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Capacitance-voltage and Auger chemical profile studies on AlGaN/GaN structures passivated by SiO_2/Si_3N_4 and SiN_x/Si_3N_4 bilayers

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AlGaN/GaN heterostructures passivated by SiO_2/Si_3N_4 and SiN_x/Si_3N_4 bilayers were characterized electrically by capacitance-voltage measurements and chemically by Auger microscopy chemical in-depth profiling. The 2-dimensional electron gas density was estimated from C-V curves and the electronic quality of the bilayers was evaluated from C-V hysteresis. Detailed variations of Auger peaks, in particular for oxygen, silicon, nitrogen, and carbon, versus argon ion sputtering time were registered. The electronic properties of these two structures were compared with each other and to their chemistry.

Keywords: gallium nitride, HEMT, insulated gate, passivation, C-V, Auger spectroscopy, chemical in-depth profiles.

1. Introduction

GaN and AlGaN are promising materials for high-frequency, high-power, and high-temperature microelectronics due to their wide bandgaps, high electron mobility, good thermal conductivity, large 2-dimensional electron gas (2DEG) density at AlGaN/GaN interface, and chemical stability. In the above-mentioned application areas, structures with an insulated gate are predicted to be more efficient than those with a Schottky contact because of better thermal stability, higher breakdown voltage, and lower gate leakage current which is crucial for the realization of low on-resistance and normally-off high-power field-effect transistors (FETs) [1]. It has been reported that the deposition of an insulator on AlGaN/GaN heterostructure leads to an increase in 2DEG density and only slight decrease in 2DEG mobility [2, 3]. Recently, metal–insulator–semiconductor heterojunction FETs (MISHFETs) with AlGaN/GaN system and with SiO_2 or SiN_x as insulating and/or passivating layers exhibited good characteristics, particularly reduced current collapse, as presented in [4–8]. However, there is little systematic research on C-V behavior of MIS AlGaN/GaN structures considering interface states [9] and the mechanism of AlGaN surface passivation has not been fully clarified yet [10]. Besides the general mechanism of passivation, *i.e.*, the reduction of interface state density [11], and the modification of stress at the AlGaN surface by an insulating cover [2], some chemical processes have been proposed as important for an improvement of AlGaN surface/interface region, *e.g.*, reduction in the density of nitrogen vacancy and of oxygen-related defects [12] and removal of carbon traces [13]. However, a direct link between chemical and electronic aspects of the passivation is often difficult to find.

Recently, the secondary ion mass spectrometry (SIMS) and Auger electron spectroscopy (AES) combined with depth profiling have been used to investigate the profiles of concentrations of elements (including dopants and impurities like Si, O, and C) in growing and passivation of nitride layers to minimize the incorporation of impurities [14, 15] which influence the electronic and optoelectronics properties of AlGaN/GaN devices [16–19]. However, this kind of chemical studies of passivation of GaN-based structures [13] is rather scarce in the literature although it is crucial for better understanding of passivation mechanism and further technology optimization.

In this work, the authors performed electrical (by capacitance-voltage measurements) and chemical (by Auger microscopy chemical in-depth profiling) characterization of AlGaN/GaN heterostructures passivated by SiO_2/Si_3N_4 and SiN_x/Si_3N_4 bilayers. The 2DEG density was estimated from C-V curves and the electronic quality of the bilayers was evaluated from C-V hysteresis. Detailed variations of element Auger peaks, in particular O, Si, N and C impurities versus Ar^+ ion sputtering were registered. The electronic properties of these two structures were compared with each other and to their chemistry.

2. Experimental

The devices under investigation were fabricated on an $Al_{0.4}Ga_{0.6}N$/GaN/sapphire wafer with the undoped AlGaN layer. The AlGaN layer was covered with an ultrathin (~1 nm) Si_3N_4 film deposited *in situ* in order to protect the AlGaN surface during the deposition of the next insulating layer [3]. The samples under study were cut from the same wafer, then they were cleaned in acetone, ethanol, and water, and dried in nitrogen. To fabricate MIS structures a SiO_2 layer was deposited by plasma-enhanced chemical vapor deposition (PECVD) using SiH_4 and N_2O with the flow rate of 1 sccm

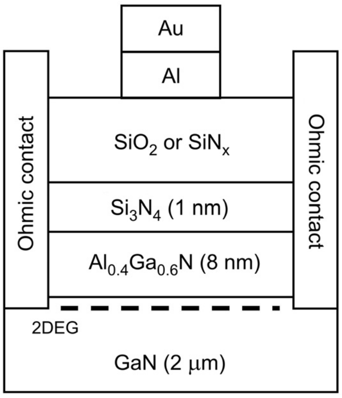

Fig. 1. A schematic view of MIS devices under study. The 2DEG is indicated by the dashed line.

and 20 sccm, respectively. A SiN_x film was obtained by electron cyclotron resonance (ECR) CVD using SiH_4 and N_2 with the flow rate of 10 sccm, proceeded by 1 min of ECR CVD N_2 plasma treatment in the same chamber. The thicknesses of SiO_2 and SiN_x layers were estimated from the ellipsometric measurements of silicon test samples to be between 20 and 30 nm. Ohmic Ti/Al/Ti/Au ring contacts were formed using photolithography, wet etching in a buffered HF (BHF) solution, metal layer deposition, liftoff, and rapid thermal annealing (RTA) in nitrogen at 800 °C for 1 min. Finally, Al/Au circular gate contacts with diameters of 200, 300, 400, and 500 μm were obtained (Fig. 1).

The electrical characterization of the devices was performed by C-V measurements at room temperature using HP 4192A LF impedance analyzer. The ac signal frequency of 100 kHz was used and the dc gate bias was swept first from zero to a negative value below the threshold voltage and next reversely to zero.

For AES measurements we applied a Physical Electronics PHI 600 Scanning Auger Microprobe (property of High-Tech International Services, Rome, Italy). The ion sputtering of the passivated AlGaN/GaN structures was performed with a differentially pumped Ar^+ ion gun (ion energy of 1 keV, incident angle of about 30°, pressure about 4×10^{-8} torr). The duration of sputter time was typically set at 15 s whereas in the sub-surface region of the passivation layer it was 6 s. The AES spectra were recorded at primary electron energy of 10 keV.

3. Results and discussion

Figures 2**a** and 2**b** show the 100 kHz C-V behavior of the MIS AlGaN/GaN structures with the gate diameter of 300 μm and with SiO_2 and SiN_x layers, respectively. The frequency dispersion of C-V curves between 10 kHz and 1 MHz is small. Only the 1 MHz characteristics of the devices with SiN_x layers differ from the 100 kHz curves significantly probably because of the larger series

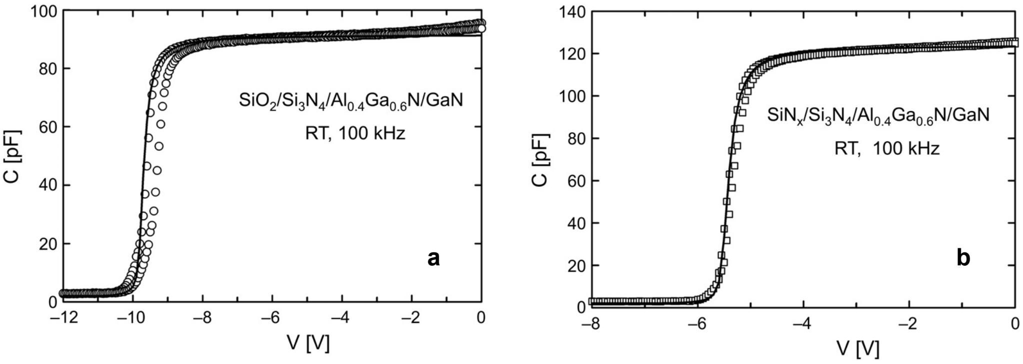

Fig. 2. The C-V characteristics of Si_3N_4/AlGaN/GaN MIS structures covered with SiO_2 (**a**) and Si_3N_4 (**b**) layer. The points represent experimental data and the lines are theoretical curves.

resistance of the Ohmic contacts as compared to that for the sample with SiO_2. Therefore, the 100 kHz C-V curves were used for analysis to limit the influence of the series resistance on the capacitance measurement results [20, 21]. The 2DEG density can be estimated from the integration of the C-V curves from zero bias to the threshold voltage [22] as equal to 1.8×10^{13} and 1.3×10^{13} cm^{-2} in the device with SiO_2 and that with SiN_x, respectively. The higher value of 2DEG density in the former structure could be attributed to a positive charge in SiO_2 or at the SiO_2/Si_3N_4 interface as reported by MAEDA *et al.* [3]. Both devices exhibited the anticlockwise C-V hysteresis but the hysteresis loop is narrower in the device with SiN_x, which suggests the better electronic quality (in terms of density of interface states and/or of traps in insulators) of the SiN_x/Si_3N_4 bilayer as compared to the SiO_2/Si_3N_4 one. The theoretical C-V curves were calculated by a numerical solver of Poisson equation using Gummel algorithm [23] and taking into account deep depletion in AlGaN and GaN layers, the AlGaN/GaN interface charge due to piezoelectric and spontaneous polarization, and interface states [24]. As can be seen in Fig. 2, the experimental points lie close to the theoretical characteristics suggesting good electronic quality of the AlGaN/GaN interfaces, however a detailed fitting and quantitative analysis of electronic interfacial parameters is beyond the scope of this paper. Moreover, it should be stressed that at room temperature only a small part of interface states in the wide bangaps of AlGaN and GaN is active and C-V measurements at higher temperatures are necessary to study deeper traps [24, 25].

The results of AES measurements for the AlGaN/GaN structure passivated by the SiO_2/Si_3N_4 bilayer are summarized in Figs. 3–5. Similar data were recorded for the structure passivated by SiN_x/Si_3N_4 bilayer. Figure 3 presents the chosen primary and differentiated AES spectra measured at different depths of the sputtered structure. In particular, it is clear that some oxygen atoms are present at the insulator/AlGaN interface, which can be a source of oxygen-related shallow levels. On the other hand, slight carbon contamination was observable only at the outer insulator surface. A detailed evolution of Auger peaks for all constituents as a function of sputtering time is shown in Fig. 4. The visible energy shifts of the Si(LVV) and Si(KLL) peaks towards the bulk correspond to a transition from the SiO_2 range to ultrathin Si_3N_4 layer. Furthermore, from Fig. 5 it is evident that oxygen content gradually decreases in the range of the insulator/AlGaN interface, which seems to be advantageous

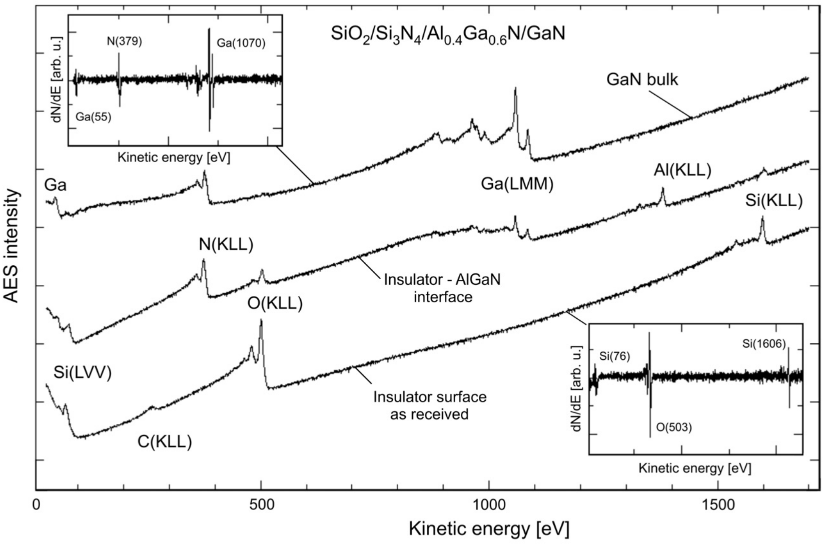

Fig. 3. Primary and differentiated AES spectra registered at different depths of the ion sputtered SiO_2/Si_3N_4/AlGaN/GaN structure.

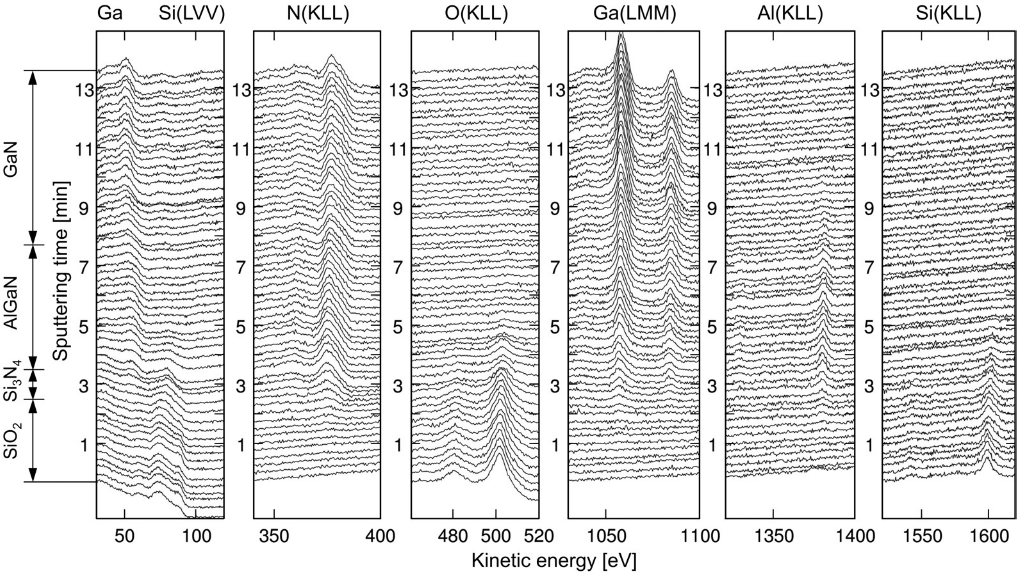

Fig. 4. AES peak evolution for SiO_2/Si_3N_4/AlGaN/GaN structure versus sputtering time.

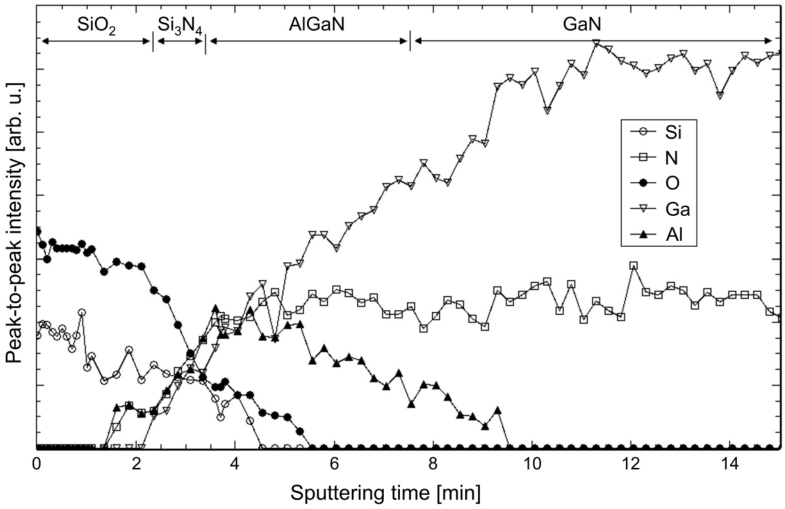

Fig. 5. AES peak-to-peak intensity profile for SiO_2/Si_3N_4/AlGaN/GaN structure.

compared to the literature reports [13], where the local maximum of oxygen concentration at the interface region was observed after different nitride passivation processes. It should however be noted that the observed peak-to-peak AES signal profile, obtained from the differentiated spectra, provides mainly qualitative information about the element distribution in the interface region. The obtained changes in the signal value (sloped lines) are related to the depth resolution of about 5 nm, typical of the scanning Auger microprobe used.

It seems that good electric characteristics can be partially attributed to relatively low levels of contamination, particularly carbon and oxygen, in the structures and especially in the insulator/AlGaN interface region. However, the high temperature C-V measurements combined with deep level spectroscopies like deep level transient spectroscopy (DLTS) and isothermal capacitance transient spectroscopy (ICTS) would be useful to clarify the link between electronic and chemical aspects of the AlGaN surface passivation.

4. Conclusions

We performed electrical (by C-V) and chemical (by Auger microscopy chemical in-depth profiling) characterization of $Al_{0.4}Ga_{0.6}N$/GaN devices passivated by SiO_2/Si_3N_4 and SiN_x/Si_3N_4 bilayers. The higher value of 2DEG density in the structure with SiO_2 was estimated from C-V curve and attributed to a positive charge in SiO_2. The structure with SiN_x exhibited a narrower C-V hysteresis loop suggesting better electronic quality of the SiN_x/Si_3N_4 bilayer compared to the SiO_2/Si_3N_4 one. From the AES measurements we obtained detailed evolution of all constituents content versus sputtering time. In particular, the in-depth profiles of AES signal for O, Si and N were determined. On this basis, a decrease of oxygen content towards the insulator/AlGaN interface was revealed without a local maximum at the interface. The slight carbon contamination was observed only at the outer insulator surfaces.

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