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Highly efficient vertical laser-liftoff GaN-based light-emitting diodes formed by optimization of the cathode structure

D. W. Kim, H. Y. Lee, M. C. Yoo, and G. Y. Yeom[a]
Department of Materials Science and Engineering, Sungkyunkwan University, Jangan-Gu, Chunchun-Dong 300, Suwon 440-746, Korea

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Vertical GaN-based light-emitting diodes (LEDs) were fabricated using a laser-liftoff process and the effect of the cathode processing conditions on the properties of the LEDs was investigated. Surface roughening by 10% Cl_2/90% BCl_3 plasma etching improved the light emission intensity at an operating current of 20 mA; however, the forward operating voltage was increased due to the thin and rough *n*-GaN layer. The use of an indium tin oxide (ITO) contact on the roughened *n*-type GaN surface decreased the forward voltage significantly, by decreasing the spreading resistance of the *n*-type GaN contact without decreasing the emission intensity. Through the combination of the ITO contact and the surface roughness of the *n*-GaN layer, a 100% increase in the extraction efficiency was obtained compared to that of a lateral GaN device, with maintaining a similar forward operating voltage. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1861497]

GaN-based light emitting diodes (LEDs) have been intensively studied for use in full color outdoor LED displays, LED lighting, etc.[1–6] In particular, researchers are currently making efforts to develop highly bright LEDs for white LEDs.[7,8] To increase the efficiency of the conventional GaN-based LED, attempts have been made to change the top electrode structure and to optimize the multi-quantum well layer, by using an indium tin oxide (ITO) contact instead of the traditional thin metal to *p*-type contact, through surface texturing, etc.[9–11]

However, many difficulties were encountered in the surface texturing and the formation of a transparent electrode on the *p*-GaN layer, in the case of the conventional GaN device having *p*-GaN on the top of the device, due to various problems such as the high sensitivity of *p*-GaN to plasma damage, the *p*-GaN top layer being too thin for texturing, the high contact resistance of ITO to *p*-GaN, etc.[9,12,13] Due to these difficulties, the successful application of surface texturing and/or the formation of a transparent contact to the conventional lateral GaN device using *p*-type GaN on the top of the device has not yet been reported.[11] Therefore, in this study, a reversely constructed GaN device fabricated by laser-liftoff (LLO) of the conventional GaN LED device was used to form a vertical LED (VLED) with *n*-GaN on the top of the device. In addition, the effect of the top cathode processing, such as the addition of the ITO layer and the surface roughening, on the properties of the LLO GaN VLEDs was investigated and its mechanism is reported.

Starting with a conventional GaN device deposited on a sapphire wafer, a highly reflective thick metal ohmic contact was deposited on the *p*-GaN side, before conducting the LLO process. The LLO process was performed using a KrF excimer laser (248 nm), and the sapphire substrate was separated from the GaN device completely. The surface of the separated GaN device was etched using BCl_3/Cl_2 inductively coupled plasmas (ICP). On the top of the *n*-type GaN, either a 100 μm diameter Ti/Al metal layer patterned by a photoresist liftoff process or a 50–175 nm thick indium tin oxide (ITO) layer deposited by sputtering without patterning was formed. The sputter deposited ITO was annealed in a N_2 ambient furnace at 300 °C for 7.5 min.

Figure 1 shows the scanning electron micrographs of the LLO GaN device surface after it was etched using an ICP with various BCl_3/Cl_2 mixtures. The ICP was operated at a power level of 1400 W, a rf frequency of 13.56 MHz, a bias voltage of −150 V and a BCl_3/Cl_2 pressure of 10 mTorr. The etching was performed until the undoped GaN remaining after the LLO process was completely etched and an

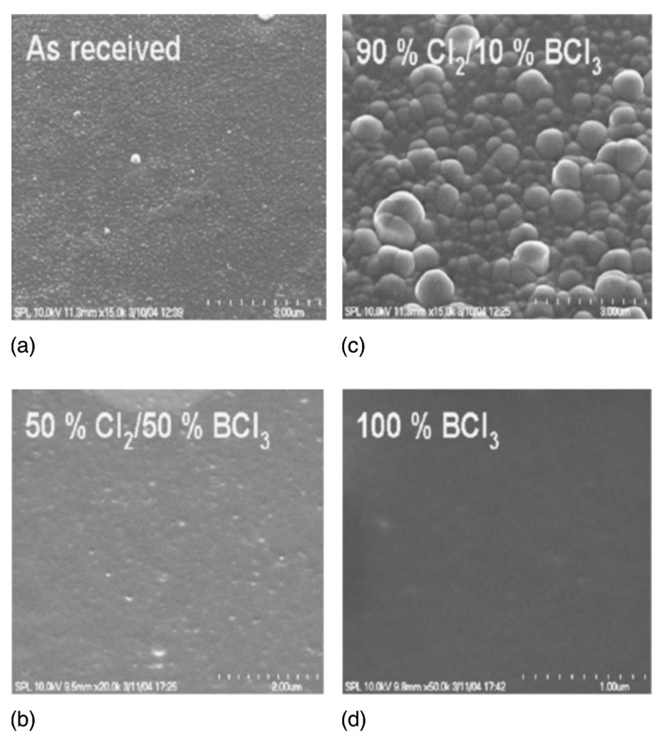

FIG. 1. Scanning electron micrographs of the LLO GaN device surface after etching using an ICP with various BCl_3/Cl_2 mixtures: (a) as-received; (b) 10% BCl_3/90% Cl_2; (c) 50% BCl_3/50% Cl_2; and (d) 100% BCl_3 at a gas flow rate of 100 sccm, a pressure of 10 mTorr, a rf power level of 1400 W, and a dc bias voltage of −150 V.

[a]Electronic mail: gyyeom@skku.edu

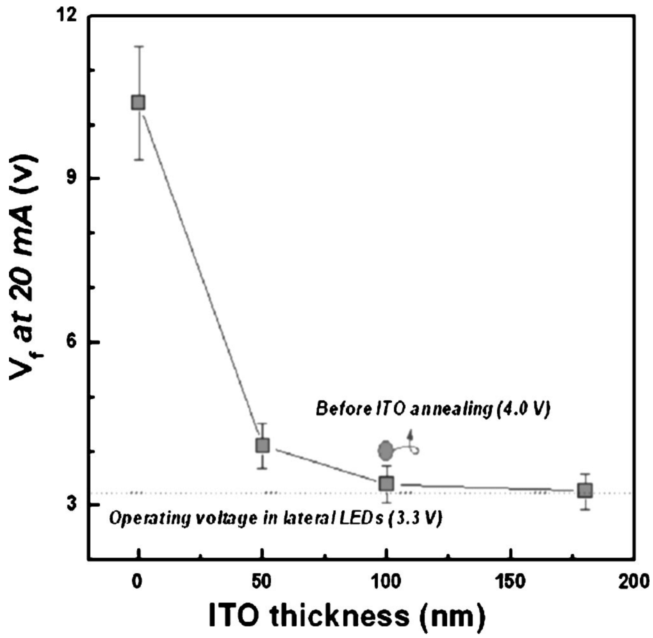

FIG. 2. Measured forward operating voltages of the LLO GaN VLEDs at an operating current of 20 mA as a function of the ITO layer thickness. When no ITO layer was deposited, a typical Ti/Al contact was used.

$\sim$1.5 μm thick *n*-type GaN layer remained on the LLO GaN device. As shown in Fig. 1, the use of 100% BCl_3 gave rise to a planar GaN surface, while the use of a chlorine-richer BCl_3/Cl_2 mixture produced a rougher surface. When a 10% BCl_3/90% Cl_2 mixture was used, ball-shaped features with diameters of 0.5–1 μm were obtained on the etched LLO GaN surface. It is believed that the presence of these ball-shaped features on the surface can increase the light extraction efficiency, by reducing the internal light reflection at the interface between the *n*-type GaN and air.

The Lambertian emission equation,[14] which indicates the extracted light intensity from a point source in the GaN to the air, I_{air}, can be written as follows;

$$I_{\text{air}} = \alpha I_{\text{GaN}} \cos \Phi_{\text{air}} \quad (1)$$

where, $I_{\text{GaN}} = P_{\text{source}}/4\pi r^2$ which is the light intensity in the GaN at a distance r from the source, $\alpha = (n_{\text{air}}/n_{\text{GaN}})^2$, where n is the refractive index, and the angle, Φ_{air}, is the escape angle into the air from the GaN, as measured from the normal to the surface. If the angle, Φ_{air}, is expressed in terms of the angle, Φ_{GaN}, which is the angle of incidence of light from the source in the GaN to the GaN/air interface, using Snell's law:

$$I_{\text{air}} = \alpha I_{\text{GaN}} \sqrt{1 - \sin^2 \Phi_{\text{GaN}}/\alpha}, \quad (2)$$

therefore, by modifying the surface morphology so as to obtain spherical shaped features through surface roughening, the angle of incidence, Φ_{GaN}, of light on the curved interface can be decreased compared to that on the flat interface and, in this way, the extraction efficiency can be increased.

Figure 2 shows the measured forward voltages at an operating current of 20 mA for the surface roughened LLO GaN VLED devices for ITO layers with various thicknesses. As shown in this figure, the conventional Ti/Al contact showed a high operating forward voltage of about 10.5 V. However, when the ITO was deposited on this device without patterning, in order for it to act as a current spreading transparent contact layer rather than a patterned Ti/Al contact, the forward operating voltage was dramatically decreased, and increasing the thickness of the ITO layer lowered the voltage even further. The high forward voltage in the case of the typical Ti/Al *n*-contact was not related to the Ti/Al contact resistivity. The Ti/Al contact resistivity to this LLO *n*-GaN layer was about $10^{-5}\ \Omega\ \text{cm}^2$ and the measured ITO contact resistivities to this LLO *n*-GaN layer were decreased from 8.5×10^{-5} to $1 \times 10^{-5}\ \Omega\ \text{cm}^2$ after annealing.

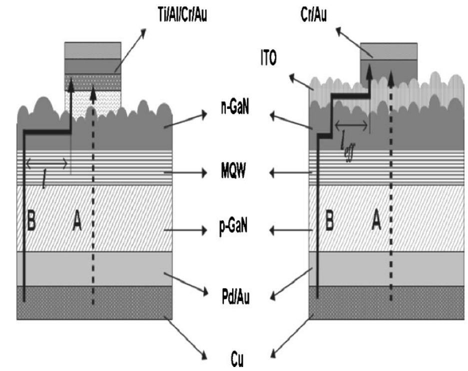

FIG. 3. Schematic diagram of the theoretical current paths of the LLO VLEDs with (a) a 100 μm diameter Ti/Al contact and (b) with the nonpatterned ITO layer as the transparent current spreading layer.

To obtain a better understanding of the high operating forward voltage observed in the case of the Ti/Al contact and the lowering of this voltage following the deposition of ITO in the case of the LLO VLED, schematic diagrams of the expected current paths of the LLO VLEDs for both contact structures were drawn, and are presented in Fig. 3(a) for the Ti/Al contact and Fig. 3(b) for the ITO layer contact. From Fig. 3(a), the difference in voltage between paths "A" and "B," $\Delta V_{n\text{GaN}(B-A)}$, can be written as;

$$\Delta V_{n\text{GaN}(B-A)} = J\rho_n(l - t_n), \quad (3)$$

where, J, ρ_n, t_n, and l represent the current density, the resistivity of the *n*-GaN layer, the thickness of *n*-GaN layer and the lateral spreading current path, respectively. To obtain uniform current spreading over the device, the voltage difference, $\Delta V_{n\text{GaN}(B-A)}$, should be close to zero, that is $J\rho_n(l-t_n) \approx 0$. The best method of minimizing the increase in the forward voltage in our LLO VLED device is to decrease the lateral current path (l) by an amount equal to the thickness of the *n*-GaN layer (t_n). That is, the contact size must be increased by an amount equal to the size of the device or the effective current spreading length (l_e) of the *n*-GaN layer, which implies the effective increased length of contact size, as measured from the edge of the contact metal, should be increased by adding a current spreading layer on the *n*-GaN.[14]

After depositing an ITO layer on the top of the *n*-GaN, in order for it to act as the current spreading layer, as shown in Fig. 3(b), the change in the voltage difference between paths "A" and "B" can be described as follows, assuming that the contact resistivities are low enough to be ignored:

$$\Delta V_{\text{ITO}(B-A)} = J\{[\rho_n(l - l_e) + \rho_{\text{ITO}} l_e] - (\rho_n t_n + \rho_{\text{ITO}} t_{\text{ITO}})\}. \quad (4)$$

If the voltage difference (ΔV) between $\Delta V_{\text{ITO}(B-A)}$ and $\Delta V_{n\text{GaN}(B-A)}$ is large, then more uniform current spreading is achieved. That is,

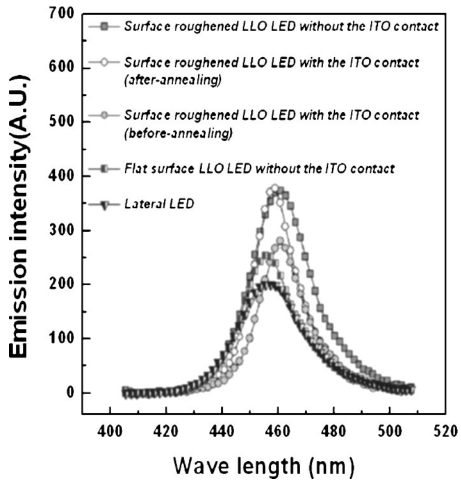

FIG. 4. Light emitting spectra of a conventional lateral GaN LED and the surface roughened LLO GaN VLEDs with a 100 μm diameter Ti/Al contact and the nonpatterned ITO contact as the transparent current spreading layer.

$$\Delta V = J[l_e(\rho_n - \rho_{\mathrm{ITO}}) + \rho_{\mathrm{ITO}} t_{\mathrm{ITO}}] \approx J l_e(\rho_n - \rho_{\mathrm{ITO}}), \qquad (5)$$

assuming that $\rho_{\mathrm{ITO}} t_{\mathrm{ITO}} \approx 0$ due to the low thickness and low resistivity of ITO. The effective current spreading length (l_e) can be represented as a function of the resistivity (ρ_{cs}) and the thickness (t_{cs}) of the current spreading layer, i.e., $l_e = \mathrm{const} \times \sqrt{t_{cs}/\rho_{cs}}$ Therefore, the voltage difference shown in Eq. (5) can be rewritten as

$$\Delta V \approx \mathrm{const} \times J\sqrt{t_{\mathrm{ITO}}/\rho_{\mathrm{ITO}}} \cdot (\rho_n - \rho_{\mathrm{ITO}}). \qquad (6)$$

From Eq. (6), it can be seen that the improvement in the forward voltage of the ITO contact device shown in Fig. 2 can be attributed to the improved lateral current spreading effect, which results from the low resistivity of the deposited ITO layer at a driving current of 20 mA.

Figure 4 shows the measured light emitting spectra of the conventional lateral LED and the surface roughened LLO VLEDs with the Ti/Al contact and the 100 nm thick ITO layer. As shown in this figure, the surface roughened LLO VLED without the ITO layer shows an increase in light emission of about 100% compared to that of the lateral LED. In addition, the surface roughened LLO VLED with the annealed ITO layer shows a similar level of light intensity to that of the surface roughened VLED with the Ti/Al contact, and a low forward operating voltage which is similar to that of the lateral GaN.

In conclusion, surface roughening by plasma etching, in order to increase the light extraction efficiency, and the deposition of an ITO layer, which acts as a transparent current spreading layer, were used as the method of obtaining a highly efficient LLO VLED with a low forward operating voltage. Although the total integrated extraction efficiency was not measured, a 100% increase in the optical emission intensity and a comparable forward operating voltage could be obtained with the fabricated LLO VLED, as compared with a conventional lateral LED.

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