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Effects of total dose irradiation on the threshold voltage of H-gate SOI NMOS devices

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Abstract This work researched the impact of total dose irradiation on the threshold voltage of N-type metal oxide semiconductor field effect transistors (nMOSFETs) in silicon-on-insulator (SOI) technology. Using the subthreshold separation technology, the factor causing the threshold voltage shift was divided into two parts: trapped oxide charges and interface states, the effects of which are presented under irradiation. Furthermore, by analyzing the data, the threshold voltage shows a negative shift at first and then turns to positive shift when irradiation dose is lower. Additionally, the influence of the dose rate effects on threshold voltage is discussed. The research results show that the threshold voltage shift is more significant in low dose rate conditions, even for a low dose of 100 krad(Si). The degeneration value of threshold voltage is 23.4 % and 58.0 % for the front-gate and the back-gate at the low dose rate, respectively.

Keywords Silicon on insulator (SOI) · Threshold voltage · Dose rate effects · Interface states

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1 Introduction

Silicon-on-insulator (SOI) technology has been regarded as having highly promising military applications for many years. With the structure of completed dielectric isolation, this technology can eliminate latch-up and has demonstrated advantages in radiation tolerance over bulk silicon technologies [1]. However, the characterization of SOI MOSFETs in irradiation environments is more complex than that of bulk silicon devices because of its buried oxide, which leads to more Si/SiO_2 interface in SOI device [2–5]. Therefore, it is challenging to develop radiation-hardened SOI devices [6–9]. The total dose has an effect on electric characteristic parameters under different irradiation dose conditions, especially on the threshold voltage of an SOI MOS device. Nevertheless, there is little concrete analysis regarding the threshold voltage under varying technology and total dose radiation. In order to estimate this influence, experiments and mechanism analysis are needed.

The paper focuses on the total dose effects. This work also researches the degradation of the threshold voltage and mobility for SOI devices, caused by not only the trapped oxide charges but also the interface states. First, the threshold voltage shift shows a "rebound" phenomenon, which usually appears under ultra-high total dose [10, 11] or during annealing at high temperatures [12]. However, in this work, the phenomenon happens when the irradiation dose is 200 krad(Si) at room temperature. Two possible reasons account for this phenomenon: the special structure of SOI MOS devices and the effects of buried oxide on carries in channel. Through the use of subthreshold separation technology [13], the paper quantitatively analyses the effects of positive charges and interface states on threshold voltage degradation in SOI devices, further explaining this "rebound" phenomenon. Moreover, the subthreshold separation technology can be used to estimate the effects of positive charges and interface states on the electricity characteristic parameters for different irradiation conditions. As far as we know, the dose rate effects in the electrical characteristics of these devices are usually considered for the bulk silicon MOSFETs [14] or bipolar transistors [15–18]. Nevertheless, little work has been conducted to investigate the dose rate effects on SOI MOS devices. At present, dose rate effects on SOI devices have remained a challenge, largely because of insufficient experimental data. In this paper, the research data show that the threshold voltage shift in low dose rate conditions is more significant when the SOI devices are exposed to γ-rays. At the low dose rate, the threshold voltage shift of the back-gate is 43.0 %. By contrast, this threshold voltage shift is just 29.1 % at the high dose rate.

2 Experiment and device structure

The experimental samples consisted of partially depleted silicon-on-insulator (PDSOI) devices with an H-gate bilateral body-contacted structure, which was fabricated by using lightly doped drain source (LDD) technology. Figure 1 shows a cross section of the sample. V_G is the gate voltage, V_D is drain voltage, and V_S is source voltage. t_{box} indicates the thickness of buried oxide, and t_{ox} indicates the thickness of gate oxide, the values of which are 375 and 17.5 nm, respectively. The gate width/length ratio is 8/0.8 μm, and the work voltage is 5 V.

The experiment uses the γ-rays of ^{60}Co sources. The dose rates in this experiment were 1 and 50 rad(Si)/s. The condition of the irradiation was ON-state (i.e., the gate was contacted to V_{dd} (i.e., 5 V), and other ports were grounded). Two types of body states (i.e., floating-body and body-grounded) were chosen for these experiments. The devices' electric characteristics were collected by HP4156, which is a precision semiconductor parameter analyzer that the experimental computer controlled. Each test was completed in half an hour.

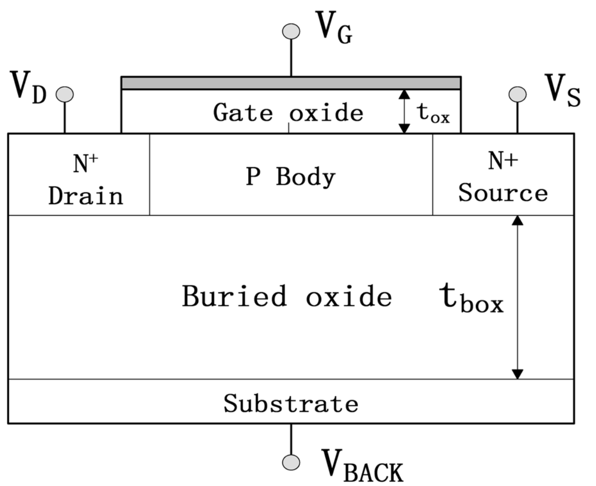

Fig. 1 Cross section of samples

3 Results and discussion

3.1 The effect of total dose irradiation on threshold voltage

Figure 2 shows the measured *I–V* characteristics of the front-gate and back-gate for PDSOI nMOSFETs before and after irradiation ($V_D = 0.1$ V). The *X*-axis indicates the gate applied voltage, and the *Y*-axis indicates the logarithm of the drain current.

Figure 2a, b shows that the OFF-state leakage current increases significantly when the irradiation dose is 300 krad(Si). The radiation bias is ON-state (i.e., $VG = 5$ V), which forms a high electric field in the gate oxide. And then, the radiation inducing electrons and holes quickly separate and migrate to the positive and negative electrodes in the oxide, respectively. Electron mobility is greater than hole mobility, so the recombination mechanism of free electrons and holes is weakened. As the density of positive charges increases, more and more effective oxide charges migrate to the SiO_2/Si interface and attract electrons near the interface. When the concentration of electrons is large enough, the parasitic conducting channel is formed, which causes the leakage current to increase.

Regarding the *I–V* characteristics of the front-gate and back-gate, shown in Fig. 2, the leakage current reaches up to 10^{-10}–10^{-9} A when the test gate voltage is 0 V. However, in the front-gate *I–V* characteristics, a greater number of positive charges migrate to the interface as the gate voltage increases, which leads to a large leakage current as a function of the total dose. When the total dose is 300 krad(Si), there is an exponential growth in the leakage current. However, the test voltage for back-gate *I–V* characteristics is applied on the substrate; substrate voltage has a slight effect on the electrons in the channel thanks to the isolation of buried oxide in SOI devices.

Using linear extrapolation, this work presents the degradation of threshold voltage as a function of total dose. Figure 3a, b indicates the different phenomena that occur between the body-grounded devices and floating-body devices. For the body-grounded devices, shown in Fig. 3a, the negative shift quantity of the threshold voltage (ΔV_{th}) increases after irradiation. When the total dose is 200 krad(Si), the shift is 30.4 % for the front-gate. When

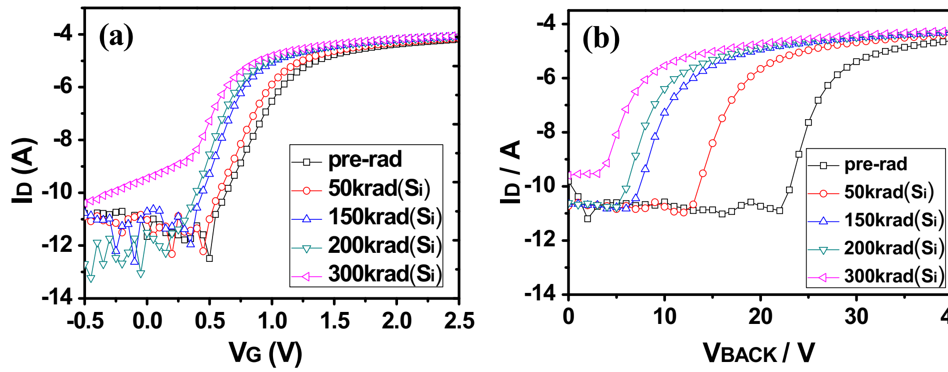

Fig. 2 Measured transfer characteristics of body-grounded device for **a** front-gate and **b** back-gate

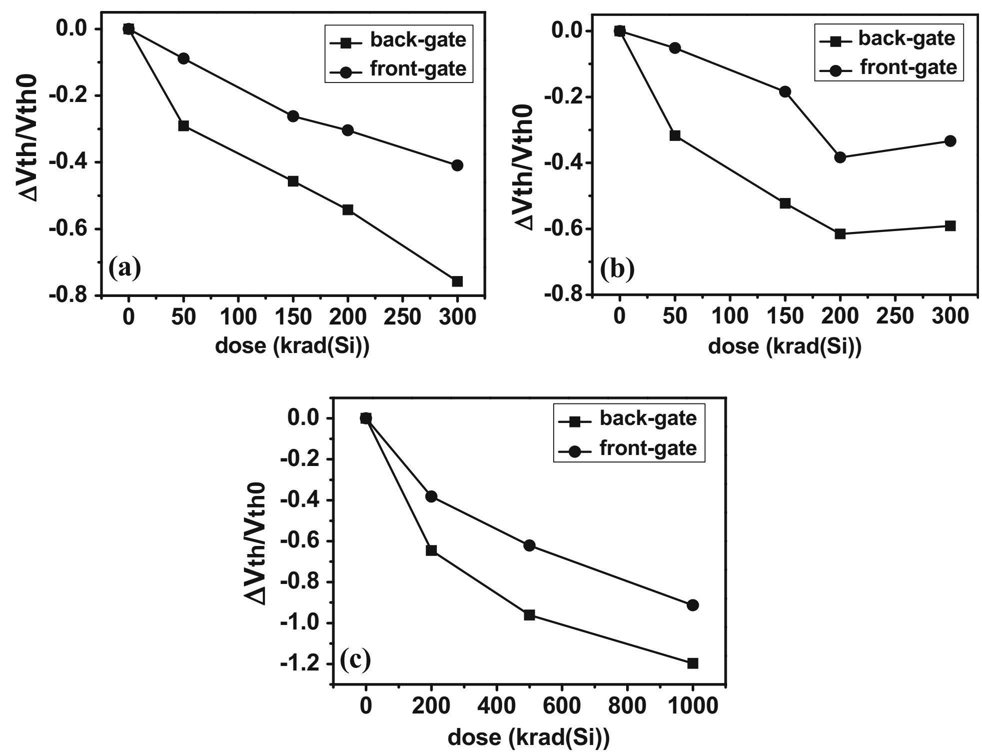

Fig. 3 Normalization ΔV_{th} of front-gate and back-gate as a function of irradiation dose for **a** body-grounded devices, **b** floating-body devices and **c** body-grounded devices in high dose conditions

the total dose is 300 krad(Si), the shift increases to 40.9 %. For the back-gate, the degradation of threshold voltage is much more significant.

When dealing with the floating-body devices, as shown in Fig. 3b, the ΔV_{th} of per unit dose shifts toward the negative direction at the outset. For the front-gate, the negative shift increases from 5.2 to 38.3 % as the dose increases from 50 to 200 krad(Si). However, the threshold voltage then shifts toward positive values as the dose increases further. The negative shift decreases from 38.3 to 33.4 % as the dose increases from 200 to 300 krad(Si).

The above phenomenon of negative drift turning to positive drift is referred to as a "rebound." This rebound phenomenon has been mentioned in some studies, appearing for higher doses (i.e., up to 1 Mrad(Si) [10, 11]). However, in this paper, the phenomenon arises when the dose increases from 200 to 300 krad(Si). Figure 3c shows that the threshold voltage of body-grounded devices shifts in a negative direction as the dose increases, even as it reaches 1 Mrad(Si). For the front-gate, the negative shift increases from 38.2 to 62.2 % as the dose increases from 200 to 500 krad(Si). The negative shift can increase even to 91.3 % when the dose is 1 Mrad(Si).

The threshold voltage of PDSOI MOS devices is similar to that of bulk silicon devices. The threshold voltage of enhancement-mode nMOSFET is given by

$$V_{\mathrm{th0}} = V_{\mathrm{FB0}} + 2\phi_{\mathrm{F}} + \frac{qN_{\mathrm{A}}x_{\mathrm{dmax}}}{C_{\mathrm{ox}}}, \tag{1}$$

where V_{FB0} is the flat band voltage, N_{A} is the doping concentration in silicon film, ϕ_{F} is Fermi potential, $\phi_{\mathrm{F}} = \frac{\mathrm{kT}}{q}\ln\left(\frac{N_{\mathrm{A}}}{n_i}\right)$, $x_{\mathrm{dmax}}\left(= \sqrt{2\varepsilon_{\mathrm{Si}}(2\phi_{\mathrm{F}} + V_{\mathrm{B}})/qN_{\mathrm{A}}}\right)$ is the maximal width of the depletion layer, V_B is the voltage of the body region, which is equivalent to the substrate bias of bulk silicon devices, C_{ox} is the oxide capacitance of front-gate.

Additionally, the threshold voltage for the irradiation condition is given by

$$V_{th} = V_{th0} + \frac{q(N_{ot} + N_{it})}{C_{ox}}, \tag{2}$$

where N_{ot} is the density of the oxide charge and N_{it} is the density of the interface state.

The factor that causes the threshold voltage shift is divided into two parts: the trapped oxide charges and interface states, given by

$$\Delta V_{th} = \Delta V_{it} + \Delta V_{ot}, \tag{3}$$

where $\Delta V_{it}(=qN_{it}/C_{ox})$ is the contribution of the threshold voltage shift due to the interface states, and $\Delta V_{ot}(=qN_{ot}/C_{ox})$ is the contribution of the threshold voltage shift due to the trapped oxide charges.

From the *I–V* characteristic of MOSFET, the drain current is given by

$$I_D = \mu\left(\frac{W}{L}\right)\frac{\alpha C_{ox}}{2\beta^2}\left(\frac{n_i}{N_A}\right)^2\left(1 - e^{-\beta V_{DS}}\right)e^{\beta\phi}(\beta\phi)^{-1/2}, \tag{4}$$

where I_D and V_{DS} are the drain current and voltage, respectively, *W/L* is the gate width/length, n_i is the intrinsic carrier concentration, $\beta = q/\mathrm{kT}$, and ϕ is the surface potential.

The constant α is given by

$$\alpha = \frac{2\varepsilon_{Si} t_{ox}}{\varepsilon_{ox} L_D}, \tag{5}$$

where t_{ox} is the oxide thickness, L_D is the Debye length given by $L_D = [\varepsilon_{Si}/(\beta q N_A)]^{1/2}$, ε_{Si} and ε_{ox} are the dielectric constants of Si and SiO_2, respectively, and μ is the carrier mobility, which is a radiation-sensitive parameter. The relationship between threshold and carrier mobility can be shown as

$$I_D = \mu C_{ox}\frac{W}{L}\left[(V_{GS} - V_{th})V_{DS} - V_{DS}^2/2\right]. \tag{6}$$

If the V_{DS} is very small (i.e., $V_{DS} \ll 2(V_{GS} - V_{th})$), (6) can be simplified into (7)

$$I_D \approx \mu C_{ox}\frac{W}{L}(V_{GS} - V_{th})V_{DS}, \tag{7}$$

The carrier mobility μ can be obtained by Eq. (7) according to the experiment data of I_D and V_{GS}. The midgap current is defined to be the current, which occurs when the surface potential equals ϕ_F [i.e., $\phi = \phi_F(= (\mathrm{kT}/q)\ln(N_A/n_i))$]. Using the carrier mobility μ and Fermi potential ϕ_F for Eq. (4), we can obtain the midgap current. Because the midgap current belongs in the range of 10^{-14}–10^{-13} A, it is essential that the subthreshold of the *I–V* curve is linearly extrapolated in the negative direction.

The midgap voltage shift in subthreshold curves due to trapped oxide charges is given by

$$\Delta V_{ot} = \left(V_{mg}\right)_2 - \left(V_{mg}\right)_1, \tag{8}$$

where the labels 2 and 1 refer, respectively, to subthreshold–current curves at different radiation levels.

The difference between the threshold voltage and midgap voltage is defined as stretchout voltage V_{so}, given by

$$V_{so} = V_{th} - V_{mg}. \tag{9}$$

The threshold voltage shift due to the interface state is as follows

$$\begin{aligned}\Delta V_{it} &= (V_{so})_2 - (V_{so})_1 \\ &= \left|(V_{th})_2 - \left(V_{mg}\right)_2\right| - \left|(V_{th})_1 - \left(V_{mg}\right)_1\right| \\ &= \Delta V_{th} - \Delta V_{ot}.\end{aligned} \tag{10}$$

Using the subthreshold separation technology, the factors ΔV_{ot} and ΔV_{it} for the floating-body and body-grounded devices are shown in Fig. 4a, b, respectively, as a function of the irradiation dose. For the body-grounded devices, the ΔV_{it} shifts toward a negative value in the first instance. When the dose increases from 150 to 200 krad(Si), this change occurs slowly. The "rebound" phenomenon arises when the dose reaches more than 200 krad(Si). Meanwhile, the ΔV_{ot} shifts toward a negative value as a function of the dose, the quantity of which is larger than it is for ΔV_{it}. The above factors cause ΔV_{th} to shift toward a negative value as a function of the dose. For the floating-body device, when the dose increases to over 200 krad(Si), the "rebound" phenomenon arises for both ΔV_{it} and ΔV_{ot}, causing the threshold voltage to shift toward a positive value.

Because of the special structure of SOI devices, the total dose radiation induces a large number of positive charges in the buried oxide layer. For floating-body devices, the potential of buried oxide increases as the charges increase. This attracts electrons to move near the interface, which weakens the channel's formation. However, for body-grounded devices, the incremental potential of buried oxide has little effect on the body because of its constant voltage. Thus, the threshold voltage shifts in a negative direction.

3.2 The effect of the dose rate on threshold voltage

Figure 5 shows front-gate and back-gate *I–V* curves for PDSOI nMOSFETs. There are discrepancies under different dose rates [i.e., the high dose rate is 50 rad(Si)/s, and the low dose rate is 1 rad(Si)/s]. A lager shift of the subthreshold current at the low dose rate is observed than that at the high dose rate. The total dose radiation induces positive charges that are proportional to the thickness of the

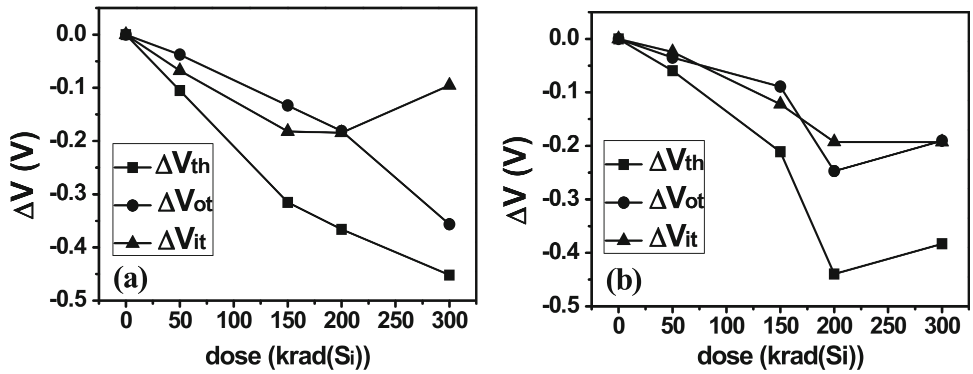

Fig. 4 ΔV_{th}, ΔV_{it} and ΔV_{ot} as a function of irradiation dose of the front-gate for **a** body-grounded and **b** floating-body devices

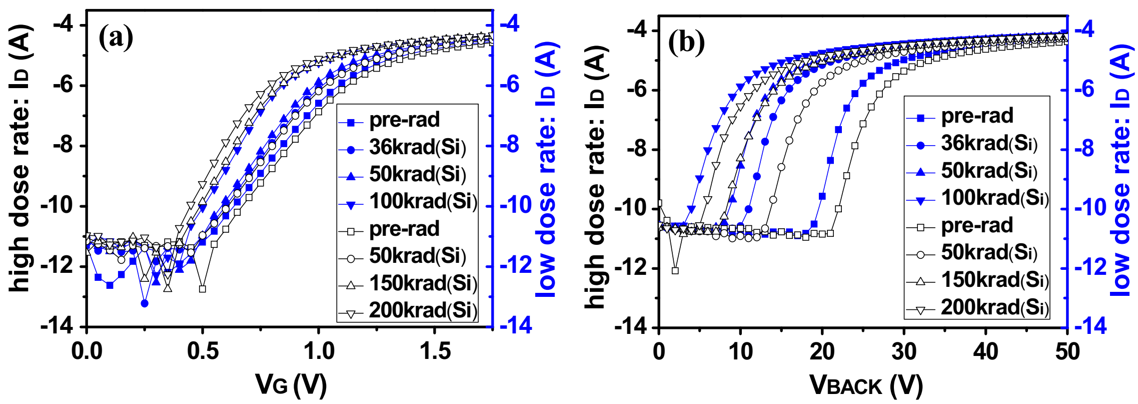

Fig. 5 Measured transfer characteristics as a function of irradiation dose for **a** front-gate and **b** back-gate under different dose rate conditions

oxide. For a measured characteristic of the back-gate, more serious degradation can be found at lower dose rates.

Figure 6 shows the threshold voltage shift for the front-gate and back-gate at different dose rates. At the beginning of irradiation, we observed a similar shift of threshold voltage at different dose rates. When the dose value increases further, the degeneration of threshold voltage worsens under low dose rate conditions. In addition, as the irradiation dose reaches 50 krad(Si), the threshold voltage shift under low dose rate conditions is larger than the shift under high dose rate conditions. For obtaining the same threshold voltage shift, more doses are needed for high dose rate conditions than those for low dose rate conditions. These results indicate enhanced low dose rate sensitivity (ELDRS) of H-gate partially depleted SOI MOSFET devices for ^{60}Co γ-irradiation.

Figure 7 shows the shift of ΔV_{th}, ΔV_{it} and ΔV_{ot} for the front-gate using subthreshold separation technology. It is noted that the trapped oxide charges, as well as the interface states, are responsible for the ELDRS effects in SOI devices. Additionally, the interface states play a significant role in the threshold shift under low dose rate conditions. This threshold voltage shift as a result of the interface states is much larger than that occurring as a result trapped

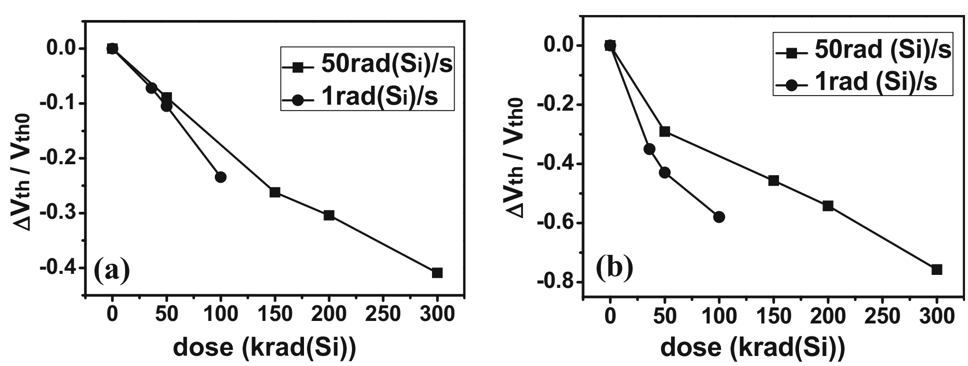

Fig. 6 Normalization ΔV_{th} of **a** front-gate and **b** back-gate under different dose rate conditions

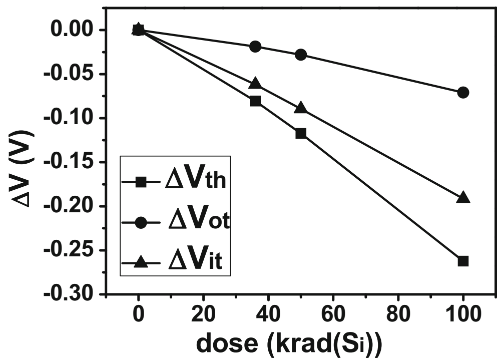

Fig. 7 ΔV_{th}, ΔV_{it} and ΔV_{ot} of the front-gate as a function of irradiation dose under low dose rate conditions

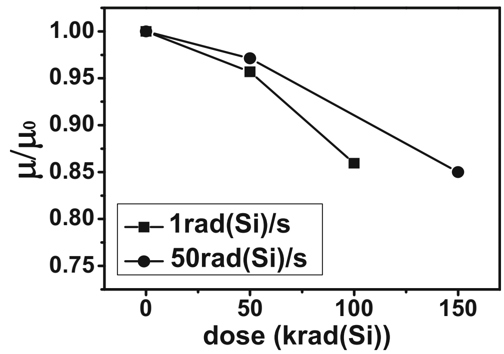

Fig. 8 Normalization μ as a function of irradiation dose under different dose rates

oxide charges [i.e., when the irradiation dose is 100 krad(Si), the ΔV_{ot} is -0.07 V, and the ΔV_{it} is -0.19 V in the lower dose rate experiments].

The interface is a transition region that constitutes oxide–nonoxide and ordered–disordered structures. This includes the bending bond of oxide cavities $\equiv \mathrm{Si}_3 - \mathrm{Si} \equiv$ and the bond of $\equiv \mathrm{Si}_3 - \mathrm{OH}$ or $\equiv \mathrm{Si}_3 - H$, which is formed during the thermal growth process. Both of these are easily broken to form the dangling bond of trivalent silicon (i.e., the interface state) under ionizing radiation. Edward H Poindexter [19] gave the name "dangling bond" to the P_b center. In most cases, the density of weak bonds is higher when the distance to the interface is shorter.

Irradiation-induced excitons react with oxide to form the neutral hydrogen atoms H^0. Consequently, the trapped hole becomes H^+, which shifts toward the interface because of the additional electric field ($V_G \geq 0$). This reaction is given by [20]

$$H^+ + e^- + \equiv \mathrm{Si}_3 \cdot H \rightarrow H_2 + \equiv \mathrm{Si}_3 \cdot . \tag{11}$$

The reaction produces the center of the interface state P_b. The above process is called the H^+ model.

Moreover, the relationship between the generation of electron–hole pairs and dose rate is given by

$$G_r = g_0 D \cdot Y(E), \tag{12}$$

$$Y(E) = \left(\frac{|E| + E_0}{|E| + E_1}\right)^m, \tag{13}$$

where g_0 is the generation rate of electron–hole pairs, D is the dose rate, E is the electric field, and E_0, E_1 and m are constants.

Because hole mobility is greater than the mobility of H^+, trapped oxide holes form electrostatic barriers, which can prevent H^+ from reaching the Si/SiO_2 interface and generating interface states. At the lower dose rate, the buildup process of oxide charges is weakened. Both the holes and H^+ can transport to nearby the Si/SiO_2 interface and participate in the formation of trapped oxide charges and interface states.

By using the experimental data from I_D and V_{GS}, the carrier mobility under varying irradiation doses can be obtained from Eq. (7), as shown in Fig. 8, where obvious mobility degradation can be observed. As the trapped oxide charges and interface states increase, the degradation of mobility should be taken into account by [21]

$$\mu_{eff} = \frac{\mu_0}{1 + \alpha_{ox} q N_{ox} C_{ox}^{-1} + \alpha_{it} q N_{it} C_{ox}^{-1}}, \tag{14}$$

where α_{ox} and α_{it} are fitting parameters.

According to Eqs. (11)–(13), when the density of the interface state increases along with dose, this enhances the scattering effect of the interface state on carriers in the channel, leading to a decrease in the carriers' mobility, as shown in (14).

Figure 8 also shows that the degradation of carrier mobility worsens at a low dose rate, which is similar to the conclusion of [22]. Thus, this work's mobility data further verify that the interface state is the one of the primary factors to cause differences in characteristic degradation under total dose radiation at different dose rates and also plays an important role in the effect of ELDRS on SOI devices.

4 Conclusion

This paper investigated the impact of total dose effects on the threshold voltage of H-gate SOI NMOS devices. The results show that the threshold voltage shifts in a negative direction as a function of the irradiation dose. However, regarding floating-body devices, when the irradiation dose is not very high, the "rebound" phenomenon occurs, indicating that the threshold voltage shifts from a negative to a positive direction. The positive charges in the buried oxide layer induced by irradiation raise its potential. Electrons are attracted to the Si/SiO_2 interface. This weakens the formation of the channel, which causes the threshold to shift to a positive direction. The degradation of the threshold voltage at different dose rates shows the enhanced low dose rate sensitivity of partially depleted SOI MOSFET devices for ^{60}Co γ-irradiation. This work also determined that the interface state is one of the primary factors to cause a difference in characteristic degradation at different dose rates, which plays an important role in the effect of ELDRS on SOI devices.

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