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Characterization of ion beam-induced SiC-OI structures by positron annihilation spectroscopy

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Effect of oxygen ion implantation to SiC at 600 °C has been studied by positron annihilation spectroscopy using energy-variable slow positron beams. The Doppler broadening of annihilation radiation and positron lifetime measurements showed that vacancy defects survive and no SiO_2 layer is formed in the as-implanted state. Following post-implantation annealing at 1400 °C, vacancy clusters were removed. Furthermore, a SiO_2-like layer is formed in the oxygen-implanted region. An interface layer, which resembles that of the SiO_2/SiC produced by conventional oxidation, was also found.

1 Introduction Silicon carbide (SiC) is a promising material for semiconductor device applications at high temperature and radiation fields due to its wide band gap and high thermal conductivity. SiC-On-Insulator (SiC-OI) structure is suitable for power SiC devices because this structure is effective for the reduction of leakage current. Several studies on the SiC-OI structure have been reported. Di Cioccio et al. reports the production of SiC-OI structure using SmartCut® method [1]. They demonstrate successful formation of SiC/SiO_2/Si structures on 100 mm silicon substrates. However, vacancy defects, which degrade crystal quality, are created by proton irradiation [2]. Heteroepitaxial growth of 3C-SiC on oxygen implanted silicon wafer has also been attempted for the SiC-OI structure [3]. This method involves still two major problems. One is the strong lattice mismatch between 3C-SiC and Si substrate. The other is the different thermal expansion coefficient between 3C-SiC and Si. In the case of Si, oxygen ion implantation is established as the separation by implanted oxygen (SIMOX) [4]. The top-Si layer formed by the SIMOX process is a homogeneous single crystal, and the buried SiO_2 layer works as an insulating layer. This method is also anticipated as a promising method to fablicate the SiC-OI structures [5–9]. Using cross-sectional transmission electron microscope (TEM), Rutherford backscattering spectroscopy (RBS) and elenctron energy loss spectroscopy (EELS), it is reported that the well-defined SiO_2 layer with amorphous Si-O bonds is formed at the oxygen-implanted layer. It has been also reported that the crystallinity of the top-SiC layer does not significantly change by ion implantation because of the high implantation temperature and post-implantaion annealing. However, the properties of radiation defects created in the buried SiO_2 layer and the top-SiC layer by the high-dose implantation of oxygen ions have not been fully elucidated.

Positron annihilation spectroscopy (PAS) is a powerful tool to detect open volume defects in solids. Using a slow positron beam, a depth profiling of defects in a subsurface region with typical depth of several microns is possible. Indeed, previous positron annihilation studies suggest the existence of open-

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volume type defects with oxygen dangling bonds at SiO_2/SiC interfaces [10–13]. We attempted to investigate defects in the SiC-OI structure using the positron annihilation method.

2 Experimental Samples used in this study (10×10 mm) were cut from a 2-inch chemical-vapour-deposition-grown *n*-type 4H-SiC epilayer on 8°-off oriented 4H-SiC(0001) substrates from a CREE Research Inc. Oxygen ions with energy of 200 keV were implanted into these samples to doses of 1.0×10^{16} /cm^2 (low-dose) and 1.0×10^{18} /cm^2 (high-dose). The oxygen implanted region is estimated at 200 ~ 400 nm from the surface by TRIM code [14]. The ion beam flux was maintained at ~10 μA. During implantation, the sample temperature was kept at 600 °C for avoiding amorphization [15, 16]. The above implantation method is commonly employed for the fabrication of SiC-OI structure by oxygen ion implantation. After implantation, the samples were annealed at 1400 °C for 30 minutes in argon ambient.

The Doppler broadening of annihilation radiation (511 keV) was measured as a function of incident positron energy (E) from 0.2~30 keV at room temperature. The obtained Doppler broadening spectra were characterized by S and W parameters, which are defined as the peak and tail intensities, respectively. The windows for S and W parameters were 510.2 to 511.8 keV and 513.6 to 514.5 keV, respectively. All the S and W parameters were normalized to those in the SiC epilayer. Using a pulsed positron beam with energies of 2.5 keV and 7 keV, positron lifetime measurements were also performed at room temperature. The time resolution was 310 ps in full width at half maximum (FWHM). In each positron lifetime spectrum, one million counts were accumulated. The obtained positron lifetime spectra were analysed using the PATFIT-88 program [17].

3 Results and discussion Figure 1 shows S and W parameters as a function of incident positron energy for the virgin, low-dose and high-dose samples. The mean implantation depth of E = 4 ~ 7 keV in the SiC crystal corresponds to the oxygen implanted region. After implantation, S parameter increases in the whole energy range. This indicates that vacancy defects are formed by ion implantation. A remarkable increase of S parameter in the top-SiC layer (E = 1 ~ 3 keV) is observed in the high-dose sample. This indicates that larger vacancy clusters are created in this region which is shallower than the oxygen implanted layer. No significant differences are observed between the low-dose and high-dose samples at above 5 keV. When positrons are trapped at vacancy defects, normally S parameter increases and W parameter decreases, i.e., *S-E* and *W-E* curves are mirror-like to each other. This occurs in the case of the low-dose sample. On the contrary, *S-E* and *W-E* curves are not mirror-like in the oxygen-implanted re-

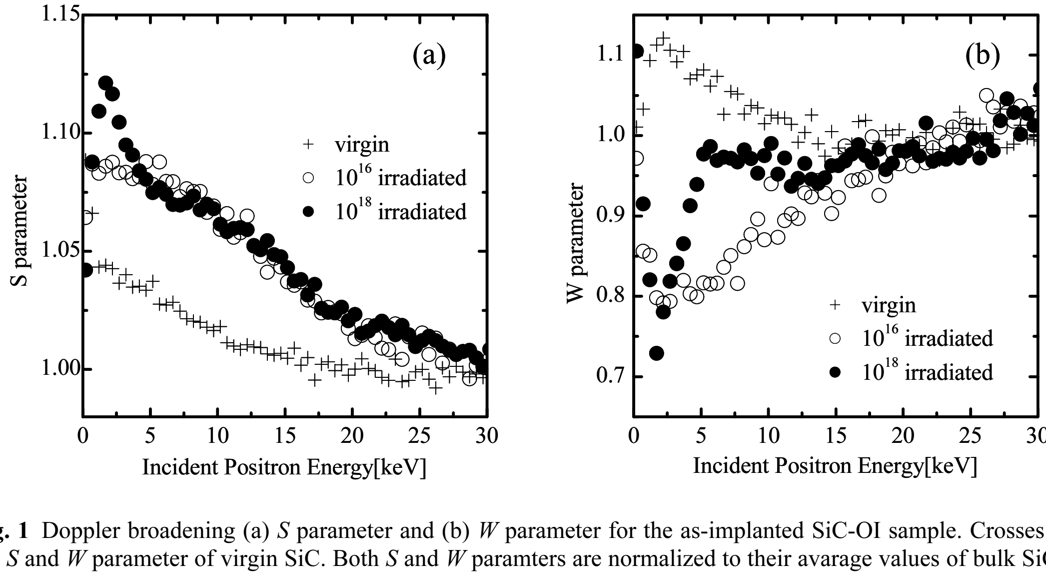

Fig. 1 Doppler broadening (a) S parameter and (b) W parameter for the as-implanted SiC-OI sample. Crosses are the S and W parameter of virgin SiC. Both S and W paramters are normalized to their avarage values of bulk SiC at high energy regions (E > 20 keV).

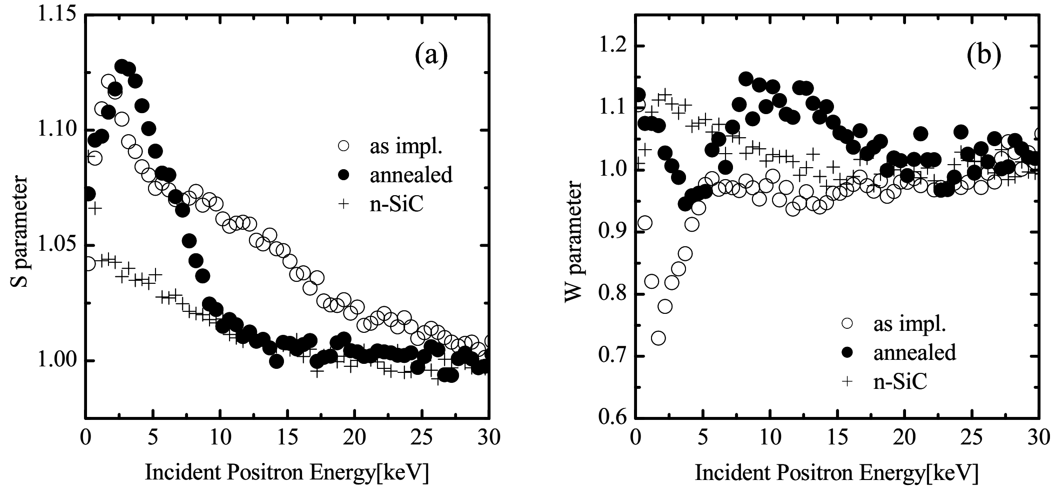

Fig. 2 (a) *S* parameter and (b) *W* parameter for the virgin SiC, as-implanted SiC and implanted SiC after annealing at 1400 °C. The implantation dose is 1.0×10^{18} /cm^2. Both *S* and *W* paramters are normalized to the avarage values of bulk SiC at high energy regions (E > 20 keV).

gion of the high-dose sample. This is probably due to the effect of oxygen atoms [18]. But, the buried SiO_2 layer is not necessarily formed because *S* and *W* parameters of this layer apparently differ from those of SiO_2 bulk [12]. Figure 2 shows the *S-E* and *W-E* curves obtained from the high-dose sample after annealing at 1400 ^{o}C. By annealing, *S* parameters at E > 10 keV decrease to the bulk value suggesting the recovery of vacancy defects. At the region of E = 3 ~ 6 keV, *S* parameters become high and a valley appears on the *W-E* curve. The *S* and *W* parameters at E = 4 keV are 1.13 and 0.95, respectively. These are close to those of well-annealed SiO_2 fabricated by thermal oxidation of the SiC [12]. This indicates that a buried SiO_2 layer may be formed. The peak of S parameter is located at E = 4 keV. This incident positron energy is slightly lower than that expected from the oxygen implantation range. Probably, this deviation is due to the change of density from SiC (3.2 g/cm^3) to SiO_2 (2.2 g/cm^3). At the deeper region (E > 7 keV), *W* parameters again increase in contrast to the increase in *S* parameters. The amount of increase of *W* parameter is greater as compared to the as-implanted state. Thus, the annihilation of positrons with oxygen valence electrons is more enhanced by annealing. This resembles the annihilation at the interface of the SiO_2/SiC interface produced by conventional oxidation. That is, the interface layer containing vacancy defects with oxygen dangling bonds are exists. In the top-SiC layer, *S* parameters are still high, while *W* parameters increase, suggesting the effect of the buried SiO_2 layer and its interface.

Table I summarizes the positron lifetimes and their intensities. As well-known, a characteristic long lifetime (τ_3) due to pick-off annihilation of ortho-positronium (o-Ps) is observed in SiO_2 [19]. The average lifetimes at E=2.5 keV and E= 7keV in the as-implanted state are 284 and 338 ps, which correspond

Table 1 Positron lifetimes and their intensites of the high-dose sample in the as-implanted state and after annealing at 1400 °C. As references, lifetimes and intensities of the bulk SiO_2 and the SiC from literature [12] are also listed.

		τ_1(ps)	τ_2(ps)	τ_3(ps)	I_1(%)	I_2(%)	I_3(%)
E=2.5 keV	as-implanted	284 ± 1	-	-	100	-	-
	annealed	125(fixed)	421 ± 12	1387 ± 23	8.0 ± 5.6	52.5 ± 4.8	39.5 ± 1.3
E=7 keV	as-implanted	338 ± 1	-	-	100	-	-
	annealed	391 ± 2	-	-	100	-	-
	SiO_2 (Reference)	125(fixed)	472 ± 2	1610 ± 5	20.0 ± 0.2	20.5 ± 0.2	59.5 ± 0.2
	SiC (Reference)	139 ± 1	-	-	100	-	-

to the vacancy clusters with sizes of 3-$V_{Si}V_C$ to 6-$V_{Si}V_C$ [20]. After annealing at 1400 °C, the long lifetime components related to o-Ps appears at E = 2.5 keV. This suggests that amorphous SiO_2 is formed in this region. The average lifetime at E = 7 keV increases to 391 ps. This lifetime is comparable to that of SiO_2/SiC interface (451 ps) [12].

Considering both the Doppler broadening and lifetime data, in the oxygen-implanted region of the high-dose sample, the buried SiO_2 layer may be formed. However, this SiO_2 layer seems to be still defective because I_3 is smaller than that of the bulk SiO_2. This means the suppression of Ps formation by the existence of competitive trapping centers, such as vacancy clusters which give shorter τ_2 and higher I_2. At the deeper region, positrons preferentially annihilate with oxygen valence electrons at voids. This situation is similar to the case of SiO_2/SiC interface.

4 Conclusion Defects in SiC implanted with oxygen ions at 600 °C were probed by positron annihilation spectroscopy. In the oxygen implanted region, Doppler broadening parameters and positron lifetimes that are attributed to the buried SiO_2 layer were observed after annealing at 1400 °C. The interface layer between buried SiO_2 and SiC substrate, which includes voids with oxygen dangling bonds, was found.

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