GaN-based semiconductors are a promising material for high-brightness light-emitting diodes (LEDs) with emission in the visible and ultraviolet wavelength range.

We report the effect of chemical etching of p-GaN using molten KOH:NaOH solution on leakage currents, light output power, and electrostatic discharge (ESD) characteristics of GaN LEDs. The photoluminescence and capacitance–voltage measurements indicated that a deep donor–acceptor pair (DDAP) was densely concentrated near the p-GaN surface region (~18 nm) and the defects were effectively removed by a chemical etching process, resulting in a remarkable reduction of defect-assisted leakage current on the forward and reverse bias, and improved light output power due to enhanced injection efficiency in etched GaN LEDs. The negative-voltage ESD characteristics of etched GaN LEDs were also improved due to the decrease in DDAP defects near the surface region of p-GaN.

**Experimental**

InGaIn/GaN MQW LEDs were grown on c-plane sapphire substrates by MOCVD. The LED structure consisted of a Si-doped n-GaN layer (2 μm) with Si concentration of 9 × 10^{18} cm^{-3}, five-period InGaIn (3 nm)/GaN (7 nm) MQW active layers with emission wavelength of 465 nm and a Mg-doped p-GaN layer (0.13 μm) with Mg concentration of 2 × 10^{20} cm^{-3}. Si and Mg concentration were measured by secondary ion mass spectrometry.

In this study, we investigated the effect of chemical etching of the p-GaN surface on the leakage current, light output power, and ESD characteristics. The etched GaN LEDs showed a reduction of defect-assisted leakage current on forward and reverse bias, resulting in an improved light output power and improved negative-voltage ESD characteristics due to the decrease of DDAP defects near the surface region of p-GaN.

**Results and Discussion**

To investigate the origin of defects affected by chemical etching of p-GaN, C–V curves were measured at a high frequency of 100 kHz using a MOS structure consisting of Al (100 nm)/SiO_{2} (15 nm)/p-GaN (1 μm)/n-GaN (2 μm) on the sapphire substrate. As shown in Fig. 1, the flatband voltage (V_{FB}) of etched p-GaN is very close to the ideal V_{FB} compared to that of nonetched p-GaN after the voltage sweep from −5 to 0 V. For this p-GaN MOS structure, the ideal V_{FB} is calculated to be −2.3 eV based on the work function difference between Al (Φ_{Al}=4.2 eV) and p-GaN (Φ_{p-GaN}=6.5 eV).

The V_{FB} of nonetched and etched p-GaN is ~3.3 and ~2.3 eV, respectively, as determined by the flatband capacitance (C_{FB}) of 3.3 × 10^{-11} F. C_{FB} is required for flatband conditions in this p-GaN MOS structure, and the C_{FB} of 3.3 × 10^{-11} F is calculated by using the equation C_{FB} = 1/(L_{ox} + L_{p-GaN}) where C_{ox} is the oxide capacitance of 3.5 × 10^{-11} F, L_{ox} is the extrinsic Debye length of 1.02 × 10^{-8} m, and ε_{o} is the GaN permittivity of 8.920 As shown in Fig. 1, the V_{FB} of etched p-GaN is very close to the ideal V_{FB} of −2.3 eV, indicating that a large amount of hole-trap states in...
the surface region of nonetched p-GaN was removed by chemical etching of the p-GaN surface. The $V_{FB}$ of the nonetched p-GaN shifted to the low-voltage side from the ideal $V_{FB}$, and this indicates that the origin of the surface trap state is the hole trap state. Furthermore, the inversion capacitance of etched p-GaN was decreased in the voltage range of −1 to 0 V, as shown in Fig. 1. In general, the p-GaN MOS structures are known to show no surface inversion at room temperature, because the generation rate of the minority carriers is extremely low. However, Nakano et al. reported the inversion of a p-GaN MOS structure at high-frequency $C-V$ measurement and suggested that the inversion can be attributed to dislocation providing an external source of minority carriers. These minority carriers are considered a dominant factor in creating an inversion capacitance at high-frequency $C-V$ measurement. Therefore, the $C-V$ curves in Fig. 1 show that many hole-trap states and minority carriers in the surface region of p-GaN were simultaneously reduced by the chemical etching of p-GaN.

In order to further identify the origin of the hole-trap state and the minority carrier source, PL spectra were measured on etched and nonetched p-GaN layers at room temperature. The PL bands at −2.85 eV (−435 nm) and −2.61 eV (−475 nm) were typically observed on the Mg-doped p-GaN layers and these bands were related to the DDAP transition between $V_N$ deep donor and MgGa acceptor. The deep-level transient spectroscopy measurement also showed that Mg-doped p-GaN has discrete acceptor levels of 0.21, 0.39, and 0.41 eV above the valence band edge ($E_V$). These energy levels can also be involved in the DDAP transition, resulting in the PL band at −2.85 eV (−435 nm) and −2.61 eV (−475 nm), as shown in Fig. 2. The PL peak intensity at −2.85 and −2.61 eV on the PL spectra of p-GaN etched by a molten KOH and NaOH solution was remarkably decreased by 2–3 orders of magnitude due to the reduction of DDAP defects densely concentrated near the p-GaN surface region (−18 nm) of p-GaN and the defects can be effectively removed by the chemical etching of p-GaN with a molten KOH and NaOH solution.

The leakage currents of etched and nonetched GaN LEDs were measured at room temperature, as shown in Fig. 3. It was reported that the forward current in the low-voltage region is closely related to the defect-assisted leakage current. The defect-assisted leakage current of $3 \times 10^{-9}$ A at 1.5 V in the nonetched GaN LEDs was decreased to $1 \times 10^{-9}$ A in the etched GaN LEDs, as shown in Fig. 3a. The large leakage current of $1 \times 10^{-5}$ A at a reverse bias voltage of −10 V in the nonetched GaN LEDs was also decreased to $7 \times 10^{-9}$ A in the etched GaN LEDs, as shown in Fig. 3b. It was reported that the defect-assisted leakage current was observed at low reverse voltage and a band-to-band tunneling current was observed at high reverse voltage. As Fig. 3a and b shows, the forward and reverse defect-assisted leakage currents in the GaN LEDs was remarkably reduced by 2–3 orders of magnitude due to the reduction of DDAP defects densely concentrated near the p-GaN surface region of −18 nm. It was also reported that defects were highly concentrated within the top 15 nm of the surface region of the p-GaN layer, and this caused a defect-assisted leakage current in the Schottky diode of p-GaN. However, the exact origin of defect-assisted leakage current at the low forward and reverse bias voltage is still unclear. In this study, our results strongly indicate that a dominant source of leakage current is closely related to the DDAP defects in p-GaN, which also corresponds to the PL band at −2.85 and −2.61 eV.

As shown in Fig. 4, the light output power of etched and non-etched GaN LEDs was measured as a function of injection current. It was found that the light output power of etched GaN LEDs was significantly improved by 58% at 20 mA compared to that of non-etched GaN LEDs. This result is attributed to the reduced DDAP defects acting as a leakage path after chemical etching of p-GaN, leading to an enhanced injection efficiency and the improved light output power of GaN LEDs.

ESD characteristics of the etched and nonetched GaN LEDs...
were measured by applying positive- and negative-voltage ESD stress to the GaN LEDs, as shown in Fig. 5. Either positive- or negative-voltage ESD stress was applied to the anode (p-GaN) of GaN LEDs, while the cathode (n-GaN) was grounded. The voltage of ESD stress in the range of 1–3 kV was used for positive-voltage ESD stress, and −300 V to −1.2 kV was used for negative-voltage ESD stress.

Figure 3. (Color online) Current–voltage curves at (a) forward bias (b) reverse bias voltage in the nonetched and etched GaN LEDs.

Figure 4. (Color online) Light output power of etched and nonetched GaN LEDs as a function of injection current.

Figure 5. (Color online) ESD characteristics of the nonetched and etched GaN LEDs: (a) forward voltage measured at 20 mA after application of positive-voltage ESD stress and (b) forward voltage measured 20 mA after application of negative-voltage ESD stress.
negative-voltage ESD stress above ~0.3 kV. The etched GaN LEDs, however, showed good diode characteristics, even after the application of ~0.9 kV ESD stress, as shown in Fig. 5b. It was suggested that the damage caused by negative-voltage ESD stress in GaN LEDs is related to a high density of defect level accelerating the impact ionization which is leading to the failure or degradation of GaN LEDs. Therefore, the improvement of negative-voltage ESD characteristics in etched GaN LEDs can be attributed to the reduction of DDAP defects that are densely concentrated near the surface region of the p-GaN layer.

Conclusions

DDAP defects were densely concentrated near the surface region (~18 nm) of the p-GaN layer and were effectively removed by using a molten KOH and NaOH solution. The defect-assisted leakage currents at the forward and reverse bias voltage were remarkably decreased due to a reduction of DDAP defect, and the light output power of etched GaN LEDs was significantly improved by 58% at an injection current of 20 mA due to enhanced injection efficiency. The negative-voltage ESD characteristics of GaN LEDs were also improved from ~0.3 to ~0.9 kV.

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References