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Electronic defect states in thermally-grown SiO_2/4H-SiC structure measured by total photoelectron yield spectroscopy

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ABSTRACT

Total photoelectron yield spectroscopy has been applied to evaluate the energy distribution of electronic defect states for thermally grown SiO_2/4H-SiC structure. A SiO_2 layer with the thickness of 3.4 nm, 7.6 nm, and 21.6 nm was grown on wet-chemically cleaned 4H-SiC surface by wet-oxidation at 1080 °C. X-ray photoelectron spectroscopy analysis shows no significant structural inhomogenities in the SiO_2 layer in the thickness range over ~2 nm. Depth profile of the defect states has been investigated from PYS measurements in combination with SiO_2 thinning by dipping in a dilute HF solution. The photoelectron yield from filled defect states in the energy region corresponding to the 4H-SiC bandgap is significantly increased near the SiO_2/4H-SiC interface.

1. Introduction

4H-SiC has been attracting much attention for the high power electronic devices from the viewpoints of high breakdown electric field, high thermal conductivity, and wide bandgap. One of the major technology challenges to improve the device performance of high power SiC metal-oxide-semiconductor field-effect-transistors (MOSFETs) is to suppress the defect generation in MOS structure based on a clear understanding of chemical and electronic properties of SiO_2/SiC interface. SiC surface can form chemically and thermally stable SiO_2 insulators by conventional thermal oxidation. Unlike the oxidation of Si, C atoms in SiC must be consumed by out diffusion during the oxidation of SiC surface. However, it has been reported that a small amount of C impurities remain at the SiO_2/SiC interface [1,2]. In addition, a formation of SiO_xC_y species have been also observed [3–5]. Such an excess C including carbon clusters and Si/C dangling bonds in the region near the interface have often been discussed as a possible cause of the interface traps [6,7]. The details in the defects generation in the region near the interface between SiO_2 and SiC are still discussed. In our previous work, the energy distribution of filled defect states in the dielectric/semiconductor structure has been evaluated without the gate electrode fabrication by using total photoelectron yield spectroscopy (PYS) [8–10]. So far, it has been reported that PYS analysis for an ultrathin SiO_2/Si structure enables us to quantify the energy distribution of electronic defects states with a high enough sensitivity for the defect states as low as 10^{10} cm^{-2} eV^{-1} [8]. In addition, the depth profile of the defect states in $HfSiO_xN_y$ have been also evaluated from the change in the PYS intensity with dielectric thinning, and we clarified that the defect state density becomes its maximum in the region where oxygen deficiency becomes significant [9,10].

In this work, PYS analysis of thermally grown SiO_2/4H-SiC structure has been performed to gain a better understanding of the energy distributions of the electronic defects in the energy region corresponding to the 4H-SiC bandgap.

2. Experimental procedure

After wet-chemical cleaning of n-type Si-face 4H-SiC(0001) surface, SiO_2 layers with a thickness of 3.4 nm, 7.6 nm, and 21.6 nm were grown by wet oxidation at 1080 °C. To characterize chemical and electronic structures of the samples, high resolution X-ray photoelectron spectroscopy (XPS) was performed utilizing monochromatized AlKα radiation ($h\nu$ = 1486.6 eV), and core levels such as Si 2p, C 1s, and O 1s spectra were taken at a photoelectron take-off angle of 90°. To evaluate the energy distribution of the

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filled defect states in the SiO_2/4H-SiC structure, PYS was carried out in the photon energy range from 3.4 eV to 5.6 eV with an energy resolution of ~20 meV. In some samples, for the depth profiling of the defect state densities, XPS and PYS measurements were conducted repeatedly at each SiO_2 thinning step with a dilute HF solution. The experimental details for PYS measurements were described elsewhere [8].

3. Results and discussion

The chemical bonding features of the samples were investigated from the Si $2p_{3/2}$ and C 1s XPS core-line spectra as shown in Fig. 1(a) and (b). A Si $2p_{3/2}$ spectrum was obtained by the spectral deconvolution of the measured Si 2p signals into two components in accordance with the spin–orbit splitting of each core line, where the energy splitting of 0.60 eV and the intensity ratio of Si $2p_{3/2}$:$2p_{1/2}$ = 2:1 was used [11–13]. In each spectrum, binding energy calibration was conducted using the Si $2p_{3/2}$ signals from Si—C bonding units at 102.2 eV. Chemically shifted Si $2p_{3/2}$ signals of Si—O bonding units (104.5 eV in binding energy scale) were markedly increased after the oxidation. On the other hands, the Si $2p_{3/2}$ and C 1s signals due to the Si—C bonding units were gradually decreased with increasing SiO_2 thickness. A significant change in the C 1s signals with the thermal oxidation was hardly detected, except for the decrease in the Si—C component. These spectral changes indicate the growth of SiO_2 layer on 4H-SiC surface. In addition, the formation of stoichiometric SiO_2 was also confirmed from the Si $2p_{3/2}$ and O 1s intensities.

Then, PYS analyses of the samples were performed (Figs. 2 and 3). In the PYS measurements, the photoelectron yields from the samples were measured as a function of photon energy in the range from 3.4 eV to 5.6 eV. From the energy band diagram of SiO_2/4H-SiC structure as shown in Fig. 2, the valence electrons in SiO_2 and 4H-SiC cannot be emitted out by the irradiation of photons in this energy region. Therefore, the observed photoelectron yields from the samples shown in Fig. 3 were attributable to the

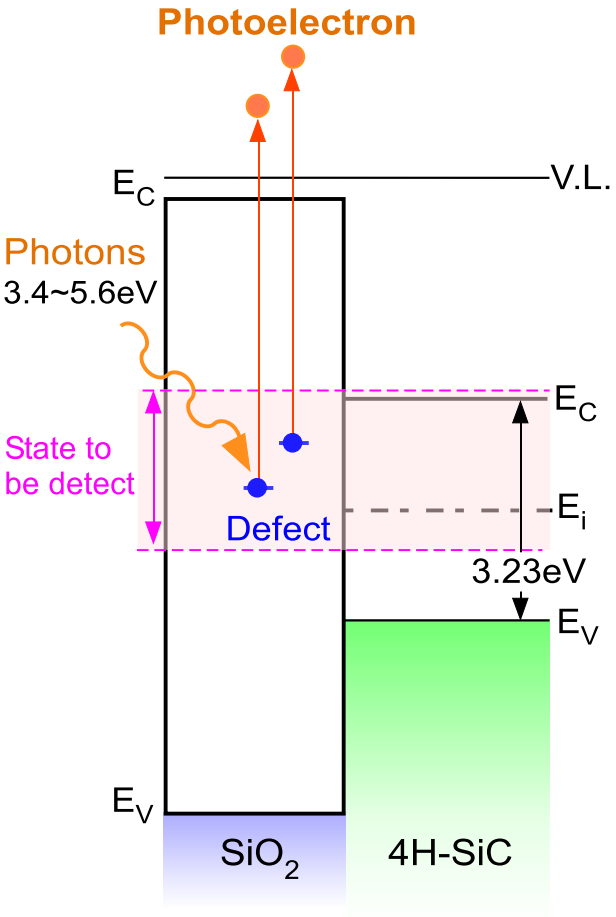

Fig. 2. Energy band diagram of SiO_2/4H-SiC structure. Bandgap energy of 4H-SiC was referred [14,15].

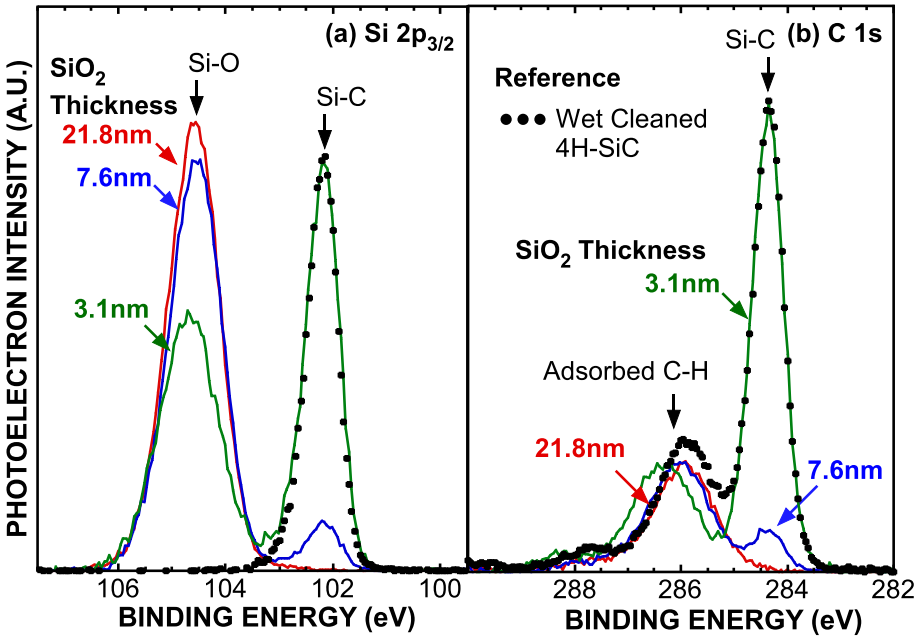

Fig. 1. (a) Si $2p_{3/2}$ and (b) C 1s core-line spectra for thermally grown SiO_2/4H-SiC structure with different SiO_2 thicknesses. A spectrum of wet-cleaned 4H-SiC substrate was also shown as a reference. In each spectrum, the photoelectron take-off angle was set at 90°.