Dose-rate effects of p-channel metal oxide semiconductor field-effect transistors at various biasing conditions

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Abstract: The total-dose response and annealing effect of p-channel metal oxide semiconductor field-effect transistors (PMOSFETs) were investigated at various dose rates and biasing conditions. The results show that the shift of threshold voltage is more obvious when the dose rate is decreased. Under the various dose rates and biasing conditions, some have exhibited a time-dependent effect and others showed enhanced low-dose-rate sensitivity (ELDRS). Finally, using the subthreshold-separating method, the threshold-voltage shift is separated into shifts due to interface states and oxide-trapped charges, and the underlying mechanisms of the observed effects are discussed. It has been indicated that the ELDRS effect results from the different quantities of the interface states generated at high and low dose rates.

Key words: PMOSFETs; bias; ELDRS; TDE; interface states; oxide-trapped charge
DOI: 10.1088/1674-4926/31/5/054004 **EEACC:** 2520

1. Introduction

Since enhanced low-dose-rate sensitivity (ELDRS) was found in the 1990s, numerous pieces of research[1−4] have been carried out. It has been shown that the ELDRS is a kind of dose-rate effect which only occurs in bipolar devices. Metal oxide semiconductor field-effect transistors (MOSFETs) are considered to show a time-dependent effect (TDE), i.e. the low-dose-rate damage could be estimated by high-dose-rate irradiation followed by room-temperature annealing; the annealing time is same as that needed at low dose rate. However, recent studies[5−7] have indicated that specific p-channel metal oxide semiconductor field-effect transistors (PMOSFETs) exhibit the ELDRS effect in the space radiation environment. These specific PMOSFETs usually work as sensors of PMOS dosimeters to monitor space radiation. The dose rates in space are low, with a range of about 10^{-6}–10^{-4} Gy(Si)/s[8], whereas the dose rates used for calibration in the laboratory are much greater, and the radiation damage for PMOSFETs between high and low dose rates is different, which seriously decreases the accuracy of the calibration and influences its space application. So, further research on the dose-rate effects in PMOSFETs is necessary.

It has been found that the PMOSFETs exhibit ELDRS as mentioned above, but is this universal phenomenon? How do the biasing conditions affect the high- and low-dose-rate damage? What are the underlying mechanisms for ELDRS in PMOSFETs? In order to solve these questions, we chose foreign commercial devices and performed irradiation and annealing experiments at various dose rates and biasing conditions. Finally, radiation induced defects such as positive oxide-trapped charges and interface-trapped charges were separated by the subthreshold-separating technique. Based on these, we discussed the mechanisms in detail.

2. Experimental samples and methods

The samples are commercial HCF4007UB manufactured by SGS-THOMSON Microelectronics Corporation, containing two pairs of p- and n-channel metal oxide semiconductor field-effect transistors and one CMOS inverter. The experiment was conducted under both strong and weak ^{60}Co-γ rays at Xinjiang Technical Institute of Physics and Chemistry. The dose rates used in the experiments were approximately 5×10^{-4}, 0.051, 0.514 Gy(Si)/s, which were calibrated with CaF_2 thermal luminescent dosimeters.

During the irradiation and annealing experiments, the devices were connected to form a CMOS inverter. $V_I = V_{DD} =$ 10 V, $V_{SS} = 0$ V, for PMOSFETs, $V_{GS} = 0$ V, and $V_{DD} = 10$ V, $V_I = V_{SS} = 0$ V, for PMOSFETs, $V_{GS} = -10$ V. Those were the two sets of biasing conditions. Three chips were chosen to ensure the precision of the results under the same conditions during the experiments. The testing was finished within 20 min after each irradiation and annealing process. The curve of the subthreshold I–V characteristics was measured, and the shift of threshold voltage was separated into shifts due to interface states and oxide-trapped charges, using the midgap-voltage method[9]. The annealing experiment was carried out after irradiation at high dose rates (0.051 and 0.514 Gy(Si)/s), and the annealing time was the same as that irradiated at the low dose rate (4×10^{-4} Gy(Si)/s).

3. Results and discussion

The shift of threshold voltage versus total dose and annealing time is shown in Fig. 1. From these curves, it can be found

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Received 25 November 2009

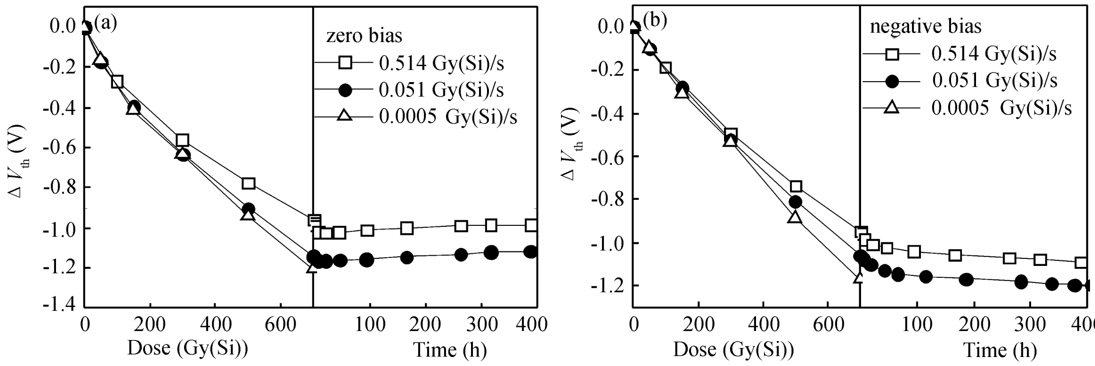

Fig. 1. Under various biases, $\Delta V_{\rm th}$ versus total dose and annealing time at room temperature. (a) Zero bias. (b) Negative bias.

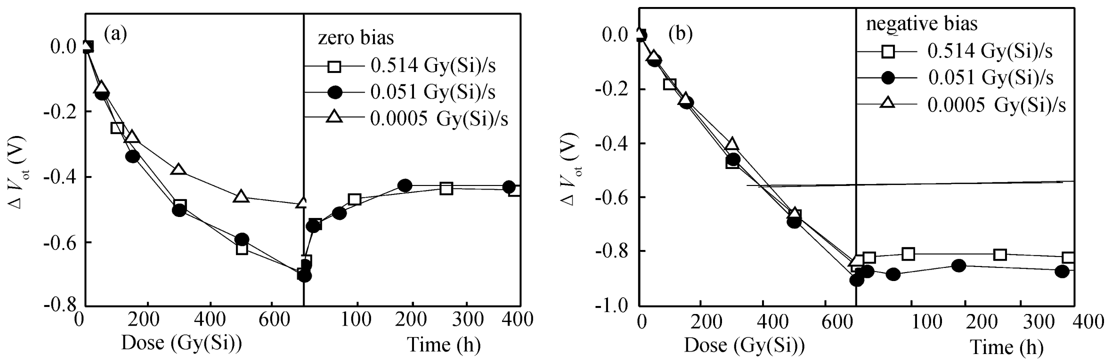

Fig. 2. Under various biases, $\Delta V_{\rm ot}$ versus total dose and annealing time at room temperature. (a) Zero bias. (b) Negative bias.

that the changes of the threshold voltage become larger with the accumulation of total dose. With the same total dose, the lower the dose rate is, the greater the threshold voltage shift is, which shows more damage at low-dose-rate irradiation. Under zero bias (Fig. 1(a)), the threshold voltage continues to shift during the initial 25 h during annealing. However, it does not reach the level of that at the low dose rate, and begins to rebound with increasing annealing time. This indicates that the radiation damage at low dose rate can not be estimated after high-dose-rate irradiation followed by room-temperature annealing, which means ELDRS. On the other hand, under negative bias (Fig. 1(b)), the threshold voltage continuously shifts during the whole annealing process. After irradiation at 0.051 Gy(Si)/s followed room-temperature annealing, the threshold-voltage shift has reached the extent of that at the low dose rate, while it does not at 0.514 Gy(Si)/s irradiation. This demonstrates that PMOSFETs exhibit ELDRS at 0.514 Gy(Si)/s, while they show TDE at dose rates below 0.051 Gy(Si)/s.

Recent research[5−7] has found that the threshold-voltage shift in MOSFETs is due to interface states ($\Delta N_{\rm it}$) and oxide-trapped charges ($\Delta N_{\rm ot}$), which are induced by ionizing radiation, i.e. $\Delta V_{\rm th} = \Delta V_{\rm ot} + \Delta V_{\rm it}$. The contribution of oxide-trapped charges to threshold-voltage shift could be derived by the changes of midgap voltage. Thus, the contribution of interface states can be given by $\Delta V_{\rm it} = \Delta V_{\rm th} - \Delta V_{\rm ot}$. The $\Delta V_{\rm ot}$ versus total dose and annealing time is illustrated in Fig. 2. The mathematical relationship between $\Delta V_{\rm ot}$ and $\Delta N_{\rm ot}$ is $\Delta N_{\rm ot} = \Delta V_{\rm ot} C_{\rm ox}/q$. So, $\Delta V_{\rm ot}$ can directly represent the quantity of oxide-trapped charges. Under zero bias (Fig. 2(a)), there would be more oxide-trapped charges induced by high dose rate than low dose rate. However, during long-term annealing at room temperature, oxide-trapped charges reduce. After the annealing, the oxide-trapped charges almost decrease to the level of low-dose-rate irradiation, while under negative bias (Fig. 2(b)), the quantity of oxide-trapped charges is almost the same at high and low dose rates. Moreover, they remain constant during room-temperature annealing. causing the same number of oxide-trapped charges as that irradiated at low dose rate after annealing at room temperature.

Figure 3 shows the $\Delta V_{\rm it}$ versus total dose and annealing time. It can be seen from Fig. 3 that under both biases, interface states created by high-dose-rate irradiation are both less than that induced by low-dose-rate irradiation. Also, they do not decrease but continue to increase during the annealing process. Finally, they become constant. There would be fewer interface states at 0.051 Gy(Si)/s, after annealing under zero bias (Fig. 3(a)), and it is nearly the same under negative bias (Fig. 3(b)), while at 0.514 Gy(Si)/s, the number of interface states is much less than that at low dose rate under any bias. These results are due to the different numbers of generated interface states at various dose rates during the annealing.

According to the results above, the dose-rate effects on threshold-voltage shift are caused by the buildup and annealing of oxide-trapped charges together with interface states. Under any bias (Fig. 2), when the total time of irradiation and annealing is the same as that irradiated at low dose rate, the $\Delta V_{\rm ot}$ is the same at both high and low dose rates. This indicates that the buildup of oxide-trapped charges is a time-dependent effect at any dose rate and bias. However, it is different for interface states. After long-term annealing under zero bias (Fig. 3(a)),

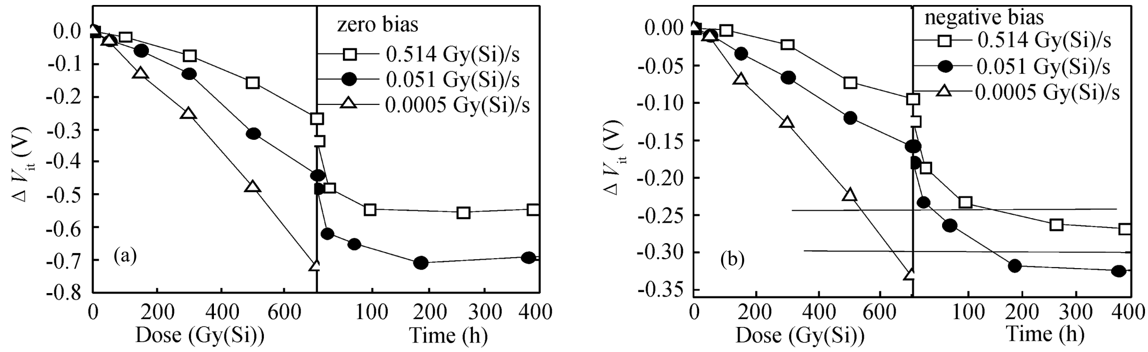

Fig. 3. Under various biases, $\Delta V_{\rm it}$ versus total dose and annealing time at room temperature. (a) Zero bias. (b) Negative bias.

the $\Delta V_{\rm it}$ induced by high dose rate is less than that by low dose rate. Thus, this is the reason that the threshold-voltage shift would be less than that at low dose rate, showing true ELDRS. Under negative bias (Fig. 3(b)), the $\Delta V_{\rm it}$ at 0.051 Gy(Si)/s is the same as that at low dose rate. Therefore, the threshold-voltage shift induced by oxide-trapped charges and interface states is the same at both high and low dose rates, showing TDE. However, the $\Delta V_{\rm it}$ at 0.514 Gy(Si)/s is less than that at low dose rate, also showing true ELDRS.

As is known, numerous electron–hole (e–h) pairs would be generated in the SiO_2, most of which can survive from recombination and transport in response to the electric field building in and out of the SiO_2. At room temperature, the intrinsic mobility of holes is about million times[10] lower than that of electrons. Thus, the holes are left behind after the electrons are driven out of the oxide, which could create trapped holes. This would cause a net positive oxide-trapped charge $\Delta N_{\rm ot}$ in the oxide layer. As for the interface traps, their buildup is primarily controlled by a process associated with hydrogen ions and holes[7, 11–13]. Firstly, the electrons and holes interact with hydride in the form of $O_3 \equiv$ Si–H and $Si_3 \equiv$ Si–OH in the oxide layer, creating neutral hydrogen atoms. The reaction is shown below:

$$O_3 \equiv Si - H \xrightarrow{\text{irradiation}} O_3 \equiv Si\cdot + H^o, \quad (1)$$

$$Si_3 \equiv Si - H \xrightarrow{\text{irradiation}} Si_3 \equiv Si\cdot + H^o. \quad (2)$$

Then, the released neutral hydrogen atoms could trap the holes, forming hydrogen ions via the reaction:

$$H^o + h^+ \rightarrow H^+. \quad (3)$$

The generated hydrogen ions in the former reaction would move into the Si/SiO_2 interface under the function of the electric field. They could react with the passivated $P_{\rm b}$ defects and electrons tunneling into SiO_2 from the substrate to form the interface states, i.e. $\Delta N_{\rm it}$.

$$H^+ + e^-_{Si} + Si_3 \equiv Si - H \rightarrow Si_3 \equiv Si\cdot + H_2. \quad (4)$$

During room-temperature annealing, electrons from the silicon conduction band tunnel into the oxide, and recombine with the positive oxide-trapped charges, causing the annealing of oxide-trapped charges, while the interface states are only annealed at temperatures above 100 °C[14]. Thus, with the same total dose, due to the long irradiation time at low dose rate, the unstable part of oxide-trapped charges would anneal during irradiation. The time needed at high dose rate is very short. Therefore, the annealing of oxide-trapped charges can be neglected. Consequently, it causes more $\Delta V_{\rm ot}$ at high dose rate under zero bias. During the annealing after high-dose-rate irradiation, the oxide-trapped charges are faded by the tunneling, making $\Delta V_{\rm ot}$ the same as that at low dose rate. This would directly induce the TDE of the $\Delta V_{\rm ot}$ as shown in Fig. 2(a). The "hole trap thin sheet" model[15] has pointed out that the cross-sectional area of a trapped hole is very small under negative bias, and the capture-rate of holes reduces with the generation of oxide-trapped charges. As a result of this, the oxide-trapped charges are same at high and low dose rates. At the same time, the potential barrier would be greater under negative bias, which prevents the electrons from tunneling into the oxide. Therefore, the oxide-trapped charges do not fade during the annealing after irradiation at high dose rates as shown in Fig. 2(b). At room temperature, the intrinsic mobility of holes is higher (4–6 orders of magnitude[16]) than that of hydrogen ions. So, the mobile holes reach the interface long before the hydrogen ions, creating oxide-trapped charges. For high-dose-rate irradiation, the oxide-trapped charges form an electrostatic barrier near the interface and prevent other mobile particles (holes and hydrogen ions) from reaching the interface. So there are only a few hydrogen ions which can reach the interface and react with Si–H to form interface states. However, for irradiation at low dose rates, the trapped rate of the holes is very slow, and the formed electrostatic barrier would be weaker. Therefore, there would be enough time for hydrogen ions to reach the interface, where they react with defects to form more interface states. This can result in higher $\Delta V_{\rm it}$ at low dose rates as shown in Fig. 3. A great amount of oxide-trapped charges fade during room-temperature annealing after irradiation at high dose rates, which weakens the electrostatic barrier. Numbers of hydrogen ions can reach the interface, and form interface states. But, the subsequent interface states could not be the same as that generated at a low dose rate. Therefore, the $\Delta V_{\rm it}$ of the high dose rate is less than that of the low dose rate, even after long-term annealing.

4. Conclusions

The experimental results have shown that there are two types of dose-rate effects in PMOSFETs irradiated under zero and negative biases. The dose-rate effect of $\Delta V_{\rm ot}$ due to oxide-trapped charges is TDE, while $\Delta V_{\rm it}$ due to the interface states is ELDRS. Both of these contributions cause true ELDRS under zero bias, while under negative bias, it is ELDRS at 0.514 Gy(Si)/s and TDE at dose rates below 0.051 Gy(Si)/s. Consequently, the existence of ELDRS in PMOSFETs is an uncertain phenomenon under various conditions. As the sensor of the PMOS dosimeter, the issue of dose-rate effects must be taken into consideration when PMOSFETs are applied in monitoring the space radiation environment.

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