Effect of photoelectrochemical etching and post-metallization annealing on gate controllability of AlGaN/GaN high electron mobility transistors

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Recessed-gate AlGaN/GaN metal-insulator-semiconductor (MIS) high electron mobility transistors (HEMTs) were fabricated by utilizing a photoelectrochemical (PEC) etching and a post-metallization annealing (PMA) process. In order to demonstrate the device performance and reliability, both electrical and optical electroluminescence (EL) properties were evaluated. The capacitance–voltage (C–V) characteristics showed that the PEC etching and subsequent PMA process enhanced the gate control of two-dimensional electron gas density. The PEC-etched-gate AlGaN/GaN MIS-HEMT showed the smallest sub-threshold slope of all the samples including planar-gate and inductively coupled plasma-etched-gate devices. Furthermore, the PEC-etched devices showed an extremely low $10^{-11}$ A mm$^{-1}$ gate leakage current with no spot-like EL. These results indicated that the PEC etching and subsequent PMA process improved the electrical properties of the AlO$_x$/AlGaN interface, resulting in enhanced device performance of the AlGaN/GaN MIS-HEMTs. © 2019 The Japan Society of Applied Physics

1. Introduction

Gallium nitride (GaN)-based electron devices are promising for high-power and high-frequency applications due to their superior electrical properties over silicon (Si), such as high-breakdown electric field and high-saturation electron velocity. AlGaN/GaN high electron mobility transistors (HEMTs) have achieved simultaneously high blocking voltage and low on-state resistance ($R_{ON}$) in their device operation by utilizing two-dimensional electron gases (2DEGs) yielded at the AlGaN/GaN hetero-interface. In particular, the insertion of high-$κ$ dielectric effectively reduces gate leakage current, $I_G$, and enables high-current drive with a large gate swing in the metal–insulator–semiconductor (MIS)-gate HEMT. However, durability and long-term reliability remain key issues for the MIS-gate devices fabricated with GaN-based materials. There has been a lot of research on improving them based on understanding and controlling the MIS interface. Reference 10 recently reported that post-metallization annealing (PMA) was effective for the Al$_2$O$_3$/GaN interface, reducing interface-state density to the detection limit of the C–V technique. Several groups have reported that the gate controllability of AlGaN/GaN MIS-HEMTs was enhanced by reducing the interface-state density after some post-annealing processes after oxide layer deposition. In order to control threshold voltage, $V_{th}$, in AlGaN/GaN HEMTs, an inductively coupled plasma reactive ion etching (ICP-RIE) has commonly been used for thinning the AlGaN layer beneath the gate electrode. However, it has been pointed out that dry-etched surfaces are generally negatively affected by various types of damage such as nitrogen vacancy defects and disordered atomic-bond arrangements. These kinds of damage and defects induce high-density surface- and interface-states in the forbidden band, which leads to severe operational stability problems such as gate leakage, current collapse and threshold voltage instability. One alternative approach to the dry-etching process is the low-energy photoelectrochemical (PEC) etching process, which utilizes anodic oxidation and the subsequent dissolution of the resulting oxide in an electrolyte. Recently, Ref. 19 reported that the dry-etching damage was effectively removed from n-GaN surfaces by the PEC process without causing any additional damage. The PEC process has been applied to the fabrication of the recessed-gate structures in AlGaN/GaN HEMTs, where good controllability of $V_{th}$ was obtained for Schottky gate devices. References 21, 22 demonstrated the excellent potential as a high-aspect-ratio deep trench structure in vertical GaN power devices by the PEC etching.

The purpose of this paper is to investigate device performance and its reliability in AlGaN/GaN MIS-HEMTs with recessed-gate structures prepared by the PEC process. For this purpose, we employed an emission microscope to evaluate the electrical properties and capture the electroluminescence (EL) observed during the on-state and off-state operations. The EL technique has been used to visualize the spatial distribution of current leakage and electrical breakdown points that correlate with dislocations or defects in p–n diodes and AlGaN/GaN HEMTs and so on. In this study, we fabricated the planar-gate and recessed-gate MIS-HEMTs and compared their electrical properties and EL observed around the MIS-gate region. Furthermore, we evaluated the effects of the PMA on the electrical properties of the AlGaN/GaN MIS-HEMTs with recessed-gate to further improve their reliability.

2. Experimental methods

We used an i-Al$_{0.24}$Ga$_{0.76}$N (20 nm)/i-GaN (900 nm) heterostructure grown on SiC substrate by metal–organic chemical vapor deposition as the starting wafer. A Ti/Al/Ti/Au (20/50/20/50 nm) multilayer ohmic electrode for the PEC etching was formed using an electron-beam evaporation method, followed by annealing at 800 °C for 1 min in N$_2$ ambient. Then, a SiO$_2$ film (100 nm) was deposited by sputtering and was patterned to define the etching region, followed by photolithography and a buffered-HF (BHF) treatment. We carried out the PEC etching using a three-electrode cell whose AlGaN/GaN MIS-HEMT working electrode (WE), Pt counter electrode and Pt/Ag|Hg reference electrode.
We carried out the PMA under 300 °C in air for several hours to further enhance the Al2O3 film quality and/or Al2O3/AlGaN interface after completing the device processing. Moreover, we measured the current–voltage (I–V) and capacitance–voltage (C–V) characteristics of the Al2O3-stacked AlGaN/GaN HEMTs with a Keysight Technologies B1500A Semiconductor Device Analyzer. Then, we attempted to observe EL from the backside of the devices through the SiC substrate under device operations to evaluate the effect of both the PEC and PMA process, as shown in Fig. 1(b). The detectable wavelength range of the emission microscope was 400–1100 nm with a PHEMOS-1000 by Hamamatsu Photonics.

3. Results and discussion

3.1. Basic electrical properties of PEC-etched MIS-HEMTs

Figure 2 shows the output characteristics of the planar-gate and PEC-etched-gate AlGaN/GaN MIS-HEMTs with a gate length, Lg, of 5 μm and a nominal Al2O3 thickness of 30 nm. The PEC etching conditions were set to achieve an 8 nm Al2O3 layer thickness in accordance with our previous work. All the samples fabricated here showed good I–V curves with constant saturation currents and pinch-off behavior at a low Vg bias. However, drain currents, Id, were suppressed in the MIS-HEMT without the PMA at the higher Vg over 0 V for the planar-gate MIS-HEMT and 4 V for the PEC-etched-gate MIS-HEMT [see Figs. 2(a) and 2(b)]. On the other hand, the AlGaNgN MIS-HEMT with the PMA showed good gate controllability of the Id even at forward gate bias over 8 V, as shown in Fig. 2(c). Figure 3 compares the transfer characteristics of the PEC-etched-gate AlGaNgN MIS-HEMTs for two kinds of devices conducted with and without the PMA process. The PMA successfully made the Vth shift in the forward bias region and enhanced the maximum transconductance, gmax, from 60 to 66 mS mm−1. A possible mechanism for the positive Vth shift and gmax enhancement after the PMA could have originated from the decrease of oxygen-related defects in the Al2O3/AlGaN system and the subsequent shrinkage of the ALD-Al2O3 film caused by the relaxation of dangling bonds.25,26)

In order to further clarify how the PEC etching affected the device performance, we compared the electrical properties of three kinds of devices: the planar-gate device without any etching, ICP-etched-gate device and PEC-etched-gate device. The dry etching was conducted by the ICP-RIE using a BCl3/Cl2 gas mixture of 10 W bias power. Figure 4 shows semi-log plots of Id–Vg and |Ig|–Vg characteristics measured for three kinds of devices at Vth = 15 V. We found that the |Ig| was effectively reduced for all devices after the PMA into the range of 10−11 A mm−1, which was the lower limit of the semiconductor parameter analyzer. However, there was a large difference in the sub-threshold slope (SS) obtained from the Id–Vg characteristics.

We obtained the SS value of 141 mV dec−1 for the planar-gate device, whose value decreased from the 171 mV dec−1 obtained from the same device before the PMA (data not shown here). On the other hand, the ICP-etched-gate device showed much larger SS of 480 mV dec−1, indicating that the ICP-RIE inevitably caused plasma-related damage to the AlGaN surfaces and/or beneath the 2DEG channel. Several
groups have reported that the depth of the etching damage induced by the ICP-RIE was several hundred nanometers,19,27) which was much larger than the initial thickness of the AlGaN barrier layer, 20 nm, in the present device. As shown in Fig.4, the PEC-etched-gate device showed the lowest SS of 121 mV dec $^{-1}$, indicating that the top of the AlGaN layer was etched through the low-energy electrochemical process.

To obtain deeper insight into the interface properties of the Al$_2$O$_3$/AlGaN gate structures, the capacitance–voltage ($C–V$) measurements were conducted on the MIS capacitors having a circular gate with a diameter of 100 $\mu$m. The $C–V$ curves obtained using a signal frequency of 1 MHz at RT are shown in Fig. 5. The vertical axis of $C/C_{ox}$ indicates the normalized total capacitance by the insulator capacitance of 251 nF cm$^{-2}$ that was calculated for the 30 nm thick Al$_2$O$_3$ film. Both the planar-gate and the PEC-etched-gate devices showed the two-step behavior typically observed in Al$_2$O$_3$/AlGaN/GaN structures. The first step at the deep-reverse-bias region indicates the depletion of the 2DEG channel at the AlGaN/GaN interface. The subsequent capacitance plateau represents the series capacitance of the Al$_2$O$_3$ film and AlGaN layer. Generally speaking, the nearly flat band-diagram leads to electron spillover from the AlGaN/GaN interface to the Al$_2$O$_3$/AlGaN interface in the forward bias region, resulting in the series capacitance approaching the insulator capacitance. In this study, the $V_{G}$ was not applied to a particularly high value in the forward direction, but the capacitance increased towards the ideal $C_{ox}$ value. In addition, the starting

Fig. 2. (Color online) $I_D$–$V_D$ (output) characteristics of Al$_2$O$_3$/AlGaN/GaN MIS-HEMTs with a gate length, $L_G$, of 5 $\mu$m of (a) a planar-gate without PMA, (b) PEC-etched-gate without PMA, and (c) PEC-etched-gate with PMA.

Fig. 3. (Color online) $I_D$–$V_D$ and $g_m$–$V_D$ (transfer) characteristics of PEC-etched-gate Al$_2$O$_3$/AlGaN/GaN MIS-HEMTs with the PMA (filled circle and filled square, respectively) and without the PMA process (open circle and open square, respectively).

Fig. 4. (Color online) Transfer characteristics of planar-gate (black), PEC-etched-gate (red) and ICP-etched-gate (blue) Al$_2$O$_3$/AlGaN/GaN MIS-HEMTs with the PMA in the saturated region ($V_D = 15$ V). AlGaN thicknesses, $d_{AlGaN}$, were 20, 8 and 6 nm for the planar-gate, PEC-etched-gate and ICP-etched-gate device, respectively.
voltages of the first C–V step were −8.0 and −2.0 V for the planar-gate and PEC-etched-gate devices, respectively, which were very close to those of the 2DEG depletion observed in the MIS-HEMTs (see Fig. 4).

On the other hand, the C–V curve of the ICP-etched-gate device showed a gentler slope of the first step compared with those of the planar-gate and PEC-etched-gate devices, as shown in Fig. 5. Such a difference in the C–V behavior is very consistent with the difference in the SS values obtained from the \( \frac{\left|I_D\right|}{V_D} \) measurements on three kinds of MIS-HEMTs. These results suggest that the ICP etching increased the interface-state density at the Al\(_2\)O\(_3\)/AlGaN interface due to the etching damage on the AlGaN surface. On the other hand, the PEC etching and subsequent PMA process effectively removed the unintentionally-induced damage or defects from the AlGaN surface, leading to the reduction of the interface-state density and enhancement of the MIS-gate controllability.

3.2. Optical and electrical investigation using an emission microscope

The effects of the PMA on the durability and reliability of the AlGaN/GaN MIS-HEMTs were evaluated by EL observation on two kinds of planar-gate and PEC-etched-gate devices. The \( \frac{\left|I_D\right|}{V_D} \) characteristics measured under the on-state condition (\( V_G = V_{th} + 6 \) V) for the planar-gate MIS-HEMT, is shown in Fig. 6(a), by comparing the devices with and without the PMA process. The emission microscope simultaneously caught the CCD images and corresponding EL images shown in Fig. 6(b). The uniform emissions along with the gate edge towards the drain side were observed in both devices, where there were no spot-like emissions around the gate region. In previous studies,\(^{24,26-31}\) these kinds of EL along the gate edge were discussed in connection with the behavior of hot-electrons generated in the 2DEG channel. In some literature,\(^{24,31}\) the relation between the EL intensity and \( V_D \) is given by:

\[
\text{EL intensity} \propto \exp \left( \frac{-V_0}{V_D - V_{DSat}} \right)
\]

where \( V_{DSat} \) represents the saturation drain voltage and \( V_0 \) is a parameter from the analogy in AlGaAs/GaAs HEMTs by plotting \( \ln(\frac{\left|I_D\right|}{I_D}) \) versus \( 1/(V_D - V_{DSat}) \). In order to clarify the EL mechanism obtained here, the data of semi-log scaled EL intensity divided by \( I_D \) was plotted in Fig. 7 as a function of \( 1/(V_D - V_{DSat}) \) by comparing the devices before and after the PMA. Open circles and filled circles represent the data obtained before and after the PMA, respectively, and the dashed lines represent the slope of the experimental data. As can be clearly seen in Fig. 7, EL intensity/\( I_D \) versus \( 1/(V_D - V_{DSat}) \) plots showed good agreement with the relation in Eq. (1), suggesting that the EL observed during on-state operations is most likely correlated with the “hot-electron” in the 2DEG channel.

In contrast to the data obtained under on-state conditions, the gate leakage current between the planar-gate and PEC-etched-gate devices differed significantly before and after the PMA. Figure 8(a) shows the \( \frac{\left|I_D\right|}{V_D} \) characteristics measured under the off-state condition (\( V_G = V_{th} - 2 \) V) for the planar-
gate MIS-HEMT by comparing the devices with and without the PMA process. In addition, Fig. 8(b) shows the CCD images and corresponding EL images simultaneously captured by an emission microscope. As shown in Fig. 8(a), the $|I_G|$ was reduced by about one or two orders of magnitude after the PMA, indicating that the factor of gate leakage pass decreased in the MIS-gate stack. As Fig. 8(b) shows, we observed the hot-spots of the emission at $V_D = 30$ V for the device before the PMA. The highest intensity of spot emissions (observed around the gate edge of the drain side) increased together with the increase of $V_D$. Reference 24 reported that the preferential emission sites were due to the contribution to the EL of electrons injected from the large band bending. This might be the same situation in our case, where large drain–gate voltage ($V_{GD} = -48$ V) was applied under the off-state operation. However, such preferential spot-like emissions were not observed even at $V_D = 40$ V after the PMA, indicating the suppression of the electron injections from the gate electrode to the channel. One mechanism to be possibly improved by the PMA is as follows. It has been reported that Poole–Frenkel (PF) electron emission has been a dominant conduction mechanism of gate leakage current for dielectrics such as Al$_2$O$_3$ and SiN$_x$ in relatively low $V_G$. 32–34 Therefore, the PMA effectively reduced the defect-related electronic states in Al$_2$O$_3$ film10,12,25,26 to suppress the PF emission conduction.

The $|I_G|–V_D$ measurement and EL observation were similarly conducted on the PEC-etched-gate MIS-HEMTs, which were compared with those obtained on the planar-gate MIS-HEMTs in Figs. 9(a) and 9(b) for on-state and off-state conditions, respectively. The $|I_G|$ of the PEC-etched-gate MIS-HEMT was the lowest of all the devices up to $V_D = 40$ V. In addition, preferential EL was not observed from the PEC-etched-gate MIS-HEMTs at such a high drain–source voltage region. Recent reports pointed out that the gate leakage path that degraded device performance was correlated with the formation of grooves or v-shaped pits that might be generated by native oxygen contamination beneath the gate electrode.35,36 Furthermore, another possibility is that the charged nitrogen vacancies induced near the AlGaN surface might accelerate the oxidation, and the subsequent generation of more nitrogen vacancy ions will cause chain reactions.35,37,38 Therefore, one possible reason for the low leakage currents observed in the PEC-etched-gate device is that the surface damage and/or contamination were effectively removed from the surface of the AlGaN layer after the PEC etching. From these results, we believed that PEC etching followed by the PMA process is an attractive way to improve the operation stability of the AlGaN/GaN MIS-HEMTs with the recessed-gate structure.

4. Conclusion

We investigated the effect of the PEC etching and subsequent PMA process on the electrical properties of an AlGaN/GaN MIS-HEMTs with a recessed-gate structure. The results of the $I–V$ characteristics showed that the PEC-etched-gate AlGaN/GaN MIS-HEMT demonstrated the steepest SS of $121 \text{ mV} \text{ dec}^{-1}$ with extremely low $10^{-11}$ A mm$^{-1}$ gate leakage after conducting the PMA. The $C–V$ characteristics of the MIS capacitor fabricated on the AlGaN/GaN
heterostructure showed that the PEC etching enhanced the gate control of 2DEG density. Furthermore, the gate leakage currents and EL were characterized for the planar-gate and PEC-etched-gate devices under on- and off-state conditions. Significant differences were observed before and after the PMA under off-state condition. A lot of spot-like EL was observed under the gate electrode before the PMA, but such spot-like EL and gate leakage currents were suppressed by the PMA and could sweep much higher drain voltage. These results showed that the PEC etching process and subsequent PMA process effectively improved the surface damage of the electrical properties of the Al$_2$O$_3$/AlGaN interface without inducing additional damage, and it enhanced the AlGaN/GaN MIS-HEMT operation stability.

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