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Impact of etching process on Al₂O₃/GaN interface for MOSc-HEMT devices combining ToF-SIMS, HAXPES and AFM

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1. Abstract

In this work we present the effect of inductively coupled plasma reactive ion etching (ICP-RIE) combined with atomic layer etching (ALE) on the Al₂O₃/GaN interface for MOSc-HEMT devices. Time of flight secondary ion mass spectrometry (ToF-SIMS) and hard x-ray photoelectron spectroscopy (HAXPES) highlight an increase of the N/Ga ratio near the interface after etching. ToF-SIMS profiles also show the presence of impurities (H, C, B) at this interface. Atomic force microscopy (AFM) also illustrates a change of the GaN surface morphology for the etched sample.

Keywords – GaN stoichiometry, MOSc-HEMT, etching, SIMS, HAXPES

2. Introduction

By virtue of the physical properties of GaN superior to Si [1], the GaN HEMT transistor is one of the most promising technology for power electronics. The AlGaN/GaN architecture in a HEMT transistor creates a 2-DEG channel at the interface, which promotes high electron mobility. Possible applications range from power converters to radio-filters devices. However, there are still aspects to be mastered, *i.e* the development of normally-off HEMT structures with a positive threshold voltage ($V_{th}>0$). These structures are preferred to normally-on devices since they are safer and easier design integration in a driver system. Among the possible ways to conceive normally-off devices [2], one is the "recessed hybrid process" in which we proceed with the complete etching of the AlGaN and a partial etching of the GaN to then deposit the gate oxide as shown in figure 1. This normally-off architecture is very promising due to its capacity to maintain a low gate leakage current and a low R_{on} temperature dependence [3].

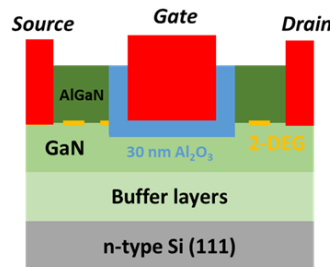


Figure 1: Schema of the MOSc-HEMT

In this research paper, we study the interface of two Al₂O₃ (10 nm)/GaN samples, where one has undergone a RIE/ALE etching process (sample A) and the other is free from it (sample B). As mentioned in different works, for instance Jackson *et al.* [4], Vauche *et al.* [5], Fernandes *et al.* [6], the Al₂O₃/GaN interface composition and hence the devices electrical properties are affected by the etching process. At the moment,

few studies were carried out on the GaN surface composition with dielectrics thicker than 3 nm due to XPS extreme surface sensitivity. Thanks to a combined approach with HAXPES, ToF-SIMS and AFM, we can go further and characterize samples that mimic the final device Al₂O₃/GaN interface with a thick gate oxide (30 nm). We will therefore present the chemical study of an Al₂O₃ (10 nm)/GaN interface by studying the final stoichiometry of GaN and the presence of various impurities due to the overall process, which makes it a novelty for the understanding of buried interfaces for MOSc-HEMT devices.

3. Experimental details

GaN n-doped was grown on Si wafers using metal organic chemical vapor deposition (MOCVD) on top of several AlGaIn/GaN buffer layers. To reproduce the recessed hybrid process, an etching step was performed using ICP-RIE with a Cl based chemistry followed by an ALE (sample A). Secondly, a chemical wet treatment was applied for both samples. Finally, Al₂O₃ was deposited by atomic layer deposition (ALD) at 300°C using Trimethylaluminium (TMA) and water (H₂O) as precursors with a final thickness of 10 nm determined by ellipsometry with an error bar of ± 1 nm.

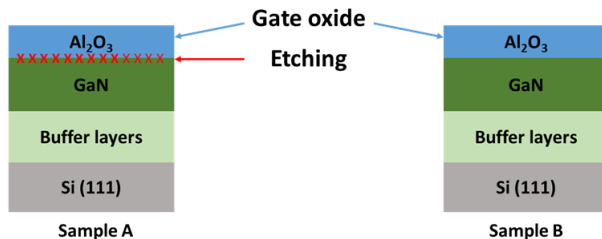


Figure 2: Schema of the studied structures

ToF-SIMS analyses were performed using a dual beam TOF 5 instrument from IONTOF GmbH. The depth profiles were performed using a Cs⁺ sputter beam at 500 eV with a sputtered area of 300 μm² and a Bi₃⁺ analysis beam at 15 kV with an analyzed area of 80 μm². The primary current for both ion beams were checked for each measurement to always operate under the same experimental conditions. Both ions guns were operated with an incidence angle of 45° with respect to the sample surface normal, which has been shown to be a suitable angle to perform SIMS measurements on Al₂O₃/GaN structures as reported by Spelta et. al [7]. To avoid matrix effects [8] and perform the most reliable depth profiles of the main elements (Ga, N), analyses were conducted in secondary ions (SI) positive mode MCs⁺ whereas impurities (BN, C, H) were detected in SI negative mode to have sufficient ionization yields. For the ToF-SIMS depth profiles, the interface between Al₂O₃ and GaN was defined when 50% of the average value of ⁶⁹GaCs₂⁺ present in the bulk GaN was reached. HAXPES measurements were made with a Quantex from ULVAC-PHI equipped with a monochromatized Cr Kα (hν=5.415 keV) X-ray source. All the measurements were carried out with a beam size of 100 μm and a pass energy of 55 eV, leading to an energy resolution of 0.9 eV. Moreover, the N 1s and Ga 2p_{3/2} peaks were acquired with a take-off angle (TOA) θ of 90° to ensure high depth sensitivity (~20 nm). AFM analyses were carried out on a Bruker Dimension Icon tool in TappingMode™ with a silicon tip having a nominal radius of 7-10 nm. For each sample, three scans of 5 μm × 5 μm (X × Y) size and 512 pixels × 512 pixel sampling were acquired to represent at best the root mean square (RMS) present on the surface.

4. Results and discussions

On Fig. 3a we report the ratio of the ¹⁴NCs₂⁺/⁶⁹GaCs₂⁺ intensities measured by ToF-SIMS, highlighting a higher N/Ga ratio at the Al₂O₃/GaN interface for the etched GaN. Indeed, for the etched sample, the N/Ga ratio shows a difference of a factor of 1.5, when comparing the intensity between the interface and the bulk, whereas, for the as-epi sample, this value is 0.9. To confirm this difference, we have performed HAXPES measurements

of the Ga 2p_{3/2} and N 1s core levels with corresponding sampling depths of approximately 21.6 and 24 nm. The HAXPES stoichiometric ratios shown in Fig. 3b are estimated with an uncertainty of 15% from the areas of these core levels normalized by relative sensitivity factors (RSFs) estimated with a GaN reference. Despite this calibration, HAXPES probably yields to an overestimated N/Ga ratio because of the probing depths difference and also the possible presence of an interfacial GaO_x layer as shown in figure 4 and reported by Duan et al [9]. In Fig. 4, we decompose the Ga 2p_{3/2} core level with two contributions: Ga-N (~1115.8 eV) and Ga-O (~1116.5 eV). In order to be able to compare the results between the different samples, the energy shift of Ga-O with respect to Ga-N was fixed at +0.7 eV [10]. Despite the chemical treatments used to remove the gallium oxide, the Ga-O contribution is clearly evidenced in both cases and is probably related to the presence of oxygen in the alumina. Comparing the two samples, we observe that the etched sample exhibits a lower oxidized gallium component. This result, together with the higher N/Ga ratio, shows that the etching step has modified the chemistry of the Al₂O₃/GaN interface. Furthermore, we evidence also the existence of several impurities due to the etching process prior to the Al₂O₃ deposition (see figure 3c). The use of BCl₃ during the RIE etching naturally favors the presence of B at the Al₂O₃/GaN interface. This process also seems to enhance the presence of contaminants such as H and C at this interface, which are probably related to the Al₂O₃ precursors. The presence of defects such as carbon or hydrogen can act as doping in the first case and as electron traps for the second and therefore modify the final performance of a normally-off structure.

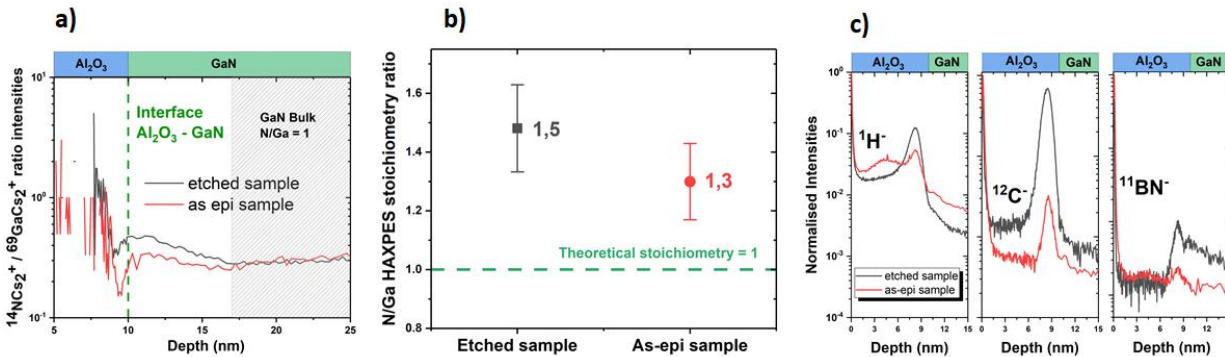


Figure 3: (a) $^{14}\text{NCs}_2^+ / ^{69}\text{GaCs}_2^+$ ratio depth profile (b) N/Ga HAXPES stoichiometry of core level spectrum N 1s/Ga 2p_{3/2} and (c) ToF-SIMS depth profiles of etched and as-epi samples of the main impurities present at the Al₂O₃/GaN interface.

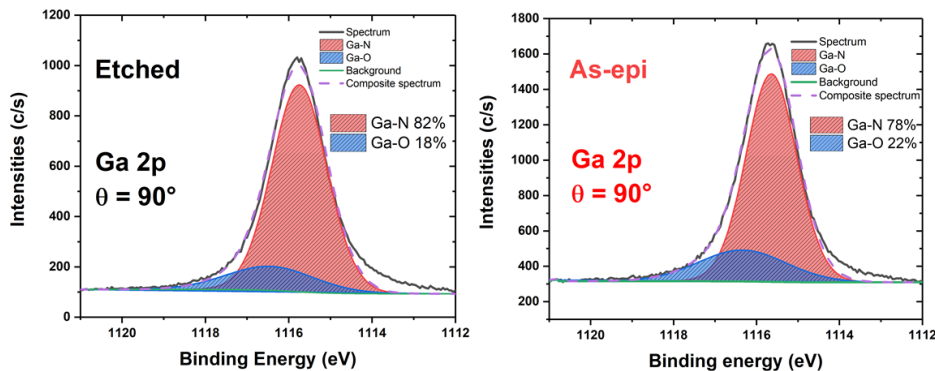


Figure 4: Ga 2p_{3/2} HAXPES core level spectrum of etched sample on the left and as-epi on the right representing the different oxidation level

The structural peculiarities of the interfaces are precisely analyzed by comparing AFM images (Figure 5), showing that the GaN surface is modified by the etching process. Despite the surface roughness quantified by the root mean square is nearly similar for both samples (A=0.28 nm, B=0.33 nm), the GaN atomic steps are nearly not seen for the etched sample.

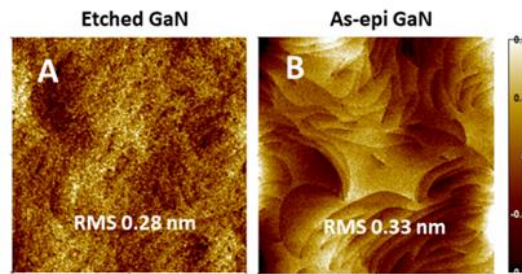


Figure 5: AFM images from the etched (left) and as-epi (right) samples.

5. Conclusions

In this paper, we demonstrated the feasibility of characterizing buried interfaces of Al₂O₃ 10 nm/GaN structure for MOSc-HEMT devices by a methodology combining ToF-SIMS, HAXPES and AFM. We studied GaN structures with an alumina thicker than 5 nm to mimic real devices. The benefit of HAXPES was clearly shown by probing chemical information up to 10 nm. Results are coherent with the information obtained by ToF-SIMS showing the impact of etching on the GaN stoichiometry, the presence of defects and the gallium oxidation. AFM has also highlighted how the ICP-RIE/ALE etching has an impact on the GaN surface roughness.

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