*Materials Science Forum* *Online: 2004-06-15*
*ISSN: 1662-9752, Vols. 457-460, pp 1301-1304*
*doi:10.4028/www.scientific.net/MSF.457-460.1301*


# Investigation of $SiO_2$/SiC interface using positron annihilation technique

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**Keywords:** $SiO_2$/SiC interface, MOS structure, Positron beam, Doppler-shift, Open-volume defect

**Abstract.** We have investigated the $SiO_2$/4H-SiC interface in the metal-oxide-semiconductor (MOS) structure using positron annihilation spectroscopy. The oxide layer was fabricated by the pyrogenic method. The Doppler broadening of annihilation quanta were measured as functions of the incident positron energy and the gate bias. With negative gate bias, significant increase in *S*-parameter was observed. This indicates that the fraction of positrons reaching the aluminium gate electrode increases with the bias voltage. By ultraviolet (UV) light irradiation, *S*-parameter was found to decrease. Considering the fact that the width of depletion layer shrinks upon UV irradiation, the drift of positrons towards the aluminium electrode may be suppressed. Even after stopping UV irradiation, the suppressed *S*-parameter was found to be persistent in the darkness. When the MOS sample was released from the circuit and was kept more than one day, *S*-parameter was found to recover. The above effect implies that the electron-hole recombination rate after UV irradiation is rather moderated even in the darkness due to low interfacial states acting as recombination centers.

## Introduction

Silicon carbide (SiC) is an attractive material for electronic device applications because of its wide band gap and excellent thermal conductivity. SiC field-effect-transistor (MOSFET) is promising devices for high-temperature, high-power and high radiation resistance device [1,2]. Thermally grown $SiO_2$ on SiC is suited for MOS applications [3]. However, the density of interface states in thermally grown $SiO_2$/SiC interface still remains about two orders of magnitude higher than that in $SiO_2$/Si interfaces [4-6]. These centers cause the reduced channel mobility due to carrier trapping and Coulomb scattering and hence prevent the fast operation of MOSFET. The electron mobility near the $SiO_2$/SiC interface is one to two orders of magnitude smaller than that of bulk. Therefore, it is needed to characterize $SiO_2$/SiC interfaces more in detail.

Positron annihilation spectroscopy (PAS) is known as a powerful tool to detect vacancy type defects in solids. Using a slow positron beam, a depth profiling of defects near the subsurface region (typically several microns depth) is possible. Various positron studies suggest the existence of vacancy type defects at $SiO_2$/Si interfaces and their passivation with some specific treatments [7-10]. In this study, we investigate the characteristics of the $SiO_2$/SiC interface in SiC-MOS using PAS measurements.

## Experimental

MOS capacitors used in this study were fabricated using the *n*-type 4H-SiC epilayer grown by chemical-vapor-deposition on $8^o$-off oriented 4H-SiC(0001) substrates (purchased from CREE Research Inc). The net donor concentration of the epilayer was about $5\times10^{15}cm^{-3}$. The size of crystal was 10 ×10 mm. The oxide layer was grown by pyrogenic oxidation at 1100 ˚C for 3h. Thickness of oxide layer is approximately 40 nm. Then aluminum film with a thickness of 25 nm was deposited on the oxide film as gate electrodes. In order to make the ohmic contact, oxides grown on backside substrate was removed and aluminum was deposited on the exposed surface.

Variable-energy (0.2~20 keV) monoenergetic positron beam was implanted into the fabricated SiC-MOS structure with applying bias voltage ($V_g$). Implanted positrons annihilate with electrons in the sample emitting two gamma($\gamma$)-rays. The energy spectrum of the annihilation $\gamma$-rays is Doppler-shifted due to the momentum of electron - positron pairs that reflect the local environment of the annihilation site. The Doppler-broadening of the annihilation $\gamma$-ray measured by a high resolution Ge detector was characterized by *S* and *W*-parameters, which are defined as the normalized peak intensity (low momentum shift, 511±0.8keV) and normalized wing region intensity (high momentum shift, 514~515 keV) of the spectrum. The *S*-parameter is related to annihilations with valence electrons and *W*-parameters are related to annihilation with high momentum core electrons. Therefore the *S*-*W* plot reflects the difference of electron momentum distribution of positron annihilation site. For example, positron annihilation at vacancy-type defect gives higher *S*-parameters and lower *W*-parameters than annihilation at perfect crystal.

## Results and Discussion

Figure 1 shows *S*-parameter as a function of incident positron energy (*E*) at various gate bias $V_g$. At $V_g$=0 V, constant *S*-parameter (=1.00) in higher energies (~8 keV) is attributed to annihilation in SiC epilayer. Higher *S*-parameters at 1 keV represent the annihilation of positrons in the aluminum gate electrode. The 1-2 keV region where *S*-parameters begin to decrease corresponds to $SiO_2$ layer. Hence the region from 2 keV to 8 keV reflect the properties of $SiO_2$/SiC interface. Figure 2 shows the S-W plot with the incident positron energy as a running parameter. The region around (*S*, *W*)=(1, 1) corresponds to annihilation in SiC. The region near (*S*, *W*)=(1.25, 0.6) is assigned to annihilation in the aluminum gate electrode. The region of $SiO_2$, (S,W)=(1.12, 0.88), was determined from the measurement without gate electrode. The *S*-*W* plots at $V_g$= 0 V shows another region at (*S*, *W*)=(1.02, 1.15). This might be attributed to $SiO_2$/SiC interface.

At $V_g$ <0 V, *S*-parameter remarkably increases(*E*>2 keV). *S*-parameter increases with increasing gate bias, and in the case of $V_g$=-10 V, *S*-parameter saturates at a value close to the Aluminum one. *S* and *W*-parameters move towards aluminum region. This indicates that the transportation of positrons to the aluminum gate electrode through the $SiO_2$ layer is enhanced with the gate bias [11]. Therefore, the observed *S*-parameter contains contributions from each layer. In addition, the *S*-parameter of $SiO_2$/SiC interface derived from *S*-*W* plots is *S*=1.02 that close to the value of SiC. It seems to be difficult to extract the changes of *S*-parameter of interface defects only from bias change.

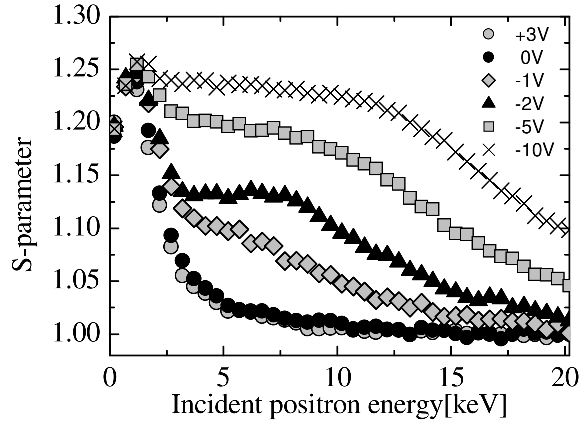


Fig. 1. *S*-parameters as a function of incident positron energy at various gate bias ($V_g$) for *n*-type MOS structure made by pyrogenic oxidation.

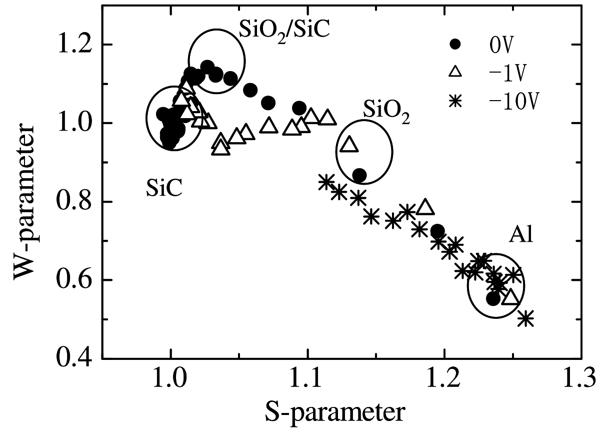


Fig. 2. *S*-*W* plot as a function of incident positron energy at various gate bias ($V_g$) for *n*-type MOS structure made by pyrogenic oxidation.

As shown above, the *S*-parameter well responds to the inner electric field generated by the gate bias. Unlike the case of Si-MOS structure, the inversion layer is hardly formed in the SiC-MOS even applying the negative gate bias because of the wide band gap[12-15]. Hence, the depletion layer extends without forming inversion layer. However, the inversion layer can be formed by electron-hole excitation up on UV irradiation. Figure 3 shows the effect of UV irradiation on *S*-*E* curve and *S*-*W* correlation. In this experiment, thickness of MOS structure (13 nm for Al gate and 20 nm for $SiO_2$ layer) is thinner than that of fig1 because of easy penetration of UV light. As shown in Fig. 3(a), the S-parameter at $E$>3 keV increases due to the negative gate bias and the *S*-*W* correlation is straight between the aluminum gate electrode and SiC. This shows that positrons pass through the $SiO_2$ layer and reach the aluminum gate electrode by the generated electric field. Under UV irradiation (Fig. 3(b)), the increase of *S*-parameter under negative gate bias is sharply

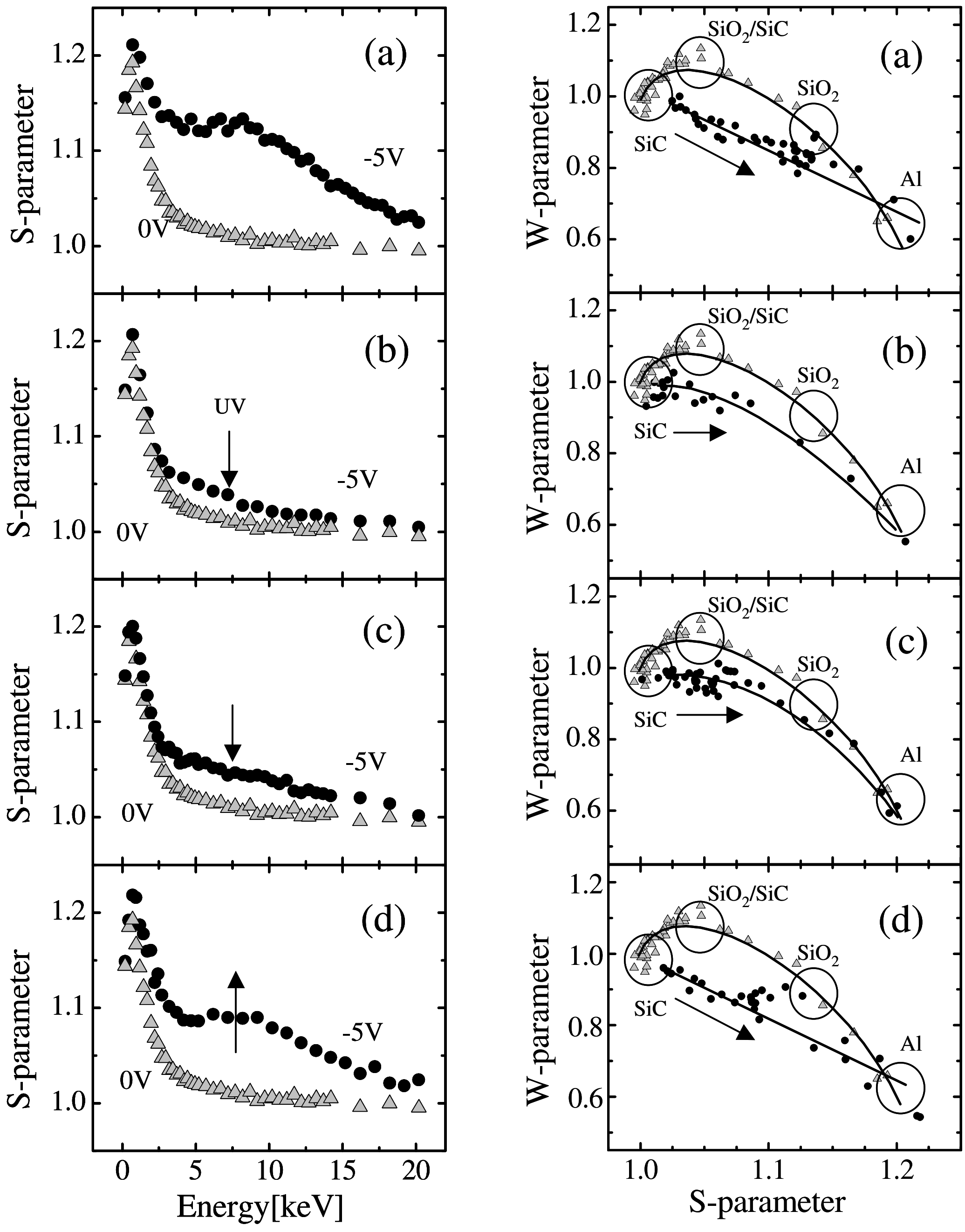


Fig. 3. *S*-*E* data and corresponding *S*-*W* plots as a function of incident positron energy at $V_g$= 0 V and $V_g$= -5V. (a):before UV irradiation, (b):during UV irradiation, (c):after UV irradiation, (d): after leaving the MOS sample in open circuit for 24 hours.

suppressed as compared with the case where the UV is not irradiated. *S-W* is no longer straight and seems to move via $SiO_2$/SiC and $SiO_2$ regions. This indicates that the transportation of positrons to the aluminum gate electrode is suppressed because of reduction of depletion region by appearance of holes. After stopping UV irradiation, the increase of *S*-parameter still remains suppressed in the darkness (Fig. 3(c)). It is suggested that the generated holes are more or less persistent at a $SiO_2$/SiC interface probably because of the low density of recombination centers. In fact, the interfacial state density in the case of pyrogenic oxidation is approximately one order of magnitude lower as compared to the case of dry oxidation. After the release of the MOS sample from the bias circuit for 24 hours (Fig. 3(d)), *S*-parameter again increases with the negative gate bias. *S-W* correlation also becomes straight between the aluminum gate electrode and SiC. Probably, when an external circuit is removed, holes recombine with majority electrons and hence the electric field inside MOS is neutralized. However, the data plotted in full circles in Fig. 3(d) can not superimpose to the data plotted in full circles in Fig.3(a). This is due to the incomplete recovery to the state measured before illumination. This shows that holes have not become extinct completely during 24 hours because of very slow recombination rate. Interface states which play such the recombination center may be located in the place distant from the $SiO_2$/SiC interface.

Thus, response of *S*-parameter reflects very well the influence of internal electric field to the positron implanted into the MOS structure. At $V_g$=0, $SiO_2$/SiC interface region appeared on the *S-W* plot. To evaluate interface states, it is necessary to analyze this region in detail. However, *S-W* plots go away from the region of an interface under negative gate bias. Although positrons may pass through the $SiO_2$/SiC interface, it seems to be difficult to consider that all positrons simply pass the $SiO_2$ layer and annihilate at the gate material because of some incomprehensible phenomena [15]; for example differences of *S-E* data between MOSs fabricated by pyrogenic oxidation and that by dry oxidation. In order to evaluate $SiO_2$/SiC interface states more clearly, it may be necessary to stuff positrons into a $SiO_2$/SiC interface from oxide layer with producing a thick oxidization film because the positron affinity of $SiO_2$ is larger than that of SiC like in the case of Si-MOS[11].

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**Silicon Carbide and Related Materials 2003**
10.4028/www.scientific.net/MSF.457-460

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