

# Impact of Oxygen Radical Treatment on Improvement of Al<sub>2</sub>O<sub>3</sub>/SiC Interface

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## Abstract

Oxygen radical treatment on a deposited-Al<sub>2</sub>O<sub>3</sub> gate insulator on 4H-SiC has been examined in order to improve the interface properties. We have investigated the relationship between the interface state density ( $D_{it}$ ) and chemical bonding states in detail. We achieved the reduction of  $D_{it}$  by  $5.6 \times 10^{11} \text{ cm}^{-2} \text{ eV}^{-1}$  at around  $E_C - 0.4 \text{ eV}$  with an oxygen radical treatment at room temperature.

## 1. Introduction

The wide-bandgap semiconductor 4H-SiC is an attractive material for high-power metal-oxide-semiconductor field effect transistors (MOSFETs) [1]. However, there is a problem of a high channel resistance due to its poor electron channel mobility. The major reasons of channel mobility limitation are trapping of channel electrons and Coulomb scattering with trapped charge due to a high interface state density ( $D_{it}$ ) of gate insulator/SiC interface [2].

Previously, thermal oxidation processes for gate insulator formation of SiO<sub>2</sub> thin film have been well reported [3]. However,  $D_{it}$  at SiO<sub>2</sub>/SiC interface is generally a quite high value of  $10^{12} \sim 10^{13} \text{ cm}^{-2} \text{ eV}^{-1}$  due to the formation of C clusters [4]. To avoid the formation of C clusters with thermal oxidation of SiC, we focused on deposition method. An Al<sub>2</sub>O<sub>3</sub> film is often prepared using atomic layer deposition (ALD) method. ALD-Al<sub>2</sub>O<sub>3</sub> gate insulator is one of the promising alternatives to SiO<sub>2</sub> for SiC MOS structure, which has a large dielectric constant, a large energy bandgap, and large conduction and valence band offsets for 4H-SiC [5]. In addition, the post-deposition oxygen radical treatment at a low temperature for ALD Al<sub>2</sub>O<sub>3</sub> film promises further reduction of  $D_{it}$  by terminating the dangling bonds on SiC surface. In this study, we investigated the effect of oxygen radical process on Al<sub>2</sub>O<sub>3</sub>/SiC interface for improving the interface properties.

## 2. Sample preparation

N-type 4H-SiC(0001) wafer with a 10  $\mu\text{m}$ -thick SiC epitaxial layer with a N concentration of  $8.2 \times 10^{15} \text{ cm}^{-3}$  was used as a substrate. After chemical cleaning with standard RCA method, a 15 nm-thick Al<sub>2</sub>O<sub>3</sub> layer was formed on SiC substrate using ALD with precursors of tri-methyl-aluminum and H<sub>2</sub>O. The substrate temperature during ALD was 350 °C. After the formation of Al<sub>2</sub>O<sub>3</sub> film, oxygen radical treatment was performed at room temperature. The oxygen radicals were generated using radical source with inductivity

coupled plasma at a RF power of 400 W. The pressure of O<sub>2</sub> gas was  $4.5 \times 10^{-2} \text{ Pa}$ . The oxidation time was ranging from 0 to 5 min. Then, Al gate electrodes were deposited on the Al<sub>2</sub>O<sub>3</sub> film with vacuum evaporation method to form MOS capacitors.

## 3. Results and discussion

Figure 1 shows the  $C$ - $V$  characteristics of as-deposited and radical-processed samples at 300 K. The larger frequency dispersion in the depletion regions is observed in the  $C$ - $V$  characteristics of the as-deposited sample than that of radical-processed one. This result suggests that the  $D_{it}$  can be reduced with oxygen radical treatment.

The  $D_{it}$  was estimated with both of the high (1 MHz)-low (1 kHz) frequency method and conductance method [6]. In the conductance method,  $G$ - $V$  measurement was carried out at 50 and 300 K, and the  $D_{it}$  was estimated based on the surface potential fluctuation model. Figure 2 shows the  $D_{it}$  distribution estimated for as-deposited and radical-processed samples. Both 1 and 5 min-radical-processed samples have a lower  $D_{it}$  under  $10^{12} \text{ cm}^{-2} \text{ eV}^{-1}$  than that of the as-deposited sample, at around  $E_C - 0.4 \text{ eV}$ . This result indicates that  $D_{it}$  is effectively reduced with the oxygen radical treatment. On the other hand, in the case of the energy region from  $E_C - 0.1 \text{ eV}$  to the conduction band edge, there is an obvious oxidation time dependence of  $D_{it}$  value. From these results, we consider a possibility that the origin of defect states would be different between the energy regions of around  $E_C - 0.4 \text{ eV}$  and near the conduction band edge.

Figures 3(a) and 3(b) show the Al1s and Si1s core-level spectra measured with hard X-ray photoelectron spectroscopy (HAXPES) for as-deposited and 1 min-radical-processed samples, respectively. In the Al1s spectra, the main peak at 1563.3 eV can be related to Al<sub>2</sub>O<sub>3</sub>. The peak positions of Al-Si and Al-O-Si are expected to be 1560.6 and 1564.6 eV, respectively, from previously reported Al2p spectrum [7, 8]. We can find that the main peak of 1 min-radical-processed sample broadens to a lower energy side. This result suggests the formation of Al-Si bonds and/or the reduction of Al<sub>2</sub>O<sub>3</sub> by radical oxidation. In the Si1s spectra, we can also observe that the main peak related to SiC substrate broadens to a lower energy side, towards the expected position of Si-Al bond at 1840.1 eV [8]. Therefore, it is reasonable to conclude that Al-Si bonds were formed by radical oxidation treatment. In addition, the Si1s

peak from SiC substrate obviously broadens to a higher energy side. This result also indicates the formation of Si sub-oxide by radical oxidation.

Here, we discuss the oxygen radical effect on the reduction of  $D_{it}$ . From the HAXPES measurement, the formation of Al-Si bonds and Si sub-oxides were observed after the oxygen radical treatment. It is considered that Al and O atoms play a role in the termination of Si dangling bonds on SiC surface. However, the formation of excess Si oxide layer might be counterproductive for the interface because of the excess C creation. Controlling the condition of radical oxidation should be a key to improve the interface properties.

#### 4. Conclusions

We examined oxygen radical treatment to improve the electrical property of  $\text{Al}_2\text{O}_3/\text{SiC}$  interface. We revealed the  $D_{it}$  distribution and discussed its relationship with chemical property. The  $D_{it}$  lower than  $10^{12} \text{ cm}^{-2}\text{eV}^{-1}$  at around  $E_C-0.4 \text{ eV}$  is achieved with the oxygen radical treatment.  $D_{it}$  value from  $E_C-0.1 \text{ eV}$  to conduction band was reduced with increasing the time of oxygen radical treatment at room tem-

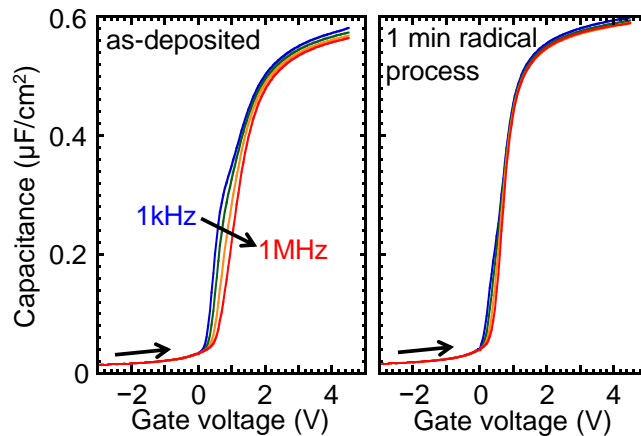
perature. The factor of these improvements is considered to be the formation of Al-Si bonds and Si suboxides to terminate the dangling bonds on SiC-substrate surface.

#### Acknowledgements

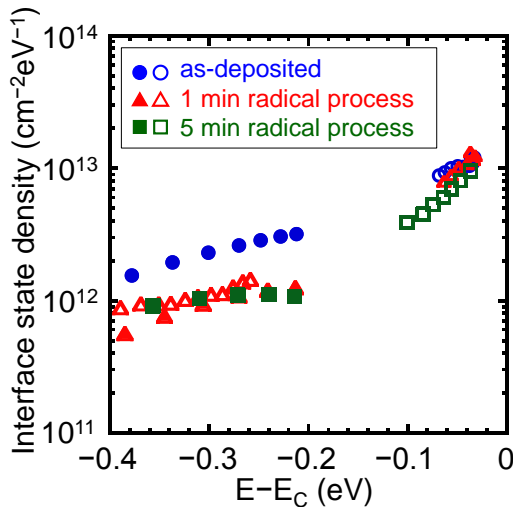
We acknowledge DENSO Corporation for supplying SiC wafer. The HAXPES measurement was performed at BL47XU in SPring-8 (proposal no.: 2017B1353).

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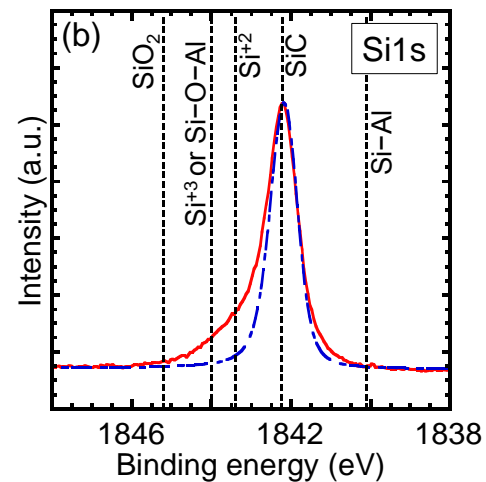
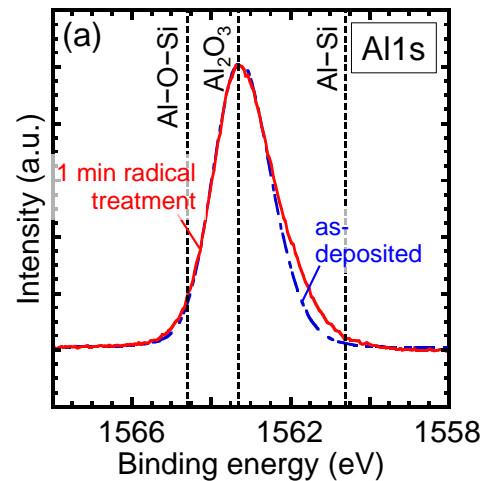
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**Fig. 1** C-V characteristics of samples before and after oxygen radical treatment for 1 min.



**Fig. 2**  $D_{it}$  distributions in as-deposited and radical-processed samples.  $D_{it}$  was estimated by high-low method (solid symbols) and conductance method (open symbols).



**Fig. 3** (a) Al1s and (b) Si1s core-level spectra measured with HAXPES for  $\text{Al}_2\text{O}_3/\text{SiC}$  structures before and after oxygen radical treatment for 1 min.