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Leakage Current Characteristic of Vertical GaN-Based Light Emitting Diodes with Passivation Structures

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We investigated the influence of passivation structure on reverse leakage current characteristic of vertical GaN-based light emitting diodes (LEDs). Proper passivation structure is important for high-performance vertical LEDs because large external or residual stress arising during device fabrication and operation can deteriorate electrical properties such as leakage current and current-voltage behavior. Unpassivated and SiO_2-passivated vertical LEDs showed relatively large leakage currents in reverse bias. In contrast, photoresist-passivated vertical LEDs showed a very low leakage current of ~4 nA for a reverse bias of −5 V, and lower forward operation voltage of 3.22–3.24 V at 20 mA compared to lateral LEDs.
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Conventional structure GaN-based light emitting diodes (LEDs) consist of n- and p-electrodes laterally positioned on the opposite side of a sapphire substrate. In the lateral LEDs, current crowding occurs at the corner of mesa structure generating local heating, and ultimately the device reliability can be degraded.[1,2] In contrast, n- and p-electrodes of vertical structure GaN-based LEDs are placed on the top and bottom of the LED structure, respectively, so that current can flow through the active well region having uniform distribution. Accordingly, the vertical LEDs have advantages of uniform current spreading and moreover efficient heat dissipation by employing a metal substrate (or supporter), which has high thermal conductivity, for high power application. In addition, light extraction can be effectively improved by adding an Al- or Ag-based reflector in the p-electrode structure.[3-5] Thin GaN-based LEDs are sustained by the metal supporter after removing the sapphire substrate by laser lift-off (LLO) method.[6] After that, the fabrication of the vertical LEDs is completed by creating n-electrode on n-GaN surface, which is exposed by the removal of the sapphire substrate and then the dry etching of buffer GaN layer.

LLO process delivers large mechanical stress to the vertical LED structure. GaN is dissociated into Ga and N_2 gas at the buffer GaN/sapphire interface by laser irradiation. Explosive force generated by rapid volume expansion of N_2 gas is mostly concentrated on the weakest locations of the vertical LED structure such as p-GaN/p-electrode interface and the sidewall of GaN-based layers. Delamination at the p-GaN/p-electrode interface can lead to an increase of device operation voltage. Considering the vertically aligned electrodes, the GaN sidewall can possibly function as another current passage so that it can induce a leakage of electrical charges. In this case, leakage current can flow partly from an electrode to the GaN sidewall, deviating from the normal current path. In addition, the vertical LEDs are supported by a ductile metal substrate less than 150 μm thick after the removal of the sapphire substrate. The ductility of the metal substrate can induce wafer bending or fatigue stress to the vertical LED structure during subsequent processing. Therefore, a passivation structure is required to protect the vertical LEDs from external damage. In this paper, we report on the leakage current characteristic and operation reliability of vertical GaN-based LEDs with Cu supporter, which are protected by various passivation structures. Vertical LEDs with no passivation, SiO_2 passivation layer, and trench-filling photoresist (PR) structure are studied compared to lateral LEDs.

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Experimental

Two-inch-diam sapphire substrate was used for epitaxial growth of GaN-based LED layers, which consisted of a buffer GaN layer, a Si-doped n-GaN layer (2.5×10^{19} cm^{-3}), InGaN/GaN multiple quantum wells (MQW), and a Mg-doped p-GaN layer (3.5×10^{17} cm^{-3}), by metallorganic chemical vapor deposition. The chip area of 350 × 350 μm was defined by creating trench lines between chips using inductively coupled plasma reactive ion etching (ICP-RIE). A reflective p-electrode of indium tin oxide (ITO)/W/Al (2500/10/4000 Å) was deposited on p-GaN using radio-frequency (rf) magnetron sputtering. The ITO/p-GaN contact was annealed at 600°C for 5 min in O_2 condition using a rapid thermal processor to form ohmic contact.

Three different vertical GaN-based LEDs were prepared in order to study the effect of passivation structure. One vertical LED had no passivation structure. Another vertical LED was passivated by 0.7 μm SiO_2 layer, which was deposited by plasma enhanced chemical vapor deposition. The third vertical LED was passivated with a commercial PR (JSR Corp.) suitable for microstructure construction. The PR passivation was 7 μm thick in trench lines and 2 μm thick over p-electrode. After forming a passivation structure, 100 μm Cu supporter was electroplated on a continuous seed layer of W/Cu (500/3000 Å). An electrolyte for Cu electroplating consisted of 92 g L^{-1} copper sulfate, 25 g L^{-1} boric acid, 32 g L^{-1} sulfuric acid, and 0.7 g L^{-1} sodium lauryl sulfate, which functioned as a wetting agent. A KrF excimer laser at 248 nm wavelength was irradiated through the sapphire substrate with an energy density of 0.3 J m^{-2} for the removal of the sapphire substrate. An n-electrode of Ti/Al/Au (200/200/3000 Å) was deposited on n-GaN using rf magnetron sputtering after n-GaN surface was exposed by ICP-RIE of the buffer GaN layer. A parameter analyzer (HP 4155 A) was used to characterize the current-voltage (*I-V*) behavior.

Results and Discussion

Schematic illustrations in Fig. 1 show vertical LED structures passivated by conformal SiO_2 layer and by trench-filling PR structure, respectively. Both vertical LED structures are under large mechanical stress by explosive volume expansion of N_2 gas during LLO of the sapphire substrate. For vertical LEDs, current leakage can occur mainly through the GaN sidewall, whereas it was reported that, for lateral LEDs, leakage current is dependent on the density of dislocations in GaN.[7] Thus, the GaN sidewall should be tightly passivated so that the free surface of the GaN sidewall is not exposed nor cracking in GaN layer and passivation structure occurs under large mechanical stress. Figure 2 shows reverse bias *I-V* curves of vertical LEDs protected by passivation structures of SiO_2 and PR. Reverse bias *I-V* curves of unpassivated vertical and lateral LEDs were also plotted for comparison in the same figure. For unpassi-

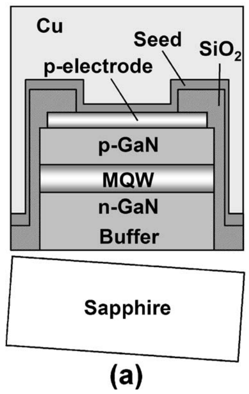

Figure 1. Schematic illustrations of vertical GaN-based LEDs with (a) SiO_2 passivation structure and (b) PR passivation structure.

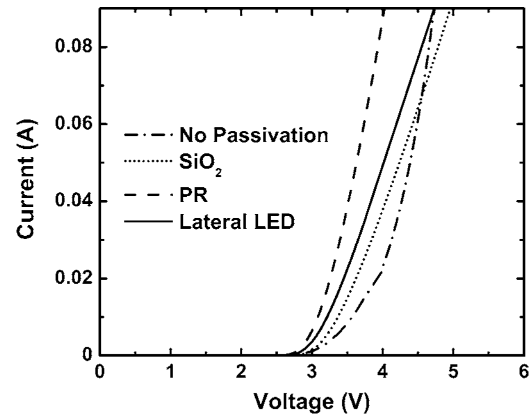

Figure 3. Current-voltage (*I-V*) curves of vertical GaN-based LEDs with no passivation, SiO_2, and PR passivation, and lateral GaN-based LED, indicating forward operation voltage at 20 mA.

vated lateral LEDs, leakage current was as low as ~5 nA for a reverse bias of −5 V. Lateral LED structure formed on the sapphire substrate does not experience large external stress during fabrication. Thus, although lateral LED is not protected by passivation structure, it may not include major structural damage that could be a passage for charge leaking. In addition, according to the lateral arrangement of n- and p-electrodes, it is preferred that current flows between the electrodes via the corner of mesa structure rather than deviating toward the unpassivated GaN sidewall. For these reasons, there is less chance for current to leak through the GaN sidewall of the unpassivated lateral LED.

For unpassivated vertical LEDs, a leakage current as high as 400 nA was found for a reverse bias of −5 V. It is not only attributed to charge leaking through the GaN sidewall, but also partly attributed to delamination at the interfaces of multilayered p-electrode/p-GaN upon mechanical stress. The interlayer delamination can occur by either the repetitious fluctuation of vertical LED structures during device fabrication or the stress concentration on the weakest interface during the LLO process. Moreover, the GaN-based layers 5 μm thick and 350 μm wide are mechanically weak under pressure in the normal direction although a ductile Cu substrate supports it on the backside. Full delamination at a p-contact interface leads to device failure, whereas partial delamination increases leakage current as well as operation voltage due to the reduction of contact area. However, when vertical LED structure was passivated by a SiO_2 layer generally used for passivation in

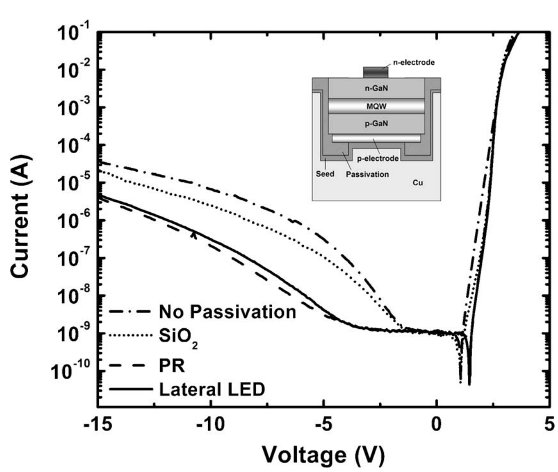

Figure 2. Reverse bias current-voltage (*I-V*) curves (logarithmic scale) of vertical GaN-based LEDs with no passivation, SiO_2, and PR passivation, and lateral GaN-based LED, showing leakage current characteristic.

electronics, leakage current was reduced to 150 nA at −5 V compared to that of the unpassivated vertical LED. Nevertheless 150 nA is still much higher than the leakage current value of the lateral LED. This implies that a thin SiO_2 passivation layer is not strong enough to effectively endure large stress generated during device fabrication and operation. Adhesion strength between SiO_2 and GaN was measured as only 32 MPa in a pull-off adhesion test. It was also found that a considerable number of cracks were generated within delaminated SiO_2 layer after LLO process because the SiO_2 layer was fragile under large mechanical stress. On the other hand, a commercial PR material was employed for passivation of vertical LEDs, filling trench lines with the PR. The main reason for using the PR is that it has large adhesion strength to Al (~120 MPa) and GaN (~96 MPa) so that the PR-passivation structure should not be delaminated from the LED surface. Mechanical force larger than 60 MPa during LLO process was locally exerted on vertical LEDs. Furthermore, the PR has low elastic modulus (~2.2 GPa) and large elongation (~5%) indicating relatively high toughness. Accordingly, the PR-passivation structure was resistant to large mechanical stress, avoiding its brittle rupture as well as protecting vertical LED structure securely. Consequently, a leakage current as low as ~4 nA, which was similar to that of the lateral LED, for a reverse bias of −5 V was found in the PR-passivated vertical LED.

With regard to higher temperatures during subsequent processing or high current operation, the optical and structural properties of the PR should also be considered. Most light generated from the active well region of vertical LEDs is extracted via the top surface of the LEDs, whereas a very small portion of light is extracted via the PR-passivated GaN sidewall. This implies that the optical property of the PR material rarely influences the total light output of the vertical LEDs. In spite of that, the PR material showed an excellent transparency of 80–90% for visible lights. It did not lose its intrinsic transparency so long as it was treated under 250°C. In addition, the PR showed no volume loss for 2 h annealing at 250°C, whereas only 3% volume loss was observed for 2 h annealing at 300°C. Consequently, in this study, any structural loss or deformation of the PR-passivation structure itself was not observed after device fabrication, and even after 500 h aging test of the PR-passivated vertical LEDs.

Figure 3 shows the *I-V* curves of vertical and lateral LEDs in forward bias depending on passivation structure. Forward operation voltage of PR-passivated vertical LED was in the range of 3.22–3.24 V at 20 mA, whereas that of lateral LED was in the range of 3.42–3.46 V at 20 mA. As expected, it was shown that vertical LEDs had lower operation voltage than lateral LEDs so long as they were passivated tightly. On the other side, unpassivated and SiO_2-passivated vertical LEDs showed higher operation voltages

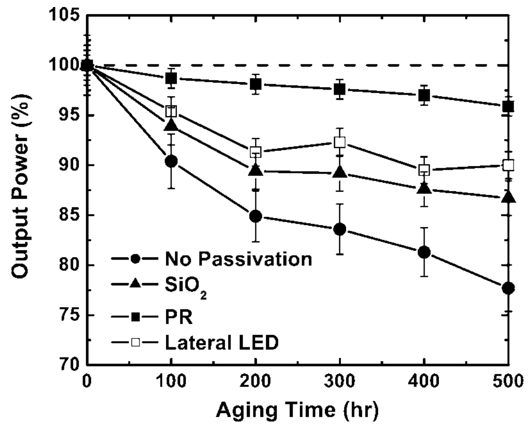

Figure 4. Variation of light output power of vertical GaN-based LEDs with no passivation, SiO_2, and PR passivation, and lateral GaN-based LED for 500 h aging at 90 mA.

than unpassivated lateral LED. It indicates that proper passivation structure is required not only for reducing leakage current, but also for efficient operation of vertical LEDs.

Aging tests of 500 h were conducted in order to estimate the operational reliability of the LEDs according to LED structure, as shown in Fig. 4. An applied forward current was 90 mA, and light output power was recorded every 100 h. The mean values of output power were plotted for 25 LED chips of each structure. PR-passivated vertical LEDs showed a slight output power drop of less than 5% after 500 h aging. However, unpassivated or SiO_2-passivated vertical LEDs showed an output power drop over 10% after 500 h aging. The results indicate the importance of passivation structure for the reliability as well as the performance of vertical LEDs.

Conclusion

Vertical GaN-based LEDs with electroplated Cu supporters were fabricated with being unpassivated or passivated by thin SiO_2 layer or trench-filling PR. Passivation structures were employed to protect vertical LEDs from mechanical stress involved during device fabrication and operation. PR-passivated vertical LEDs showed a very low leakage current of ~ 4 nA for a reverse bias of -5 V, which was very similar to that of unpassivated lateral LEDs. In addition, PR-passivated vertical LEDs showed lower operation voltage than unpassivated lateral LEDs. Furthermore, the output power drop of PR-passivated vertical LEDs was restricted to less than 5% after 500 h operation at 90 mA. On the other hand, unpassivated or SiO_2-passivated vertical LEDs showed inferior properties in leakage current, operation voltage, and operation reliability because they were not properly passivated. Consequently, proper passivation structure is necessary for high performance and reliability of vertical GaN-based LEDs.

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