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Research Article

Sensitivity of P-Channel MOSFET to X- and Gamma-Ray Irradiation

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Investigation of Al-gate p-channel MOSFETs sensitivity following irradiation using 200 and 280 kV X-ray beams as well as gamma-ray irradiation of ^{60}Co in the dose range from 1 to 5 Gy was performed in this paper. The response followed on the basis of threshold voltage shift and was studied as a function of absorbed dose. It was shown that the most significant change in threshold voltage was in the case of MOSFET irradiation in X-ray fields of 200 kV and when the gate voltage was +5 V. For practical applications in dosimetry, the sensitivity of the investigated MOSFETs was also satisfactory for X-ray tube voltage of 280 kV and for gamma rays. Possible processes in gate oxide caused by radiation and its impact on the response of MOSFETs were also analyzed in this paper.

1. Introduction

Since the introduction of the space-charge dosimeter concept [1], radiation sensitive p-channel MOSFETs (also known as RADFETs) have been developed for applications such as space, nuclear industry and research, and radiotherapy [1–4]. Other types of dosimeters that are commonly used or are being developed for these applications include thermoluminescent dosimeters (TLDs), semiconductor diodes, and optically stimulated luminescence dosimeters (OSDLs). A comprehensive review of radiation dosimetry issues and devices can be found in [5]. The RADFET advantages over other dosimetric systems include immediate, nondestructive readout of dosimetric information, small size, low-power consumption, electric interfaces fully compatible with microprocessors, high-dose range, and very competitive price. The RADFET disadvantages are in a need for calibration in different radiation fields, relatively low resolution (starting from about 10^{-2} Gy), and nonreusability. The concept of RADFETs is based on converting threshold voltage shift, ΔV_T, induced by radiation into radiation dose D. Their behavior during irradiation is the result of complex contribution of energy-dependent processes: (1) electron-hole generation, (2) electron-hole recombination, (3) hole transport, (4) deep hole trapping, and (5) radiation-induced interface traps and positive oxide trapped charge. These processes induce threshold voltage shift ΔV_T [2]. Usually a RADFET is operated in an integral mode, where the dose is determined from the threshold voltage, before and after it is irradiated. As in the case of many detectors, they need to be calibrated to an accurate dosimetric reference, such as an ionizing chamber traceable to an accurate dosimetry calibration laboratory. The calibration factor relates the threshold voltage shift of RADFET dosimeters to the dose which is received.

The aim of this work was to investigate the sensitivity of RADFET to X-rays in kilovoltages as well as gamma rays from ^{60}Co. Also analysis of possible processes in gate oxide caused by irradiation and their impact on the sensitivity of RADFETs was conducted.

2. Materials and Methods

The RADFETs of Tyndall National Institute (earlier National Microelectronics Research Centre or NMRC for short), Cork, Ireland, have been used for analyses. Devices represent p-channel MOSFETs fabricated in Al-gate process. A single RADFET has a 1 μm thick gate oxide, grown at 1000°C in dry

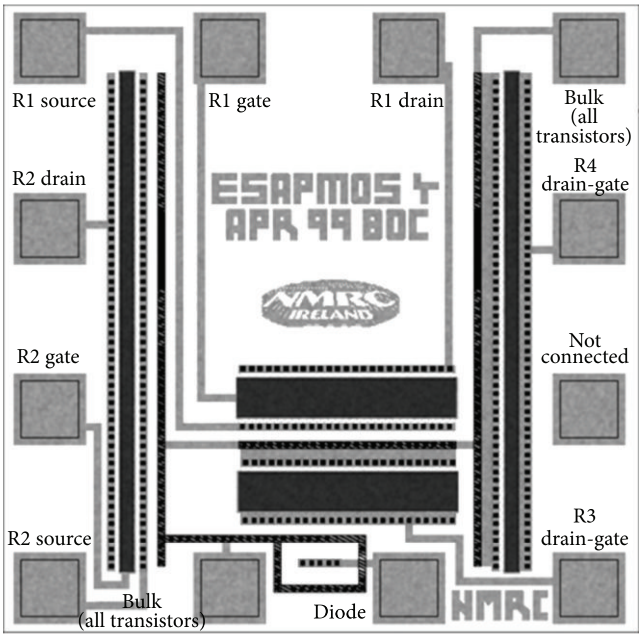

Figure 1: Diagram of a single RADFET used in this study.

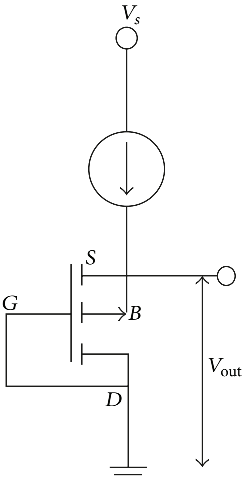

Figure 2: Electronic scheme for reader circuit measurement.

oxygen, and annealed for 15 min at 1000°C in nitrogen. The postmetalization annealing was performed at 400°C in forming gas for 60 min. Figure 1 shows a layout of a single chip. The size of the chip is $1 \times 1\,\text{mm}^2$, and there are two 300/50 and two 690/15 devices in the chip, which represent the width and length given in micrometers of the RADFETs channels, respectively. The first 300/50 device (R1) has four terminals, which are bulk, drain, gate, and source. The first 690/15 device (R2) has the same structure. The bulk connections for R1 and R2 transistors are joined together and connected to the bond pad, which thus represents the bulk connection for both transistors. In both second 300/50 (R3) device and the second 690/15 (R4) device, the gate and the drain are physically tied, and the source and the bulk are also connected. This means that R3 and R4 are two terminal devices, which enables their use in the reader circuit configuration (reader circuit configuration is explained further on in the text).

RADFETs were divided into three groups. The first RADFET group was irradiated using 200 kV (90 keV) X-rays. The second was irradiated by 280 kV (140 keV) X-rays, and the third group was irradiated by gamma rays with energies of 1.17 MeV and 1.33 MeV which derive from ^{60}Co. The irradiation was performed at the Secondary Standard Dosimetry Laboratory of the Vinča Institute of Nuclear Sciences, Vinča, Belgrade, Serbia. All measurements were conducted in a climate-controlled laboratory environment with ambient temperature of 20 ± 0.2°C. The air kerma at the reference point was measured with a calibrated vented $0.6\,\text{cm}^3$ ionization chamber (Model 30012, PTW, Freiburg, Germany) and electrometer Unidos (PTW, Freiburg, Germany). The calibration of the chamber in terms of air kerma for all radiation qualities had been performed at the Secondary Standards Dosimetry Laboratory of the International Atomic Energy Agency (Vienna, Austria), to provide traceability to BIPM (Bureau International des Poids et Mesures, the standards body that ensures worldwide uniformity of measurements and their traceability to the international system of units (SI)). The irradiation was carried out with the beam perpendicular to the gate oxide plane. The RADFETs were irradiated in the range of absorbed doses from 1 to 5 Gy in low-field mode (with zero voltages, $V_{\text{irr}} = 0$, on the gate, that is all terminals shorted together) and high-field mode (with a positive bias, $V_{\text{irr}} = +5\,\text{V}$ applied on the gate). It was emphasized that the low-field mode during irradiation could be particularly useful considering that no additional power supplies are required during irradiation, while on the other hand high-field mode increases the sensitivity and improves the linearity of the response. The threshold voltage was measured immediately after each irradiation in order to minimize drift effect.

In order to detect the absorbed dose, threshold voltage before irradiation V_{T0} and threshold voltage after irradiation V_T were determined. Threshold voltage shift ΔV_T can be expressed as $\Delta V_T = V_T - V_{T0} = AD^n$ [6], where A is the constant, n is the degree of linearity, and D is the absorbed dose. Two methods were used for determining threshold voltage. One of the methods is based on determining threshold voltage from the transfer characteristics of RADFETs in saturation, that is, as an intersection between V_G axis and extrapolation of linear region of $I_D^{1/2}$-V_G characteristics [7], where I_D is drain current and V_G is the gate voltage. The second method is based on determining threshold voltage at a fixed point of the transfer I-V characteristics using so-called reader circuit configuration (Figure 2) [8]. In this configuration the gate and the drain are connected together, as well as the bulk and the source. In this arrangement a RADFET is treated as two terminal devices. Through the channel a steady current I_D is established (in our case $10\,\mu\text{A}$), and the voltage V_{out} which corresponds to this current is then measured. This voltage represents threshold voltage [8]. Reader circuit configuration is commonly used with MOSFET dosimeters

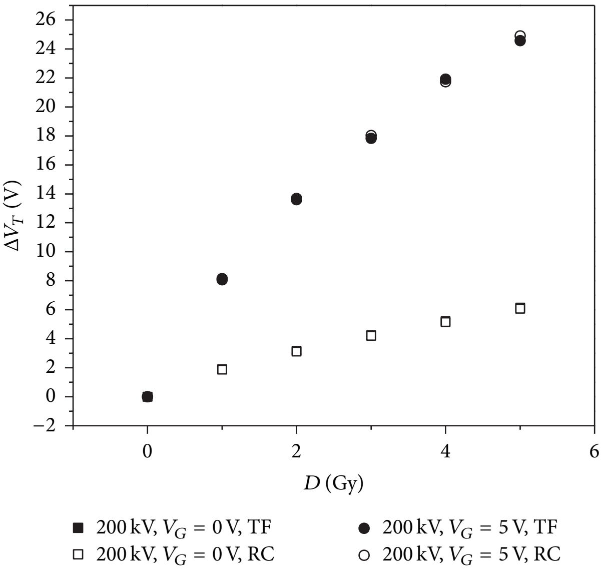

FIGURE 3: Extrapolated (TF) and reader circuit (RC) ΔV_T during 200 kV X-ray irradiation with zero and +5 V gate bias.

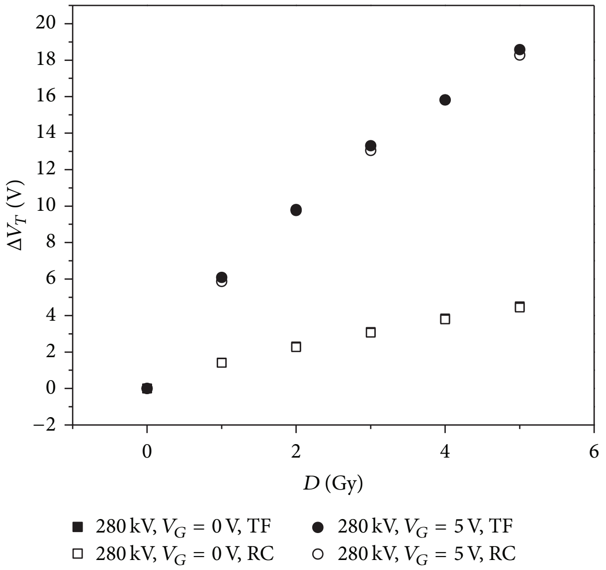

FIGURE 4: Extrapolated (TF) and reader circuit (RC) ΔV_T during 280 kV X-ray irradiation with zero and +5 V gate bias.

since it provides a quick V_T measurement and thus minimizes the temperature sensitivity of the reading.

Transfer characteristics were obtained by a Keithley 4200 Semiconductor Characterization System (SCS). 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, 2 V, 20 V, and 200 V) and three current ranges (100 μA, 100 mA, and 1 A). One of the source measuring units is equipped with a preamplifier to measure very weak currents (of the order of 1 pA).

3. Results and Discussion

Previous research into RADFETs, which are considered in this paper, was mostly based on their response to gamma irradiation for doses ranging from several tenths to several hundreds of Gy [8–14]. Our recent research [15] showed that these RADFETs are also sensitive to gamma-ray doses from 0.1 to 1 Gy. Also, our recently conducted research [16, 17] showed the possibility of reusing the RADFETs, when after the first irradiation by gamma-rays annealing is carried out at room and elevated temperature. Results shown in this paper represent a continuation of the research into widening the application of these RADFETs for cases when X-rays are used, predominantly in radiotherapy and interventional radiology.

Figures 3 and 4 show both extrapolated and reader circuit ΔV_T during X-ray irradiation of 200 kV and 280 kV, respectively. These figures show values of ΔV_T for cases when RADFET dosimeters were irradiated in low-field mode ($V_{\text{irr}} = 0$) and high-field mode ($V_{\text{irr}} = +5$ V). The agreement between extrapolated and reader circuit ΔV_T is satisfactory (less than 1%) in all cases, justifying the use of the reader circuit configuration in practical applications. It can be seen that lower X-ray energies lead to a greater change in ΔV_T for the same irradiation dose. Similar behavior is detected in TN-502RDI MOSFET (Thomson and Nielson Electronic Ltd, Ottawa, Canada) [18].

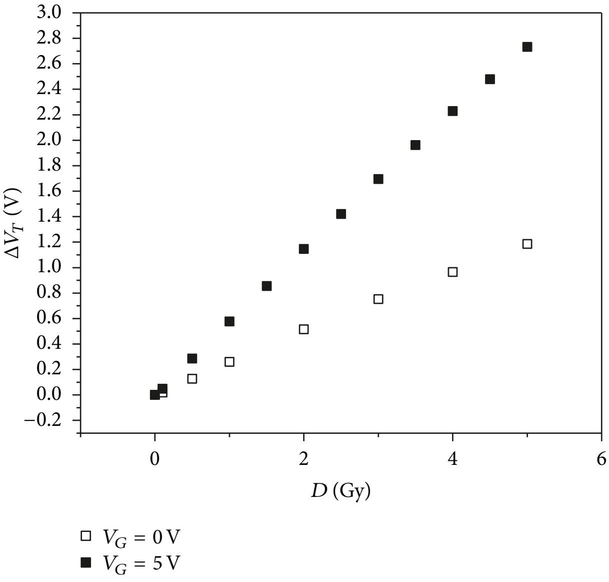

FIGURE 5: ΔV_T during gamma-ray irradiation with zero and +5 V gate bias.

Also, the increase in electric field during RADFET dosimeter irradiation (Figures 3 and 4) leads to a significant change in ΔV_T value. Similar response of these RADFETs had been detected in gamma-ray irradiation cases for doses from several tenths to several hundreds of Gy [10–12].

Figure 5 presents the values of ΔV_T for gamma-ray irradiation doses up to 5 Gy when RADFETs were in a low-field mode ($V_{\text{irr}} = 0$) and also in high-field mode ($V_{\text{irr}} = +5$ V). One can notice that the behavior is the same as in the case when they are irradiated by X-rays (Figures 3 and 4);

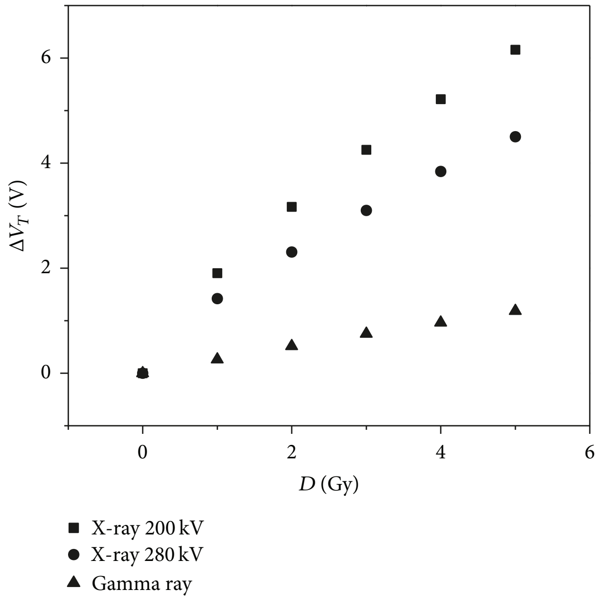

Figure 6: ΔV_T during 200 kV and 280 kV X-ray as well as gamma-ray irradiation with zero gate bias.

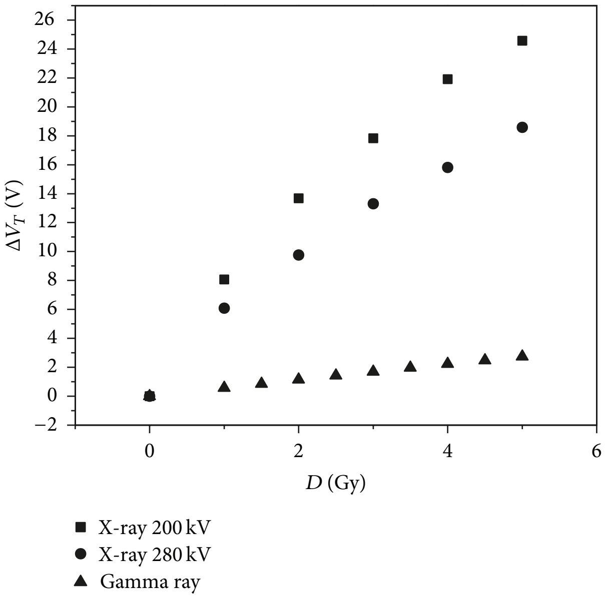

Figure 7: ΔV_T during 200 kV and 280 kV X-ray as well as gamma-ray irradiation with +5 V gate bias.

however, the increase in ΔV_T with the increase in dose is significantly lower. This shows that RADFETs response to gamma rays is significantly lower than their response to X-rays. This can clearly be seen in Figures 6 and 7 where collective values of ΔV_T as a function of dose D for $V_{\text{irr}} = 0$ and $V_{\text{irr}} = +5$ V and for both gamma and X-ray irradiation are presented. Significantly lower RADFETs response during irradiation by gamma rays than by X-rays is a consequence of different photon energies which interact with atoms in the material. Namely, X-ray photons with energies of 90 and 140 keV lead to atom ionization by photoelectric effect, and also this process is more dominant for lower photon energies (in our case this was for energies of 90 keV).

Gamma-ray photons with energies of 1.17 and 1.33 MeV lead to atom ionization by Compton's effect. Since the probability for atom ionization by photoelectric effect is significantly higher than that by Compton's effect, during X-ray irradiation a larger number of positive trap charge is formed during X-ray irradiation than during gamma-ray irradiation which directly effects the change in ΔV_T values. Moreover, ΔV_T represents the sum of threshold voltage shift $\Delta V_{\text{ot}} = q\Delta N_{\text{ot}}/C_{\text{ox}}$ caused by the presence of positive oxide trap charge and threshold voltage shift $\Delta V_{\text{it}} = q\Delta N_{\text{it}}/C_{\text{ox}}$ caused by the presence of interface traps [19], where C_{ox} is the capacitance per unit array, q is the absolute value of electron charge, and ΔN_{ot} and ΔN_{it} are the change in areal density of positive oxide trapped charge and areal density of interface traps, respectively. ΔN_{ot} and ΔN_{it} were determined from the subthreshold I-V curves using the midgap technique of McWhoter and Winokur [20]. It was shown that for doses up to 5 Gy during irradiation by both X-rays and gamma rays $\Delta N_{\text{ot}} \gg \Delta N_{\text{it}}$; that is, positive oxide trapped charge ($\Delta V_{\text{ot}}/\Delta V_T > 90\%$) has the dominant influence on threshold voltage shift.

ΔN_{ot} during X-ray irradiation by energies of 90 and 140 keV as well as during gamma irradiation is presented in Figures 8 and 9. As it can be seen from the figures lower irradiation energy leads to a higher generation of positive oxide trapped charge. Also, applied voltage on the gate during irradiation (high-field mode) generates a greater density of this charge, increasing the value of ΔV_T, that is, the sensitivity of RADFETs. Namely, it was shown [21] that during irradiation E'_γ centers are formed, which represent a weak Si–Si bond in the oxide caused by an oxygen atom vacancy between two Si atoms, each back-bonded to three oxygen atoms [22]. The E'_γ center acts as a hole trap, and it is predominantly responsible for the increase in oxide trapped charge during irradiation [23]. The number of created positive oxide trapped charge rises with the number of holes which have avoided electron recombination. In the case of irradiation in low-field mode ($V_{\text{irr}} = 0$) the electric field in the oxide is only due to the work function difference between the gate and the substrate of RADFETs (zero bias conditions are equal to gate bias of 0.3 V), so the probability for electron-hole recombination is higher than that in the case when RADFETs are in high-field mode ($V_{\text{irr}} = +5$ V). During irradiation in high-field mode the large number of holes will escape the initial recombination, which therefore further increases the probability for their capture at E'_γ centers and consequently increases in positive oxide trapped charge. This is in agreement with results shown in Figures 8 and 9.

4. Conclusion

The sensitivity of p-channel MOSFETs fabricated in Al-gate technology process (also known as RADFETs) with 1 μm thick gate oxide to kilovoltage X-ray and gamma-ray irradiation with dose range from 1 to 5 Gy was studied.

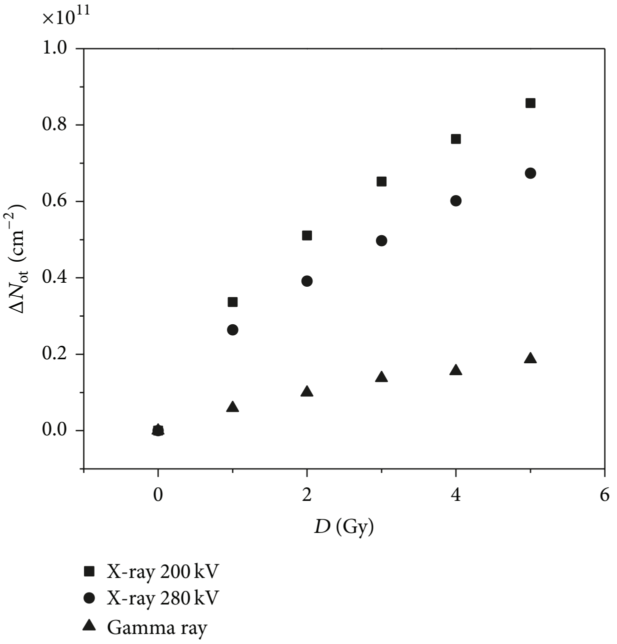

FIGURE 8: ΔN_{ot} during 200 kV and 280 kV X-ray as well as gamma-ray irradiation with zero gate bias.

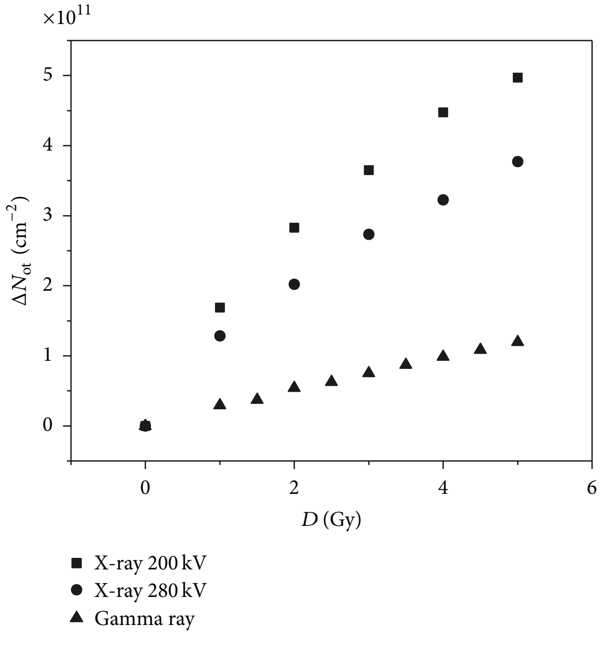

FIGURE 9: ΔN_{ot} during 200 kV and 280 kV X-ray as well as gamma-ray irradiation with +5 V gate bias.

The sensitivity was characterized by the threshold voltage shift determined from transfer characteristics in saturation and reader circuit measurements. Results have shown that the response is greater when RADFETs are irradiated by X-rays. It was concluded that this is a consequence of the dominant influence of photoelectric effect in X-ray cases in comparison to Compton's effect in gamma-ray cases. In order to optimize RADFETs fabrication process, the analysis of defects formed during irradiation was performed. It was shown that positive oxide trapped charge which is formed by trapping holes at E'_{γ} centers has the dominant effect on threshold voltage shift. The centers are formed during irradiation and their number increases with the decrease in photon energies. According to the results it can be concluded that a satisfactory response of these RADFETs could be achieved for significantly lower doses especially in X-ray cases, which would enable their efficient application for measuring low doses order of several mGy used in diagnostic and interventional radiology. Taking this into consideration our further research will focus on the application of RADFETs for measuring low doses for a wide range of X-rays.

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