Characterization of near-interface border-traps in GeO$_2$/Ge gate stacks grown by low and high temperature thermal oxidation using deep-level transient spectroscopy

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Abstract
We developed a method for characterizing the near-interface border-traps (BTs) in GeO$_2$/Ge gate stacks using deep-level transient spectroscopy. The BT density ($N_{BT}$) in p-MOS grown by low temperature oxidation is smaller than that by high temperature oxidation. By contrast, the $N_{BT}$ in n-MOS is almost the same regardless of the temperature oxidation. In addition, the $N_{BT}$ in p-MOS is drastically decreased by Al post metallization annealing (Al-PMA), but the $N_{BT}$ in n-MOS is not decreased. These results suggest that the species of BT in n-MOS are different from that of p-MOS.

1. Introduction
To fabricate high-performance Ge MOSFETs, a high-quality gate-stack formation on Ge is essential. However, border-traps (BTs) near the GeO$_2$/Ge interface are still a serious issue that degrades the performance of Ge MOSFETs, although a GeO$_2$/Ge structure is beneficial to a decrease in interface-traps (ITs). This is the reason why the BT characterization is important to realize high-performance Ge MOSFETs. In this study, we prepared two kinds of MOS capacitors (CAPs) with a structure of SiO$_2$/GeO$_2$/Ge. One was relatively thick GeO$_2$ by thermal oxidation at 550°C, at which GeO volatilization should be occurred at the GeO$_2$/Ge interface. Another was thin GeO$_2$ by the oxidation at 425°C, at which the volatilization should not be occurred. We investigated BTs in these MOSCAPs using deep-level transient spectroscopy (DLTS) method. The Al post metallization annealing (PMA) effect on BT passivation was also studied.

2. Experimental
Both p- and n-type (100) Ge substrates with respective doping concentrations of $2.3 \times 10^{16}$ and $9.3 \times 10^{15}$ cm$^{-3}$ were used. After substrate cleaning, SiO$_2$/GeO$_2$ bilayer passivation was performed [1]. Here, the thicknesses of SiO$_2$ and GeO$_2$ layers were $\sim$1 nm each. Next, post thermal oxidation (PTO) was performed at 550°C for 15 min or 425°C for 9 h in O$_2$ ambient. After 14-nm-thick SiO$_2$ was deposited on the both samples, the annealing at 400°C for 30 min in N$_2$ was performed. Then, the Al gate film was deposited on the SiO$_2$ surface by thermal evaporation. Before the electrode patterning, an optional PMA was carried out at 300°C for 30 min in N$_2$, which is the Al-PMA. Finally, electrode patterning and back-contact formation by In-Ga alloy were performed. A schematic diagram of sample structure is shown in Fig. 1(a). The equivalent oxide thicknesses (EOTs) of the MOSCAPs with PTO at 550 and 425°C were $\sim$19.5 and 16.8 nm, corresponding to GeO$_2$ thicknesses of 6.6 and 2.6 nm, respectively.

DLTS measurements were performed using a lock-in integrator. The rectangular injection pulse is shown in Fig. 1(b). $V_R$ is the quiescent reverse-bias voltage, which was set at a value corresponding to band bending of $\phi_B$ ($\phi_B$ is the energy difference between Fermi-level and intrinsic Fermi-level) [2]. $V_F$ is the pulse height from $V_R$, and $V_{FW}$ is the flat band voltage. $V_{AP}$ (=|$V_F$-$V_{FW}$) is the accumulation pulse voltage, which is an important parameter for the BT analysis, because the injection pulse intensity ($E_{AP}$) at the GeO$_2$/Ge interface is given by $E_{AP}$=-$V_{AP}$/EOT. Frequency ($f$) and pulse width ($t_s$) are also important parameters for selecting the observed BT position ($\Delta t$) and for filling with carriers into BTs, respectively. In this work, $f=10$ Hz were used, which corresponds to $\Delta t=1.4$ nm from the interface for p-MOS and $\Delta t=2.0$ nm for n-MOS.

3. Results and discussion
Figure 2 shows DLTS signal intensity ($I_{DLTS}$) dependence on $V_F$ with a maximum $t_s$ of 5 ms at different temperatures ($T_s$) for a MOSCAP with PTO at 550°C and without Al-PMA. Here, $\Delta C/C(\infty)$ is plotted as $I_{DLTS}$ because both BT density ($N_{BT}$) and IT density ($D_{IT}$) are proportional to $\Delta C/C(\infty)$ ($\Delta C$ is the DLTS raw signal and $C(\infty)$ is the capacitance at equilibrium). Let us pick up the result at 80 K as an example. The $I_{DLTS}$ drastically increased when the $V_F$ increased from 0 to 0.5 V. Note 0.5 V is approximately the $V_{FW}$ at 80 K for this sample. Therefore, this increase is dominated by the capture process of IT [2]. We believe that the weakest injection condition ($t_s=2$ ms) under $E_{AP}=0$ MV/cm is enough to compose the IT signals. Therefore, we use these data for $D_{IT}$ calculation. In the case of $V_F>0.5$ V,
namely accumulation was established, the contribution of IT would be saturated due to the completion of IT capture. As the result, the increase in $I_{DLTS}$ with $V_F > 0.5$ V was governed by the capture process of BT because of an increase in hole numbers at Ge side of the GeO/Ge interface. After subtracting the IT signal from $I_{DLTS}$, we calculate the $N_{ht}$, details of which will be presented in the conference.

Figures 3 (a) and 3(b) represent energy distributions of $D_{sh}$ for MOSCAPs with PTO at 550 and 425°C, respectively. It was confirmed that $D_{sh}$ values are almost identical despite the PTO temperature difference, implying that the interface properties is not influenced by GeO volatilization. The Al-PMA is effective for a decrease in $D_{sh}$ near the valence band edge but is not near the conduction band edge (rather worsen), which are consistent with our previous conclusion [2, 3].

Figures 4 (a) and 4(b) represent dependence of $N_{ht}$ on $T$ for p-MOSCAPs with PTO at 550 and 425°C, respectively; Figures 5 (a) and 5(b) represent the similar results for n-MOSCAPs with PTO at 550 and 425°C, respectively. It was confirmed from these results that 1) the $N_{ht}$ for p-MOS with 425°C-PTO is a half of that with 550°C-PTO under $E_A$=2 MV/cm, suggesting BT in p-MOS is associated with GeO volatilization; 2) the $N_{ht}$ for p-MOS is drastically decreased by Al-PMA; 3) the $N_{ht}$ for n-MOS with PTO at 425 and 550°C are almost the same and is not decreased by Al-PMA, suggesting the species of BT in n-MOS are different from that of p-MOS.

4. Conclusions

Near-interface BT in GeO$_2$/Ge structures were characterized by DLTS. The $N_{ht}$ in p-MOS were drastically decreased by Al-PMA, but the $N_{ht}$ in n-MOS was not decreased. This is a reason for difficulty of the electron mobility enhancement.

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References