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LETTER

Fading of pMOS dosimeters over a long period of time

1 | INTRODUCTION

The radiation dosimeters based on specially designed, radiation-sensitive p-channel metal-oxide-semiconductor field-effect transistors with Al gate (Al-gate pMOSFETs), better known as pMOS dosimeters or radiation-sensitive MOSFETs (RADFETs), have been widely researched for years [1–4]. The threshold voltage shift, ΔV_T, induced by irradiation, of pMOS dosimeter, is converted into the absorbed dose, D. In addition to radiation sensitivity, another characteristic of irradiated pMOS dosimeters is fading—recovery of the threshold voltage during ambient (room temperature) annealing without gate voltage. For many pMOS dosimeter applications, it is very important to keep the dosimetric information, i.e. have as little fading as possible. Fading is also very important when the irradiation lasts for a long time, because if there is a fading then the threshold voltage, V_T, will change during the irradiation, which further complicates the determination of the radiation dose. Sensitivity undoubtedly increases with both the thickness of the gate oxide and positive voltage of the gate, which cannot be said for fading whose nature is much more complex. This paper considers the fading of irradiated pMOS dosimeters over about 85,000 h (∼10 years). The fading values up to 1 year after pMOS dosimeters irradiation can be found in the literature, but not for such a long period.

2 | EXPERIMENTAL DETAILS

The pMOS dosimeters used here were produced by Tyndall National Institute, Cork, Ireland, and had the thicknesses of $t_{ox1} = 400$ nm and $t_{ox2} = 1000$ nm. They were irradiated with an absorbed dose of $D = 50$ Gy (H_2O) at the Vinča Institute, Belgrade Serbia. During irradiation (IR), the gate voltages were $V_{G,i} = 0$ and 5 V (in the case of $V_{G,i} = 0$ V, all pins were grounded). During IR, the positive radiation-induced fixed traps (FTs) in the gate oxide, with ΔN_{ft} areal density, and radiation-induced switching traps (STs) near and at the silicon/silicon-dioxide (Si/SiO_2) interface, with ΔN_{st} areal density, are created.

The threshold voltage shift ΔV_T can be expressed as [5]

$$\Delta V_T = \Delta V_{ft} + \Delta V_{st} = \frac{e}{C_{ox}}\Delta N_{ft} + \frac{e}{C_{ox}}\Delta N_{st}, \quad (1)$$

where ΔV_{ft} and ΔV_{st} are the components of ΔV_T due to FTs and STs, respectively, $C_{ox} = \varepsilon_{ox}/t_{ox}$ is the gate oxide capacitance per unit area, $\varepsilon_{ox} = 3.45 \cdot 10^{-13}$ F/cm is the silicon-dioxide permittivity, and e is the electron charge.

3 | EXPERIMENTAL RESULTS AND DISCUSSION

The results of IR are presented in reference [6]. It is shown that ΔV_T is linear with D for used dose of 50 Gy ($\Delta V_T = S \cdot D$, where S is the sensitivity of pMOS dosimeters; see Table 1).

It was also shown [6] that S is proportional to t_{ox}^2 ($S \sim t_{ox}^2$), which can be seen in Table 1. Namely, for a given $V_{G,i}$, $S_{1000}/S_{400} \approx 6.25 = 2.5^2$. Also, $(t_{ox2}/t_{ox1})^2 = (1000/400)^2 = 2.5^2 = 6.25$.

After IR, pMOS dosimeters were annealed at ambient (room) temperature without a gate polarization ($V_{G,a} = 0$ V). This annealing is known as a spontaneous annealing (SA). Another characteristic of dosimeters, in addition to sensitivity, is fading, which represents the recovery of transistor threshold voltage during SA. This paper considers the fading of irradiated pMOS dosimeters over about 85,000 h (∼10 years).

The fading, f, can be calculated as [6,7]

$$f = \frac{V_T(0) - V_T(t)}{V_T(0) - V_{T0}} = \frac{\Delta V_T(0) - \Delta V_T(t)}{\Delta V_T(0)} = 1 - \frac{\Delta V_T(t)}{\Delta V_T(0)}, \quad (2)$$

where $V_T(0)$ is the threshold voltage after irradiation, $V_T(t)$ is the threshold voltage during spontaneous annealing, V_{T0} is the threshold voltage before irradiation, $\Delta V_T(0)$ is the threshold voltage shift after irradiation, and $\Delta V_T(t)$ is the threshold voltage shift during SA. The fading results are shown in Figure 1.

TABLE 1 The threshold voltage before IR, V_{T0}, the threshold voltage shift after IR, ΔV_T at 50 Gy, and sensitivity, S, of used pMOS dosimeters [6]

t_{ox}	$V_{G,i}$ (V)	V_{T0} (V)	ΔV_T at 50 Gy (V)	S (V/Gy)
400 nm	0	3.46	1.42	0.0287
	5	3.49	2.25	0.0459
1000 nm	0	1.96	8.40	0.1778
	5	2.16	13.91	0.2880

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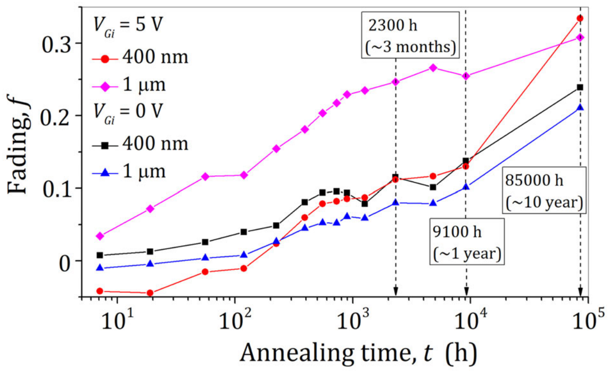

FIGURE 1 Fading of irradiated pMOS dosimeters during spontaneous annealing (SA)

The general thought is that SA cannot lead to significant changes in FTs and STs, which are responsible for the behaviour of $\Delta V_T(t)$, and therefore for fading behaviour, and that fading saturates after same time (usually after 3 months). Looking at Figure 1, it can be seen that the fading after about 1000 h is slightly saturated, having significantly higher values for the gate oxide thickness of 1000 nm and a gate voltage of 5 V, whereas for other RADFETs it has approximately the same values. However, further monitoring of fading showed different behaviour. In reference [6], the fading up to 9100 h (about 1 year) is investigated (as shown in Figure 1). Fading saturation was assumed and fading was well fitted by the proposed function [6]. However, further examination of the fading for 10 years shows a different behaviour, as also shown in Figure 1.

It is interesting that after a long recovery period of 10 years, the fading is higher for RADFETs irradiated with a higher positive electric field, regardless of the oxide thickness. Also, the values of fading for $V_{G,i}$ = 5 V are similar for both oxide thicknesses. Here it should be noted that the case without an external voltage on the gate ($V_{G,i,a}$ = 0) of Al-gate pMOSFETs corresponds to a small internal positive voltage on the gate of V_{wf} = 0.33 V due to the difference in a work function between the Al-gate and n-type silicon substrate, resulting in small external positive electric field in the gate oxide [8].

It is shown [6] that ΔN_{ft} decreases, but ΔN_{st} increases during SA. At the beginning of SA, the small negative fading, as a consequence of a greater increase in STs than a decrease in FTs, can be seen in Figure 1 for two transistor types. However, the ΔN_{ft} decreases more significantly than ΔN_{st} increases [6], meaning ΔN_{ft} has a more significant impact on ΔV_T than ΔN_{st}, so that the influence of ΔN_{st} on ΔV_T can be neglected, i.e. it can be assumed that $\Delta V_T(t) \approx \Delta V_{ft}(t)$.

During IR, gamma photons collide with electrons bound in the silicon-dioxide (SiO_2), releasing bound electrons (so-called primary electrons) and leaving unoccupied electron sites (so-called holes). Since non-strained silicon–oxygen bonds (NSBs), $\equiv Si_o{-}O{-}Si_o\equiv$, are the most numerous bond in SiO_2, collisions between photons and electrons in NSBs are most likely [9]:

$$\equiv Si_o-O-Si_o\equiv + \text{photon} \rightarrow \equiv Si_o-O^{\bullet} + {}^{+}Si_o\equiv + e^-, \quad (3)$$

where the index 'o' denotes oxide, but '–' denotes covalent bond (a pair of electrons). An unpaired electron e^- is usually at the $\equiv Si_o-O^{\bullet}$ trap (e^- is denoted by a dot), but a hole h^+ (positively charged virtual particle) is at ${}^{+}Si_o\equiv$ trap (h^+ is denoted by a plus sign).

Primary electrons have very high kinetic energy, and either recombine with holes at the site of formation or avoid recombination. Due to their high kinetic energy, recombination is a very low probable process. The primary electrons, avoiding recombination, travel through the oxide and collide with the bound electrons in the covalent bonds of the NSBs. In these collisions, they lose kinetic energy and release so-called secondary electrons [9]

$$\equiv Si_o-O-Si_o\equiv + e^+ \rightarrow \equiv Si_o-O^{\bullet} + {}^{+}Si_o\equiv + 2e^-. \quad (4)$$

Primary and secondary electrons, before leaving the oxide, break many covalent bonds in the oxide and create many new high-energy secondary electrons because they have very high kinetic energies [9]. Otherwise, incident photons of ionizing radiation are not responsible for radiation defect creations, but for the realization of primary electrons that move freely through the oxide, breaking a lot of covalent bonds and realizing a lot of secondary electrons before leave the oxide.

Electrons leave the oxide very quickly (in a few picoseconds), while the holes remain in the oxide. The holes are created in reactions (3) and (4), usually in the bulk of the oxide, where there are no energy-deep hole traps, so that they are only temporary, but not permanently trapped at the point of origin [9]. However, the holes move towards an interface, depending on the oxide electric field's direction, where they can be trapped in the energy-deep hole traps. It is unlikely that electrons are trapped at electron traps during irradiation [9].

In the area of 3–5 nm from the SiO_2/Si interface, there are a lot of both the oxygen vacancies (OVs), $\equiv Si_o{-}Si_o\equiv$, and the strained silicon–oxygen bonds (SBs), $\equiv Si_o{-}O{-}Si_o\equiv$, which bonds can be broken by the holes [9]. The OVs and SBs are the main precursors of FTs with ΔN_{ft} density.

When the holes, under a positive electric field, reach the area near SiO_2/Si interface, they break the OVs, $\equiv Si_o{-}Si_o\equiv$ [9]:

$$\equiv Si_o-Si_o\equiv + h^+ \rightarrow \equiv Si_o^{\bullet} + {}^{+}Si_o\equiv, \quad (5)$$

where the ${}^{+}Si_o\equiv$ trap is named the E_γ trap.

The holes also break the SBs, $\equiv Si_o{-}O{-}Si_o\equiv$ [9]:

$$\equiv Si_o-O-Si_o\equiv + h^+ \rightarrow \equiv Si_o-O^{\bullet} + {}^{+}Si_o\equiv, \quad (6)$$

where the $\equiv Si_o{-}O^{\bullet}$ is an amphoteric non-bridging-oxygen (NBO) trap, while ${}^{+}Si_o\equiv$ is the E_s trap. E_γ and E_s represent energy deep hole traps [9].

During SA, electrons tunnel from the substrate (Si) to the gate oxide (SiO_2) due to a low positive electric field, where they compensate or/and neutralize the E_γ and E_s traps:

$$\equiv Si_o^{+\bullet}Si_o\equiv + e^- \rightarrow \equiv Si_o^{\bullet\bullet}Si_o\equiv, \quad (7)$$

$$\equiv Si_o^{+\bullet}O-Si_o\equiv + e^- \rightarrow \equiv Si_o^{\bullet\bullet}O-Si_o\equiv. \quad (8)$$

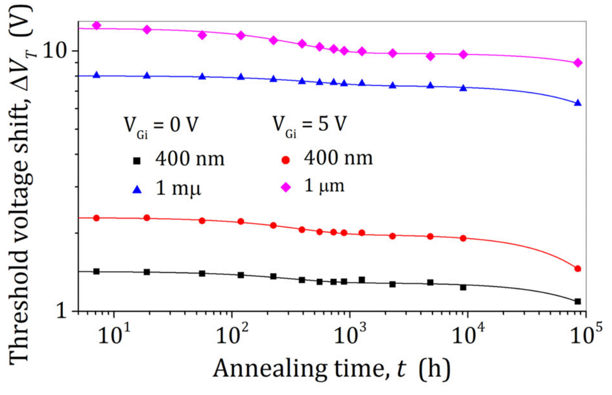

FIGURE 2 Threshold voltage shift during spontaneous annealing fitted by Equation (12)

To fit the $\Delta V_{\rm ft}$, i.e. $\Delta V_{\rm T}$, during SA, we will use the model for the annealing of radiation-induced defects developed in reference [7], which is confirmed in other experiments [8,10]. Using Equations (8)–(10) from reference [7] and reactions (7) and (8), the dependence of densities of E_γ, $\Delta N_{E_\gamma}(t)$, and of $E_{\rm s}$, $\Delta N_{E_{\rm s}}(t)$, respectively, on time during SA, can be obtained as follows:

$$-\frac{d[N_{E_\gamma}]}{dt} = k_\gamma[N_{E_\gamma}][e] \Rightarrow \Delta N_{E_\gamma}(t) = \Delta N_{E_\gamma}(0)\cdot e^{-t/\tau_\gamma}, \tag{9}$$

$$-\frac{d[N_{E_{\rm s}}]}{dt} = k_{\rm s}[N_{E_{\rm s}}][e] \Rightarrow \Delta N_{E_{\rm s}}(t) = \Delta N_{E_{\rm s}}(0)\cdot e^{-t/\tau_{\rm s}}, \tag{10}$$

where $\Delta N_{E_\gamma}(0)$ and $\Delta N_{E_{\rm s}}(0)$ are the densities of E_γ and $E_{\rm s}$ after irradiation, i.e. at the beginning of SA, respectively, k_γ and $k_{\rm s}$ are rate constants, but $\tau_\gamma = 1/k_\gamma$ and $\tau_{\rm s} = 1/k_s$ are the time constants that show annealing rates for these two trap types. Obviously, on the basis of the above discussion, it can be written that

$$\Delta N_{\rm ft}(t) = \Delta N_{E_\gamma}(t) + \Delta N_{E_{\rm s}}(t) = \\ = \Delta N_{E_\gamma}(0)\cdot e^{-t/\tau_\gamma} + \Delta N_{E_{\rm s}}(0)\cdot e^{-t/\tau_{\rm s}}, \tag{11}$$

$$\Delta V_{\rm ft}(t) = \Delta V_{E_\gamma}(t) + \Delta V_{E_{\rm s}}(t) = \\ = \Delta V_{E_\gamma}(0)\cdot e^{-t/\tau_\gamma} + \Delta V_{E_{\rm s}}(0)\cdot e^{-t/\tau_{\rm s}}, \tag{12}$$

where $\Delta V_{E_\gamma}(t)$ and $\Delta V_{E_{\rm s}}(t)$ are the components of $\Delta V_{\rm ft}$(t) due to the radiation-induced E_γ and $E_{\rm s}$ traps during SA, respectively, $\Delta V_{E_\gamma}(0)$ and $\Delta V_{E_{\rm s}}(0)$ are the initial values of where $\Delta V_{E_\gamma}(t)$ and $\Delta V_{E_{\rm s}}(t)$ at the beginning of SA, i.e. after irradiation ($t = 0$), respectively, but τ_γ and $\tau_{\rm s}$ are time constants of these traps.

Figure 2 shows the experimental values of $\Delta V_{\rm T}$ during SA, and the fitting of $\Delta V_{\rm T}$ on SA time using Equation (12) and $\Delta V_{\rm T}(t) \approx \Delta V_{\rm ft}(t)$. It can be seen a very good agreement between experimental and fitted values. The values of fitting parameters are given in Table 2. Using this fitting and Equation (2), the fitted fading is presented in Figure 3. All fittings were performed using GNU Octave, version 6.2.0 program.

TABLE 2 The parameters of $\Delta V_{\rm T}$ fit by Equation (12) during SA

	$\Delta V_{E_\gamma}(0)$ (V)	τ_γ (h)	$\Delta V_{E_{\rm s}}(0)$ (V)	$\tau_{\rm s}$ (h)
400 nm, 0 V	0.135	300.93	1.289	502,614
400 nm, 5 V	0.317	332.06	1.977	278,783
1000 nm, 0 V	0.651	491.05	7.373	527,901
1000 nm, 5 V	2.427	347.92	9.806	978,335

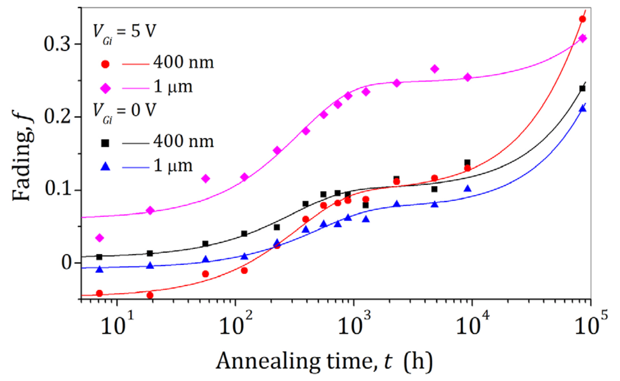

FIGURE 3 Fading fitting using Equations (2) and (12)

4 | CONCLUSION

Experimental results show that fading does not saturate even after 10 years after pMOS dosimeter irradiation. Although the behaviour of fading is very complex, it can be fitted very well with two types of radiation-induced traps (E_γ and $E_{\rm s}$ traps) involved in modelling. A very important result is that the fading does not depend on the thickness of the gate oxide, but depends on the voltage at the gate applied during irradiation.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data openly available in a public repository that issues datasets with DOIs.

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