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Effective AlN-passivation for Improving ALD-Al_2O_3/GaAs Interface in MOS Structures Using MOCVD

T. Aoki, N. Fukuhara, T. Osada, H. Sazawa, M. Hata, T. Inoue
Sumitomo Chemical Co., Ltd., IT-related Chemicals Research Laboratory
6 Kitahara, Tsukuba, Ibaraki 300-3294, Japan
Phone: +81-029-864-4192 E-mail: aokit@sumitomo-chem.co.jp

Abstract

We have successfully demonstrated AlN-passivation on GaAs surface prior to Atomic Layer Deposition of Al_2O_3 using MOCVD equipment, for the first time. It is found that AlN-passivation causes nitrogen incorporation at Al_2O_3/GaAs interface, leading to improvements of the interfacial properties. The Al_2O_3/GaAs structure with AlN-passivation shows remarkable reduction in D_{it} obtained from CV/GV measurements at various temperatures. Particularly, the mid-gap D_{it} values of 1~4 x 10^{12} $cm^{-3}eV^{-1}$ are achieved.

1. Introduction

III-V semiconductors have attracted a lot of attention as the nMOS channel material for digital VLSI applications. GaAs is one of the alternative candidates, owing to high bulk mobility of electron, good lattice constant matching to that of Ge, and sufficiently wide bandgap. The dielectric/GaAs interface, however, commonly shows high interfacial density of states (D_{it}), resulting in serious Fermi-level pinning. In addition, large frequency dispersion of accumulation capacitance is also problematic [1]. Although several previous works showed effective improvements [2-4], industrially feasible GaAs MOSFETs have not been demonstrated so far. In this work, we demonstrate, for the first time, novel AlN-passivation process using MOCVD equipment combined with ALD-Al_2O_3 process, leading significant improvement of the interfacial properties and remarkable reduction in mid-gap D_{it}.

2. Experiments

n- (Si, $N_D = 4\times10^{16}$ cm^{-3}) and p- (Zn, $N_A = 2\times10^{16}$ cm^{-3}) GaAs layers were grown on GaAs (100) wafers by MOCVD, respectively. The wafers were placed into MOCVD equipment after a pretreatment with NH_4OH solutions. After a thermal cleaning above 500ºC to remove the redundant native oxide, ~1 nm-thick AlN film was deposited by MOCVD using TMA and NH_3 at the substrate temperature of 400°C. Continuously, an ALD-Al_2O_3 film was deposited in the same equipment. Adjusting parameters such as pulse time and purge time allowed self-limiting growth [5]. Afterward, MOS-CAPs were fabricated via shadow mask process as shown in Fig. 1.

3. Results and Discussion

Fig. 2(a) shows AFM image of GaAs (001) surface after AlN-passivation and ALD-Al_2O_3 deposition. The flat surface with step and terrace structures was observed. Fig. 2(b) shows a cross-sectional STEM image of this dielectric stack. The MOS interface is abrupt and atomically flat. In addition, an interface roughness value of 0.17 nm deduced from XRR result (Fig. 2(c)) is sufficiently low. These results reveal a well-controlled dielectric stack with the AlN-passivation process. Note that we could not identify visible AlN layer, because such a thin (~ 1 nm) AlN film is immediately oxidized during ALD process. Actually, the XRR result with AlN layer agree well with the simulation result assuming a simple Al_2O_3/GaAs structure (Fig. 2(c)). Nevertheless, a SIMS depth profile shows a peak distribution of nitrogen content at the interface (Fig. 3). Thus, the applied AlN-passivation process causes slight nitrogen incorporation at Al_2O_3/GaAs interface (Fig. 4).

Properties of MOS interface have been characterized by photoluminescence (PL) and capacitance-voltage (C-V) measurements. Fig. 5 shows PL spectra measured under various interface conditions. PL spectrum with AlN-passivation exhibited the highest peak intensity, indicating effective reduction in the interface recombination velocity [1]. Fig. 6 and 7 show typical C-V characteristics of Al_2O_3/GaAs with or without AlN-passivation, respectively. In terms of frequency dispersion, the AlN-passivation had produced effect on reducing the frequency dispersions on both n-type and p-type sides. Both PL and C-V results reveal superior quality of the Al_2O_3/GaAs interface with AlN-passivation. This is attributed to the nitrogen incorporation at Al_2O_3/GaAs interface. Nitrogen passivation mechanism was pointed out by Robertson, *et al.* [6], that nitrogen can replace the interfacial arsenic (As), leading to a efficient removal of critical As-dimer or As-DB (dangling bond) states. Fig. 8 and 9 show multi-frequency C-V curves, conductance-voltage (G-V) spectroscopy maps for Al_2O_3/GaAs with or without AlN-passivation, respectively. The hump features at negative bias in C-V curves measured at 150ºC reflect the mid-gap D_{it} (Fig. 9). These are significantly small compared to those of conventional Al_2O_3/GaAs (Fig. 10). The $D_{it}(E)$ distributions were estimated from C-V/G-V measured at various temperatures, assuming $D_{it} = 2.5/q \times G_p/\omega$ (Fig. 11). Note that elevating the substrate temperature is necessary to probe the $D_{it}(E)$ in the mid-gap region by conductance method [7]. It was found that D_{it} values were significantly reduced by AlN-passivation over the entire energy range. Particularly, D_{it} values in the mid-gap region were reduced from over 1 x 10^{13} $cm^{-3}eV^{-1}$ to 1~4 x 10^{12} $cm^{-3}eV^{-1}$. Also, G-V spectroscopy maps (Fig. 8 and 9) show smooth Fermi-level movements against gate bias both in upper and lower regions of bandgap. Slightly increasing slopes around mid-gap region, however, indicate small pinning behaviors. Finally, Fig. 12 shows the I-V characteristics, demonstrating excellent leakage characteristic with the electron barrier height of 2.94 eV extracted using FN tunneling model.

4. Conclusions

The AlN-passivation for improving Al_2O_3/GaAs interface using MOCVD equipment was investigated, for the first time. This process causes nitrogen incorporation at Al_2O_3/GaAs interface, leading to improvements of the interfacial properties. Also, CV/GV measurements at various temperatures showed remarkable reduction in D_{it}. Particularly, mid-gap D_{it} values of 1~4 x 10^{12} $cm^{-3}eV^{-1}$ were achieved.

Acknowledgements

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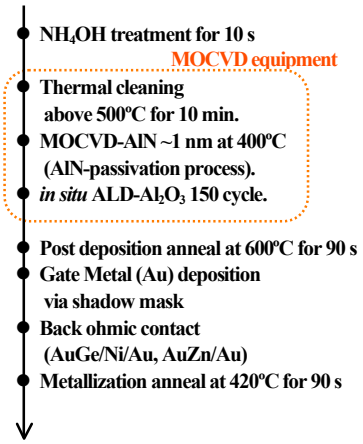

Fig. 1 Fabrication process flow of MOS capacitors in this work.

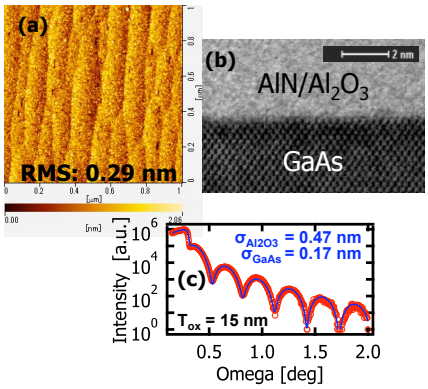

Fig. 2 Surface/interface properties of ALD-Al_2O_3/GaAs structure with AlN-passivation: (a) AFM image, (b) Cross-sectional STEM image after RTA at 600ºC, (c) XRR data with best-fit result.

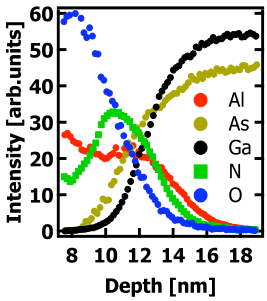

Fig. 3 SIMS depth profile of Al_2O_3/GaAs with AlN passivation. Nitrogen component shows peak distribution at the interface.

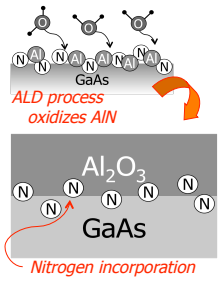

Fig. 4 Schematic image of Al_2O_3/GaAs structure with AlN-passivation.

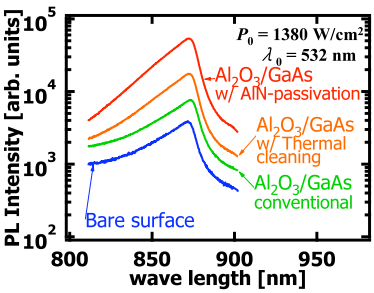

Fig. 5 Photoluminescence intensity *vs* wavelength of bare GaAs surface, Al_2O_3/GaAs, with thermal cleaning, and with AlN-passivation.

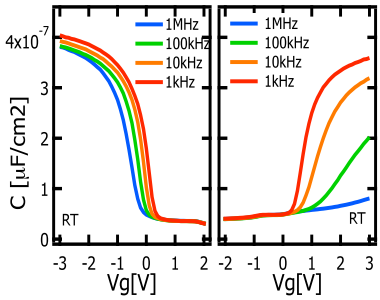

Fig. 6 C-V characteristics of Al_2O_3/GaAs.

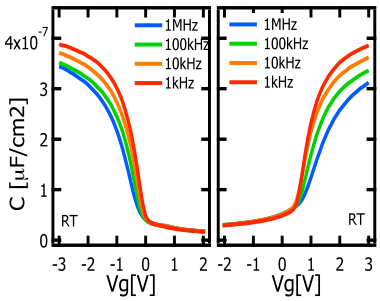

Fig. 7 C-V characteristics of Al_2O_3/GaAs with AlN-passivation.

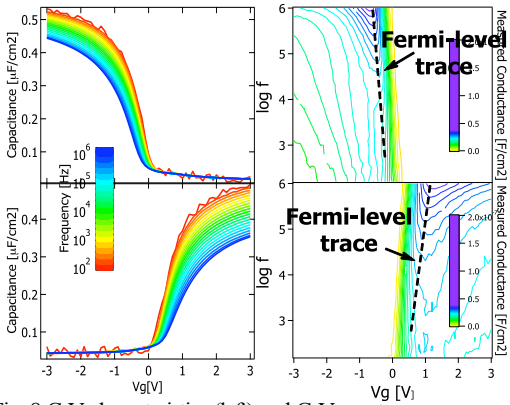

Fig. 8 C-V characteristics (left) and G-V spectroscopy maps (right) of Al_2O_3/GaAs with AlN-passivation measured from 100 Hz to 1 MHz under room temperature.

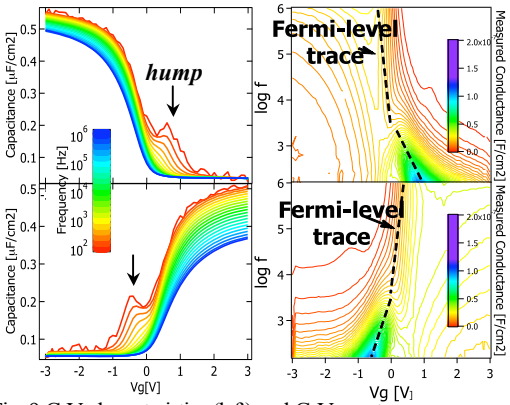

Fig. 9 C-V characteristics (left) and G-V spectroscopy maps (right) of Al_2O_3/GaAs with AlN-passivation measured from 100 Hz to 1 MHz at 150 ºC.

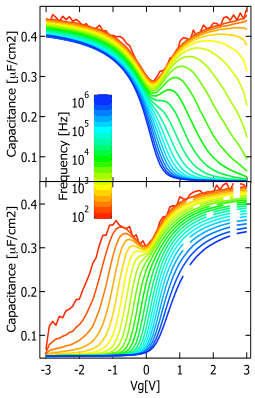

Fig. 10 C-V characteristics of conventional Al_2O_3/GaAs measured from 100 Hz to 1 MHz at 150 ºC.

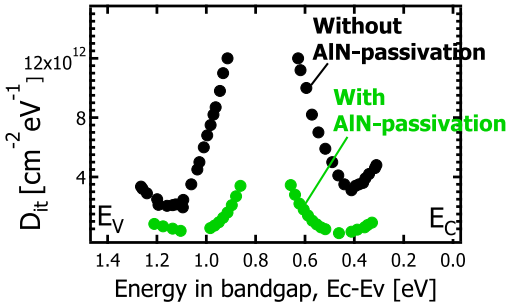

Fig. 11 $D_{it}(E)$ distributions estimated from C-V/G-V measured at RT, 60, 100 and 150ºC

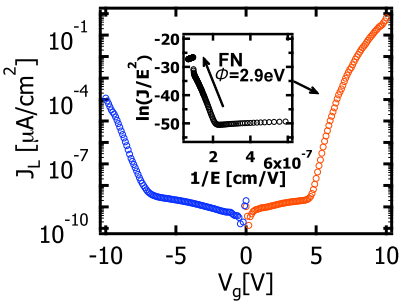

Fig. 12 IV characteristics of Al_2O_3/GaAs with AlN-passivation.