800 mJ/cm^2 .

In summary, InGaN/GaN MQW LEDs fabricated by nano-roughening the p-GaN surface using Ni nano-masks and laser etching were demonstrated. The nano-roughened surface could improve the escape probability of photons inside the LED structure and has increased the maximum light output and wall-plug efficiency of 55 and 68%, respectively, over the conventional InGaN/GaN LEDs at 20 mA when the energy of laser etching was 300 mJ/cm^2 . 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.

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