

GAMMA-RAY IRRADIATION AND POST-IRRADIATION AT ROOM AND ELEVATED TEMPERATURE RESPONSE OF pMOS DOSIMETERS WITH THICK GATE OXIDES

by

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Gamma-ray irradiation and post-irradiation response at room and elevated temperature have been studied for radiation sensitive pMOS transistors with gate oxide thickness of 100 and 400 nm, respectively. Their response was followed based on the changes in the threshold voltage shift which was estimated on the basis of transfer characteristics in saturation. The presence of radiation-induced fixed oxide traps and switching traps – which lead to a change in the threshold voltage – was estimated from the sub-threshold I-V curves, using the midgap technique. It was shown that fixed oxide traps have a dominant influence on the change in the threshold voltage shift during gamma-ray irradiation and annealing.

Key words: pMOS dosimeter, gamma-ray irradiation, threshold voltage shift, absorbed dose

INTRODUCTION

It is well known that ionizing radiation causes the degradation of electronic components and materials [1]. It is also known that gamma-radiation leads to the creation of defects responsible for the increase in the positive charge of the gate oxide and interface states on the Si/SiO₂ interface of MOS components and integrated circuits [2-4]. Radiation defects lead to the instability of MOS transistors by changing their electric parameters [1]. Recognizing these defects is important if MOS components resistant to this type of radiation are to be realized.

Originating in the 1970s [5], the idea of using a pMOS transistor with an Al-gate as a dosimeter of gamma-ray irradiation (also known as the pMOS dosimeter or RADFET) based on the increase of transistor sensitivity to irradiation, has since been further developed [6-9]. Possible practical applications of pMOS dosimeters are, indeed, wide: their use as personal dosimeters, in the laboratory, radiation therapy, spacecraft, nuclear equipment, and so on [10]. The pMOS dosimeter, apart from the expressive threshold voltage shift during irradiation, has to satisfy another criterion upon irradiation: long-term stability of the

threshold voltage shift at room temperature (fading), *i. e.*, the necessity of saving the information on the radiation dose absorbed.

The basic concept of a pMOS dosimeter is to convert the threshold voltage shift, ΔV_T , induced by radiation, into the absorbed radiation dose, D . This dependence can be expressed in the form of [11, 12]

$$\Delta V_T = AD^n \quad (1)$$

where $\Delta V_T = V_T - V_{T0}$, V_T is the threshold voltage after irradiation, V_{T0} – the one before radiation, A – the constant and n – the degree of linearity. Ideally, this dependence is linear, *i. e.*, $n = 1$, where A represents the sensitivity, S of the pMOS dosimeter

$$S = \frac{\Delta V_T}{D} \quad (2)$$

Irradiation results in the trapping of holes in the SiO₂ and creation of interface states at the Si/SiO₂ boundary. Both the trapped holes and interface states contribute to the threshold voltage shift of pMOS dosimeters in the same direction. This is why pMOS transistors, instead of nMOS transistors, were used as radiation dosimeters in our study. We have shown that the radiation sensitivity of a pMOS dosimeter can be increased with the increase of oxide thickness [8, 9, 13], as well as by stacking more transistors [14, 15]. It has

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also been shown that the sensitivity of a pMOS dosimeter is energy-dependent [16, 17], expressed by the dose enhancement factor which represents the radiation between the sensitivity at incident radiation energy and the sensitivity of photons from the source $^{60}_{27}\text{Co}$.

EXPERIMENTAL DETAILS

The experimental samples used in this study were Al-gate pMOS transistors manufactured by the Tyndall National Institute, Cork, Ireland [18]. Gate oxides of 100 and 400 nm, respectively, were grown at 1000 °C in dry oxygen and annealed for 15 minutes at 1000 °C in nitrogen. The post-metallization anneal was performed at 440 °C in forming gas for 60 minutes.

Irradiation was performed in the Metrology Laboratory of the Vinča Institute of Nuclear Sciences, Belgrade. The pMOS dosimeters were irradiated at room temperature using a source to the absorbed dose of $D = 35$ Gy (Si), at the absorbed dose rate $D = 0.02$ Gy (Si) s^{-1} . The gate bias during irradiation was $V_{\text{irr}} = 5$ V (the other pins were grounded). Immediately after irradiation, pMOS dosimeters were annealed at room temperature for a time period of 5232 hours without polarization (all pins were grounded). After that, annealing on a temperature of 120 °C, also without polarization on the gate and lasting 423 hours, was continued. The pMOS dosimeter threshold voltage before irradiation, V_{T0} , as well as during irradiation and annealing, V_T , were determined by transfer characteristics in saturation, *i. e.*, the intersection between the V_G -axis and extrapolated linear region of the $(I_D)^{1/2} - V_G$ [19], where V_G is the gate voltage and I_D is the drain current.

The IV characterization was performed by a Keithley 4200 SCS (Semiconductor Characterization System) unit. The system is equipped with three medium power source-measuring units (4200 SMU) for IV characterization. The source-measuring units have four voltage ranges: 200 mV, 2 V, 20 V, and 200 V, while the current ranges are 100 μA , 1 mA, 100 mA, and 1 μA . One of the source-measuring units is equipped with a preamplifier which provides the measurement of very low currents (in the order of pA).

Aerial densities of radiation-induced fixed traps, ΔN_{ft} , and switching traps, ΔN_{st} , during irradiation and annealing were determined from the sub-threshold I-V curves, using the midgap technique (MGT) of

McWhoter and Winocur [20]. Fixed traps (FT) represent traps created in the oxide, while switching traps (ST) represent traps created near and at the Si/SiO₂ interface. The ST created in the oxide, near the SiO₂/Si interface, are called slow switching traps (SST), ST created at the interface, fast switching traps (FST) or true interface traps. FT represent traps in the oxide that do not capture the carriers from the channel, but SST and FST, making the ST, represent traps that do capture (communicate with) the carriers from the channel within the time frames of electrical MGT measurements.

The contribution of FT (ΔV_{ft}) and ST (ΔV_{st}) to the net threshold voltage shift ΔV_T is [11]

$$\Delta V_T = \Delta V_{\text{ft}} + \Delta V_{\text{st}} \quad (3)$$

while the densities of ΔN_{ft} and ΔN_{st} after irradiation and annealing may be determined as [20]

$$\Delta N_{\text{ft}} = \frac{C_{\text{ox}} \Delta V_{\text{ft}}}{q}; \quad \Delta N_{\text{st}} = \frac{C_{\text{ox}} \Delta V_{\text{st}}}{q} \quad (4)$$

where C_{ox} is the oxide capacitance per unit area and q the absolute value of the electron charge.

RESULTS AND DISCUSSION

Figures 1(a) and 2(a) represent the $\Delta V_T = f(D)$ dependence during irradiation of pMOS dosimeters with a gate oxide thickness of 100 nm and 400 nm, respectively. It is obvious that the changes in the threshold voltage shift during irradiation are significantly higher in dosimeters with larger oxide thickness, a result to be expected.

Symbols in the figures shown represent the $\Delta V_T = V_T - V_{T0}$ values obtained from pMOS dosimeters transfer characteristics in saturation, while the solid lines are determined by the fitting of this data with the expression (1) for the degree of linearity $n = 1$. The values of fitting correlation factors for pMOS dosimeters with gate oxide thickness of 100 nm and 400 nm were 0.99291 and 0.99852, respectively. Because the correlation factors are very close to one, it can be assumed that there is a linear dependency between ΔV_T and D , *i. e.*, that the sensitivity of these dosimeters can be determined on the basis of expression (2).

Figures 1(b) and 2(b) show the ΔV_T evolution of irradiation pMOS dosimeters with a gate oxide thickness of

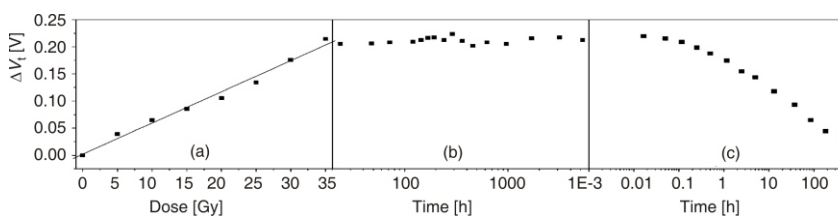


Figure 1. Threshold voltage shift, ΔV_T , during (a) irradiation, (b) spontaneous annealing, and (c) annealing at 120 °C for a pMOS dosimeter with oxide thickness of 100 nm

100 nm and 400 nm, respectively, during annealing at room temperature (also known as spontaneous recovery of fading). In pMOS dosimeters with gate oxide thickness of 100 nm, the value ΔV_T changes insignificantly during spontaneous recovery, *i. e.*, in these transistors the dosimetric information is saved. In pMOS dosimeters with gate oxide thickness of 400 nm, fig. 2(b), the value of ΔV_T decreases during spontaneous recovery in the first 1000 hours and afterwards ΔV_T remains an approximately constant value. Therefore, in these transistors there is a loss of the dosimetric information at the beginning of spontaneous recovery.

For the purpose of checking whether the process of the loss of dosimetric information after spontaneous annealing occurred, the annealing of pMOS dosimeters at a temperature of 120 °C was continued and the results of this kind of annealing shown in figs. 1(c) and 2(c). It can be seen that in pMOS dosimeters with gate oxide thickness of 100 nm, fig. 1(c), there is a rapid loss of value of ΔV_T during annealing. It shows that, for the times of annealing lower than 423 hours, in these dosimeters there is a complete loss of dosimetric information. In pMOS dosimeters with gate oxide thickness of 400 nm, fig. 2(c), further loss of dosimetric information is slight.

Figures 3(a) and 4(a) show the behavior of ΔN_{ft} during irradiation for pMOS dosimeters with gate oxide thickness of 100 nm and 400 nm, respectively. It could be seen that the value ΔN_{ft} for pMOS dosimeters with larger oxide thickness is approximately an order of magnitude higher than in pMOS dosimeters with smaller oxide thickness. During spontaneous annealing in pMOS dosimeters with gate oxide thickness of 100 nm, fig. 3(b), there is an insignificant change in ΔN_{ft} value. In pMOS dosimeters with gate oxide thickness of 400 nm, at the beginning of spontaneous recovery, there is a significant decrease of ΔN_{ft} value, fig. 4(b), after which this change is insignificant.

Figures 3(c) and 4(c) show the behavior of ΔN_{ft} during continuous annealing at an elevated tempera-

ture. As could be seen, elevated temperature in pMOS dosimeters with gate oxide thickness of 100 nm leads to a rapid decrease in ΔN_{ft} value during annealing to 100 hours. In pMOS dosimeters with gate oxide thickness of 400 nm, fig. 4(c), ΔN_{ft} value insignificantly changes during annealing.

During irradiation and later annealing at room and elevated temperature, besides the change in ΔN_{ft} , a change of ΔN_{st} occurs. However, the change of ΔN_{ft} in both types of pMOS dosimeters is an order of magnitude higher than the change of ΔN_{st} (results for ΔN_{st} are not shown in this paper). This shows that the dominant influence on ΔV_T , *i. e.*, on the dosimetric information, lies in FT which are formed in the gate oxide during gamma-ray irradiation. For this reasons, the role of FT in the formation and saving of dosimetric information will be discussed in this paper.

Experimental results shown in figs. 3 and 4 can be most readily explained within the model given in papers [21-23]. The critical role in this model belongs to the E_γ center, a weak Si-Si bond in the oxide caused by an oxygen atom vacancy between two Si atoms, each back-bounded to three oxygen atoms [24]. The E_γ center acts as a hole trap and is predominately responsible for the increase in the oxide trapped charge during irradiation [25]. We will accept the convincing arguments of Lelis and Oldham [23] that the switching oxide traps in irradiated oxides are E_γ centers close to the Si/SiO₂ interface. The fixed oxide traps are, microscopically, E_γ centers as well – however, further from the Si/SiO₂ interface and hence incapable of exchanging charge with Si during the time frame of the measurements.

The oxide trapped charge involves both the charge trapped at fixed oxide traps and that trapped at switching oxide traps. Namely, under the influence of the positive electric field in the oxide (caused by positive gate bias) during annealing, the hole trapped at the E_γ center can be either compensated or neutralized by the electron tunneling from Si.

Figure 2. Threshold voltage shift, ΔV_T , during (a) irradiation, (b) spontaneous annealing, and (c) annealing at 120 °C for a pMOS dosimeter with oxide thickness of 400 nm

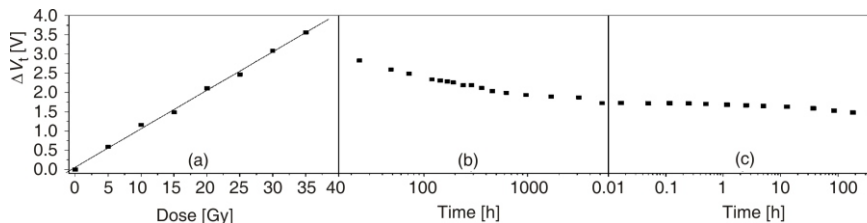
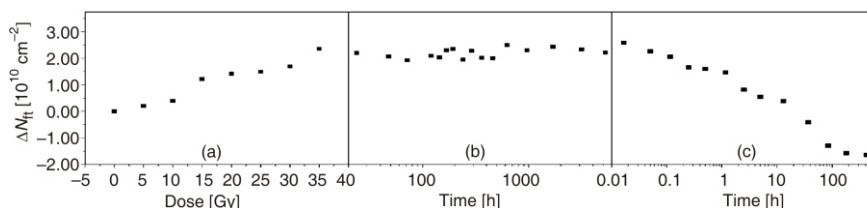


Figure 3. The change in the areal density of fixed traps, ΔN_{ft} , during (a) irradiation, (b) spontaneous annealing, and (c) annealing at 120 °C for a pMOS dosimeter with oxide thickness of 100 nm



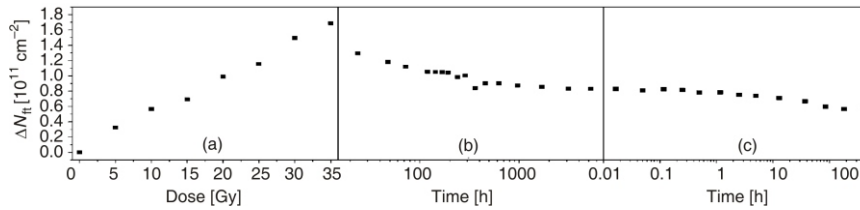


Figure 4. The change in the areal density of fixed traps, ΔN_{ft} , during (a) irradiation, (b) spontaneous annealing, and (c) annealing at 120 °C for a pMOS dosimeter with oxide thickness of 400 nm

Based on the behavior of ΔN_{ft} during spontaneous annealing of pMOS dosimeters with gate oxide thickness of 100 nm, fig. 3(b), it can be concluded that the tunneling of electrons from Si does not have a significant effect on the compensation or neutralization of E_γ centers. In pMOS dosimeters with gate oxide thickness of 400 nm, fig. 4(b), in the first 1000 hours, the tunneling of electrons from Si leads to a partial compensation or neutralization of E_γ centers during annealing.

When exposing pMOS transistors to elevated temperatures after spontaneous annealing, an added mechanism appears which leads to the compensation or neutralization of FT. Namely, besides the neutralization or compensation of the charge trapped at E_γ centers by electrons tunneling from Si under the influence of the electrical field, electrons thermally emitted from the oxide valence band also contribute to the neutralization of the E_γ center [26].

As can be seen in figs. 3(c) and 4(c), decrease in the value of ΔN_{ft} during annealing at an elevated temperature is much faster in pMOS dosimeters with gate oxide thickness of 100 nm. This shows that in these dosimeters the neutralization of E_γ is due to the electrons thermally emitted from the oxide valence band much more efficiently than in pMOS dosimeters with a gate oxide thickness of 400 nm. Namely, elevated temperatures in pMOS dosimeters with gate oxide thickness of 100 nm, fig. 3(c), lead to complete neutralization of E_γ centers which were formed during irradiation, along with parts of E_γ centers formed during technological processes used in the manufacturing of these components. In pMOS dosimeters with a gate oxide thickness of 400 nm, the loss of remaining dosimetric information slightly decreased after 423 hours of annealing, which goes to say that the electrons thermally emitted from the oxide valence band do not have a significant influence on the neutralization of E_γ centers.

CONCLUSIONS

On the basis of what was stated above, the following conclusion may be reached. During gamma-ray irradiation to the dose of 35 Gy, there is an approximately linear dependency between the threshold voltage shift and the absorbed dose in both types of

pMOS dosimeters, making these components useful as sensors of high dose range gamma-ray irradiation. However, pMOS dosimeters with gate oxide thickness of 400 nm are more suitable as sensors because they exhibit higher threshold voltage changes during irradiation. During spontaneous annealing in pMOS dosimeters with a gate oxide thickness of 100 nm, the threshold voltage shift retains an approximately constant value, *i. e.*, at room temperature dosimetric information is kept for a period of 218 days. In pMOS dosimeters with gate oxide thickness of 400 nm, during spontaneous annealing of 50 days, the threshold voltage shift decreases, *i. e.*, a partial loss of dosimetric information occurs. The continuation of annealing at a temperature of 120 °C leads to a complete loss of dosimetric information in pMOS dosimeters with a gate oxide thickness of 100 nm – which is not the case with pMOS transistors with a gate oxide thickness of 400 nm. E_γ centers play a critical role in the pMOS dosimeter response, being responsible for both fixed and switching traps in the oxide and hole and electron trapping. Therefore, the need to optimize the pMOS dosimeter fabrication process in terms of E_γ center numbers, location and energy, is of paramount importance. This can be done by optimizing the highest temperature process, usually gate oxidation and subsequent anneal, in an inert atmosphere. However, one should be careful when coming to conclusions, because sometimes the whole process sequence rather than individual process steps can impact the radiation and post-irradiation response of the devices.

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**ОДЗИВ pMOS ДОЗИМЕТАРА СА ДЕБЕЛИМ ОКСИДИМА УПРАВЉАЧКЕ
ЕЛЕКТРОДЕ, ТОКОМ ГАМА ЗРАЧЕЊА И ПОСЛЕ ОЗРАЧИВАЊА
НА СОБНОЈ И ПОВИШЕНОЈ ТЕМПЕРАТУРИ**

Истраживан је одзив радијационо осетљивих pMOS транзистора чије су дебљине оксида 100 nm и 400 nm током гама зрачења и каснијег опоравка на собној и повишеној температури. Одзив ових транзистора је праћен на основу промене напона који је процењиван из преносних карактеристика у сатурацији. Присуство центара у оксиду управљачке електроде као и центара на међуповршини силицијум-силицијумдиоксид, који доводе до промене напона прага, процењивани су техником која користи претпраговске струјно-напонске криве. Показано је да доминантну улогу у промени напона прага током озрачивања и касније опоравка имају центри захвата у оксиду гејта.

Кључне речи: pMOS дозиметар, гама зрачење, промена напона прага, апсорбована доза