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Band Offset of Al_2O_3/SiO_2 Nano-laminate on GaN Evaluated by Hard X-ray Photoelectron Spectroscopy

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Abstract

An Al_2O_3/SiO_2 nano-laminate was deposited on GaN by plasma enhanced atomic layer deposition (PE-ALD). Hard x-ray photoelectron spectroscopy (HAXPES) was performed for the first time to evaluate the band diagrams of the nano-laminates with various thickness ratios on GaN. The band gap of the nano-laminate, E_g^{lam}, determined from O 1*s* plasmon loss spectrum becomes larger with increasing SiO_2 thickness ratio. From the results of the core levels and the valence band (VB) maxima, higher conduction band offset (CBO) have been estimated for the nano-laminate with larger SiO_2 thickness ratio. We have successfully obtained the band diagrams of Al_2O_3/SiO_2 nano-laminates on GaN to design GaN metal-oxide-semiconductor (MOS) devices.

1. Introduction

GaN-based metal-oxide-semiconductor field-effect transistors (MOSFETs) are promising devices for high-voltage and highly efficient power applications. We have expected to realize the devices for the highly efficient electric and hybrid vehicles. Now we are concentrating the development of the MOS gate technology to realize the normally-off and highly reliable gate characteristics.

Al_2O_3 is one of the useful candidates as high-k gate oxide with high quality interface on GaN. However, the leakage current is larger than that through SiO_2. Komatsu *et al.* have reported that AlSiO mixed oxide has higher electrical resistivity compared to Al_2O_3, which was deposited by radio frequency magnetron sputtering on Si and SiC [1]. Kikuta *et al*. have also shown that the Al_2O_3/SiO_2 nano-laminates deposited by PE-ALD on GaN decreased the leakage current [2]. They pointed out the lower leakage current due to the higher CBO.

The band offsets play a key role to determine the electric characteristics of the MOS structures. In this study, we have examined the band diagrams of Al_2O_3/SiO_2 nano-laminates on GaN with various structures by HAXPES.

2. Experimental

The nanometer-scale alternating layers of Al_2O_3 and SiO_2 were stacked on *n*-type GaN template at 250℃ by PE-ALD shown by Fig. 1. Trimethylaluminum (TMA) and tris(dimethylammino)silane (TDMAS) were used as precursors of Al and Si, which were oxidized by O_2 remote plasma. The thickness ratio of SiO_2 in the nano-laminate, *r*, was controlled by the number of the ALD cycles of Al_2O_3 and SiO_2. The set of samples with two different total thicknesses, 10 and 50 nm, was prepared for each r. Post deposition anneal (PDA) was performed at 850℃ for 10 min in nitrogen ambient except for Al_2O_3. Al_2O_3 was annealed at 650℃ to avoid the micro-crystallization [3].

HAXPES was performed to evaluate the band gap of the nano-laminate and the valence band offset (VBO) between the nano-laminate and GaN. HAXPES is useful to analyze a buried interface because of its larger analysis depth due to the higher kinetic energy of the photoelectrons compared to conventional x-ray photoelectron spectroscopy [4]. The band gap was estimated from O 1*s* plasmon loss spectrum using 50-nm-thick nano-laminate, and the energy level of the VB maximum was determined from the leading edge of VB spectrum referred to the core levels, O 1*s*, Al 1*s*, and Si 1*s*. Similar measurements were performed to GaN template without oxide deposition to evaluate the band gap from N 1*s* plasmon loss and the energy level of the VB maximum referred to the core levels, N 1*s* and Ga $2p_{3/2}$.

VBO was estimated from the measurement results of 10-nm-thick nano-laminate on GaN. From the energy difference between the core levels of the oxide and GaN, such as O 1*s* and N 1*s*, we calculated the VBO by the same manner as the reference [5]. CBO was also calculated from the results of the band gap and VBO.

3. Results and Discussion

Figure 2 shows the O 1*s* plasmon loss spectra of the nano-laminates with various thickness ratios *r*. The onsets of the plasmon loss peak shifts to the higher energy with increasing *r*. This result indicates the larger band gap has been obtained with larger SiO_2 thickness ratio. The measured band gaps of Al_2O_3 and SiO_2 correspond to the other report [6]. E_g^{lam} is formulated in eq. (1) using quadratic function of *r*.

$$E_g^{lam}(r) = 6.70 + 0.54\, r + 1.76\, r^2 \qquad (1)$$

VB spectra and O 1*s* core levels are shown in Fig. 3. They shift to higher energy with increasing *r* except for SiO_2. Figure 4 shows the band offsets as a function of *r*, which were estimated from the energy difference of core levels using 10-nm-thick nano-laminate on GaN. Al_2O_3/SiO_2 nano-laminate acts as the energy barriers for both electrons and holes in GaN, and CBO has larger bowing dependence

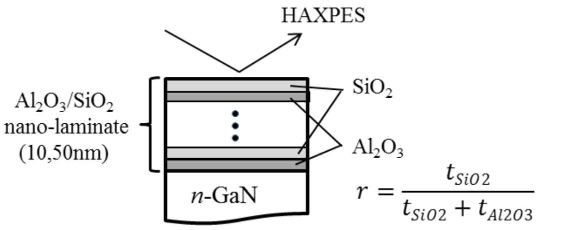

Fig. 1 Sample structure of an Al_2O_3/SiO_2 nano-laminate on n-GaN. SiO_2 thickness ratio in the nano-laminate was denoted as *r*.

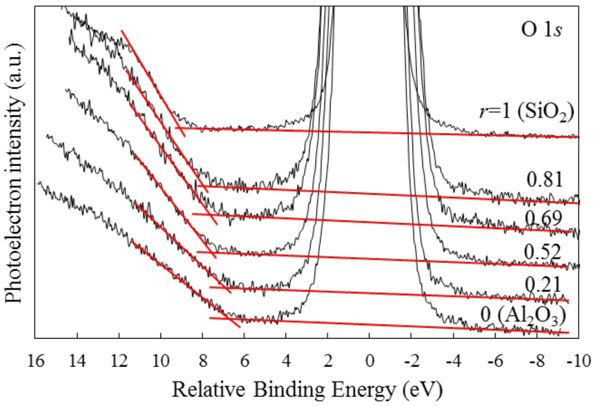

Fig. 2 Oxygen 1*s* plasmon loss spectra of Al_2O_3/SiO_2 nano-laminates with various SiO_2 thickness ratios *r*.

on thickness ratio *r* compared to VBO. Yang *et al*. [5] reported the lower CBOs of Al_2O_3 and SiO_2 than that of our results. It might result from the difference of the deposition conditions of the oxides. We can obtain the higher CBO compared to Al_2O_3 using the nano-laminate, and that could reduce the leakage current [2].

4. Conclusions

Al_2O_3/SiO_2 nano-laminate was deposited on GaN by PE-ALD. The band gap of the nano-laminate and the band offsets of the nano-laminate/GaN interface were successfully determined by HAXPES with larger analysis depth than conventional method. The band gap increased with SiO_2 thickness ratio in the nano-laminate. The nano-laminate acts as higher barriers for both electrons and holes in GaN compared to Al_2O_3. It would be expected to design GaN MOS structures with lower gate leakage current and to realize highly reliable MOS devices by using Al_2O_3/SiO_2 nano-laminate.

Acknowledgements

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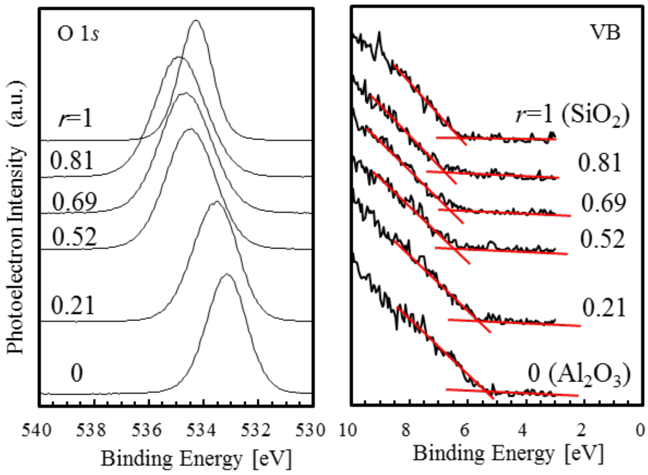

Fig. 3 Oxygen 1*s* core levels and valence band spectra of Al_2O_3/SiO_2 nano-laminates with various SiO_2 thickness ratios *r*.

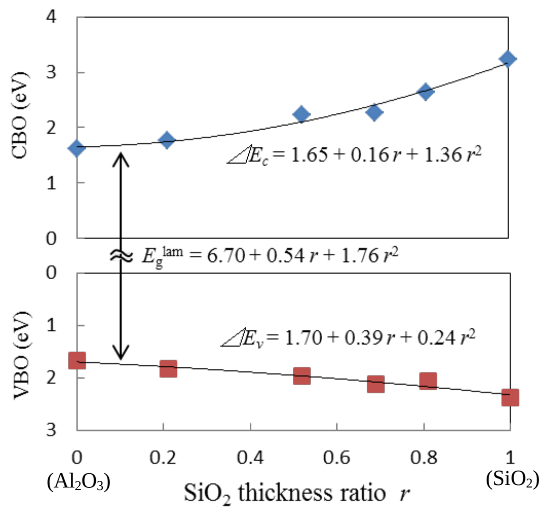

Fig. 4 The band offsets between Al_2O_3/SiO_2 nano-laminate and GaN as a function of SiO_2 thickness ratio *r*.

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