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Comparison of p-Side Down and p-Side Up GaN Light-Emitting Diodes Fabricated by Laser Lift-Off

Chen-Fu CHU, Chang-Chin YU, Hao-Chun CHENG, Chia-Feng LIN and Shing-Chung WANG*

Institute of Electro-Optical Engineering, National Chiao Tung University, Hsinchu, Taiwan, R.O.C.

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The performance characteristics of laser lift-off (LLO) freestanding InGaN/GaN multiple quantum well (MQW) light-emitting diodes (LEDs) mounted on a Cu substrate with p-side up, and p-side down configurations were determined and compared. The InGaN/GaN MQW LED structures, which were originally fabricated on a sapphire substrate, were transferred to a Cu substrate by the LLO process into two different configurations, namely p-side up and p-side down with the same Ni/Pd/Au p-contact metallizations. Both p-side down and p-side up LLO-LEDs showed a higher current operation capability up to 400 mA than the original LEDs on the sapphire substrate. The p-side down LLO-LEDs showed a nearly eightfold increase in the light output power compared to the p-side up LLO-LEDs. The p-side down LLO-LEDs also showed a more stable wavelength emission spectrum than the p-side up ones. [DOI: 10.1143/JJAP.42.L147]

KEYWORDS: GaN, laser lift-off (LLO), freestanding LLO-InGaN/GaN multiple quantum well (MQW) light-emitting diode (LED), p-side up and p-side down LLO-LEDs

The GaN-based wide band gap semiconductors are widely used for optoelectronic devices such as blue light-emitting diodes (LED) and laser diodes. These devices were grown heteroepitaxially onto dissimilar substrates such as sapphire and SiC because of difficulties in the growth of bulk GaN. Sapphire is the most commonly used substrate because of its relatively low cost. However, due to the poor electrical and thermal conductivity of the sapphire substrate, the device process steps are relatively complicated compared with other compound semiconductor devices. Therefore, free-standing GaN optoelectronics without sapphire are most desirable. Kelly *et al.*¹⁾ first demonstrated the laser lift-off (LLO) technique to separate a hydride vapor phase epitaxy-grown 2 inch GaN wafer from sapphire using a third harmonic of a Q-switched Nd:YAG laser of 355 nm wavelength. Recently, the LLO technique has been used to fabricate the free-standing InGaN LEDs.^{2–4)} These include p-side up GaN LEDs with Ti/Al as p- and n-contacts, the p-side down In_xGa_{1-x}N LEDs on Si substrates with Pd-In as p-GaN contact and bonding metal, and p-side up InGaN laser diodes on copper substrates. However, in these reports, either the original LED and LLO-LED had different p-GaN contact metals or the LLO-LEDs were mounted in the same substrate. Therefore, the comparison of LED performance before and after LLO was not fully investigated. The conventional GaN-based LEDs on sapphire with the p-side up configuration required semitransparent p-metal deposited on the top of mesa to enhance the emitting area, and the emitting area was typical small due to low holes mobility.⁵⁾ For increasing the emitting area and high light output power operation, an interdigitated mesa geometry was recently reported.⁶⁾ However, the LED process was relatively complicated. In this paper, we report the fabrication of LLO-LEDs with the p-side up and p-side down configurations with the same p-GaN contact metallizations of Ni/Pd/Au⁷⁾ and the demonstration of high current operation and large area emission.

The LED wafer structure was grown by metalorganic chemical vapor deposition on a (100) sapphire substrate.

The LED structure consists of a 25-nm-thick GaN low-temperature buffer layer, a 1.5- μm -thick undoped u-GaN layer, a 1.5- μm -thick highly conductive n-type GaN layer, a multiple quantum wells (MQW) region consisting of five-period u-GaN 2/5-nm-thick InGaN/GaN multiple quantum wells, and a 0.3- μm -thick p-type GaN layer.

Figures 1(a)–1(g) show the schematics of the fabrication steps of the p-side down LLO-LEDs, which involve LLO first followed by LED fabrication. The original GaN LED sample with a size of 1 cm \times 1 cm was deposited with Ni/Pd/Au (20 nm/20 nm/100 nm) metals as p-GaN contact and the backside of sapphire substrate was polished. Then the sample was bonded onto an indium-coated Cu substrate and annealed in oxygen at 550°C for 5 min to form a structure of sapphire/GaN LED/Ni/Pd/Au/In/Cu. In this process, the Ni/Pd/Au contact is also used as the bonding material without using any other bonding substances. The bonded structure was then subjected to the LLO process. A KrF excimer laser (Lambda Physik LPX200) at a wavelength of $\lambda = 248$ nm with a pulse width of 25 ns was used to remove the sapphire substrate. The incident laser fluence was set to a value of about 0.6 J/cm² which was based on our earlier established threshold laser fluence of 0.3 J/cm²⁸⁾ by taking into account the attenuation of sapphire and the reflection in the sapphire/GaN interface. The laser beam with a size of 1.2 mm \times 1.2 mm was incident from the polished backside of the sapphire substrate into the sapphire/GaN interface to decompose GaN into Ga and N₂. After the entire GaN LED sample was scanned by the laser beam, the sample was placed on a hot plate at a Ga melting point of about 30°C to separate the GaN LED structure from the sapphire substrate to form a LLO u-GaN/n-GaN/MQW/p-GaN structure on the Cu substrate. Then u-GaN was etched away to expose the n-GaN layer by inductively coupled plasma reactive ion etching (ICP RIE) (SAMCO ICP RIE 101ipH). The typical rough and uneven surface of u-GaN after the LLO process²⁾ was also even out by the ICP etching process to provide a smooth surface for the n-contact formation. Then, a square mesa of 300 μm \times 300 μm was also created by ICP/RIE for current isolation purpose. Finally, a Ti/Al layer with a 50 μm^2 circular pad was deposited as the n-type contact at the center of a 300 μm^2 region without any other semitrans-

*Author to whom correspondence may be addressed. E-mail address: scwang@cc.nctu.edu.tw

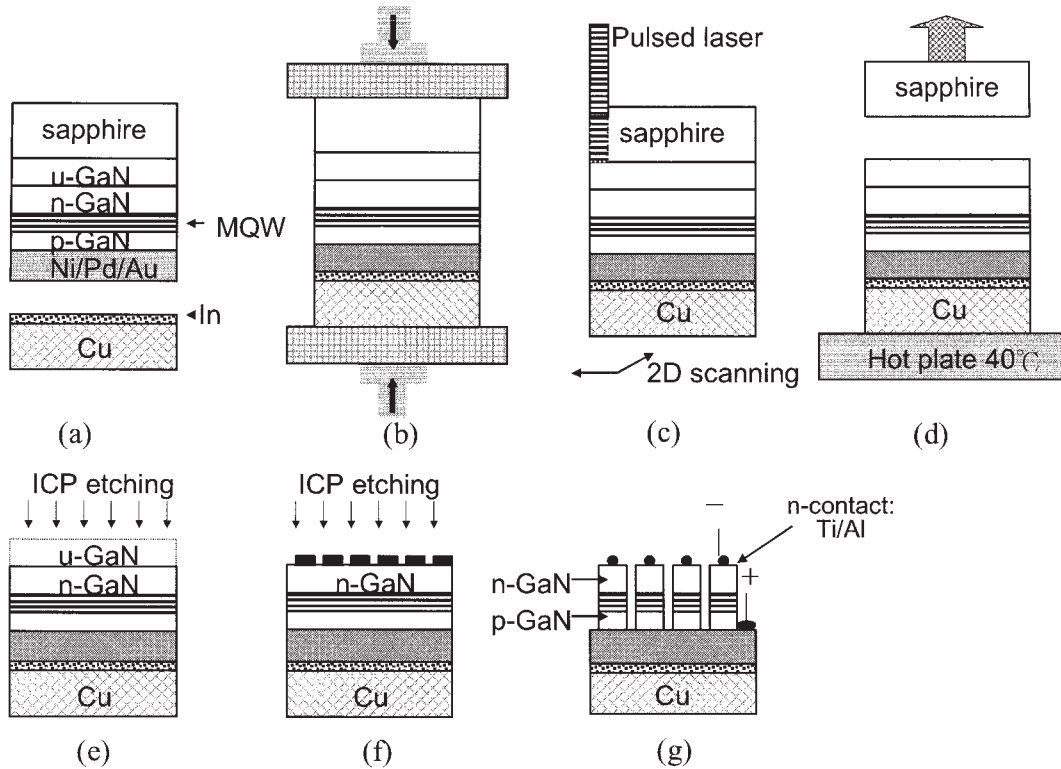


Fig. 1. Schematics of the fabrication steps for the p-side down LLO-LEDs on Cu. (a) P-type metal deposition. (b) Cu substrate bonding. (c) Laser processing. (d) Separation. (e) Etching of u-GaN layer. (f) 300 μm square mesa formation and device isolation. (g) N-type contact deposition.

parent contact layers. The completed p-side down LLO-LED shown in Fig. 1(g) has a key feature that is different from the p-side up configuration. It has a low resistivity n-GaN top layer to facilitate better current spreading⁹⁾ without the need of an additional semitransparent ohmic contact metallization typical of the p-side up GaN LEDs. However, due to the bonding of the Ni/Pd/Au p-contact at the bottom of p-GaN layer, the current-voltage (I - V) characteristics of this configuration were slightly compromised.

For fabrication of p-side up LLO-LEDs on Cu, the schematics of the fabrication steps, which involve LED fabrication first followed by the LLO process and an additional transfer process, are shown in Figs. 2(a)–2(h). A mesa with the same dimensions of 300 μm \times 300 μm was patterned first on the original LED wafer sample by standard photolithography. Then ICP/RIE was used to etch through the p-type and MQW layer of about 0.8 μm . A Ni (5 nm) semitransparent layer was deposited on the top of the mesa top and the same p-contact metallizations using Ni/Pd/Au (20 nm/20 nm/100 nm) with a diameter of 50 μm was deposited and annealed in oxygen at 550°C for 5 min. The Ti/Al metallization was deposited as n-type contact. The LED wafer sample of about 1 cm \times 1 cm with the backside polished was bonded to a glass carrier by using epoxy to form a structure of glass/epoxy/GaN LEDs/sapphire. The structure was then subjected to the LLO process as described previously. The lift-off LED structure with u-GaN exposed was then deposited with Au-based metal layers as bonding material and bonded to an indium-coated Cu substrate to form a structure of glass/epoxy/GaN LEDs/metals/In/Cu. In this process, the bonding interface is u-GaN, which has a relatively uneven and rough surface that could affect the

light output. By dipping the structure into an acetone solution to remove the glass carrier, a freestanding p-side up LLO-LED on Cu was produced.

Figure 3 shows the I - V characteristics for the p-side up GaN and p-side down LLO-LEDs, and the original p-side up LEDs on sapphire. The turn-on voltage of the p-side down LLO-LEDs on Cu was about 3.0 V, which is lower than that of about 3.5 V for the original p-side up LEDs on sapphire and p-side up LEDs on Cu. The I - V characteristics of the p-side up LLO-LEDs on Cu and the original p-side up LEDs on sapphire are similar showing no effect due to LLO. For the p-side down LLO-LEDs, the I - V characteristics are slightly different with a higher average dynamic resistance. This could be caused by the degradation of the p-contact during the bonding process as described earlier.

Figure 4 shows the light output power-current (L - I) characteristics for the p-side down LLO-LEDs compared with the p-side up LLO-LEDs and original p-side-up LEDs. The light output power of the p-side up LLO-LEDs is about 50% lower than that of the original p-side up LEDs before LLO. As discussed in the lift-off process, the p-side up LLO-LEDs have a relatively uneven and rough surface between u-GaN and the In-coated Cu substrate. This could cause poor light reflection from the bottom surface, and possible residual absorption in the interface layer as previously reported.²⁾ The light output power of the p-side down LLO-LEDs is about eightfold higher than that of the p-side up LLO-LEDs. The increase in the output power could be due to several factors. First, the increase in the output power could be due to the better current spreading of the n-GaN layer. For the p-side down LLO-LEDs, the current was injected from the top of n-GaN, allowing the current to

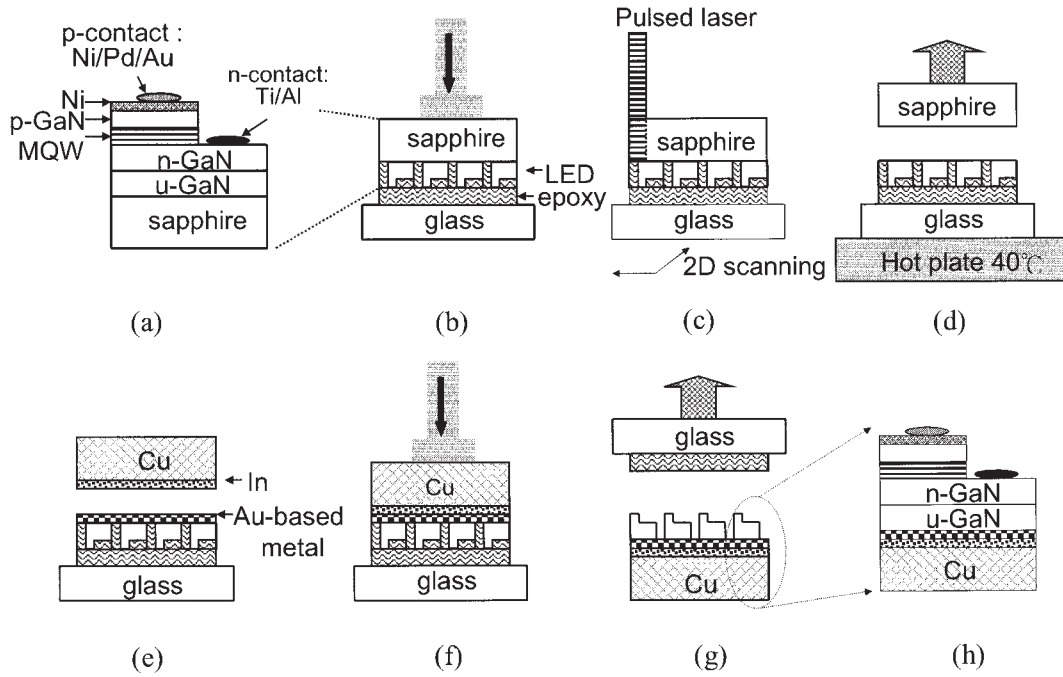


Fig. 2. Schematics of the fabrication steps for the p-side up LLO-LEDs on Cu. (a) The structure of p-side up LEDs on sapphire. (b) First bonding process. (c) Laser processing. (d) Separation. (e) Metal deposition. (f) Second bonding. (g) Epoxy stripping. (h) Freestanding p-side up LLO-LED structure.

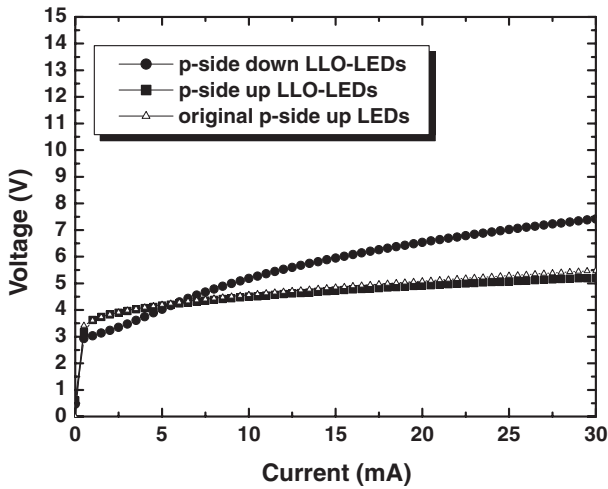


Fig. 3. Current-voltage (I - V) characteristics for the p-side down and p-side up LLO-LEDs, and the original p-side up LEDs on sapphire.

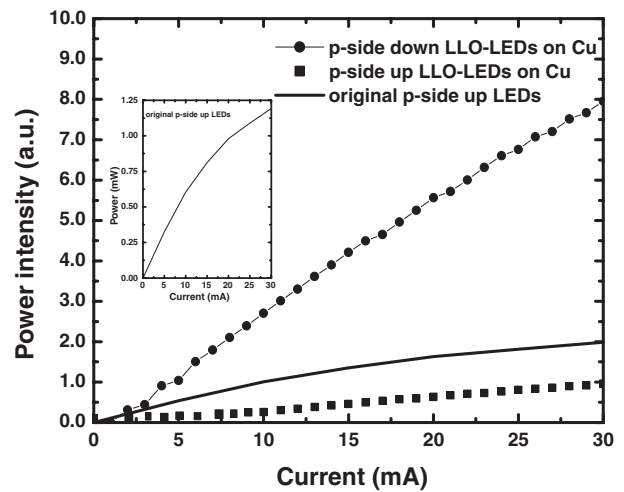


Fig. 4. Light output power-current (L - I) characteristics for the p-side down and p-side up LLO-LEDs, and the original p-side up LEDs on sapphire. The inset shows the L - I data of the original p-side up LEDs on sapphire.

spread easier into the entire top n-GaN layer because of the higher mobility of electrons in n-GaN than the holes in p-GaN.⁵⁾ Second, the GaN LED with the n-side up configuration tends to have a higher light output power according to a report.⁹⁾ Because of no light absorption by the semitransparent contact metal and no current crowding effect, the twofold higher light output power than that of the p-side up GaN LEDs was demonstrated.⁹⁾ Finally, based on the original p-side up LEDs' L - I data shown in the inset of Fig. 4, we estimated the external quantum efficiency for the p-side up LLO-LEDs and p-side down LLO-LEDs to be about 0.4% and 2.1%, respectively.

Furthermore, the p-side down LLO-LEDs require no additional semitransparent metal layers, which simplifies the fabrication process. These results suggest that the p-side

down LLO-LEDs are suitable for fabrication of large-emission-area GaN LEDs. Our preliminary results showed that an emission of area as large as 1 mm² can be fabricated.

Figure 5 shows the L - I characteristics for p-side down and p-side up LLO-LEDs, and original p-side up LEDs under high-current operation conditions. The light output power of the p-side down LLO-LEDs increased with increasing current from 0 to 200 mA and saturated after 200 mA. However, the light output power of the p-side up LLO-LEDs only increased up to 150 mA, then decreased at more than 150 mA. For the p-side down LLO-LEDs bonded to Cu, the heat generated at high-current operation conditions can be dissipated much easier than that of the p-side up LLO-LEDs;

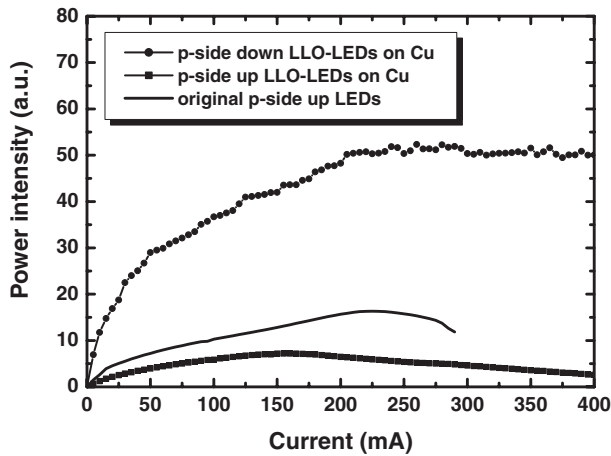


Fig. 5. Comparison of the light output power characteristics at high-current operation conditions for the p-side down and p-side up LLO-LEDs and the original p-side up LEDs on sapphire.

therefore, the light output is higher. In addition, the original p-side up LEDs showed deterioration in light output when the operation current exceeds 300 mA, while the p-side down, and p-side up LLO-LEDs are still operational up to 400 mA. Furthermore, the p-side down LLO-LEDs can still be operated at a high current injection of 1 A under continuous wave conditions. This result suggests that the LLO-LEDs, particularly the p-side down LLO-LEDs, have a higher current operation capability than the original LEDs fabricated on the sapphire substrate due to the better heat conduction of the Cu substrate.

Figure 6 shows the variation of emission peak wavelength of the LLO-LEDs under high-current operation conditions. The peak wavelength of the p-side up LLO-LEDs showed a gradual red shift from about 470 nm at 10 mA to 481 nm at 400 mA while that of the p-side down LLO-LEDs showed only a slight red shift from about 469 nm to 471 nm as the driving current increases from 10 mA to 400 mA. For comparison, the original conventional p-side up LEDs on sapphire was also included as shown in Fig. 6. It also showed a similar gradual red shift with increasing current, indicating that the shift is due to device heating. This result suggests that the p-side down LLO-LEDs not only have a higher thermal capability, but also have a more stable emission wavelength.

In conclusion, we have fabricated and compared the performance characteristics of two types of LLO-LEDs with p-side up and p-side down configurations on the Cu substrate with the same contact metallizations. A high operation current up to 400 mA for both p-side up LLO-LEDs, and p-side down LLO-LEDs on Cu was demonstrated. A substantial improvement in the light output power of the p-side

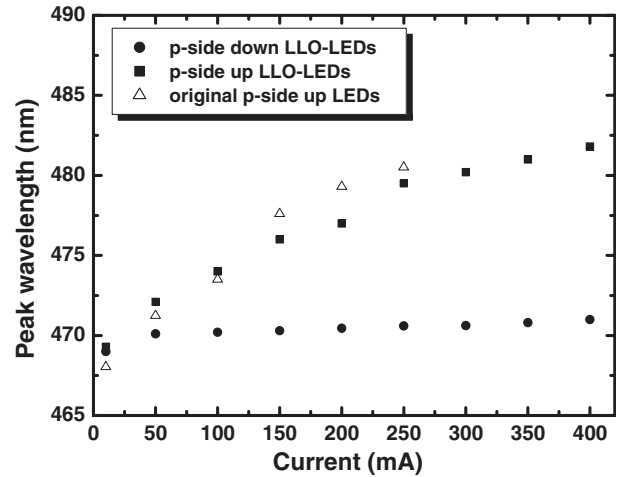


Fig. 6. Comparison of the peak wavelengths under high-current operation conditions for the p-side down and the p-side up LLO-LEDs, and the original p-side up LEDs on sapphire.

down LLO-LEDs compared to the p-side up LLO-LEDs on Cu and the conventional p-side up LEDs was obtained. The p-side down LLO-LEDs also showed a more stable wavelength emission spectrum than the p-side up ones. The LLO process should also be applicable to other GaN light-emitting devices, and the p-side down configuration in particular should be suitable for high-power, large-area GaN LEDs.

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