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Processes in radiation sensitive MOSFETs during irradiation and post irradiation annealing responsible for threshold voltage shift

Milić M. Pejović

University of Niš, Faculty of Electronic Engineering, Aleksandra Medvedeva 14, 18000 Niš, Serbia

HIGHLIGHTS

- The behavior of radiation-induced fixed oxide and switching traps has been investigated.
- Post-irradiation annealing at room temperature has been monitored for 100 days period.
- Irradiation was performed with gate bias ranging from 0 to 5 V.
- Annealing was performed without gate bias.
- Mechanisms responsible for ΔV_T shift during irradiation and annealing are discussed.

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ABSTRACT

The behavior of radiation-induced fixed oxide traps and radiation-induced switching traps near and at Si/SiO_2 interface during gamma-ray irradiation up to 50 Gy and post-irradiation annealing at room temperature has been investigated. These processes lead to threshold voltage shift, ΔV_T, which is dosimetric parameter employed in total absorbed radiation dose determination. Irradiation was performed with gate bias from 0 to 5 V and annealing was performed without gate bias. The midgap-subthreshold technique was used to separate fixed traps and switching traps which for p-channel MOSFETs contribute to ΔV_T in the same direction. It was shown that the increase in gate bias lead to the increase in fixed oxide traps density and switching traps density, what further increases ΔV_T for the same radiation dose. The density of fixed traps created during irradiation is higher than the switching traps density. Post irradiation annealing at room temperature without gate bias, for 100 days period, lead to relatively small decrease in ΔV_T, what is a consequence of both, decrease in fixed oxide traps density and increase in switching traps density.

1. Introduction

As a consequence of the influence of ionizing radiation on commercial MOSFETs (Metal-Oxide-Semiconductor Field Effect Transistors), the positive trapped charge in the oxide and interface traps at Si/SiO_2 interface are formed. To understand the behavior of these defects is very important, since they can degrade *of several electrical parameters including threshold voltage V_T as the most important one (*Badila et al., 2001, *Park et al., 2001,* Bo et al., 2010 *and* Moon et al., 2014*).* Post irradiation effects in these devices have received a considerable attention during the last several decades, since the knowledge of post irradiation behavior of gate oxide and Si/SiO_2 interface defects is very useful for determination of fundamental properties of these defects and their interactions (Schwank et al., 1992, *Pejovic, M and Ristic G., 1997,* Pejovic et al., 1997, Jaksic et al., 2000; Pejovic et al., 2012a *and* Davidovic et al., 2016). Beside this, the sequence of irradiation and subsequent annealing can help predict device response in real radiation environments, such as space. Also, the investigation of radiation defects is very important for ionizing radiation dosimetry (Holmes-Siedle and Adams, 1986; Ristic, 2008; Pejovic et al., 2012a and Pejovic, 2016). Namely p-channel MOSFETs, also known as radiation-sensitive field effect transistors (RADFETs) or pMOS dosimeters, have been shown to be suitable for dose measurements in various applications such as in space technology, nuclear industry, radiotherapy, skin dosimetry and clinical monitoring (Holmes-Siedle, 1974; Adams and Holmes-Siedle, 1978; Sarrabayrouse and Siskos, 1998; Peet and Proyer, 1999; Quach et al., 2000; Rosenfeld, 2002; Pejovic, 2016 and Pejovic et al., 2016). The detecting principle of RADFETs is based on the electron-hole pairs creation induced by radiation in the gate oxide, which creates additional oxide-trapped charge and interface traps, which lead to

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threshold voltage shift, ΔV_T. Namely, the basic function of RADFETs is to convert the value of ΔV_T induced by radiation into the absorbed radiation dose (Pejovic, 2013; Pejovic et al., 2014 and Pejovic, 2016). RADFET have number advantage over traditional dosimetry units, such as immediate and non-destructive readout, easy calibration, permanent storage of doses, reasonable sensitivity and reproducibility, small volume and weight, robustness and accuracy (Holmes-Siedle and Adams, 1986; Hughes et al., 1988). In recent years, many investigations are driven toward applications of low-cost commercial p-channel MOSFETs as a sensors of ionizing radiation in radiotherapy (Martinez-Garcia et al., 2014 and Asencio et al., 2006). It is also shown (Pejovic et al., 2015a) that the commercial p-channel VDMOSFETs IRF9520 can be used as a high gamma-ray radiation dose sensor.

As a dosimeter RADFET must satisfied two fundamental dosimetric demands: a good compromise between sensitivity to irradiation and stability with time after irradiation. The stability means insignificant change in ΔV_T of irradiated RADFET at room temperature for a long period of time, i.e., dosimetric information should be saved for a long period. There are two important reasons for this: first, being the fact that the dose cannot always be acquired immediately after irradiation, but after a certain period of time; second, as by individual monitoring, the exact moment of irradiation is often unknown, and the radiation dose measurements are performed periodically. *Sensitivity and dosimetric information preservation for these devices is often monitored using threshold voltage shift experimental data as a function of radiation dose and annealing time (*Ehringfeld et al., 2005, Lipovetzky et al., 2010, Lee et al., 2010, Carvajal et al., 2012, Frohlich et al., 2013, Pejovic et al., 2013, Alshaikh et al., 2014, Pejovic, 2015b *and* Martinez-Garicia et al., 2015*). However, the analysis of processes inducing threshold voltage shift hasnt been considered in detail. This paper presents the analysis of processes in gate oxide and at Si/SiO$_2$ interface responsible for threshold voltage shift during irradiation for different values of gate bias as well as for annealing without gate bias at room temperature.*

2. Material and method

2.1. Experimental samples

The experimental samples were *aluminum* gate p-channel enhanced MOSFETs with 100 nm gate oxide thickness, specially designed for radiation dose measurements (RADFETs, Tyndall National Institute, Cork, Ireland). The gate oxide was grown at 1000 °C in dray oxygen, and annealed for 15 min in nitrogen. The post-metallization annealing was performed at 440 °C in forming gas for 60 min. The chip size is 1×1 mm^2 contains four individual RADFETs (*cross section of RADFET is given in* Fig. 1) and is organized in two pairs with of unique geometry (Pejovic et al., 2013). *Two of them have a channel width of W=300 µm, and channel length of L=50 µm (300/50), and the other two transistors have a channel width of W=690 µm and channel length L=15 µm (690/15).* Two transistors (one 300/50 and another of 690/15) have a common substrate pin, while the other pins (gate, drain and source) are independent. The other two RADFETs (one 300/50 and another of 690/15) are internally connected to the source and bulk, and drain and gate, respectively. All of them were packaged in standard ceramic 14-pin DIP package with cover lids.

RADFETs were irradiated at room temperature using $^{60}_{27}$Co radiation source up to 50 Gy at radiation dose rate of 0.02 Gy(Si)/s. During irradiation RADFETs were divided in five groups. *Every experimental samples in each group had specific gate bias during the irradiation*: 0, 1.25, 2.5, 3.75 and 5 V, respectively. *Our earlier results (*Pejovic et al., 2011*) showed that gate bias higher than 5 V don't lead significant changes in value ΔV_T.*

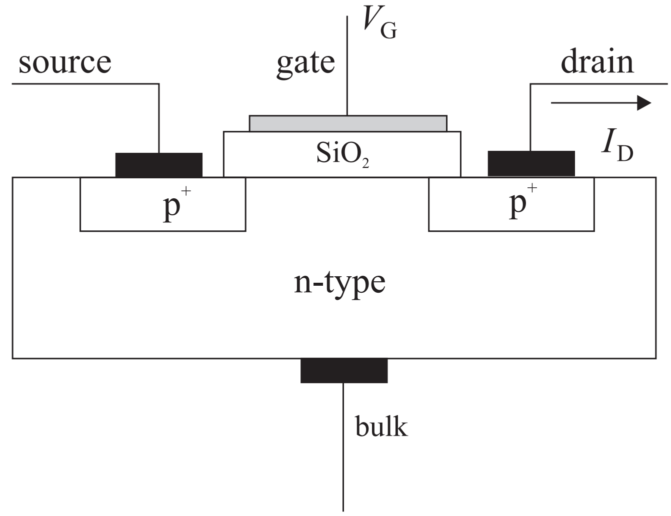

Fig. 1. RADFET schematic cross section.

2.2. Electrical characterization

The threshold voltage V_T was determined using two methods. Firstly, using transfer characteristics in saturation, i.e. as the intersection between the V_G-axis and the extrapolated linear region of the $(I_D)^{1/2} - V_G$ curve (V_G is the gate voltage and I_D is the drain current) (Sze, 1981, Pejovic et al., 2011). Secondly, direct measurement of threshold voltage (Kelleher et al., 1992) when V_T *was determined with RADFETs in so-called reader circuit configuration, whose electronic scheme is shown in* Fig. 2*. In this arrangement, a RADFET is treated as two terminal devices. Through the channel a steady current $I_D = 12$ µA is established and the voltage V_{out} which corresponds to this current is then measured. This voltage represents threshold voltage. The current $I_D = 12$ µs was selected because it was close to the zero temperature coefficients for RADFETs. Namely, when reader circuit characteristics are measured at different temperature, all of them intersect for the current value of approximately 12µA corresponding to zero temperature coefficient (ZTC point) (*Pejovic, 2015b*). Thus, the $V_T = V_{out}$ readout at 12µA is temperature independent.*

The ΔV_T was determined as $\Delta V_T = V_T - V_{T0}$, where V_{T0} is the threshold voltage before irradiation and V_T is the threshold voltage

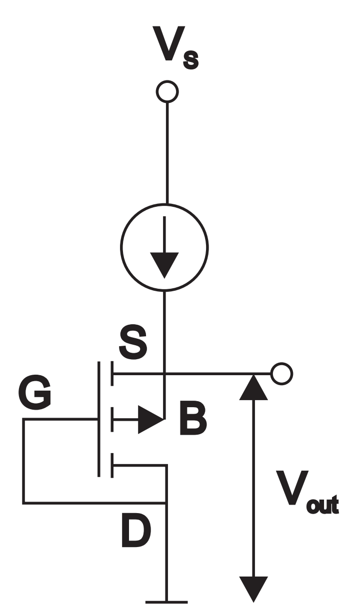

Fig. 2. Reader circuit (single point) measurement configuration.