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Structural defects at SiO_2-SiC interfaces detected by positron annihilation

M. Maekawa, A. Kawasuso, M. Yoshikawa, and H. Itoh

Japan Atomic Energy Research Institute, Takasaki Establishment
Watanuki, 1233, Takasaki, Gunma, 370-1292, JAPAN

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Abstract. Defects in SiO_2/SiC interfaces fabricated by pyrogenic and dry oxidation techniques were proved using MOS structures and a monoenergetic positron beam. The Doppler broadening of annihilation radiation were measured as functions of the positron incident energy and gate voltage. We observed significant increases in *S*-parameters when negative bias was applied to the gate electrode. This suggests that open volume type defects exist at the SiO_2/SiC interfaces. Positron data were further compared with *C-V* measurements. It was found that the increase of the *S*-parameter due to the bias voltage was well correlated with the change of capacitance. That is, the threshold voltages for the increase in *S*-parameter coincide with the flat-band voltage in the *C-V* measurements. Higher *S*-parameters were observed in MOS samples with higher interface trap density. Thus, open-volume type defects may be one of the candidates responsible for interfacial defects at SiO_2/SiC.

Introduction

Passivation of interfacial defects in SiC-MOS devices is the most important issue in the SiC device technology because these centers eventually reduce the channel mobility and hence prevent the fast operation of MOSFET. Despite of many extensive works[1,2], the interfacial defect density in ordinarily produced SiO_2/SiC is still far above the feasible level for the commercial production of MOS devices. It is therefore needed to characterize SiO_2/SiC interfaces more in detail. Beside the conventional techniques such as capacitance-voltage measurement, previous positron annihilation studies show the existence of open-volume type defects at SiO_2/Si interfaces and their passivation with some specific treatments [3-5]. Successful positron studies on SiO_2/Si interface owes to the facts that (i) positrons are easily trapped by open volume-type defects, (ii) positrons can be implanted at a certain depth near interface, and (iii) positrons are drifted by applying bias voltage similar to holes. In this study, we attempted to detect open-volume type defects at SiO_2/SiC interfaces using the positron beam technique.

Experimental setup

Crystals used in this study were CVD-grown *n*- and *p*-type 4*H* SiC epilayers on 8^o-off oriented 4*H* SiC(0001) substrates. Two sets of MOS samples were fabricated: One has an approximately 35 nm oxide layer (pyrogenic oxidation at 1100 ˚C for 3h) and the other an approximately 40 nm oxide layer (dry oxidation at 1200 ˚C for 2h). Aluminum films (250 Å thick) were deposited on both oxide films as gate electrodes. Figure 1 shows the experimental setup of positron annihilation measurement performed here. Variable-energy (0.2~20 keV) monoenergetic positron beam was injected into the above MOS samples through the Al electrodes, which were

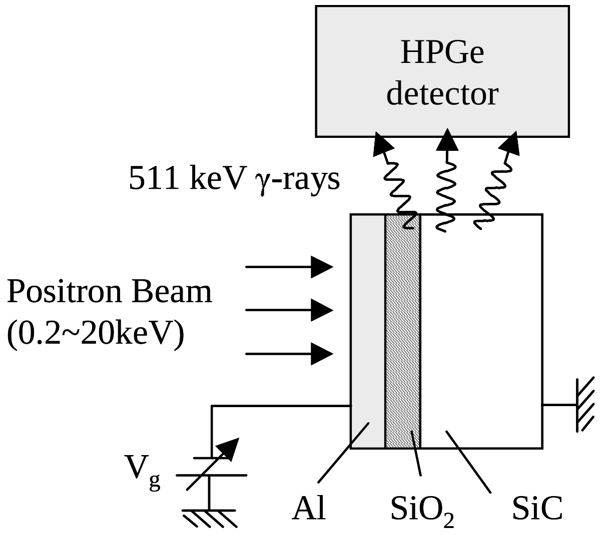

Fig. 1 Experimental setup

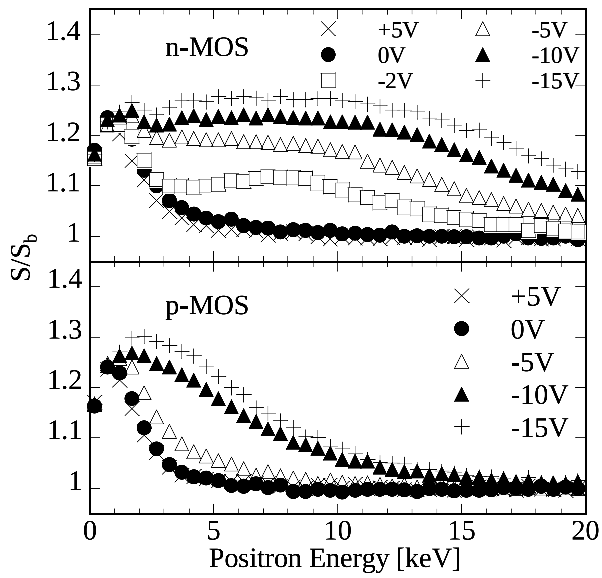

Fig.2 *S*-*E* data as a function of gate bias V_g for *n*- and *p*-MOSs with pyrogenic oxidation.

applied with a bias voltage (V_g). The bias polarity is referred to the Al gate. Implanted positrons slow down, diffuse, and finally annihilate with electrons in the sample emitting two γ-rays (~511 keV). The energy spectrum of the annihilation γ-ray is Doppler-shifted due to the motion of electron-positron pairs. As the momentum distribution of electrons in defects is different from that in bulk, defects are detected through measurements of Doppler broadening profiles of the annihilation γ-ray. The Doppler spectra measured by a high resolution Ge detector were quantified by so-called *S*-parameter, which is defined as the normalized peak intensity of the Doppler spectrum. *S*-parameter tends to increase at open-volume type defects because of the narrowing of the Doppler spectrum due to the reduction of core electron annihilation rate which gives rise to a greater Doppler shift. All the *S*-parameters were normalized to the bulk *S*-parameters for SiC substrate.

Result and discussion

Figure 2 shows *S*-parameter as a function of incident positron energy at various V_g for *n*- and *p*-MOS samples made by pyrogenic oxidation. At $V_g = 0$ V, *S*-parameter remains constant in high energy region (> 8 keV). This shows that most positrons are implanted into SiC epitaxial layers and annihilate there. In lower incident energy region, positrons are implanted into SiO_2 and Al layers. The low *S*-parameters at $0 < E < 1$ keV mostly come from positron annihilation in the Al layer. An increase of *S*-parameter at 2 keV regions can be attributed to the annihilation of positrons in the SiO_2 layer. Hence the regions at 2 keV < E < 8 keV reflect the properties of SiO_2/SiC interface. When $V_g < 0$ V, *S*-parameter increases at $E > 1$ keV in both *n*- and *p*-MOSs. This fact indicates that positrons drift back to the SiO_2/SiC interface with negative gate bias and trapped by open-volume type defects. The increase of *S*-parameter in *n*-MOS extends to higher incident positron energy, i.e., deeper region, than in *p*-MOS. This means that positrons in the *n*-MOS layer drift more easily toward the interface than in *p*-MOS. Negative V_g makes *n*-MOS to be in 'inversion' and wide depletion layer appears in SiO_2/SiC interface. Positrons feel the external electric field, and many of them are collected near the interface to be trapped by vacancy-type defects. Contrary, *p*-MOS applied with a negative V_g is in 'accumulation'. Both positrons and holes are gathered to the

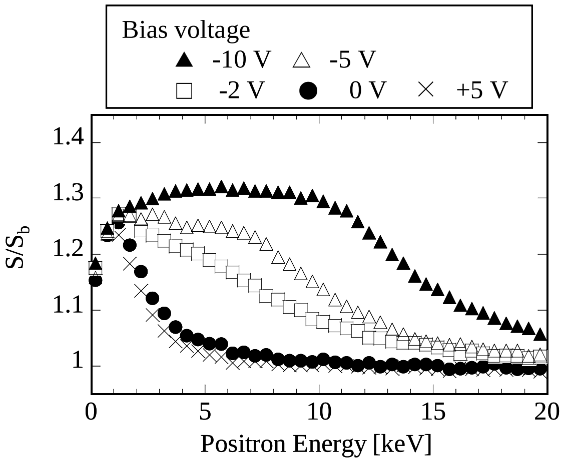

Fig. 3 S-E data as a function of gate bias V_g for n- MOSs with dry oxidation

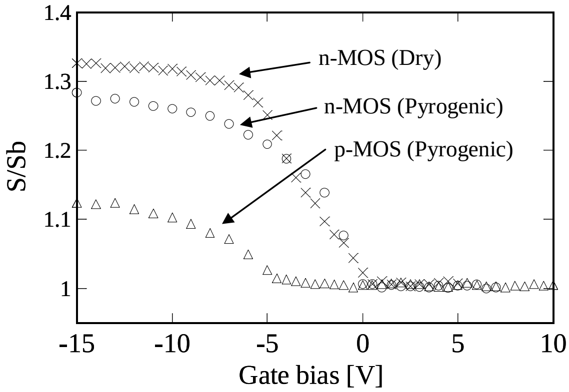

Fig. 4. Results of S-V measurements at E = 8 keV of various MOSs. Allows shows the increase points of S-parameter.

interface. Since in this mode, no depletion layers are formed, the increase in S-parameter does not extend to higher energy region unlike to the case of n-MOSs. Accumulated holes may be trapped by defects and hence defect charge states become to be more positive suppressing positron trapping rate. Thus, the relatively small increases of S-parameter in p-MOS may be interpreted because of positron trapping rate. The electric field due to holes also suppresses the transfer of positrons to the near SiO_2/SiC interface. If $V_g > 0$, no rise of the S-parameter is observed. This is probably because positrons drift toward the SiC substrate by electric field.

Figure 3 shows similar data on dry oxidation. Distinct differences from the case of pyrogenic oxidation were observed as follows. For n-MOS, the S-parameter is higher than that for pyrogenic oxidation at the same bias voltage. This suggests that the quantity of the defect near the interface is more abounding. As the incident positron energy increases, the S-parameter is reduced more rapidly than in pyrogenic condition. This indicates that the movement of positrons implanted into deep region becomes insensitive with external electric field due to the narrower depletion layer with dry oxidation. This point will be confirmed later in the C-V measurements.

To demonstrate the response of S-parameter to gate bias voltage more in detail, S versus V_g curves were determined at the incident positron energy of 8 keV where most positrons are implanted into the SiC close to the SiO_2/SiC interface. Figure 4 shows thus obtained S-V curves. The S-parameter rapidly increases from near 0 V in two n-MOSs. For p-MOS made by pyrogenic oxidation, S-parameter starts to increase at V_g = -3.5 V.

Table 1 shows the result of C-V measurements for the same MOSs. The flat-band voltages (V_{fb}) for n-MOSs are close to 0 V. This closely matches with the threshold voltages for the increases in S-parameters in Fig. 4. Table 1 also shows that the widthes of depletion layers of the n- MOSs at V_g = -5 V were 850 nm and 570 nm for the pyrogenic and dry oxidations, respectively. The quick decrease of S-parameter in the S-E curve for the dry oxidation in the high energy region (Fig. 3) can be explained as due to the narrow depletion layer. The interface state density N_{it} of the dry oxidation MOS is one order of magnitude higher than that of the pyrogenic oxidation sample. This can be correlatedd with the fact that S-parameter of dry oxidation MOS is higher than pyrogenic one at V_g < -10 V as shown in Fig.4.

Sample		V_{fb} [V]	Depletion layer [nm]	N_{it} [cm^{-2}]
n-type	pyrogenic	0.7	850	6.6×10^{11}
	dry	-0.4	570	7.7×10^{12}
p-type	pyrogenic	-3.4		5.0×10^{12}

Table 1. Results of *C*-*V* measurements of *n*-, *p*-MOS with pyrogenic oxidation and n-MOS with dry oxidation. V_{fb} is the flat-band voltage. Depletion layer is obtained at V_g= -5 V. N_{it} is the interface state density.

Thus, that there is the good correlation between the interface state from the electrical measurement and information about defect detected in positron measurement.

Summary

In summary, we studied defects in SiO_2/SiC interfaces of MOSs fabricated by pyrogenic and dry oxidation using a positron beam. From the dependence of *S*-parameter on gate bias voltage, we demonstrated the presence of open-volume type defects at SiO_2/SiC interfaces. The positron data are compared with *C*-*V* measurements. The differences of *S*-*E* curves in high energy region between pyrogenic and dry oxidation condition under the gate bias are caused by the widths of depletion layer. The threshold gate bias voltage of the increase of *S*-parameter is due to the transfer of positrons to the interfaces because of the appearance of electric filed determined by the flatband voltage. The increase of the *S* parameter is larger when the interface state density is high. It may be said that these open-volume type defects should be passivated to improve the interface quality.

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