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In-situ Cyclic Metal Layer Oxidation for Further Improving Interface Properties of Al_2O_3/4H-SiC(0001) Gate Stacks

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Abstract
The formation of Al_2O_3/4H-SiC(0001) structure by a novel oxide formation method of in-situ cyclic metal layer oxidation (MLO) has been examined. Using this method, the abrupt Al_2O_3/4H-SiC interface without SiC_xO_y interlayer was obtained. It was demonstrated that the interface state density (D_{it}) of Al_2O_3/4H-SiC prepared by in-situ cyclic MLO is 10^{11} $cm^{-2}eV^{-1}$ order for a whole energy range. Especially, at E_C–0.04 eV, a quite low D_{it} value of 4.5×10^{11} $cm^{-2}eV^{-1}$ was achieved.

1. Introduction

In order to improve the field-effect mobility of the 4H-SiC MOSFETs, it is essential to reduce the interface state density (D_{it}). We have focused on Al_2O_3/4H-SiC structure because of its lower D_{it} value near the conduction band edge (E_C) compared with SiO_2/4H-SiC interface [1]. Previously, we reported that a SiC_xO_y interlayer is formed at the atomic layer deposition (ALD)-Al_2O_3/4H-SiC interface, and the decarbonization of the SiC_xO_y layer can be realized by radical oxidation process at room temperature (RT) [2]. D_{it} of the ALD-Al_2O_3/4H-SiC interface is comparably low to a thermally grown SiO_2/4H-SiC interface. We found that D_{it} between E_C and midgap can be further reduced by the decarbonization process, but D_{it} near E_C cannot. It is reported that some SiC_xO_y structures can be origins of D_{it} near E_C of 4H-SiC [3]. This suggests that it is mandatory to develop an alternative method to ALD realizing the formation of abrupt insulator/SiC interface without forming SiC_xO_y interlayer.

We focused on the metal layer oxidation (MLO) method whose theoretical concept is latter mentioned. There is only a few reports about employing this method for a 1~2-nm-thick Al layer at 200 °C or more [4]. In this paper, we report advantages of the novel MLO method, called the in-situ cyclic MLO, from aspects of engineering the interface structure and electrical property.

2. Concept of in-situ cyclic MLO

Concept of MLO is based on the thermodynamics. The standard free energy for Al_2O_3 formation from Al and O_2 is larger than that for SiO_2 and CO and/or CO_2 [5]. Thus, it is expected that the oxidation of Al/4H-SiC should lead the abrupt Al_2O_3/4H-SiC interface with no oxidation of SiC. **Figure 1** shows the schematic diagrams of (a) conventional MLO method using thermal oxidation at high temperature (HT-MLO) and (b) novel MLO method (In-situ cyclic MLO). For HT-MLO in this study, a 2.2-nm-thick Al layer was deposited by RF sputtering at RT. After taking out the sample in the atmosphere, thermal oxidation at 500 °C for 30 s or 5 min was performed.

We considered that there is a concern of natural oxidation of the Al layer easily occurs in the atmosphere, and the quality of such Al_2O_3 layer is questionable. Moreover, in order to suppress interlayer formation, the Al should be oxidized at low temperature and under low pressure as well as possible. To satisfy these demands, the in-situ cyclic MLO at RT was examined. A 0.1-nm-thick Al layer was deposited by RF sputtering method at RT, and subsequently O_2 was flowed into the chamber to oxidize the Al layer at RT. The O_2 partial pressure was 1.2×10^{-1} Pa.

3. Results and discussion

3.1 The advantage of in-situ cyclic MLO for interface design

N-type 4H-SiC(0001) wafer with an epitaxial layer doped with a concentration of 1.0×10^{16} cm^{-3} was used as a substrate. After chemically cleaning substrate with diluted HF, an about 5-nm-thick Al_2O_3 layer was formed by in-situ cy-

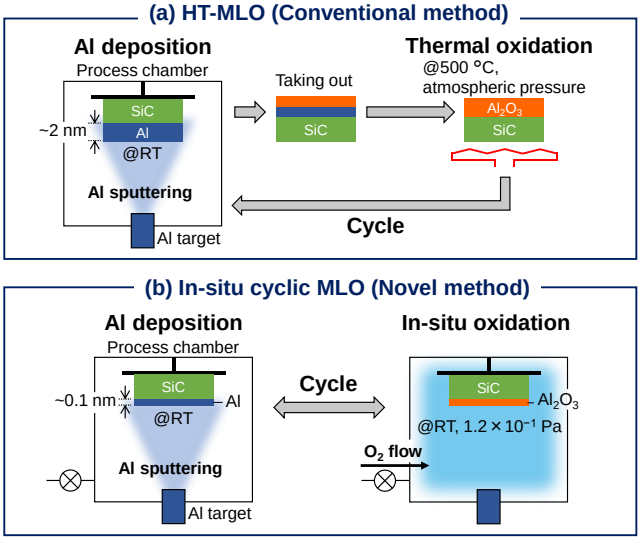

Fig. 1 Schematics of (a) HT-MLO and (b) in-situ cyclic MLO.

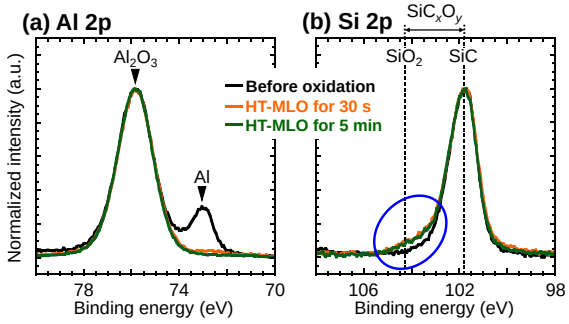

Fig. 2 (a) Al 2p and (b) Si 2p core-level spectra of samples before and after HT-MLO for 30 s or 5 min.

clic MLO. Whether a SiC_xO_y interlayer is formed or not was verified by X-ray photoelectron spectroscopy (XPS). The Si 2p core-level spectrum for the sample of in-situ cyclic MLO is almost same as that of cleaned SiC substrate, suggesting no SiC_xO_y formation.

On the other hand, for the sample of HT-MLO, the formation of SiC_xO_y layer was verified. **Figures 2** shows (a) Al 2p and (b) Si 2p core-level spectra, respectively, of the 2.2-nm-thick Al/4H-SiC samples without and with HT-MLO. The binding energy of Al 2p and Si 2p spectra were corrected with the peak positions of Al_2O_3 and SiC, and the intensity were normalized with that of the Al_2O_3 peak and SiC peak, respectively. For the Al 2p core-level spectrum of the sample before oxidation, two peaks which should be related to Al_2O_3 and metallic Al are observable. Al_2O_3 should be formed by natural oxidation when the sample was exposed to atmosphere. For the samples oxidized for 30 s and 5 min, the peak intensity of metallic Al decreases with increasing the oxidation time. The Al layer is oxidized sufficiently for 5 min, although 30 s is not sufficient. Meanwhile, from the Si 2p spectra shown in **Fig. 2(b)**, the Si-oxide peak is observed for samples after thermal oxidation regardless of the oxidation time as illustrated by a blue circle. This result infers that the oxidation of metal Al and SiC substrate occurs simultaneously. Thus, it is difficult to achieve the complete oxidation of the Al layer simultaneously with suppressing the oxidation of SiC by HT-MLO.

3.2 The impact of in-situ cyclic MLO on electrical property

For Al/Al_2O_3/4H-SiC MOS capacitors, the Al_2O_3 thickness was designed to be an about 20 nm to suppress leakage current. For the sample prepared with HT-MLO, the MLO process was repeated 6 times. For the sample prepared with in-situ cyclic MLO, the 5-nm-thick Al_2O_3 is formed by repeating the process for 20 times. Subsequently, a 15-nm-thick Al_2O_3 layer was additionally deposited on the 5-nm-thick MLO-Al_2O_3 layer with ALD at 250 °C.

Figure 3 shows the capacitance-voltage (*C-V*) curves measured from 1 kHz to 1 MHz for the sample of (a) HT-MLO and (b) in-situ cyclic MLO, respectively. For the in-situ cyclic MLO sample, the *C-V* curves measured at RT and 50 K are both shown. The larger frequency dispersion is observable in the *C-V* curve of the sample of HT-MLO than in-situ cyclic MLO. This result suggests that the sample prepared with in-situ cyclic MLO has lower D_{it}. In addition, the *C-V* curve measured at 50 K of the in-situ cyclic MLO sample shows small frequency dispersion, indicating low D_{it} near the E_C.

In order to estimate D_{it}, conductance method was used [6]. **Figure 4** shows the energy distribution of D_{it}. For comparison, the result of the sample prepared with ALD at 350 °C is also shown. D_{it} of the HT-MLO sample is larger than 10^{12} $cm^{-2}eV^{-1}$ in the obtained energy range at RT measurement. Since a SiC_xO_y interlayer was formed in this sample, this large D_{it} result is reasonable. On the other hand, D_{it} of the sample prepared only with ALD is about 2/3 to half of the HT-MLO sample. Moreover, the in-situ cyclic MLO sample realizes D_{it} lower than that of the ALD sample in a whole energy range measured in this study. The D_{it} value of 4.5×10^{11} $cm^{-2}eV^{-1}$ at E_C−0.04 eV was achieved, which is the lowest compared with previous reports such as thermally-oxidized-SiO_2/4H-SiC [7] and CVD-SiO_2/4H-SiC [8] to our knowledge. The results obtained in this study strongly suggest suppressing the SiC_xO_y interlayer formation promises lowering D_{it} of Al_2O_3/4H-SiC gate-stack.

4. Conclusions

We examined the in-situ cyclic MLO method at RT to form the abrupt Al_2O_3/4H-SiC interface. The in-situ cyclic MLO method simultaneously realized both the perfect oxidation of Al layer and suppressing SiC_xO_y interlayer formation by the SiC oxidation. In addition, a D_{it} value lower than that of the ALD sample in a whole energy range was realized by the in-situ cyclic MLO. Furthermore, a D_{it} value of 4.5×10^{11} $cm^{-2}eV^{-1}$ was achieved at E_C−0.04 eV. This is the lowest value near E_C to our knowledge. These results support the great advantage of utilizing the surface of 4H-SiC substrate as the MOS interface.

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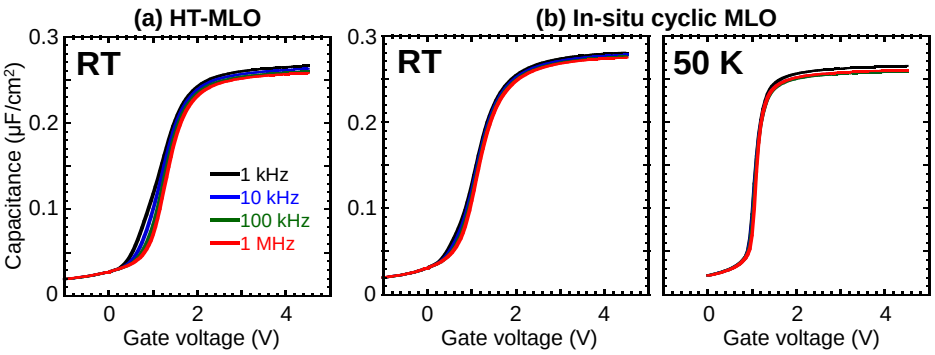

Fig. 3 *C-V* curves measured at RT and 50 K for the samples prepared with (a) HT-MLO and (b) in-situ cyclic MLO.

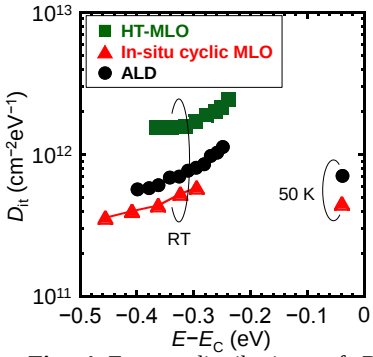

Fig. 4 Energy distributions of D_{it} estimated by conductance method.