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Off-Angle Dependence of Characteristics of 4H-SiC–Oxide Interfaces

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Abstract. SiC-Oxide interfaces on 4H-SiC epitaxial substrates of various off-angles have been characterized by C–V measurements, synchrotron radiation excited photoemission spectroscopy and atomic force microscopy. We found that the interface state density (N_{it}) and the amount of sub-oxides (S_i) for small off-angle substrates were smaller than those for large off-angle ones. It was also found that there is a good correlation between the amount of the interface states and that of sub-oxides. Step-terrace structures were clearly observed in the surface morphology after the removal of oxide layers for small off-angle substrates, which shows that the interfaces were atomically smooth. These results suggest that the small N_{it} and S_i values for small off-angle substrates relate to the smoothness of the interface and that high performance SiC MOS devices are expected by using small off-angle substrates.

Introduction

To reduce the channel resistance and to improve the long-term reliability of oxide films on SiC are very important technologies to put SiC MOSFETs to practical use. Because the high channel resistance results from the high interface state density, to clarify the structure of SiC-oxide interfaces should lead to solve them. SiC MOS devices are usually fabricated on off-axis (0001) epitaxial substrates. In the cases of (0001) Si- and (000$\bar{1}$) C-faces, epi-substrates with the off-angle around 8 degrees have been used. A recent work has succeeded in the growth of high quality epitaxial films on SiC (000$\bar{1}$) face of small off-angle less than 1 degree [1]. However, it has not been clarified yet whether the electrical characteristics of MOS devices depend on the magnitude of off-angle, or not. In this report, SiC-oxide interfaces on the 4H-SiC epitaxial substrates of 0.5° and 8° off-angles have been characterized by capacitance to voltage (C–V) measurements, synchrotron radiation excited photoemission spectroscopy (SR-PES) and atomic force microscopy (AFM).

Experiments

4H-SiC (000$\bar{1}$) C-faces of epitaxial layers with 0.5 and 8° off-angles (n-type, $N_d - N_a = 10^{15}$ cm^{-3} order) were oxidized by two oxidation methods: dry oxidation and wet oxidation. After

standard RCA cleaning, the specimens were oxidized up to around 15 nm in oxide thickness. In the case of dry oxidation, 0.5 and 8° off-angles substrates were oxidized in pure dry O_2 flow at 1100°C (denoted as (05Dry) and (8Dry), respectively), and were quenched at room temperature. In the case of wet oxidation, the SiC specimens were oxidized in mixed O_2 and H_2 flow (O_2:H_2 = 2 : 1) at 900°C (denoted as (05Wet) and (8Wet), respectively). Aluminum was deposited on the surfaces of oxide films and the backside surfaces as gate electrodes and ohmic contacts, respectively. High-frequency (1 MHz) C–V measurements were carried out and the interface state density (D_{it}) was derived using the *Terman* method [2]. The oxide layers of the samples for SR-PES measurements were etched off by buffered HF solution, resulting in the oxide thickness of around 1.1 nm, measured by a spectroscopic ellipsometer. SR-PES measurements were performed with synchrotron radiation (an undulator beam line BL27US of SPring-8) and a hemispherical analyzer (Gammadata Scienta SES2002) as a light source and an electron analyzer, respectively. The photon energies of 1050 and 714 eV were used for the measurements of Si2p and C1s spectra, and O1s spectra, respectively. The normalized energy resolution $\Delta E/E$ in the measurements was 2×10^{-4}. AFM measurements were carried out after the removal of oxide layers.

Results and discussion

Figure 1 shows RF C–V curves and the distributions of D_{it}. Inboth the cases of 0.5° and 8° off-angles, D_{it} for wet oxidation samples is much smaller than that for dry oxidation samples at any energy. Also the figure indicates that D_{it} for 0.5° off is smaller than that for 8° off. Figure 2 shows the Si2p spectrum for the sample (05Wet). The measured spectrum (denoted by open circles) was decomposed into component peaks following Ref. [3]. The solid lines in (a) and the bold line in (b) denote the component peaks and the sum of component peaks, respectively. Three oxidation states, i.e. Si^{1+}, Si^{3+} and Si^{4+}, were found. The amounts of sub-oxides (S_i [ML]) can be estimated from the Si2p photoelectron spectra at the photoelectron take-off angle of 52°, where the effect of elastic scattering can be effectively neglected, by use of the relation as in [4],

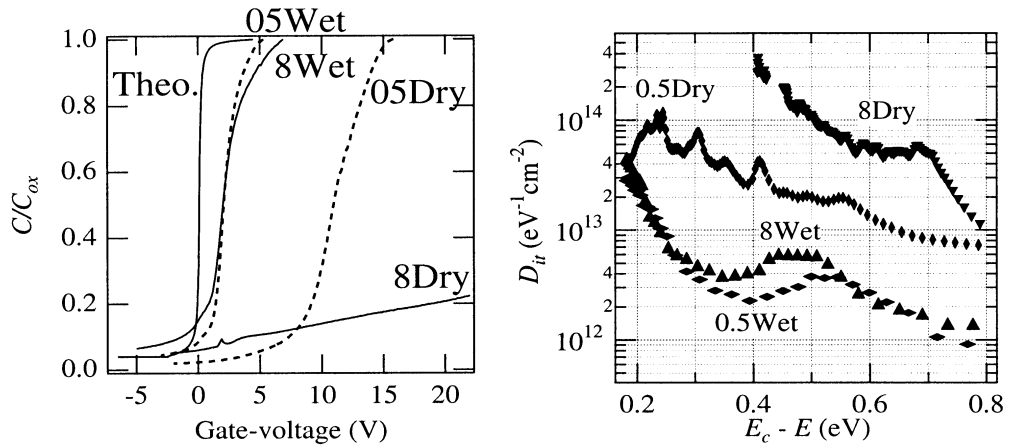

Fig. 1: RF C–V curves and D_{it} distributions.

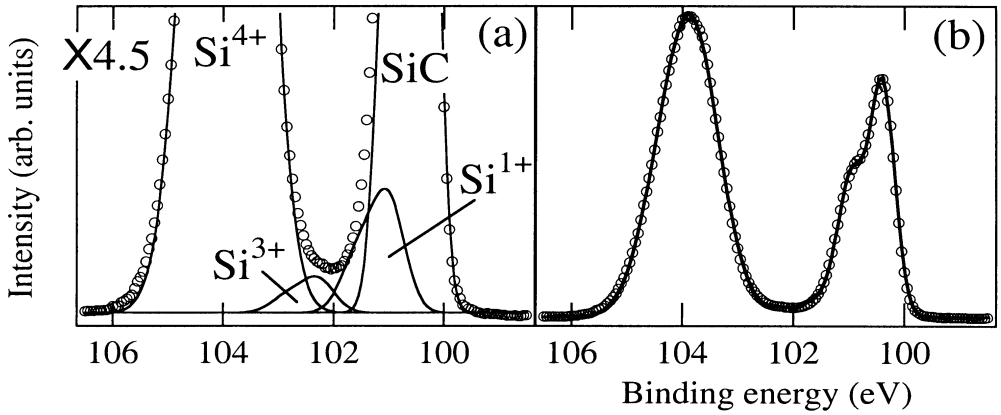

Fig. 2: Si2p photoelectron spectrum for sample (05Wet); (a) zoom in suboxide peaks, (b) full spectrum.

$$\frac{\mathrm{NI}}{\mathrm{NS}} = \frac{S_i S_s}{n_s \lambda_s \sin\theta}, \tag{1}$$

where NI/NS, n_s, S_s, and λ_s represent the sum of Si^{1+} and Si^{3+} peak intensities normalized by the intensity of SiC peak, the density of Si atoms in SiC ($= 4.80 \times 10^{22}$ cm^{-3}), the areal density of Si atoms in the suboxide, and electron escape depth of Si2p photoelectrons excited by 1050 eV photons in the SiC substrate. The value of λ_s for 1050 eV is around 2.0 nm, estimated from the value in the case of Mg$K\alpha$ radiation ($=$ 2.3 nm [5]) by considering the dependence of the electron escape depth on the kinetic energy of electrons. We assumed 1.21×10^{15} cm^{-2} for S_s under the condition that S_s is equal to the areal density of Si atoms in SiC. Figure 3 shows the integration of interface state densities at the region of $E_c - E = 0.2 \sim 0.8$ eV (N_{it}) and the values of S_i for the four samples. The figure suggests that there is a good correlation between the values of S_i and N_{it}. Figure 4 shows the surface morphology of the samples (8Dry) and (05Dry) after the removal of oxide layers. We can clearly see step-terrace structures for sample (05Dry), which reveals that the interface is atomically smooth. Therefore, the small N_{it} and S_i values for the small off-angle substrate may relate to the smoothness of its interface.

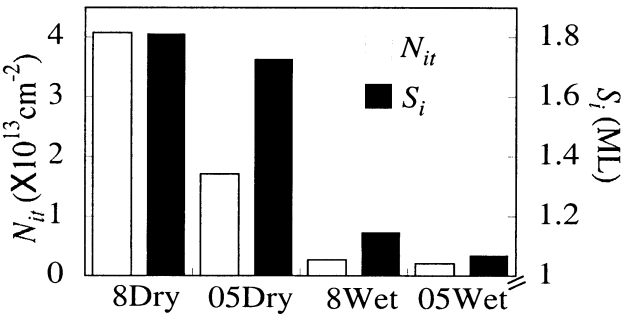

Fig. 3: Integration of D_{it} at $E_c - E = 0.2 \sim 0.8$ eV (N_{it}) and area density of suboxides (S_i).

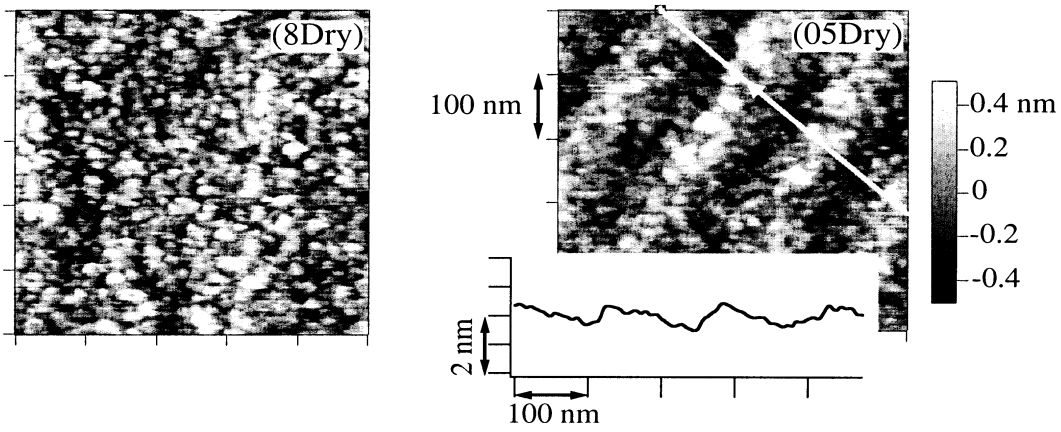

Fig. 4: Surface morphology of the samples (8Dry) and (05Dry) after removal of oxide layer.

Conclusion

The interface state density and the areal density of the sub-oxides for small off-angle epitaxial layers are smaller than those for large off-angle one in both the cases of dry and wet oxidation. These results suggest that high performance SiC MOS devices are expected by using the small off-angle substrates.

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References

[1] K. Kojima, H. Okumura, S. Kuroda and K. Arai: J. Cryst. Growth Vol. 269 (2004), p.367

[2] S. M. Sze: *Physics of Semiconductor Devices*, 2nd ed., Wiley-Interscience, New York (1981)

[3] Y. Hijikata, H. Yaguchi, S. Yoshida, Y. Takata, K. Kobayashi, S. Shin, H. Nohira, and T. Hattori: Mater. Sci. Forum Vol. 483-485 (2005), p.585

[4] M. Shioji, T. Shiraishi, K. Takahashi, H. Nohira, K. Azuma, Y. Nakata, Y. Takata, S. Shin, K. Kobayashi, and T. Hattori: Appl. Phys. Lett. Vol. 84 (2004), p.3756

[5] Y. Hijikata, H. Yaguchi, M. Yoshikawa, and S. Yoshida: Appl. Sur. Sci. Vol. 184 (2001), p.163