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Interface analysis of AlN/InAs(001) and AlN/Ge/InAs(001) by angle-resolved X-ray photoelectron spectroscopy

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1 Introduction

InAs is an important narrow-gap compound semiconductor with potential applications to ultra-high-speed electron devices. In particular, heterogeneous integration of InAs devices on foreign host substrates with low dielectric constants and high resistivities [1, 2] has advantages for high-speed applications. Since InAs metal-insulator-semiconductor field-effect transistors (MISFETs) are important devices for such applications, controlling of insulator-InAs interfaces, in particular for high-k insulators, is an important technological issue. We previously investigated sputtering-deposited AlN as an important high-k insulator, with a possible high breakdown field $\gtrsim$ 10 MV/cm, a high dielectric constant $\sim$ 9, which are comparable to those of Al_2O_3, and also a high thermal conductivity, $\sim$ 10 times higher than that of Al_2O_3. As a result, we realized a low interface state density and reduction of frequency dispersion in C-V characteristics for AlN/Ge/GaAs(001) MIS structures, and analyzed their interfaces by X-ray photoelectron spectroscopy (XPS) [3]. In this work, we fabricated AlN/InAs(001) and AlN/Ge/InAs(001) MIS structures, and their insulator-semiconductor interfaces are analyzed by angle-resolved XPS (ARXPS).

2 Experiments and Results

We fabricated AlN/InAs(001) and AlN/Ge/InAs(001) MIS structures as follows. For Si-doped n-InAs(001) substrates ($n = 5.0 \times 10^{16}$ cm^3) with backside Ohmic Ni/Au electrodes, we carried out a surface oxide removal using Semicoclean followed by a sulfur treatment using ammonium sulfide solution, which is effective to prevent surface oxidation. Subsequently, 18-nm thickness AlN was directly deposited on InAs(001) for the AlN/InAs(001), by RF magnetron sputtering at room temperature in N_2 mixed (3 %) Ar ambience using an AlN target. On the other hand, for the AlN/Ge/InAs(001), 1-nm thickness Ge interlayer was deposited by electron-beam evaporation, followed by the 18-nm thickness AlN sputtering deposition. After annealing in H_2-mixed (10 %) Ar ambience, the formation of 100-μm diameter Ni/Au gate electrodes on the AlN insulator completed the MIS structure.

Both MIS structures show good insulating properties. Figure 1 shows frequency-dependent C-V characteristics of the MIS structures, in which we observe small frequency dispersions attributed to the insulator-semiconductor interface states. In order to elucidate the interface states, we carried out an analysis using the conductance method [4] based on an equivalent circuit consisting of a semiconductor capacitance C_s, an interface state capacitance C_i, and an interface state conductance G_i in parallel, with an insulator capacitance C_0 connected in series. As the result, we obtain G_i/ω maps shown in Figs. 2(a) and (b), where ω is the angular frequency. From the maps, G_i/ω of AlN/Ge/InAs(001) is smaller than that of AlN/InAs(001), suggesting that the interface state density of the former is lower than that of the latter.

In order to analyze the interfaces, we carried out ARXPS measurements of four samples, InAs(001), Ge(1 nm)/InAs(001), AlN(1 nm)/Ge(1 nm)/InAs(001), and AlN(1 nm)/InAs(001), where all the sample preparation processes follow the MIS structure fabrication. Owing to the thin AlN and Ge interlayers, the XPS spectra include the information of not only the surface but also the interface. XPS spectra for smaller take-off angle θ reflect shallower region, while those for larger θ reflect deeper region. Figure 3(a) shows As3d XPS spectra for $\theta = 35°$, exhibiting no As-O bonding for all the samples. In4d XPS spectra for $\theta = 35°$ are also shown in Fig. 3(b). In spite of a small ratio of In-O bonding in InAs(001), we observe a large ratio of In-O bonding in AlN/InAs(001). This indicates that In oxidation takes place during the initial stage of the AlN deposition, despite of non-oxide deposition, which may be due to oxygen or water adsorbed on the surface. However, In-O bonding is significantly reduced for Ge/InAs(001) and AlN/Ge/InAs(001), suggesting that the Ge interlayer prevents the surface oxidation. Figure 4(a) shows In4d spectra of AlN/InAs(001) for θ = 20, 35, 45, and 75°. Since In-O bonding ratio decreases with increasing θ, we conclude that the shallow region is more oxidized. On the other hand, In4d spectra of AlN/Ge/InAs(001) shown in Fig. 4(b) exhibit weak angle dependence of In-O bonding ratio due to the prevention of the surface oxidation by the Ge interlayer. Figure 5 shows the relation between As3d/In4d intensity ratio and In-As/In4d or In-O/In4d intensity ratios, obtained from the ARXPS results. We observe a negative correlation between As3d/In4d and In-O/In4d, and a positive correlation between As3d/In4d and In-As/In4d. This indicates a correlation between As deficiency and In-O bonding. During the initial stage of the AlN sputtering deposition on InAs(001), As deficiency is increased, and In-As bonding changes to In-O bonding, while As oxidation does not take place. On the other hand, the Ge interlayer prevents increase in As deficiency and oxidation of In during sputtering deposition. Therefore, the suggested lower interface state density of AlN/Ge/InAs(001) can be attributed to the suppression of the As deficiency and the In-O bonding.

3 Summary

We fabricated AlN/InAs(001) and AlN/Ge/InAs(001) MIS structures, and their insulator-semiconductor interfaces are analyzed by ARXPS. From the conductance method, it is suggested that the interface state density of AlN/Ge/InAs(001) is lower than that of AlN/InAs(001). The ARXPS analysis shows that the lower interface state density can be attributed to the suppression of the As deficiency and In-O bonding.

References

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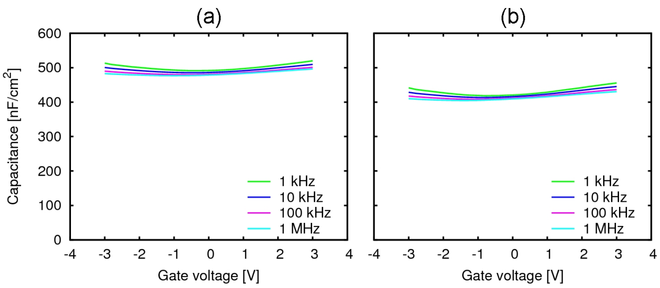

Fig. 1: Frequency-dependent C-V characteristics of (a) AlN/InAs(001) and (b) AlN/Ge/InAs(001) MIS structures.

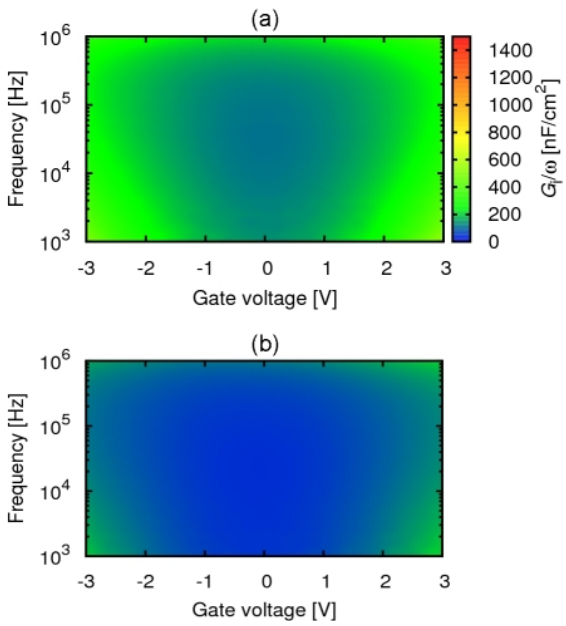

Fig. 2: G_{i}/ω maps for (a) AlN/InAs(001) and (b) AlN/Ge/InAs(001) MIS structures.

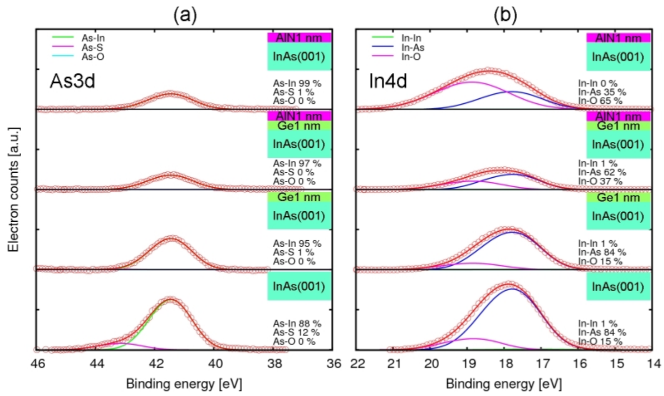

Fig. 3: XPS As3d sprctra (a) and In4d spectra (b) of InAs(001), Ge/InAs(001), AlN/Ge/InAs(001), and AlN/InAs(001), for take-off angle $\theta = 35°$.

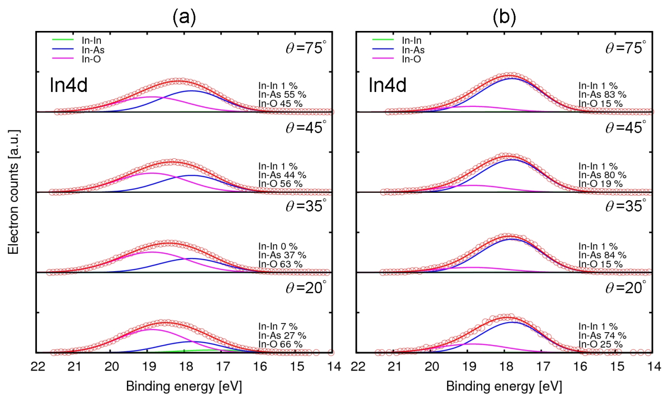

Fig. 4: XPS In4d spectra of AlN/InAs(001) (a) and AlN/Ge/InAs(001) (b), for $\theta = 20$, 35, 45, and 75°.

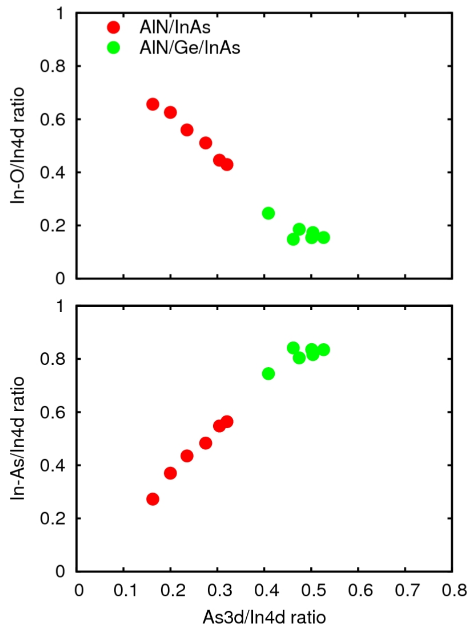

Fig. 5: Relation between As3d/In4d ratio and In-O/In4d or In-As/In4d ratios.