The Study of Voltage Shift in the Post-Radiation Response

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ABSTRACT: *The voltage shift in the gamma-irradiation and post irradiation response was studied with elevated temperature. The gate polarization of 0, 2.5 and 5V are used with gate oxide thickness. The relation between* ΔV_T *and absorbed dose was observed. The* ΔV_T *decrease while the zero-gate polarization during irradiation and 100 nm RADFETs* ΔV_T *remains approximately during the annealing at room temperature. The decrease of* ΔV_T *is associated with the continued annealing at 120*^{o}*C. Thus, the fluctuations and various impact of the gate polarization is well addressed in this work.*

Keywords: RADFET Sensor, Dosimeter, Gamma-ray Irradiation, Gate Oxide Thickness, Linear Dependence, Annealing, Zero Gate Polarization

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1. Introduction

Radiation sensitive Al-gate p-channel MOSFETs (also known as RADFETs, or pMOS dosimeters) have been developed for applications such as space, nuclear industry and radio therapy [1-3]. The basic concept of RADFET is to convert the threshold voltage shift, ΔV_T, induced by gamma-ray irradiation into absorbed dose D. This dependence can be expressed in the form [4]

$$\Delta V_T = AD^n , \tag{1}$$

where A is the constant and n is the degree of linearity which depends from electric field, oxide thickness and absorbed radiation dose. Ideally, the dependence should be linear, i.e. $n = 1$ and in that case A represents sensitivity, S of RADFETs:

$$S = \frac{\Delta V_T}{D} \tag{2}$$

Irradiation leads to the creation of positive gate oxide charge and interface traps at Si/SiO_2 interface. Both the positive gate oxide charge and interface traps in p-channel MOSFETs contribute to the ΔV_T in same direction and this fact is one of the main reasons for transistor application as a detector of absorbed dose of gamma irradiation. The RADFETs must satisfy two fundamental demands: a good compromise between sensitivity to irradiation and insignificant recovery at room temperature after irradiation, i.e. the information about radiation dose must be preserved over time.

2. Experiment

The experimental samples were RADFETs manufactured by Tyndall National Institute, Cork, Ireland [5]. Oxide thickness was 100 and 400 nm, and they were grown at 1000°C in dry oxygen and annealed for 15 minutes 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 Vinca Institute of Nuclear Science, Belgrade. The RADFETs were irradiated at room temperature using $^{60}_{27}$Co source up to absorbed dose of 35 Gy(Si) at absorbed dose rate of 0.002 Gy(Si)s^{-1}. The gate polarization, V_{irr}, during irradiation of RADFETs with the gate oxide thickness of 400 nm was 0, 2.5 or 5 V, while for the samples with oxide thickness of 100 nm polarization was 5 V (all other pins were grounded). After irradiation the samples were annealed at room temperature for 218 days without polarization (all pins were grounded). After that, the annealing was continued at elevated temperature of 120 °C also without gate polarization for 15 days.

The change in threshold voltage shift ΔV_T due to gamma-ray irradiation and annealing can be expressed as [6]

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

where ΔV_{ot} and ΔV_{it} are contributions to the change in threshold voltage due to the positive oxide charge and interface traps, respectively. ΔV_{ot} and ΔV_{it} can be expressed as a function of areal density of positive gate oxide charge ΔN_{ot} and areal density of interface traps ΔN_{it} [7]

$$\Delta V_{ot} = \pm \frac{q}{C_{ox}} \Delta N_{ot}, \Delta V_{it} = \frac{q}{C_{ox}} \Delta N_{it}. \tag{4}$$

In the above expression, the upper sign refers to n-channel MOSFETs and the lower sign refers to p-channel MOSFETs (the absolute value of p-channel MOSFETs threshold voltage is given throughout the paper), C_{OX} is the gate capacitance per unit area and q is absolute value of electron charge.

In order to detect the radiation and post irradiation response, the RADFETs transfer characteristics were measured, and the threshold voltage was determined as the intersection between V_G axis and extrapolated linear region of $(I_D)^{1/2} - V_G$ curve. The sub threshold charge separate technique [7] was used to determine the contributions of ΔV_{ot} and ΔV_{it} to the threshold voltage shift ΔV_T.

The 1-5 characterization was performed by Keithley 4200 SCS (Semiconductor Characterization System). The system is equipped with three medium power source measuring units (4200 SMU) for I-V characterization. The source measuring units have four voltage ranges: 200 mV, 2V, 20 V and 200 V, while the current ranges are 100 μA, 1 mA, 100 mA and 1A. One of the source-measuring units is equipped with a preamplifier which provides the measurements of very small currents (in the order of 1 pA).

To illustrate the influence of irradiation on RADFETs behavior in Figure 1 we have plotted transfer characteristics in saturation before irradiation (curve (0)) and after irradiation for absorbed dose of 35 Gy(Si). The threshold voltage shift ΔV_T can be expressed as $\Delta V_T = V_T - V_{T0}$, where V_{T0} is the threshold voltage before irradiation and V_T is the threshold voltage after irradiation (in Figure 1 V_T is the threshold voltage after absorbed dose of 35 Gy). During annealing V_T represents the threshold voltage after determined time of annealing at room or elevated temperature.

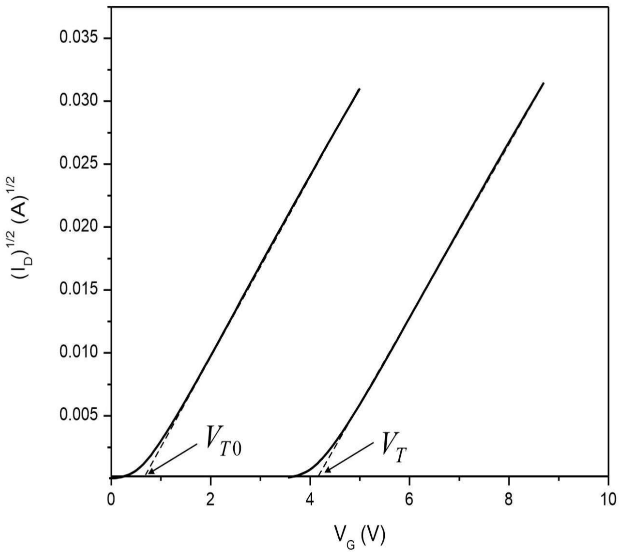
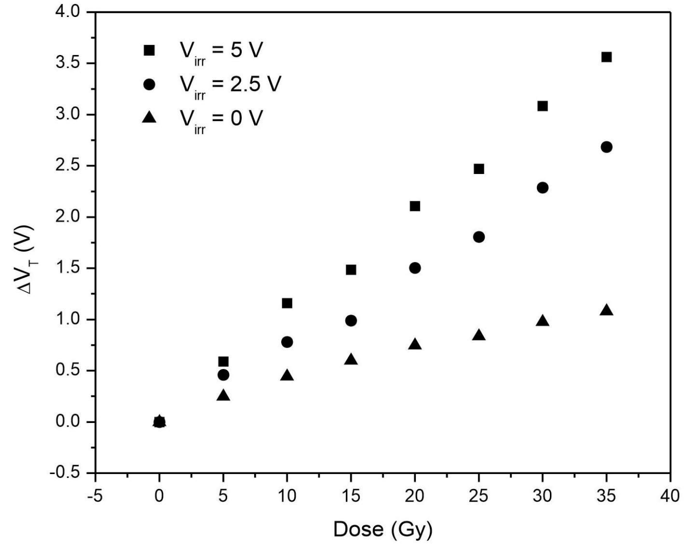


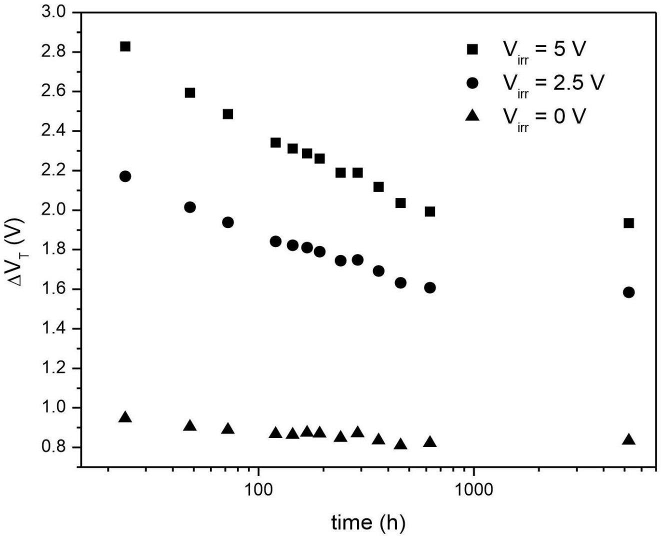
Figure 1. Transfer characteristics and values of threshold voltage shift before irradiation (ΔV_{T0}) and after irradiation of 35 Gy and V_{irr} = 5V (V_T) for RADFET with 400 nm gate oxide thickness

3. Results and Discussion

Figure 2a gives $\Delta V_T = f(D)$ dependence of RADFETs with gate thickness of 400 nm for V_{irr} 0, 2.5 and 5 V. It can be seen that ΔV_T strongly depends on V_{irr} values during irradiation. For example, for the dose of 35 Gy the ratio of ?VT for V_{irr} = 2.5V and V_{irr} = 0V is about 2.7 V, while for V_{irr} = 5V and V_{irr} = 0V the ration is about 4.2. It can be concluded that the polarization on the gate can cause significant influence on the range of measured gamma-ray dose. Namely, with the increase of gate polarization the threshold voltage shift is higher for the same irradiation dose, what can drive the RADFET away from the area of linear dependence between threshold voltage shift and irradiation dose and also transistor is much more likely to fail. Doses used in our experiments are relatively small so they don't lead to significant degradation of RADFETs, i.e. there is approximately linear dependence between ΔV_T and D.



(a)



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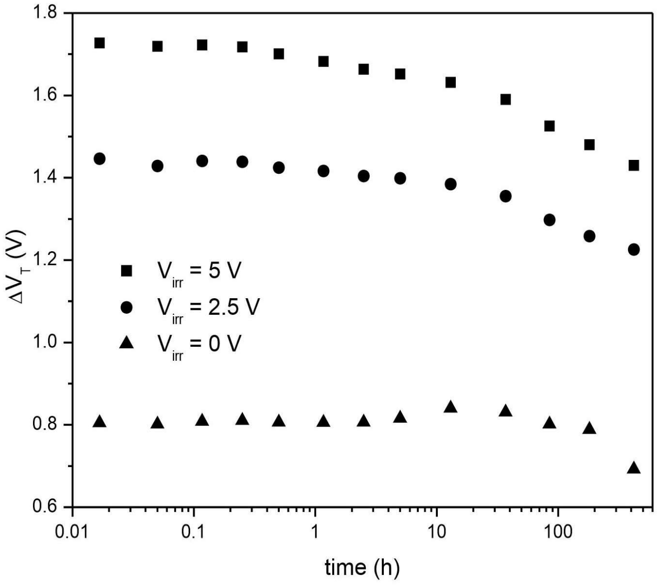
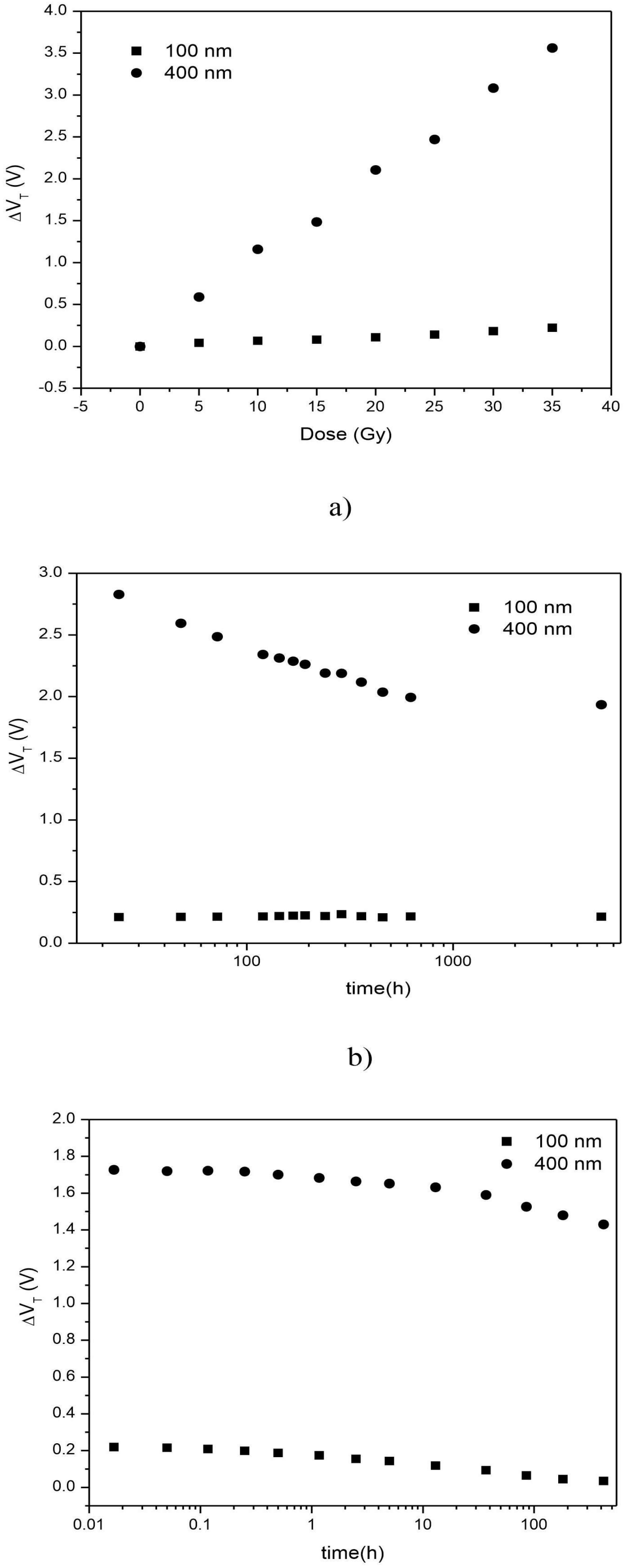


(c)

Figure 2. Threshold voltage shift ΔV_T during a) irradiation, b) spontaneous annealing and c) annealing at 120 ^{o}C for RADFETs with 400 nm gate oxide thickness and gate polarization of 0, 2.5 and 5 V

Figure 3a presents $\Delta V_T = f(D)$ dependence for RADFETs with 100 and 400 nm thick oxide, respectively with the gate polarization of V_{irr} = 5V. It can be seen that there is also approximately linear dependence between ΔV_T and D for RADFETs with the 100 nm oxide thicknesses, but these values are smaller than for RADFETs with the 400 nm oxide thicknesses. This shows that the sensitivity to gamma irradiation is bigger for RADFETs with thicker gate oxide due to larger density of positive oxide charge and interface traps for the same value of absorbed dose.



a)

b)

c)

Figure 3. Threshold voltage shift ”*VT* during a) irradiation, b) spontaneous annealing and c) annealing at 120 oC for RADFETs with 100 and 400 nm gate oxide thickness and gate polarization *Virr* = 5V

Figure 2b presents ΔV_T evaluation during annealing at room temperature (spontaneous recovery) of irradiated RADFETs with the gate thicknesses of 400 nm for the duration of 218 days. It can be seen that the rate of dosimetric information loss (fading), i.e. the rate of ΔV_T decrease in the early phase of spontaneous recovery depends on V_{irr} values during irradiation. For bigger Virr values the rate of ΔV_T decrease during annealing is higher. For RADFETs with V_{irr} = 0V during irradiation, ΔV_T remains approximately constant, while for RADFETs with V_{irr} = 2.5V and V_{irr} = 5V , ΔV_T decreases during spontaneous recovery during 1000 h, and after that period of time it remains approximately constant.

Figure 3b presents ΔV_T evolution during spontaneous recovery for RADFETs with gate oxide thickness of 100 and 400 nm which were irradiated with gamma ray radiation up to 35 Gy and with V_{irr} = 5V gate polarization. It can be seen that ΔV_T insignificantly changes during spontaneous recovery for RADFETs with 100 nm gate thickness, i.e. the dosimetric information is saved over time.

In order to determine whether the process of dosimetric information loss is finished after spontaneous annealing, the annealing is continued at the temperature of 120^{o}C for the 15 days. The threshold voltage shift, ΔV_T, during such annealing for RADFETs with gate oxide thickness of 400 nm and gate polarization of 0, 2.5 and 5 V, is presented in figure 2c. It can be seen that the changes in ΔV_T for RADFETs with gate polarization of 2.5 and 5 V are much smaller than the changes in the beginning of spontaneous annealing.

The continuation of annealing at 120^{o}C for RADFETs with 100 and 400 nm oxide thickness and gate polarization of V_{irr} = 5V is presented in figure 3c. It can be seen that 100 nm RADFETs show rapid ΔV_T loss during annealing. For the time of 15 days RAFETs with 100 nm gate thickness loses all of the dosimetric information. For RADFETs with 400 nm gate thickness loss of dosimetric information is very small. It should be pointed out that mechanisms responsible for threshold voltage shift during irradiation and later annealing at room and elevated temperature are discussed in detail in the papers [8, 9].

4. Conclusion

On the basis of above consideration, the following conclusion can be derived. In the range of absorbed dose of gamma radiation from 5 to 35 Gy there is approximately linear dependence between threshold voltage shift ΔV_T and absorbed dose D and the degree of linearity rises with the increase of gate polarization during irradiation. Also, the sensitivity of RADFETs to gamma radiation increases with the increase of gate oxide thickness and gate polarization during irradiation. During spontaneous recovery for RADFETs with the gate oxide thickness of 100 nm and with gate polarization of 5 V as well as for RADFETs with gate oxide thickness of 400 nm and with no polarization on the gate, ΔV_T remains approximately constant, i.e. dosimetric information is very well preserved. The continuation of annealing at 120 ^{o}C leads to complete loss of dosimetric information for RADFETs with gate oxide thickness of 100 nm and to partial loss of dosimetric information for RADFETs with gate oxide thickness of 400 nm.

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