Thermal oxidation enhancement using barium on 4H-SiC(0001) substrates

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Silicon carbide (SiC) is the only wide bandgap semiconductor that yields a thermally grown silicon dioxide (SiO_2) film as a gate insulator in power metal-oxide-semiconductor field-effect-transistors (MOSFETs). Although thermal oxidation of SiC can be performed similarly to silicon (Si), in fact, it is required higher temperature (> 1100°C) to grow tens of nm-thick oxides on SiC. We also reported the large activation energy of about 3.2 eV for dry oxidation of 4H-SiC(0001) [1]. Nevertheless, the oxidation rate of SiC greatly increases by incorporating sodium (Na) impurities called metal enhanced oxidation (MEO), despite the bias-temperature instability (BTI) due to mobile ions [2]. Recently, Lichtenwalner *et al.* fabricated SiC-MOSFETs with deposited oxides on a thin layer of heavy alkaline earth metal, *i.e.* barium (Ba) by subsequent post-deposition annealing in 20% O_2/N_2 ambient [3]. Thus, in this work, we studied the effect of Ba on MEO on 4H-SiC(0001) in detail.

The substrates are 4H-SiC(0001) wafers with *n*-type epilayers. After wet cleaning, 0.5-nm-thick Ba layers were deposited on the SiC surfaces using the Knudsen cell of a metallic Ba source. Then, the samples were oxidized in pure ambient O_2 gas (99.9999%) at 950°C. The oxidation time was varied from 30 to 480 min. The samples without Ba were simultaneously oxidized as references.

Figure 1 shows oxidation time dependence of oxide thickness measured by spectroscopic ellipsometry for samples with and without Ba layers. Although it was difficult for the 4H-SiC(0001) substrates to grow thick SiO_2 layers at 950°C, we observed the increase in oxidation rate for the samples with Ba layers due to MEO. The MEO rate using Ba at 950°C was higher than the oxidation rate for bare 4H-SiC at 1150°C.

To investigate the location of Ba atoms after oxidation, the sample before and after MEO were measured by x-ray photoelectron spectroscopy (XPS). As shown in Fig. 2(a), the Ba 4d core level spectrum with two spin-orbit splitting components ($4d_{3/2}$ and $4d_{5/2}$) was observed for the as-deposited Ba sample. It should be noted that the Si 2p spectrum only contained a single component of Si–C bonds arising from the substrates. After MEO at 950°C for 30 min to form 11-nm-thick oxides, we observed a clear Ba peak in the spectrum taken from the SiO_2 surface (Fig. 2(b)). As shown in Fig. 2(c), the Ba peak was disappeared after partial oxide etching in 1% HF. Although the remaining oxide thickness after the HF etching was about 3 nm, Ba signals could not be detected by XPS due to a very small amount of Ba atoms in the oxide and/or at the oxide/SiC interface. These results indicate that most of Ba atoms were located at the SiO_2 surface but still effective in enhancing oxidation rate.

Next, we fabricated SiC-MOS capacitors by depositing Al gate electrodes on the 100-nm-thick SiO_2/SiC samples. It should be noted that many Ba atoms would be located at the Al/SiO_2 interfaces. Fig. 3 represents bidirectional capacitance-voltage (C-V) curves obtained at room temperature (RT) and 200°C. Since small clockwise C-V hysteresis due to electron injection were observed at both temperatures, Ba atom does not act as a mobile ion in SiC-MOS devices.

[1] D. Nagai *et al.*, 76th JSAP Autumn Meeting, **16a-1A-7**.
[2] F. Allerstam *et al.*, J. Appl. Phys. **101**, 124502 (2007).
[3] D. J. Lichtenwalner *et al.*, Appl. Phys. Lett. **105**, 182104 (2014).

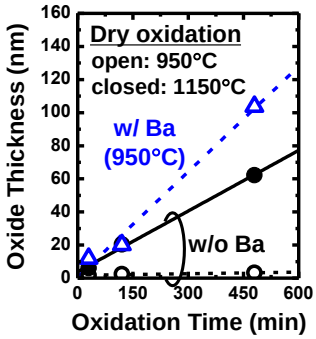

Fig. 1 Oxide thickness versus oxidation time for samples with and without Ba grown in pure O_2 gas.

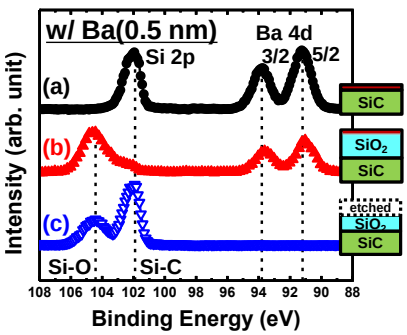

Fig. 2 Si 2p and Ba 4d core level spectra of samples after (a) Ba deposition, (b) MEO at 950°C for 30 min, and (c) partial oxide etching.

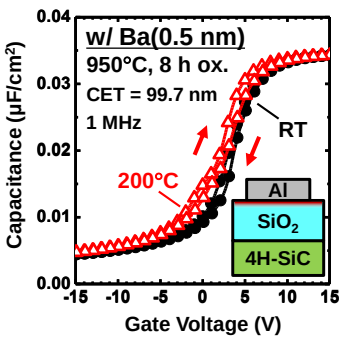

Fig. 3 Bidirectional C-V curves measured at RT and 200°C for the capacitor with MEO using Ba.