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Normally-off AlGaN/GaN MIS-HEMT with low gate leakage current using a hydrofluoric acid pre-treatment

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ABSTRACT

We demonstrate the electrical performances of an AlGaN/GaN metal–insulator–semiconductor high electron mobility transistor (MIS-HEMT) with low gate leakage current (I_g). A low gate leakage current as low as the order of 10^{-11} A/mm was achieved from normally-off MIS-HEMT device (V_{th} = 2.16 V) with a partially recessed gate, fluorine treatment, and ALD Al_2O_3 gate dielectric layer. The gate leakage current decrease is attributed to the pre-treatment of the gate region with hydrofluoric acid (HF) and deionized water (DI) solution, which acts to remove the native oxide layer and thus decrease interface traps. X-ray photoelectron spectroscopy (XPS) and atomic force microscopy (AFM) analyses demonstrate that the AlGaN surfaces are modified such that the surface roughness and native oxide introduced by the treatments used to achieve normally-off operation are remedied with the use of the pre-treatment.

1. Introduction

GaN based high-electron mobility transistors (HEMTs), owing to the intrinsic advantages of GaN such as wide bandgap, high electron mobility, and high breakdown voltage, have proven their superiority for high power and high frequency applications. The primary drawbacks of GaN based transistors are normally-on operation and high gate-source leakage current resulting from the conventional Schottky gate structure. Approaches such as gate recess [1], p-GaN gate [2], and fluorine treatment [3] have been demonstrated to achieve normally-off operation. Gate recess on its own results in higher ON-state gate leakage current and decreased gate voltage swing; thus, normally-off devices are commonly fabricated combining gate recess and metal–insulator-semiconductor (MIS) approaches [4,5]. A fully recessed barrier, however, results in degraded channel mobility and increased channel resistance, which leads to low current densities and large on-resistance [6,7]. These issues are overcome with a partial recess, in which a thin barrier layer remains, at the cost of a less positive threshold voltage. Fluorine treatment of the gate region using plasma based systems is used to implant fluorine ions in the barrier layer and recover the threshold voltage, however, it has been demonstrated that fluorine implantation results in trap generation in the barrier layer [8], which indicates that there is possibility for improvement of the gate leakage characteristics in such devices.

Many methods for the reduction of gate leakage current have been reported in the literature such as post-gate annealing [9], pre-gate surface treatments [10], plasma treatments [11], p-InGaN cap [12], and oxide-filled isolation technique [13]. For normally-on devices, minimum reported gate leakage currents are in the order of 10^{-10}–10^{-11} A/mm [13,14]. Ref. [15] reports gate leakage currents on the order of 10^{-8} A/mm for recessed-gate normally-off MOS-HEMT devices, and [16] reports forward gate leakage currents on the order of 10^{-11} A/mm for a normally-off GaN MIS-HEMT with fluorine doped gate insulator.

In a previous study [17], we have demonstrated that for a hybrid approach of obtaining normally-off operation using recess etching and

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fluorine treatment, gate leakage characteristics display minimal variation with process modifications. Thus, an alternative approach is required in order to obtain improvement in the gate leakage. In this study, we report a fabrication process of a normally-off GaN MIS-HEMT with a gate leakage current as low as on the order of 10^{-11} A/mm by exploiting a hydrofluoric (HF) acid pre-treatment prior to gate formation.

2. Device structure and fabrication

The fabricated HEMT structures consist of a 300 nm AlN nucleation and AlGaN strain managing layer stack on a Si substrate, followed by 1150 nm of a low Al content $Al_xGa_{1-x}N$ (x: 0.05) buffer, 110 nm of a high mobility channel GaN, 1 nm AlN spacer, 27 nm $Al_{0.26}Ga_{0.84}N$ barrier, and a 3 nm unintentionally doped GaN cap layer. The mobility and 2DEG density were found to be $6.7 \times 10^{12}\,cm^{-2}$ and $1425\,cm^2V^{-1}s^{-1}$, respectively, by contactless Hall measurements. The fabrication started with mesa isolation by inductively coupled plasma reactive ion etching (ICP-RIE) using BCl_3 and Cl_2 gases. E-beam evaporation method was used to deposit Ti/Al/Ni/Au metals for Ohmic contacts, followed by rapid thermal annealing (RTA) with a 3-step annealing process in N_2 ambient. The RTA process consisted of steps at 400 °C for 180 s, 700 °C for 40 s, and 830 °C for 30 s, respectively. The Ohmic contact resistance was extracted as 0.40 Ohm.mm using the transfer length method (TLM). Gate fingers were defined with optical lithography, and partially recess etched using ICP-RIE with a low power (RF: 5 W, ICP: 300 W) BCl_3/Cl_2 recipe to achieve an etch depth of 10 nm. Subsequently, F^- treatment was carried out for 10 min using SF_6 gas with ICP-RIE. Prior to atomic layer deposition (ALD) in the gate regions, acid pre-treatment consisting of hydrofluoric acid (HF) and deionized water (DI) (1:14) rinse for 8 s was applied. It has been reported that an appropriate acid pre-treatment prior to ALD Al_2O_3 deposition has a mitigating effect on interface trap densities [18,19]. After the cleaning procedure, a 10-nm-thick Al_2O_3 layer was deposited at 200° C by ALD, employing Trimethylaluminium as the Al precursor, and DI water as the O precursor. Pulse times of the Al precursor and O source were both 0.015 s, and the purge times were chosen as 10 s. The process was conducted in an N_2 ambient with gas flow of 20 sccm. The gate regions were redefined with optical lithography. Ni/Au (50/300 nm) e-beam evaporation and lift off were carried out to form the gate electrodes. For device passivation, 240 nm SiN_x dielectric layer was deposited with plasma enhanced chemical vapor deposition (PECVD). The fabrication was completed with the formation of connection pads. A standard normally-off MIS-HEMT with a similar process flow except for the omission of HF pre-treatment was fabricated as a reference. The dimensions of the devices were $L_{DS} = 9\,\mu m$, $L_{GS} = 2\,\mu m$, and $L_G = 2\,\mu m$. The fabricated devices have gate finger dimensions of $10 \times 1000\,\mu m$. Fig. 1 shows the schematic cross-section with dimensions and a micrograph of the AlGaN/GaN normally-off MIS-HEMT.

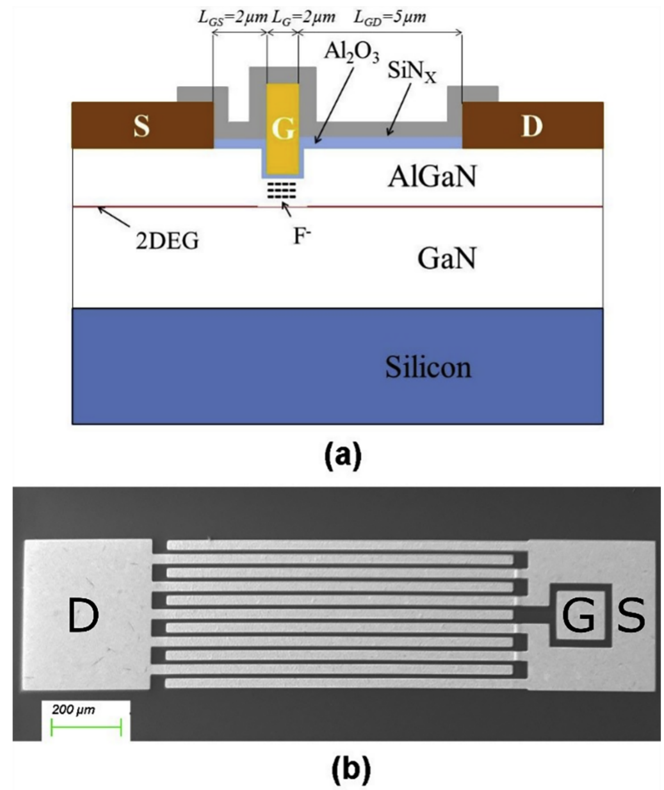

Fig. 1. a) Schematic cross-sectional view with gate length, gate to source distance, and gate to drain distance, and b) micrograph of the GaN MIS-HEMT. (single column figure).

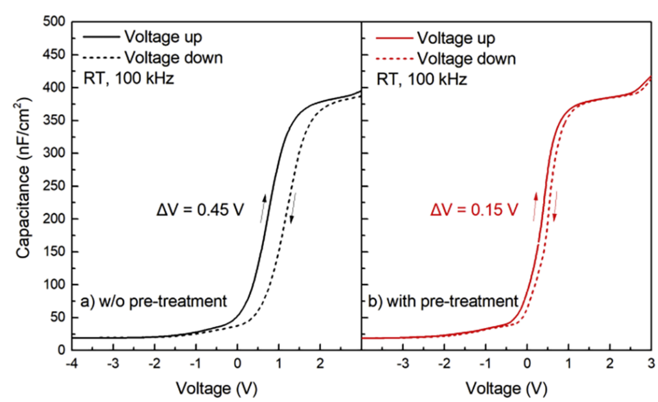

Fig. 2. C-V characteristics of Al_2O_3/GaN MIS-diode a) without and b) with HF pre-treatment measured at room temperature at a frequency of 100 kHz. (single column figure).

3. Measurement results and discussion

C–V measurements were performed on treated Al_2O_3/GaN MIS diodes without and with HF pre-treatment at a frequency of 100 kHz in order to investigate the impact of the HF pre-treatment on the interface quality. The capacitors went through the same device process steps. For the Al_2O_3/GaN MIS-diode without the HF pre-treatment, Fig. 2(a) shows a voltage hysteresis of 0.45 V when the bias is swept from −4 V to 3 V and 3 V to −4 V. The diodes with the HF-treatment display a smaller hysteresis of 0.15 V under the same sweep conditions, indicating that the HF pre-treatment effectively reduces the interface states of the Al_2O_3/GaN MIS diode.

Two identical transistors from the sample with pre-treatment and the reference sample without pre-treatment were used for characterizations. The transfer characteristics for both of the devices are given in Fig. 3 in semi-log scale. Threshold voltage values were extracted using the drain current density of 1 mA/mm as the criteria. Both devices show normally-off characteristics. $V_{th} = +2.05$ V was obtained for the device with pre-treatment and $V_{th} = +2.16$ for the device without pre-treatment, indicating that the HF pre-treatment maintains the threshold voltage. When the device is pinched off, 2 orders of magnitude decrease is observed in the drain and gate current for the device with the pre-treatment. The reduction in the gate current leads in an increase in the drain ON/OFF drain–current ratio (I_{ON}/I_{OFF}), from the order of 10^4–10^6.

Gate leakage characteristics were measured by sweeping V_G from −8 V to +6 V with the drain contact floating (Fig. 4). The reverse gate leakage current was extracted on the order of 10^{-10} A/mm for the device with pre-treatment and 10^{-7} A/mm for the device without pre-treatment. The HF pre-treatment provided around 3–4 orders of magnitude improvement in gate leakage current. The device employing HF

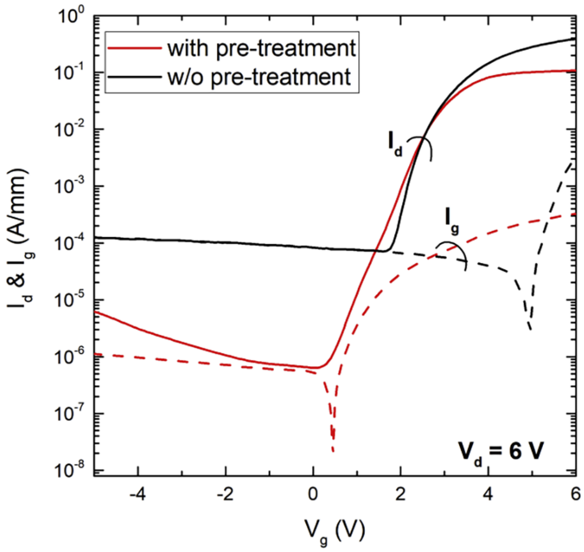

Fig. 3. Transfer characteristic of normally-off GaN MIS-HEMT with (red line) and without (black line) pre-treatment shown in semi-log scale. (single column figure).

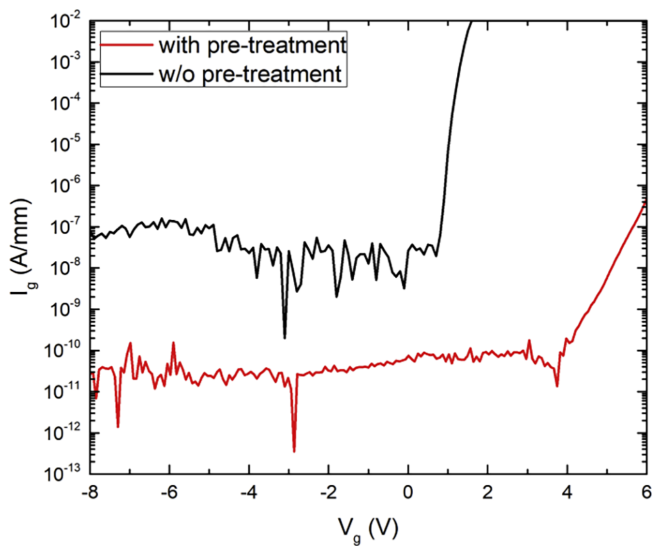

Fig. 4. Gate leakage current characteristics of the GaN MIS-HEMT with (red line) and without (black line) pretreatment. (single column figure).

pre-treatment also exhibits improved forward gate leakage current and a higher gate turn-on voltage. The low leakage for the device with pre-treatment maintains up to 4 V after which it gradually increases to 5×10^{-7} A/mm.

Pulsed hysteresis measurements were carried out to investigate the impact of the HF pre-treatment on the trapping behavior. The pulse width and pulse period are 500 µs and 50 ms respectively. The hysteresis curves are shown in Fig. 5. Transfer characteristics were obtained at a drain bias of $V_d = 10$ V. For the I_d-V_g hysteresis measurement the gate bias was swept from −4 V to 6 V and from 6 V to −4 V. As shown in Fig. 4, the observed threshold voltage hysteresis ΔV_{th} decreases from 0.58 V to 0.3 V for the device with pre-treatment, indicating that HF pre-treatment can effectively reduce interface trapping effects. A positive hysteresis is obtained for the device with pre-treatment and a negative hysteresis is obtained for the device without pre-treatment ($\Delta V_{th} = V_{g-down} - V_{g-up}$). The output characteristics with step-up and step-down measurements were obtained for gate biases V_g between 0 V and 5 V. A positive and a negative V_{th} hysteresis were obtained for the sample with and without pre-treatment, respectively. The hysteresis in the device with pre-treatment is attributed to acceptor-like interface states, whereas the negative shift in the threshold voltage with the application of relatively negative gate bias in the device without pre-treatment is thought to be additionally due to capture of electrons tunnelling from the gate by the localized states in the GaN buffer layer [20,21]. The opposite signs of voltage hysteresis for the devices without pre-treatment and with pre-treatment leads to an apparent higher threshold voltage for the device without pre-treatment. Both devices exhibit a maximum drain current of $I_d = 180$ mA/mm at $V_g = 5$ V. The MIS-HEMT with pre-treatment displays no obvious current slump, whereas current slump is observed for the device without the pre-treatment.

The off-state breakdown/leakage characteristics of both devices are in shown Fig. 6. Gate electrodes were biased at $V_g = -6$ V. The breakdown voltages, defined as the drain bias at a drain leakage current of 1 mA/mm, are measured as 36 V and 32 V for the device with and without pre-treatment, respectively. It can be observed that the off-state gate leakage has been substantially suppressed by the pre-treatment.

To gain an insight on the structural properties of treated samples, X-ray photoelectron spectroscopy (XPS) is employed. Fig. 7(a–b) shows the Ga3d, and N1s spectra of three different samples labeled as F1 (bare sample), F3 (recess and fluorine treated sample), and F4 (recess and fluorine treated sample with HF pre-treatment). X-ray photoelectron spectroscopy (XPS, Thermoscientific, Al K-Alpha radiation, hυ = 1486.6 eV) measurement has been performed at survey mode by operating flood gun for surface charge neutralization with 30 eV pass energy, 0.1 eV step size, to determine surface elemental composition and the binding energy (BE) values. The calibration of the binding energy scale is performed by fixing the aliphatic C1s component at 284.8 ± 0.1 eV and shifting other peaks in the spectrum accordingly. As previously investigated, the dominant surface defects of GaN are Ga and N vacancies (or dangling bonds). Based on the calculation of free energy by classical nucleation theory, most of the oxygen-derived hydroxyl groups such as OH radicals and H_2O or O_2 will be chemisorbed near imperfections such as dangling bonds and vacancies. As clearly illustrated in Fig. 7(a), the Ga3d spectrum is deconvoluted into three Gaussian profiles [22]; a broad and weak response originated from N2s orbitals, a dominant peak assigned to Ga-N bond, and a high energy response from Ga-O bonds. As we go from F1 to F3, this oxide peak has been intensified, while it has been significantly suppressed in the F4 sample. The same behavior can be probed by exploring the N1s spectra. The N1s spectra is deconvoluted into five main peaks [23]; three of which are assigned into Auger Ga LMM peaks, the dominant one comes from Ga-N bond, and the one in the higher energy tail is attributed to N-O bonds. As we can see, the same trend has been followed for N-O related peak. From the above-mentioned results, it can be envisioned that the partial oxide layer on the starting sample has become dominant throughout the recess and etching process. However, the oxide layers have been removed from the surface via acid treatment process. Therefore, the final outcome (sample F4) has been efficiently passivated and the oxide layer has been removed.

Surface morphologies of the recess etched and fluorine treated regions before and after pre-treatments were determined by atomic force microscopy (AFM) in terms of root mean square (RMS) roughness over a $4.5 \times 4.5\ \mu m^2$ region, as shown in Fig. 8. The results of AFM measurement reveal that the surface morphologies improved with the HF wet etch cleaning pre-treatment. The RMS surface roughness displayed an improvement from 0.95 nm to 0.33 nm with the application of the pre-treatment. Additionally, AFM images of the Al_2O_3 dielectric surface both with and without HF pre-treatments are obtained (Fig. 9). A surface roughness of 0.47 nm is obtained for the Al_2O_3 surface without the pre-treatment and a surface roughness of 0.30 nm is obtained for the Al_2O_3 surface with the pre-treatment from a $2 \times 2\ \mu m^2$ region. The AFM measurements demonstrate that conformal coverage is obtained in both cases, with a slight improvement in smoothness observed for the sample with the pre-treatment.

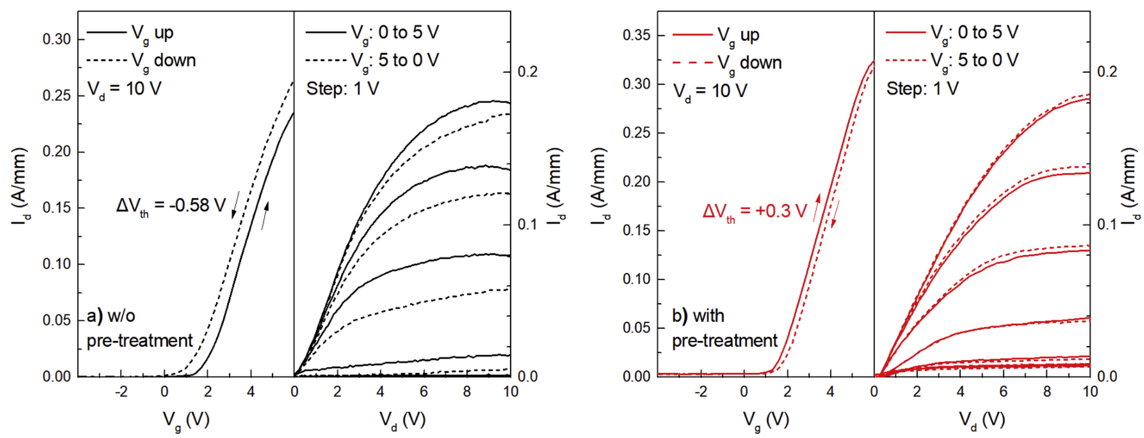

Fig. 5. Pulsed hysteresis measurements for the normally-off GaN MIS-HEMT a) without and b) with pretreatment. (double column figure).

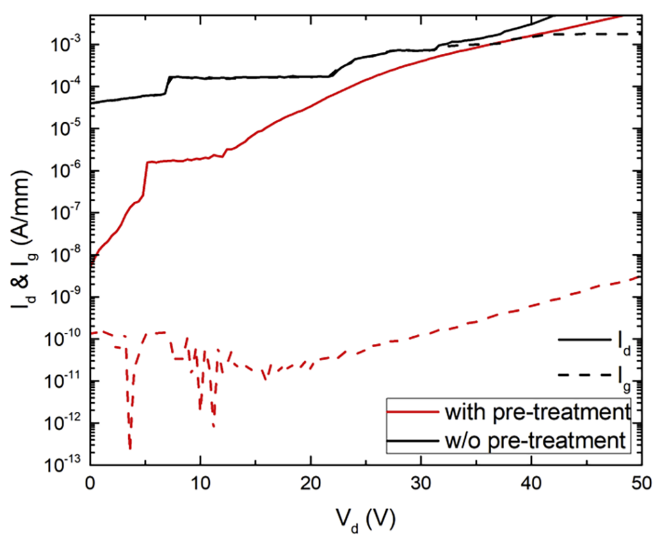

Fig. 6. Breakdown voltage characteristics of the device with (red line) and without (black line) pre-treatment. (single column figure).

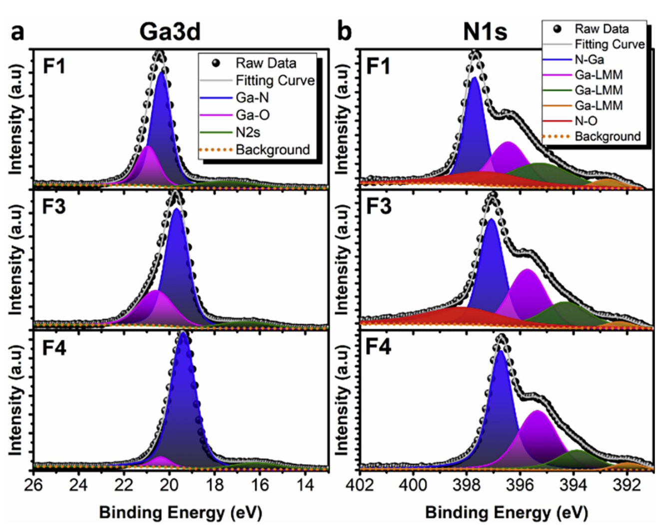

Fig. 7. High resolution XPS patterns of (a) Ga3d and (b) N1s the resulting F1, F3, and F4 samples, respectively. (single column figure).

It is known from previous reports that the dry etching methods used for recess etching method strongly affects the surface morphology of the etched regions, resulting in nitrogen vacancies and thereby more

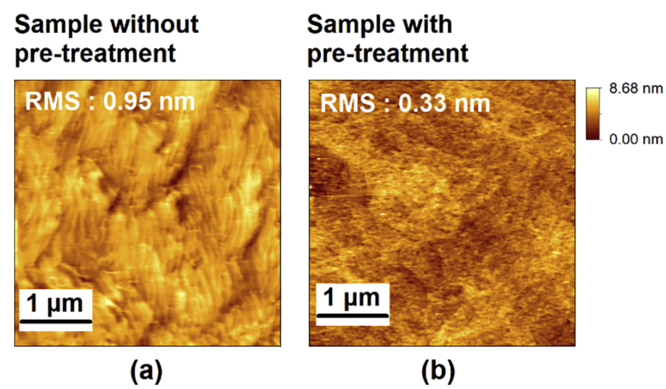

Fig. 8. Comparison of the AFM images for the AlGaN/GaN MIS-HEMT a) before and b) after HF pre-treatment. (single column figure).

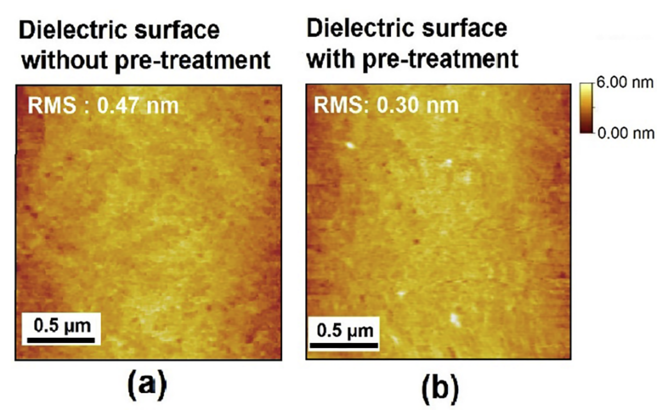

Fig. 9. Comparison of the AFM images for the Al_2O_3 dielectric surface a) without and b) with HF pre-treatment. (single column figure).

surface oxidation occurs [24,25]. Ref. [26] states that HF-based and other types of pre-treatments prior to ALD Al_2O_3 are advantageous for providing an optimal surface. The X-ray photoelectron spectroscopy (XPS) and atomic force microscopy (AFM) analyses carried out confirm that the HF pre-treatment reduces the surface oxides and roughness while maintaining normally-off operation.

4. Conclusion

An AlGaN/GaN normally-off MIS-HEMT with utilizing a hydrofluoric acid pre-gate surface treatment is reported to improve the gate leakage current. A gate leakage current as low as on the order of

10^{-11} A/mm is obtained. The comparative results of our study between the reference sample without pre-treatment and with pre-treatment show that HF pre-treatment results in a 3–4 order of magnitude improvement in the gate leakage current. Normally-off operation is maintained no degradation is introduced to the on-state performance.

Declaration of Competing Interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.sse.2019.05.008.

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