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Total ionizing dose effect of gamma rays on H-gate PDSOI MOS devices at different dose rates

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Abstract The total dose effect of ^{60}Co γ-rays on 0.8-μm H-gate partially depleted-silicon-on-insulator NMOS devices was investigated at different irradiation doses. The results show that the shift in saturation current at high dose rate is greater than that at low dose rate, due to increase in interface-state density with decreasing dose rate; the scattering effect of interface state on electrons in the channel causes degradation in carrier mobility; and the body current and transconductance of the back gate enhance low-dose-rate sensitivity when the irradiation is under OFF-bias. A double transconductance peak is observed at 3 kGy(Si) under high dose rates.

Keywords PDSOI device · Total dose irradiation · Interface states · Mobility

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1 Introduction

Silicon-on-insulator (SOI) technology has been regarded as a good candidate for radiation-hardening applications in military and space. SOI is advantageous over traditional bulk silicon CMOS primarily because of its insusceptibility from the latch-up effect of four layers with p-n-p-n structure as a result of the complete dielectric isolation of individual transistors [1, 2]. However, ionizing radiation generally degrades electrical performance of MOS devices by creating interface traps and oxide-trapped charge in gate dielectric. Introducing buried oxide layers increases the susceptibility of SOI devices, while bulk transistors suffer total-ionizing-dose (TID) radiation damage in deep submicron processes [3–5]. The precise underlying mechanism of this effect, particularly the role of impact ionization, remains controversial.

Studies on the TID effect on circuits of SOI device [6–10] have mainly focused on the degradation of electrical performance and physical mechanisms by irradiation. However, differences in manufacturing process, layout design, irradiation bias condition, and testing voltage can cause different degeneration activities. Consequently, experiments and mechanism analysis for this special phenomenon should be conducted.

The space environment is generally of low radiation dose rates, whereas ground tests encounter a considerably larger range of dose rates. Such a difference may have diverse impacts on radiation degradation of the devices, hence the need to study differences in damage mechanisms of the devices in the space and on the ground. The dose rate effects on electrical characteristics of bulk silicon MOS devices [11, 12] or bipolar transistors [13–16] are usually considered. However, very few studies on the dose rate effect of SOI MOS devices, especially the with H-gate structure, have been conducted.

This study is focused on the radiation effects on 0.8-μm H-gate partially depleted-silicon-on-insulator (PDSOI) NMOS devices exposed to ^{60}Co γ-rays at different dose rates. The shift in output characteristic curves, the irradiation bias-state effect on decays of the body current at different dose rates, and the dose rate effect of back-gate transconductance were analyzed. The carrier mobility degenerated because of the reduction in the interface state density and the scattering effect of the interface state on the channel electrons. The shift in the saturation current at high dose rate was greater than that at low dose rate, when the total dose was not high. In addition, the body current and the transconductance of the back gate had the enhanced-low-dose-rate- sensitivity (ELDRS) under OFF-bias irradiation condition.

2 Experimental and device structures

PDSOI nMOSFETs fabricated using light doped drain–source technology, with an H-gate bilateral body-contacted structure, were used in this study. Ceramic package was applied to all test samples. Their layout structure is shown in Fig. 1. The thicknesses are: the top silicon film, t_{Si} = 160 nm; the gate oxide, t_{ox} = 17.5 nm; and buried oxide, t_{box} = 375 nm. The gate width/length ratio(W/L) was 8 μm/0.8 μm, and the working voltage was 5 V.

The sample irradiations were performed on the ^{60}Co γ-ray source at Northwest Institute of Nuclear Technology, at does rates 36 and 1800 Gy(Si)/h. Accordingly, the radiation doses for the low dose rate conditions are 0.36, 0.5, and 1 kGy(Si), whereas 0.5, 1, 1.5, 2, and 3 kGy(Si) are considered high dose rates. The irradiation bias states of test devices are given in Table 1, where V_G, V_S, V_D, V_B, and V_{Sub} are the voltage of the gate, source, drain, body, and substrate, respectively. The break time between two irradiations was limited within half an hour to avoid the anneal effect. During these break times, the electric characteristic parameters and the I–V curves before and after irradiation were collected using a computer-controlled HP4156 precision semiconductor parameter analyzer at room temperature.

Table 1 Bias states (in volt) of test samples in the TID experiment

Bias state of sample	V_G	V_S	V_D	V_B	V_{Sub}
ON-bias	5	0	0	0	0
OFF-bias	0	0	5	0	0

3 Results and discussion

3.1 Dose rate effect on front-gate characteristic

Figure 2 shows the front-gate I_D-V_D curves of 0.8-μm PDSOI NMOS devices before and after irradiation at dose rates of 36 and 1800 Gy/h, under the gate voltage of V_G = 1, 3, and 5 V, the total dose of 0.5 and 1 kGy(Si), and the irradiation state of OFF-bias. The drain current at 1 kGy(Si) was greater than that at 0.5 kGy(Si). At V_G = 1 V, the drain current increased significantly with the drain voltage V_D, reaching 0.573 mA at 1 kGy(Si), i.e., the TID effects. Given that the threshold voltage shifts in a negative direction, the conducting channel is formed and the devices are more easily switched at V_G = 1 V and TID = 1 kGy(Si).

From the results of 36 Gy(Si)/h (low dose rate, Fig. 2a–c) and 1.8 kGy(Si)/h (high dose rate, Fig. 2d–f), the drain shift at high dose rate is considerably worse than that at low dose rate. The saturation currents are especially sensitive to the dose rate effect at 1 kGy(Si) and V_G = 5 V.

When $V_{DS} \geq V_{DSsat}$ and $V_{GS} \geq V_{th}$, the saturation current is determined as follows:

$$I_{Dsat} = \frac{WC_{ox}\mu}{L}\left[\left(V_{GS} - V_{th} - \frac{V_{Dsat}}{2}\right)V_{Dsat}\right] = \frac{WC_{ox}\mu}{L}(V_{GS} - V_{th}), \quad (1)$$

$$V_{DSsat} = (V_{GS} - V_{th}), \quad (2)$$

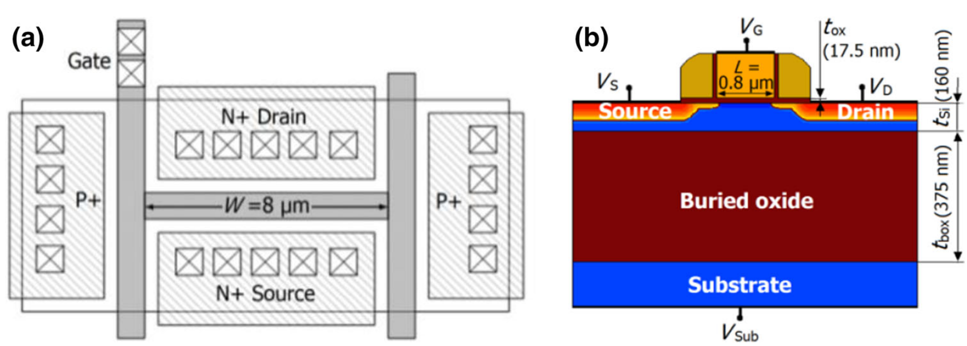

Fig. 1 (Color online) The layout structure (**a**) and cross-sectional view (**b**) of the H-gate partially depleted-silicon-on-insulator (PDSOI) devices

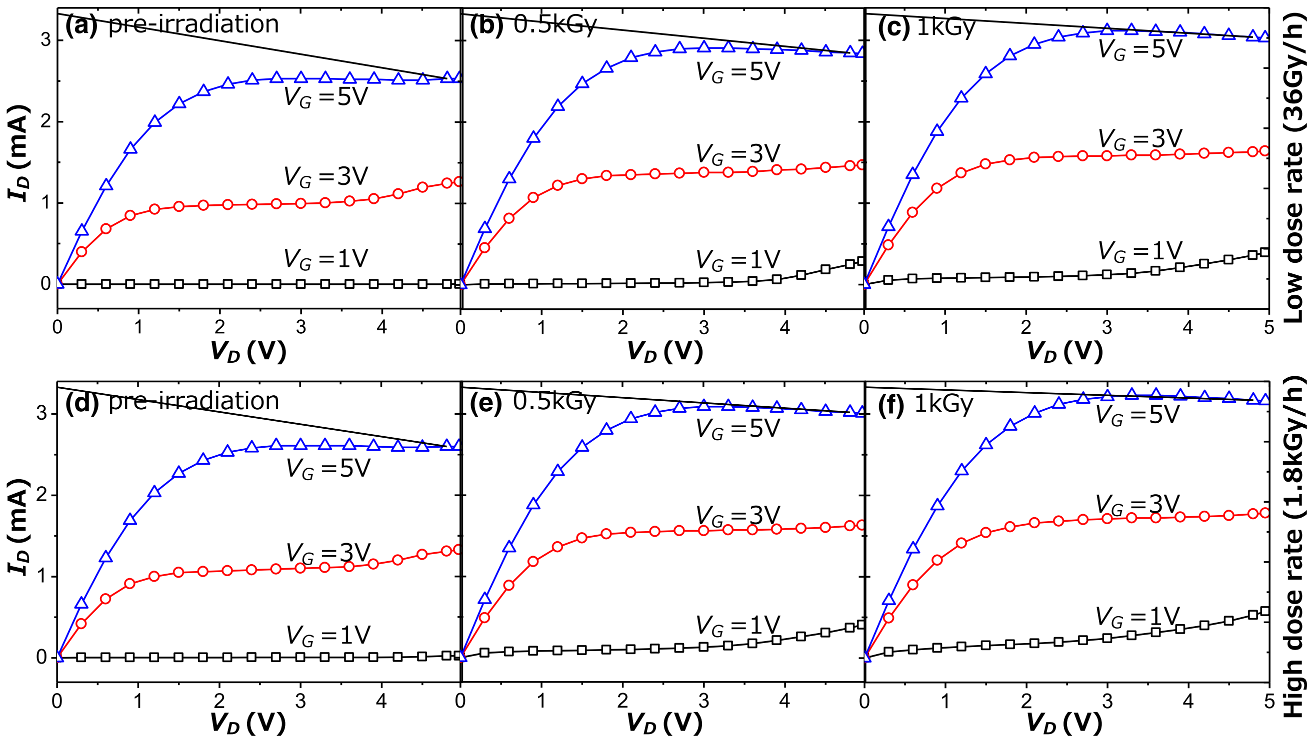

Fig. 2 (Color online) $I_D - V_D$ curves of front gate as a function of radiation dose at different dose rates

where I_{Dsat} and V_{Dsat} are the saturation current and voltage, respectively, V_{GS} is the gate-to-source voltage, V_{th} is the threshold voltage, C_{ox} is the capacitance of the gate oxide, and μ is the carrier mobility.

The dose rate effects at low dose rate result in more serious degeneration of threshold voltage than that at high dose rate [17, 18], i.e., $V_{th(low\text{-}dose\text{-}rate)} < V_{th(high\text{-}dose\text{-}rate)}$. Substituting this into Eq. (2), we have $V_{DSsat(low\text{-}dose\text{-}rate)} > V_{DSsat(high\text{-}dose\text{-}rate)}$.

Considering the above factors for Eq. (1), the shift in V_{DSsat} at low dose rate should be greater than that at high dose rate. However, Fig. 2 shows that the shift in V_{DSsat} at low dose rate is smaller than that at high dose rate. This inconsistency between the calculated and measured data may be caused by excluding the dose rate effect on carrier mobility.

The drain current, gate-to-source voltage, and drain-to-source voltage can be related by

$$I_D = \mu C_{ox} \frac{W}{L} (V_{GS} - V_{th}) V_{DS} - V_{DS}^2/2. \quad (3)$$

In this section, we mainly study the TID effect on saturation characteristics of SOI MOS devices. Thus, carrier mobility can be determined from Eq. (3) using the I_D and V_{GS} data at measured at $V_D = 5$ V as shown in Fig. 3, where the mobility degradation at 36 Gy/h is more serious than that at 1.8 kGy/h.

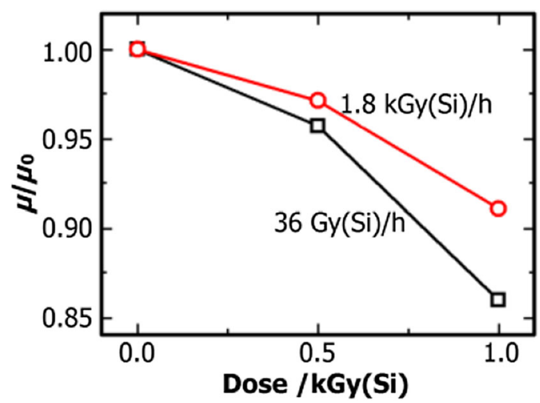

Fig. 3 (Color online) Normalization mobility as a function of irradiation dose under different dose rates

The radiation–degradation of mobility should be taken into account by [19]

$$\mu_{eff} = \frac{\mu_0}{1 + \alpha_{ot} q N_{ot} C_{ox}^{-1} + \alpha_{it} q N_{it} C_{ox}^{-1}}, \quad (4)$$

where μ_0 is the mobility before irradiation, N_{ot} is the density of trapped oxide charges, N_{it} is the density of interface state, and α_{ot} and α_{it} are the fitting parameters. Equation (4) shows that the factor causing the shift in carrier mobility is classified into two parts, namely trapped oxide charge and interface state. The space-charge model [20] is a widely accepted model to explain the differences in degeneration of electrical characteristics of devices at different dose rates. The local electrical field formed by trapped hole at high dose rate prevents protons from transporting toward the interface, which enhances the density of interface state at low dose rate than at high dose rate. Thus, only minor differences are found in N_{ot} for the same irradiation dose at different dose rates and the interface state is the main reason for dose rate effect of mobility.

Other bimolecular mechanisms affecting the buildup of interface state include the recombination of free electrons and holes; recombination of free electrons and hole trapping defects; and hydrogen dimerization reaction to form hydrogen molecule. The low-dose-rate irradiation is effective, because bimolecular recombination has little effect. Consequently, effective trapped oxide charges and interface states are increasingly induced. However, the less effective irradiation at high dose rate causes interface traps, because the hole and electron densities increase with the dose rate. Thus, an electron is more likely to recombine with a trapped hole before that hole simulates the release of a proton.

The combination of space-charge model and bimolecular recombination model leads to different densities of interface state at different dose rates. The relationship between dose rate and interface state can be described by a constant at low dose rates, a linear function in the transition region, and another constant at high dose rates [21–23]. The first crossover dose rate is 0.36 Gy(Si)/h and the second, 3.6 kGy(Si)/h. In comparison, the dose rates in this work, 36 Gy(Si)/h and 1.8 kGy(Si)/h, belong to the linear region, and the interface state is linearly related to dose rate. In this case, the density of interface state at 36 Gy(Si)/h is greater than that at 1.8 kGy(Si)/h. Therefore, the increase in interface-state density can enhance the scattering effect of the interface state on carriers in the channel, decreasing the carrier mobility at 1.8 kGy(Si)/h. Consequently, the shift in the saturation drain current at 36 Gy(Si)/h is slightly worse than that at 1.8 kGy(Si)/h (Fig. 2).

3.2 Dose rate effect of body current under different irradiation bias states

Figure 4 shows the body current dependence of gate voltage under test conditions at drain bias of 5 V. The curves of empty and solid dots are the I_B-V_G characteristic at 36 Gy(Si)/h and 1 kGy(Si)/h, respectively. Both the pre- and after-irradiation I_B-V_G curves have the upside down hump-shaped variations of the body current with increasing gate voltage.

In the I_B-V_G curves after radiation under ON-bias (Fig. 4a), the conductive channel is formed when the gate voltage is greater than the threshold voltage. Electrons can drift from source to drain regions, and then, large numbers of ehps (electron–hole pairs) are created by the electron impact ionization under high electrical field of the depletion region. Most of the electrons generated are swept to the drain side and contribute to the drain current. Meanwhile, holes are collected to the body area because of their heavy equivalent mass. However, the threshold voltage gradually decreases with increasing TIDs. So, the gate voltage of the first detected body current shifts in the negative direction. The holes trapped in the buried oxide can also significantly weaken the lateral electric field [24], which influences the body current strongly, hence the decrease of the maximum body current with increasing doses. However, the shift value is not affected by the dose rate.

Figure 4b shows the test results of I_B–V_{GS} curves after radiation at OFF-bias. The strong electric fields are mainly located at the space-charge region of the drain–body junction, the bottom of body region and source region, and back-interface of buried oxide [25, 26], all of which can promote the trap to capture numerous holes. By contrast, ON-bias just applies the work voltage on the gate, which remarkably reduces the density of trapped hole near the Si/SiO_2 interface on the side of buried oxide than that in OFF-bias. Consequently, OFF-bias facilitates the conduction of the back channel. Body current is collected when the device is OFF state and increases with the density of trapped hole and the TID.

The inset of Fig. 4b illustrates a convex–concave peak of body current at 36 Gy(Si)/h and TID = 1 kGy(Si), while it does not appear at 1.8 kGy(Si)/h and TID = 1 kGy(Si). The body current at 36 Gy(Si)/h is greater than that at 1.8 kGy(Si)/h when the gate voltages are negative. This indicates that more holes transport in the body region at 36 Gy(Si)/h. When the gate voltage is negative, the maximum body currents are −5.17 and −4.12 μA at 1 kGy (Si)–36 Gy(Si)/h and 3 kGy(Si)–1.8 kGy(Si)/h, respectively. However, these are not observed under ON-bias conditions because of asymmetrical distribution of the electric potential under OFF-bias conditions, at drain voltage of 5 V with the source and gate being grounded, rather than symmetrical distribution of the electric potential under ON-bias and the same conditions of the gate, drain, and source. Thus, ehps induced by total dose irradiation are separated quickly by an applied electric field, which is mainly the gate voltage. Then, main effect of a positive gate bias is to remove the electrons, thereby decreasing the fraction that recombines with the trapped holes and resulting in no-dose-rate sensitivity. Therefore, we can see clearly that OFF-bias can lead to ELDRS of the body current for H-gate PDSOI MOSFET devices.

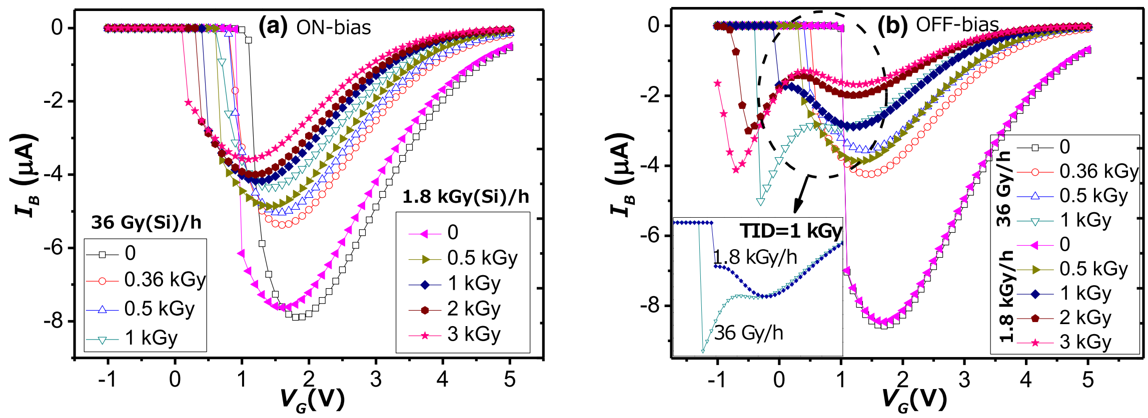

Fig. 4 (Color online) I_B-V_G curves before and after irradiation for ON-bias (**a**) and OFF-bias (**b**)

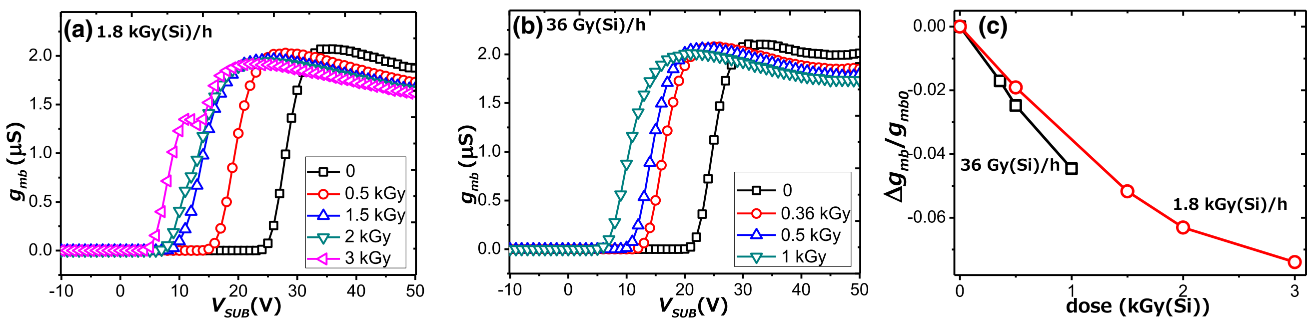

Fig. 5 (Color online) Transconductance of back gate at different TIDs at high (**a**) and low (**b**) dose rates, and the normalized maximum transconductance (**c**)

3.3 Dose rate effect in buried oxide for PDSOI devices

Figure 5 shows the transconductance of back gate at different dose rates and TIDs. The back-gate voltage of the peak transconductance shifts in a negative direction with TIDs, for both the dose rates. This is because those changes in the position of maximum transconductance are mainly influenced by the shift in the threshold voltage. The threshold voltages at TID $<$ 1 kGy(Si) do not differ obviously.

In Fig. 5a, the double peak of back-gate transconductance is seen at 3 kGy(Si). This characteristic is not evident in both the pre-irradiation and doses of $\leq$2 kGy(Si). The interface state at the SiO_2/Si interface between the buried oxide and silicon layer may cause the double-peak phenomenon. The interface state can introduce local permitted state in the band gap of Si, which will further form continuous or discrete electronic energy levels. These energy levels increase with the dose, enhancing the capture of the channel electron by the donor interface state of the back gate.

Figure 5c shows the normalized maximum transconductance of the back gate at low and high dose rates as a function of irradiation dose, which are extracted from Fig. 5b. The decay of maximum transconductance at 36 Gy(Si)/h is much worse than at 1.8 kGy(Si)/h, and the decay trend for 1.8 kGy(Si)/h is gradually retarded as the dose increases. MOSFET is a device with a surface channel. On the one hand, the channel electron is scattered by the interface state, resulting in decreasing mobility. On the other hand, the channel electron can fill the interface trap, leading to decreased trap density. These can cause the reduction in transconductance with increasing dose. Meanwhile, the interface-state density at 36 Gy(Si)/h is larger than that at 1.8 kGy(Si)/h. Thus, the ELDRS effect appears in the decay of back-gate transconductance.

4 Conclusion

The impact of total irradiation dose on 0.8-μm H-gate PDSOI NMOS devices exposed to ^{60}Co γ-rays at different dose rates is investigated. The shift in the output characteristics curves, the effect of radiation bias state on the body current decay, and the dose rate effect of back-gate transconductance are analyzed. The results indicate that the shift in the saturation current at high dose rate is greater than that at low dose rate, when the irradiation dose is not high. This is primarily due to the scattering effect of interface state on channel electrons, which leads to carrier mobility degradation. Meanwhile, the recombination of free electrons and trapped holes is enhanced gradually at high dose rate, hence the reduction in density of the interface state.

The ELDRS effect appears in the decay tendency of the body current under the OFF-bias conditions, but not the ON-bias. This is due to that the applied voltage for ON-bias propels the ehps to separate more quickly and weaken the bimolecular recombination mechanisms. In addition, the differences in the distribution of the strong electric field facilitate the easier inversion of the back channel under OFF-bias conditions, which cause the body current to be collected, as the device is still in OFF state. The convex–concave peak of body current is observed under low dose rate conditions at 1 kGy(Si).

The donor interface state of the buried oxide induced by irradiation can capture the channel electrons, inducing the double transconductance peak of back gate at 3 kGy(Si) under high dose rate. These indicate that the decay of back-gate transconductance has ELDRS effect. Thus, the interface state is the main factor that causes the difference in the characteristics degradation under total dose radiation at different dose rates.

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