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Comprehensive Physical and Electrical Characterizations of NO Nitrided SiO_2/4H-SiC(11-20) Interfaces

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Abstract

Physical and electrical characterizations of nitrided SiO_2/4H-SiC(11-20) interfaces were conducted. Sub-nm-scale nitrogen profiling at the SiO_2/SiC interface by means of scanning XPS microprobe showed that nitrogen atoms are incorporated just at the interface and that nitridation of (11-20) surface proceeds much faster than on the (0001) Si-face surface, resulting in a higher nitrogen concentration (about 2.3 times). The optimal conditions for NO annealing were determined on the basis of the hysteresis, flatband voltage, and interface state density through capacitance-voltage (*C-V*) measurements. The impact of the interface nitridation on defect passivation near the valence band was also investigated by making *C-V* measurements under illumination with ultraviolet light.

1. Introduction

Nitridation is indispensable for improving the electrical properties of SiO_2/SiC interfaces. High-temperature NO annealing is commonly used, and it has achieved a significant reduction in the interface state density (D_{it}) and enhancement in field-effect mobility (μ_{FE}) for SiC MOSFETs [1]. In addition, nitridation of SiO_2/SiC interfaces has been proven to be beneficial for (1-100) m-face and (11-20) a-face substrates [2], which are advantageous for the development of advanced trench-type MOSFETs. So far, the nitrogen concentration and its depth profile have been investigated by secondary-ion mass spectrometry (SIMS) and x-ray photoelectron spectroscopy (XPS) for SiC MOS structures fabricated on {0001} and (1-100) m-face substrates [3,4]. However, there are few reports on interface nitridation of (11-20) a-face substrate or optimization of the NO treatment. In this study, we conducted systematic physical and electrical characterizations of nitridation of SiO_2/SiC interfaces with high-temperature NO annealing and examined the optimal conditions.

2. Experiment

A-face 4H-SiC substrates with n-type epilayers were oxidized at 1200°C to form base oxides (50-60 nm). Nitridation of SiO_2/SiC interfaces was performed in NO ambient at 1250°C for 10, 30, 60, and 120 min; hereafter, these samples are denoted as NO10, NO30, NO60, and NO120. A reference sample on the (0001) Si-face was prepared by NO annealing at 1250°C for 60 min, which is the optimal condition for the Si-face substrate. Sub-nm-scale nitrogen depth profiling was achieved by using a scanning XPS microprobe, as shown in the inset of Fig. 1(a) [5]. After the thick SiO_2 layers were thinned down to about 5 nm, sloped SiO_2/SiC samples were prepared in a diluted HF solution (1%). Then, Si 2*p* and N 1*s* spectra were acquired along the slope to estimate the remaining oxide thickness and nitrogen in the SiO_2/SiC structures. MOS capacitors were also fabricated by depositing Al gate electrodes after NO annealing. The electrical properties of the SiO_2/SiC interfaces were examined through *C-V* measurements, in which a conventional high-low method was used to estimate the D_{it} distribution near the conduction band. Moreover, *C-V* curves were obtained under ultraviolet (UV) illumination to investigate electrical defects near the valence band [6].

3. Results and discussion

Figure 1 shows typical results of the scanning XPS analysis of the sloped SiO_2/SiC sample (NO60). All the spectra sets were obtained along the slope, as shown in Fig. 1(a). The change in SiO_2 thickness can be estimated from the chemical shift components (Si-O bonds) around 104 eV. Here, the N 1*s* spectra normalized by the bulk SiC peak (Si-C component around 102 eV) did not change much regardless of the SiO_2 thickness (Fig. 1(b)), indicating that most of the incorporated nitrogen atoms were localized at the interface. Figure 2 summarizes the changes in the normalized N 1*s* intensity (I_{N1s}/I_{Si2p}) plotted against SiO_2 thickness for the NO-treated SiO_2/SiC samples fabricated on the a-face and reference Si-face surfaces. The selective interface nitridation of the a-face sample proceeded much faster than that of the Si-face and saturated at around 30 min. The resulting nitrogen content was about 2.3 times higher than that of the optimized nitrogen content for the Si-face sample. Moreover, most of the nitrogen atoms remained even after the SiO_2 had been completely removed by the 10% HF solution. This means that NO treatment of the SiO_2/SiC interface incorporated a significant number of nitrogen atoms at the uppermost surface and/or in the subsurface of the a-face SiC substrates.

Next, *C-V* measurements were conducted to examine the impact of interface nitridation. Figure 3 shows bidirectional *C-V* curves obtained from SiC MOS capacitors subjected to

NO annealing for various times. Judging from the *C-V* hysteresis, the flatband voltage (V_{FB}) with respect to the ideal value, and the slope (steepness) of the *C-V* curves, the optimal conditions appear to be the NO treatment for 60 min (NO60). Moreover, as shown in Fig. 4, D_{it} distributions taken from the capacitors show that the NO annealing for 10 min (NO10), resulting in an equivalent nitrogen concentration to the optimized Si-face sample (see Fig. 2), is insufficient for defect passivation.

Finally, we evaluated hole trapping at the interfaces with the n-type MOS capacitors. Hole generation and accumulation at the interface were realized by conducting *C-V* measurements at a low measurement frequency (1 kHz) under UV illumination. Figure 5 shows bidirectional *C-V* curves of SiC MOS capacitors fabricated with various NO-annealing times. Although hole accumulation for the shortest treatment time (NO10) was hard to see because of hole trapping with defects near the valence band, well-behaved hole accumulation was observed for the optimized annealing time (NO60). The NO treatments that took over 60 min degraded the interface quality in terms of a V_{FB} shift and carrier trapping near the SiO_2/SiC interface (Figs. 3 and 5), despite that the nitrogen concentration was nearly identical to the optimal conditions.

4. Conclusions

Scanning XPS analysis of NO nitridation of the SiO_2/SiC interface on a-face substrate showed faster and more intense interface nitridation compared with on the Si-face. Electrical characterizations also showed that a large amount of nitrogen incorporation (more than double the concentration for the Si-face) is needed to minimize *C-V* hysteresis, the V_{FB} shift with respect to the ideal value, and D_{it} near the conduction and valence bands.

Acknowledgements

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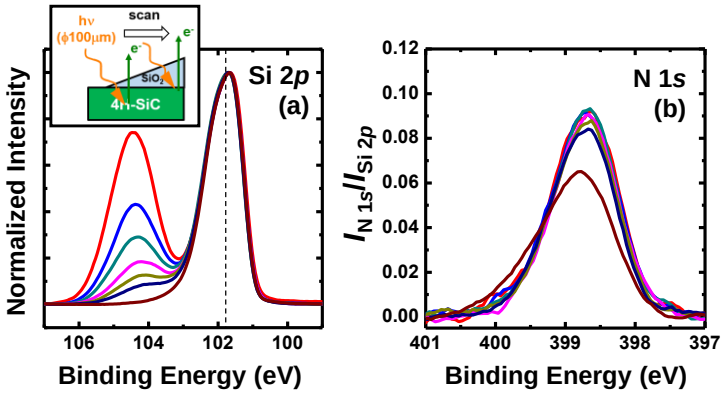

Fig. 1 Results from scanning XPS analysis of NO-treated SiO_2/SiC structure (NO60) fabricated on a-face substrate. Normalized (a) Si 2*p* and (b) N 1*s* core-level spectra.

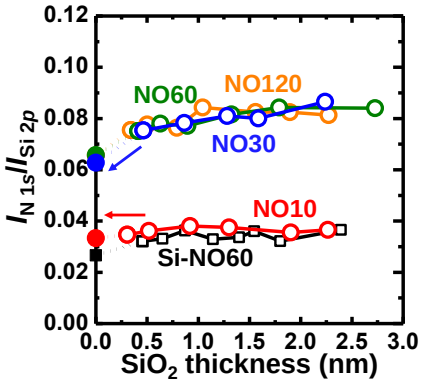

Fig. 2 Normalized N 1*s* areal intensity plotted as a function of SiO_2 thickness.

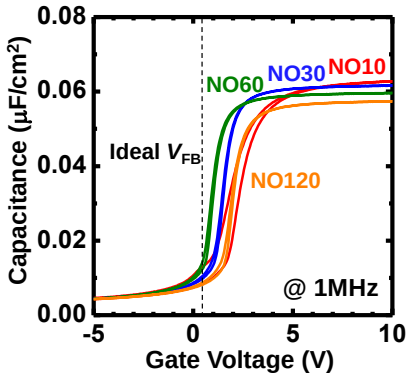

Fig. 3 Change in bidirectional *C-V* curves of n-type MOS capacitors fabricated on a-face substrates depending on duration of NO annealing.

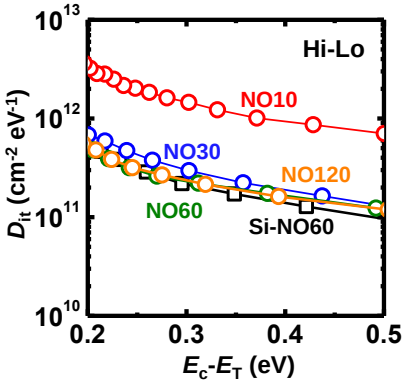

Fig. 4 D_{it} distributions of SiC MOS capacitors estimated by high-low method. A typical result for the Si-face sample treated by optimized NO annealing is also shown (Si-NO60).

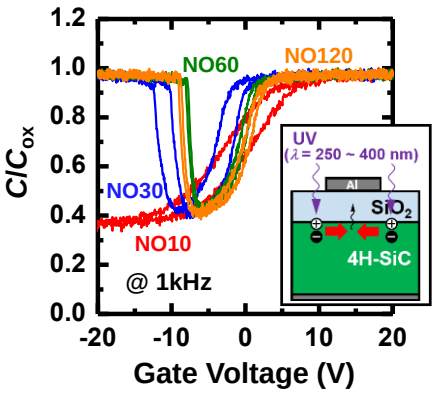

Fig. 5 Bidirectional *C-V* curves obtained under UV illumination at 1 kHz measurement frequency.