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# Enhanced Extraction Efficiency of Vertical Conducting InGaN LEDs with Micro-Pillar Surface

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## 1. Introduction

Recently, near-ultraviolet (UV) light-emitting diodes (LEDs) have been demonstrated for several applications as a pumping source for exciting phosphor, [1] [2] a medical air cleaner and environmental sensor. It well knows that the refractive indexes of GaN and air are 2.5 and 1.0, respectively. The critical angle for the emission light generated in the InGaN-GaN active layer to escape can be calculated approximately 23° [3]. Hence, most of the light emitted from the LED active region and remain trapped in the high refractive index of GaN due to total internal reflection at the LED-air interface. It this letter, we propose a new approach for efficient light extraction combination a patterned sapphire substrate (PSS) [4]-[5] and laser lift off (LLO) process [6]. This technique eliminates the surface defects such as residual and electrical deterioration during dry etching process. Furthermore, it is also avoid destroying the p-n junction region where emission light is effectively generated. Details of the optical and electrical properties of the near-UV vertical conducting (VC) LEDs will be described.

## 2. Experimental

The InGaN-based LED samples were grown using a low-pressure metalorganic chemical vapor deposition method on (0001)-oriented two-inch PSS and conventional sapphire substrates. Then a 200-nm-thick Pt film was deposited onto the p-GaN top layer as the ohmic contact and reflective mirror. Furthermore, the Pt metal can also be used as a conductive layer for the subsequent copper electroplating process. Photo-resist was then coated onto the sidewall and dicing channel to prevent copper from being electroplated into this area. Copper was electroplated to a thickness of 100 μm as a metallic substrate for the LED epitaxy wafer. After the entire LED wafer was scanned by the laser beam, the sapphire substrate was separated from the LED structure and the GaN LED epi-layers were transferred onto a copper substrate. Finally, the electron-beam evaporated Ti/Al metal film on the n-GaN epilayer was used as the n-contacts. Fig. 1 shows the micro-pillar VC near-UV LED structure then completed corresponding field-emission scanning electron microscopy image of the micro-pillar on n-GaN surface

## 3. Results and discussion

Fig. 2 shows the micro-Raman spectra taken from the as-grown GaN and the GaN after LLO, where a 514.5 nm line of argon ion laser was focused on the sample surface than the reflectance beam of Raman shift was obtained. The Raman peak of as-grown GaN sample near 570 $cm^{-1}$ correspond to the TO phonon. For the LLO GaN sample the TO phonon peak shift to a lower wave number of 557 $cm^{-1}$, which correspond to cubic GaN. This result suggests that the GaN might be melted by laser radiation and changed from hexagonal wurtzite to cubic zinc blende during re-crystallization. Furthermore, the full width at half maximum (FWHM) of the TO mode GaN before LLO was estimated to be 11 $cm^{-1}$. For the TO mode of GaN after LLO, the FWHM has increased to 13 $cm^{-1}$. The increase of FWHM after LLO GaN can be attributed to the higher degree disorder in the crystal. Such a result was also reported by Ho et al [7].

Fig. 3 shows the room-temperature electroluminescence (EL) spectra of VC LEDs with and without micro-pillar operated at 350 mA. It can be seen clearly that the EL peak positions of the both LEDs were located at 409 nm. Note that the active layers in the both of the LEDs were grown under the same growth run. The EL intensity of the micro-pillar LED is higher than that of the conventional one. Moreover, the FWHM of micro-pillar and conventional VC LED was estimated to be approximately 14 and 15 nm, respectively. These result indicated that the significant enhancement in EL intensity could be attributed to the increase of the extraction efficiency by scattering the emission light at the patterned surface. Additional, it is also possible that the improvement in the internal quantum efficiency as the reason for the large EL intensity of micro-pillar VC LED by using PSS.

Fig. 4 shows a plot of the light output power (L-I) characteristics of the VC LEDs with and without micro-pillar as a function of dc injection current up to 500 mA at RT. As shown in Fig. 3 both of these LEDs L-I curves showed linear characteristics up to 350 mA than saturates with increase injection current at 400 mA, the saturates current caused by thermal heating effect. The light output was greatly increased by 39% for the LED having micro-pillar on n-GaN surface compared to conventional VC LED at a forward injection current 350 mA. This result indicated that the improvement in EL intensity is due to the increase of extraction efficiency by scattering the emission light at the micro-pillar on n-GaN surface. Such a result was also reported by Morita et al [8]. Generally, the light extraction efficiency in the InGaN-based LED is mostly limited mainly due to the refractive index of GaN layer is higher than that of the surrounding air. In addition, a part of the propagation light is absorbed by the metal electrode. However, when raised ring pattern are formed on the n-GaN surface, the propagation emission light is scattered via the rugged surface and resulted in an increase light output power of LED.

Fig. 5 presents the schematic drawing of the complete micro-pillar LED sample including photon trajectory. It can be seen that for the VC near-UV LED with micro-pillar on the n-GaN surface the photons can be scatter from the microroughened top surface of the LED. Hence, the improvement in probability of escaping photons from the LED resulted in an increase in light extracting efficiency.

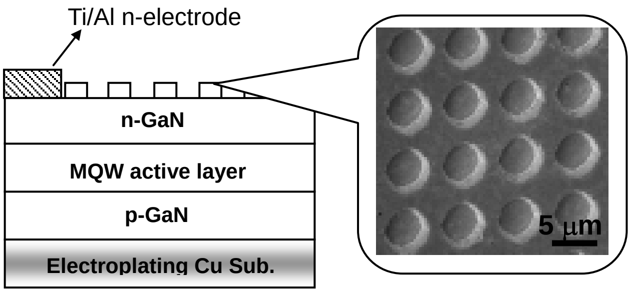


Fig. 1 Schematic diagram structure of the micro-pillar VC near-UV LED, corresponding FE-SEM image of the micro-pillar on n-GaN surface.

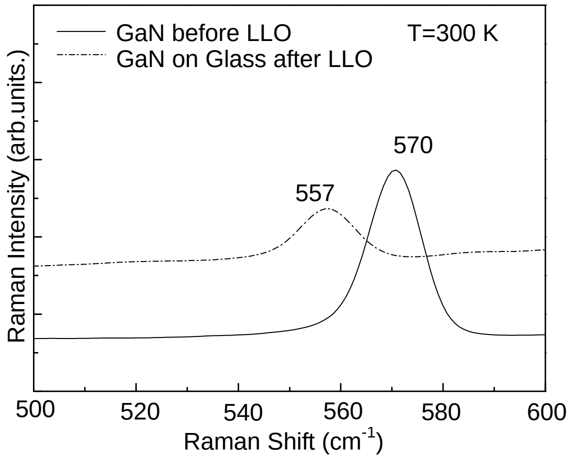


Fig. 2 Room-temperature micro-Raman spectra of GaN films before and after laser lift-off process.

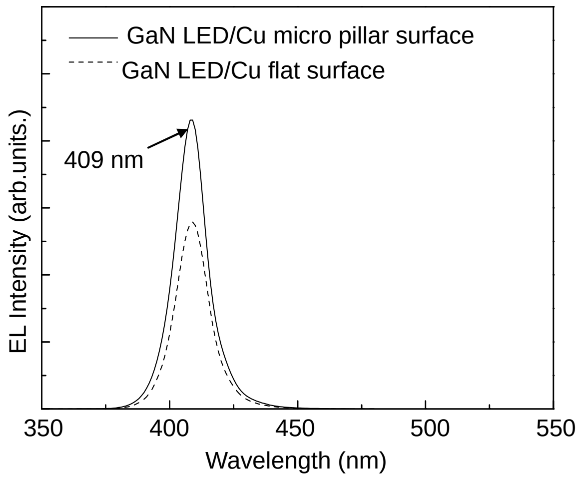


Fig. 3 Typical electroluminescence spectra of VC LED with and without micro pillar on n-GaN surface.

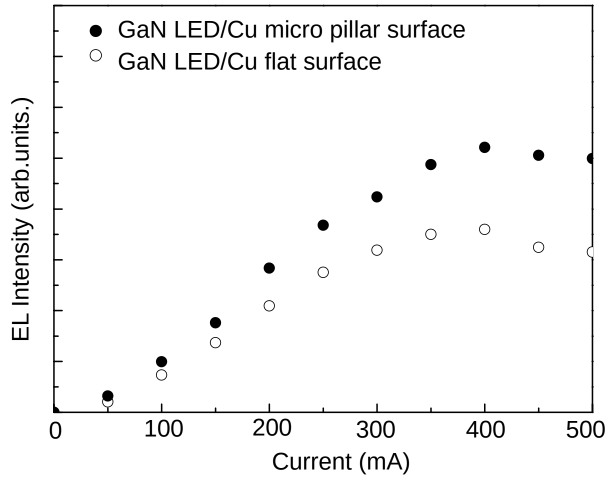


Fig. 4 Light output power of the large area VC near-UV LED with and without micro-pillar.

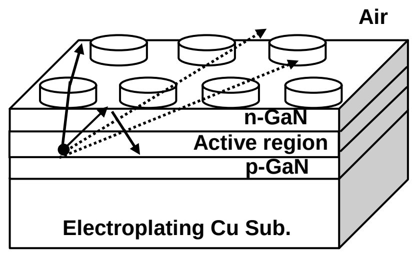


Fig. 5 Possible photon paths at patterned n-GaN/air interface.

## 4. Conclusion

Fabrication and characteristics of the near-UV vertical conducting InGaN LED with a novel micro-pillar surface have been demonstrated. A 39% enhancement in light output power of the micro-pillar-surface LED was observed. The enhanced performance can be attributed to the improvement the escape probability of photon from inside of the LED, resulting in an increase in the light extraction efficiency of the LED sample.

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