SUCCESSIVE GAMMA-RAY IRRADIATION AND CORRESPONDING POST-IRRADIATION ANNEALING OF pMOS DOSIMETERS

by

Milić M. PEJOVIĆ [1*], Momčilo M. PEJOVIĆ [1, 2], Aleksandar B. JAKŠIĆ [3], Koviljka Dj. STANKOVIĆ [4], and Slavoljub A. MARKOVIĆ [4]

[1]Faculty of Electronic Engineering, University of Niš, Niš, Serbia
[2]Center of Scientific Research of the Serbian Accademy of Sciences and Arts, University of Niš, Niš, Serbia
[3]Tyndall National Institute, Lee Maltings, Cork, Ireland
[4]Faculty of Electrical Engineering, University of Belgrade, Belgrade, Serbia

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The paper investigates a possibility of pMOS dosimeter re-use for the measurement of gamma-ray irradiation. The dosimeters were irradiated to the dose of 35 Gy, annealed at room and elevated temperatures, after which they were irradiated again to the same dose value. Changes in the threshold voltage shift during those processes were followed, and it was shown that their re-use depends on a gate polarization during irradiation. For the gate polarization of 5 V during irradiation the pMOS dosimeters can be re-used for measurements of the irradiation dose after annealing without prior calibration. The pMOS dosimeters with the gate polarization during irradiation of 2.5 V can also be re-used for irradiation dose measurements but they require calibration. It is shown that for their re-use it is necessary to anneal the pMOS dosimeter so that the fading is higher than 50%.

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

INTRODUCTION

Over the past few years, there has been an increasing interest in MOSFET (metal-oxide-semiconductor field effect transistor) dosimetry. This has been stimulated by a new technology development leading to the use of new types of detectors [1-9]. The idea to use radiation sensitive p-channel MOSFET with Al-gate as a dosimeter (known as pMOS dosimeter or RADFET) has been around since the beginning of the 1970's. These dosimeters have been developed for applications such as space, nuclear industry, and radiotherapy [10-13]. The application of pMOS dosimeter is based on converting the threshold voltage shift ΔV_T, induced by radiation, into the radiation dose D. The pMOS dosimeter must satisfy two fundamental dosimetric demands: a good sensitivity to irradiation and an insignificant change in the threshold voltage of irradiated dosimeter for a long time. The radiation sensitivity can be achieved by increasing oxide thickness [14-16], by stacking more transistors [17, 18] or applying a positive bias at the gate during irradiation [19, 20]. Beside the above mentioned requirements, it is very important, for practical applications, to achieve a linear dependence between ΔV_T and D [21]. After irradiation the usually changes, what leads to a loss of dosimetric information. The dosimetric information loss during annealing can be observed by calculating fading, $F(t)$. Fading, expressed in %, is obtained by evaluating the ratio $\Delta V_T(R)/\Delta V_T(0)$, where $\Delta V_T(R)$ is the change in the pMOS dosimeter threshold voltage with time after irradiation and $\Delta V_T(0)$ is the change in the threshold voltage due to radiation.

There are several types of dosimeters like thermoluminescent dosimeters (TLD), semiconductor diodes, and optically stimulated luminescence dosimeters (OSDL). The TLD are rather small, well characterized and standard in use; however, they are not suitable for measurements and readout of dosimetric information that is destructive. Semiconductor diodes are also miniature in size, but they produce a small dosimetric signal and require high voltage. The optically stimulated luminescence (OSL) dosimetry concept has recently re-emerged with promising results [22], however, OSLD require integration of electronic and optic elements in the readout system and dosimetric information is read destructively. The pMOS dosimeters advantages include immediate,

* Corresponding author; e-mail: milic.pejovic@elfak.ni.ac.rs

nondestructive readout of dosimetric information, extremely small size, very low power consumption, wide dose range and very competitive price. However, the disadvantages imply a need for calibration in different radiation fields, relatively low resolution (starting from about 10^{-2} Gy) and inability to be re-used [20]. Previously published results [23] have suggested a possibility to re-use the pMOS dosimeters. The aim of this paper is to investigate such a possibility for radiation doses of several tenths of Gy for different values of gate bias during radiation.

EXPERIMENTAL DETAILS

The experimental samples used in this paper were radiation sensitive Al-gate p-channel MOS transistors (pMOS dosimeters or RADFET) manufactured by Tyndall National Institute, Cork, Ireland. The transistors have 400 nm thick oxides grown at 1000 °C in dry oxygen and annealed for 15 minutes at 1000 °C in nitrogen. The post-metallization annealing was performed at 440 in forming gas for 60 minutes (see ref. [20] for more details). The samples were irradiated at room temperature using $^{60}_{27}$Co radiation source up to 35 Gy(Si) and a dose rate of 0.02 Gy(Si)/s. The irradiation was performed in the Secondary Standard Dosimetry Laboratory of the Vinča Institute of Nuclear Sciences, Vinča, Belgrade. All measurements were conducted in a climate controlled laboratory environment at the ambient temperature of 20   20 °C. The air kerma rate in the reference point was measured using a calibrated, vented 0.6 cm^3 ionization chamber (Model 30012, PTW, Freiburg, Germany) and electrometer Unidos (PTW, Freiburg, Germany). The standard calibration of the chamber in terms of air kerma and absorbed dose in water in $^{60}_{27}$Co beam quality was performed in the Secondary Standard Dosimetry Laboratory of the International Atomic Energy Agency, Vienna. The calibration coefficients obtained in this way are traceable to BIPM. The values obtained were transformed to absorbed dose in relevant material. Taking into account relevant influencing quantities, as the electrometer range, ambient temperature, and pressure conditions, energy, material, polarity, and charge recombination, combined and expended uncertainty of air kerma measurement (k = 2) is estimated to be 1.1% (for more details about measurement uncertainty see refs. [24, 25]). The gate bias during irradiation, V_{irr}, was 5, 2.5, and 0 V. After irradiation, the pMOS dosimeters were annealed at room temperature for 5232 hours without gate polarization. Further annealing process was continued at the 120 °C for 432 hours without gate polarization. After that, the pMOS dosimeter were irradiated and annealed under the same conditions for the second time. The transfer characteristics were measured using Keithley model 4200 SCS (see ref. [26] for more details). All measurements on samples were performed at room temperature by interrupting the radiation or annealing process. The pMOS dosimeter threshold voltage before irradiation V_{T0} as well as during irradiation and annealing V_T ($\Delta V_T = V_T - V_{T0}$) was determined from transfer characteristics, *i. e.* as intersection between V_G axis and extrapolation of linear region of the $I_D^{1/2} - V_G$ characteristics [27], where I_D is the drain current and V_G is the gate voltage.

RESULTS AND DISCUSSION

Figures 1-3 show $\Delta V_T = f(D)$ dependence for both first and second irradiation for V_{irr} values of 5, 2.5, and 0 V, respectively. It can be seen that there is approximately a linear dependence between ΔV_T and D for V_{irr} of 5 V and 2.5 V which proves that sensitivity of pMOS dosimeters for radiation doses to 35 Gy can be determined as $\Delta V_T/D$ [26]. For the first and the sec-

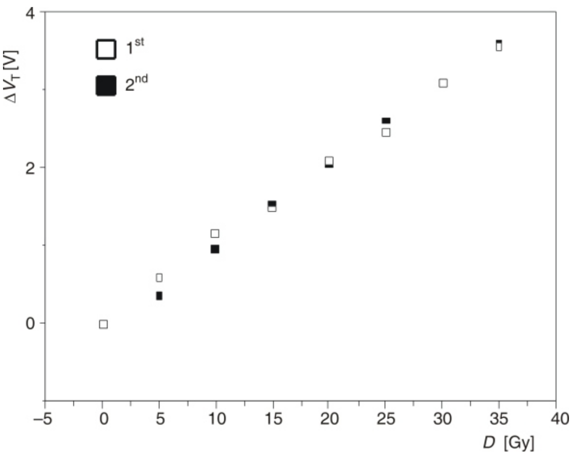

Figure 1. Threshold voltage shift ΔV_T as a function of dose for 1st and 2nd irradiation; the gate voltage during irradiation was V_{irr} = 5 V

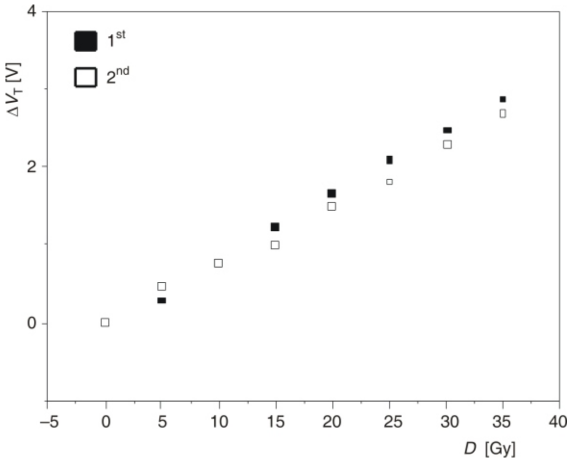

Figure 2. Threshold voltage shift ΔV_T as a function of dose for 1st and 2nd irradiation; the gate voltage during irradiation was V_{irr} = 2.5 V

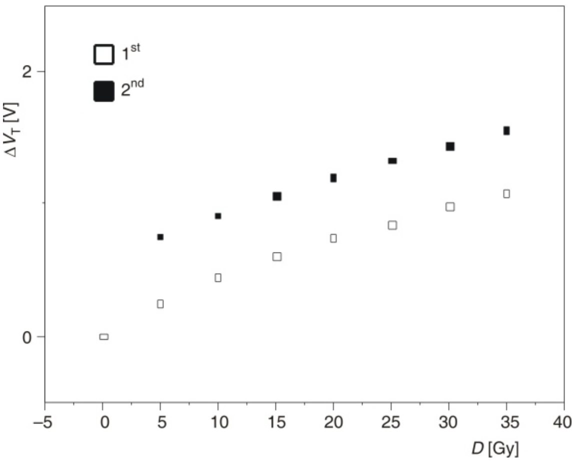

Figure 3. Threshold voltage shift ΔV_T as a function of dose for 1st and 2nd irradiation without polarization on the gate

ond irradiation for V_{irr} = 5 V the values of ΔV_T practically overlap (fig. 1), for V_{irr} = 2.5 V, ΔV_T values during the second irradiation are slightly higher (fig. 2), while for V_{irr} = 0 V, ΔV_T values for the second irradiation are considerably higher (fig. 3). These results are in opposition with the results presented in [23] for pMOS dosimeters irradiated up to 400 Gy. Namely, in paper [23] it was shown that the values of ΔV_T during the first irradiation (for V_{irr} = 5 V and V_{irr} = 0 V) are larger than the values obtained after the second irradiation. It can also be seen from the figs. 1-3 that the increase of V_{irr} leads to the increase of ΔV_T for the same irradiation dose, *i. e.* the sensitivity of pMOS dosimeters is increased with increase of V_{irr}, what is in good agreement with our previous results [21, 26].

Figures 4, 5, and 6 represent fading, *F* (*t*) for pMOS dosimeters with a gate polarization during irradiation V_{irr} of 5, 2.5, and 0 V, respectively. It can be seen that fading at room temperature is larger after the first irradiation than after the second one as well as that it is larger for pMOS dosimeters with higher value of gate polarization during irradiation, figs. 4(a), 5(a), and 6(a). The continuation of annealing at 120, figs. 4(b), 5(b), and 6(b), leads to a considerably smaller fading after the first irradiation then after the second irradiation. After the first irradiation for samples with

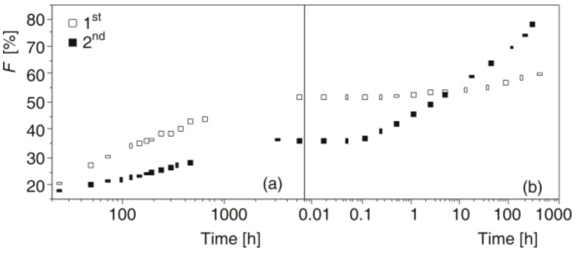

Figure 4. Fading *F* after first and second radiation: at room temperature (a) and at 120 °C (b); the gate voltage during irradiation was V_{irr} = 5 V

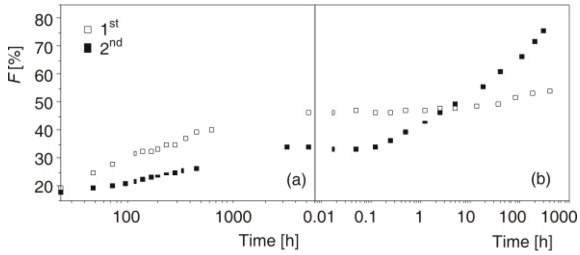

Figure 5. Fading *F* after first and second radiation: at room temperature (a) and at 120 °C (b); the gate voltage during irradiation was V_{irr} = 2.5 V

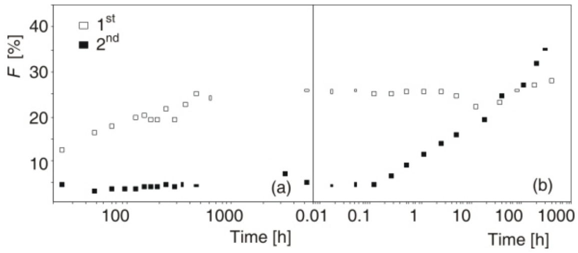

Figure 6. Fading *F* after first and second radiation: at room temperature (a) and at 120 °C (b); the gate voltage during irradiation was V_{irr} = 0 V

the gate polarization during irradiation of 5 V and 2.5 V the fading is increased at 120 °C for 60% and 53%, respectively, figs. 4(b) and 5(b), while for the samples without gate polarization during the first irradiation the fading remains approximately constant, and it has value of about 27%, fig. 6(b). After the second irradiation the fading is increased at 120 for samples with the gate polarization of 5 and 2.5 V for 81%, figs. 4(b) and 5(b), while the fading for samples without the gate polarization is about 35%, fig. 6(b).

As it can be seen from fig. 1, ΔV_T values for the first and the second irradiation for V_{irr} = 5 V are practically the same although the fading after the first irradiation was 60%. It shows that fading is not a limiting factor for pMOS dosimeters re-use. Hence, after annealing at room and elevated temperature those dosimeters can be used again for a radiation dose measurement. The latter also implies the samples with 2.5 V gate polarizations during irradiation (fig. 2), but it is necessary to perform additional re-calibration of the $\Delta V_T = f(D)$ curve. The pMOS dosimeters irradiated without a gate polarization (fig. 3) cannot be used for additional radiation dose measurement due to a large difference between ΔV_T values after the first and the second irradiation.

Because the fading at 120 °C after the second annealing is higher than after the first one, figs. 4(b) and 5(b) it is expected that the considered pMOS dosimeters can be used for the third measurement of radiation doses. Further investigations under various conditions such as gate polarization during irradiation and annealing, gate oxide thickness, irradiation dose range, annealing temperature should confirm the possibility of these dosimeters re-use.

CONCLUSIONS

The paper presents the response of pMOS dosimeters during two successive gamma irradiations to 35 Gy and further annealing at room and elevated temperature. The response was monitored on the bases of the threshold voltage shift change as a function of absorbed dose or annealing time. It was shown that the threshold voltage shift values after the first and the second irradiation are approximately the same when the gate polarization was 5 V, while they slightly differ for the gate polarization of 2.5 V. Such relatively good agreement between the threshold voltage shifts values was achieved in spite of the fact that fading after the first annealing was not 100%, but slightly above 50%.

Based on the obtained results it can be concluded that pMOS dosimeters can be re-used for the measurement of radiation dose if they are annealed after the first irradiation at room and elevated temperature. Because the fading during the second annealing is much higher than during the first annealing, it may be concluded that these dosimeters can be used for multiple measurements of absorbed dose of gamma-ray irradiation. Additional investigations should provide a more detailed information regarding the pMOS dosimeters re-use.

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AUTHOR CONTRIBUTIONS

Theoretical analysis was carried out by Milić M. Pejović, Momčilo M. Pejović, and Aleksandar B. Jakšić. Experiments were carried out by Milić M. Pejović, Momčilo M. Pejović, Koviljka Dj. Stanković, and Slavoljub A. Marković. All of the authors have analyzed and discussed the results. The manuscript was written by Milić M. Pejović and Momčilo M. Pejović. The figures were prepared by Milić M. Pejović.

REFERENCES

[1] Rowbottom, C. G., Jaffray, D. A., Characteristics and Performance of Micro-MOSFET: an "Imageable" Dosimeter for Image-Guided Radiotherapy, *Med. Phys., 31* (2004), 3, pp. 609-615

[2] Jornet, N., *et al*., Comparision Study of MOSFET Detectors and Diodes for Entrace in Vivo Dosimetry in 18 MV X-Ray Bems, *Med. Phys., 31* (2004), 9, pp. 2534-2542

[3] Scarantino, C. W., *et al*., An Implantable Radiation Dosimeter for Use in External Beam Radiation Therapy, *Med. Phys., 31* (2004), 9, pp. 2658-2671

[4] Cygler, J. E., *et al*., Measurement of Urethral Dose Profiles in Prostate Brachytherapy using a Linear MOSFET Array Dosimeter, *Radiother Oncol., 71* (2004), Supll. 2, pp. 592-593

[5] Beddar, A. S., *et al*., Preliminary Evaluation of Implantable MOSFET Radiation Dosimeters, *Phys. Med. Biol., 50* (2005), 1, pp. 141-149

[6] Halvorsen, P. H., Dosimetric Evaluation of a New MOSFET *in Vivo* Dosimeter, *Med. Phys., 32* (2005), 11, pp. 110-117

[7] Scalchi, P., Francescon, P., Rajaguru, P., Characterization of a New MOSFET Detector Configuration for in Vivo Skin Dosimetry, *Med. Phys., 32* (2005), 6, pp. 1571-1578

[8] Briere, T. M., Beddar, A. S., Gillin, M. T., Evalution of Pre-Calibration Implantable MOSFET Radiation Dosimeters for Megavoltage Photons Beams, *Med. Phys., 32* (2005), 11, pp. 3346-3349

[9] Briere, T. M., *et al*., Single-Use MOSFET Radiation Dosimeters for the Quality Assurance of Megavoltage Photons Beams, *Phys. Med. Biol., 51* (2006), 5, pp. 1139-1144

[10] Holmes-Siedle, A. G., The Space Charge Dosimeter-General Principles of a New Method of Radiation Dosimetry, *Nucl. Instr. Methods, 121* (1974), 1, pp. 169-179

[11] Holmes-Siedle, A., Adams, L., RADFET: A Review of the Use of Metal-Oxide-Silicon Devices as Integrating Dosimeters, *Radiat. Phys. Chem., 28* (1986), 2, pp. 235-244

[12] Kelleher, A., *et al*., The Effects of Gate Oxide Process Variations on the Long-Term Fading of pMO Dosimeters, *Sensors Actuators A, 37-38* (1993), pp. 370-374

[13] Gladstone, D. J., *et al*., Miniature MOSFET Radiation Dosimeter Probe, *Med. Phys., 21* (1994), 11, pp. 1721-1728

[14] Ristić, G., Golubović, S., Pejović, M., Sensitiviti and Fading of pMOS Dosimeters with Thick Gate Oxide, *Sensors and Actuators A, 51* (1996), 2-3, pp. 153-158

[15] Ristic, G., Jakšić, A., Pejović, M., pMOS Dosimetric Transistors with Two-Layer Gate Oxide, *Sensors and actuators A, 63* (1997), pp. 129-134

[16] Pejović, M. M., *et al*., Gamma-Ray Irradiation and Post-Irradiation at Room and Elevated Temperature Response of pMOS Dosimeters with Thick Gate Oxides, *Nucl Technol Radiat, 26* (2011), 3, pp. 261-265

[17] Kelleher, A., Lane, L., Adams, L., A Design Solution to Increasing the Sensitivity of pMOS Dosimeters: the Stacked RADFET Approach, *IEEE Trans. Nucl. Sci., 42* (1995), 1, pp. 48-51

[18] O'Connel, B., *et al*., Stacked RADFETs for Increased Radiation Sensitivity, *IEEE Trans. Nucl. Sci., 43* (1996), 3, pp. 985-990

[19] Ristić, G., Goluboviš, S., Pejović, M., P-Channel Metal-Oxide-Semiconductor Dosimeter Fafding Dependencies on Gate Bias and Oxide Thickness, *Appl. Phys. Lett., 66* (1995), 1, pp. 88-89

[20] Jakšić, A., *et al*., Gamma-Ray Irradiation and Post-Irradiation Response of High Dose Range RADFET, *IEEE Trans. Nucl. Sci., 49* (2002), 3, pp. 1356-1363

[21] Pejović, M. M., Pejović, M. M., Jakšić, A. B., Radiation-Sensitive Field Effect Transistor Response to Gamma-Ray Iirradiation, *Nucl Technol Radiat, 26* (2011), 1, pp. 25-31

[22] Knoll, G. F., Radiation Detection and Measurement, 1989, John Wiley and Sons, New York, USA

[23] Kelleher, A., *et al.*, Investigation Into the Re-Use of PMOS Dosimeters, *IEEE Trans. Nucl. Sci., 41* (1994), 3, pp. 445-451
[24] Stanković, Dj. K., Influence of the Plain-Parallel Electrode Surface Dimensions on the Type A Measurement Uncertainty of GM Counter, *Nucl Technol Radiat, 26* (2011), 1, pp. 39-44
[25] Vujisić, M., Stanković, K., Osmokrović, P., A Statistical Analysis of Measurement Results Obtained from Nonlinear Physics Laws, *Applied Mathematical Modelling, 35* (2011), 7, pp. 3128-3135
[26] Pejović, M. M., Pejović, M. M., Jakšić, A. B., Contribution of Fixed Oxide Traps to Sensitivity of pMOS Dosimeters During Gamma Ray Irradiation and Annealing at Room and Elevated Temperature, *Sensors and Actuators A, 174* (2012), pp. 85-90
[27] Asensio, L. J., *et al.*, Evaluation of a Low-Cost Commercial MOSFETs as Radiation Dosimeter, *Sensors and Actuators A, 125* (2006), pp. 288-295

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Милић М. ПЕЈОВИЋ, Момчило М. ПЕЈОВИЋ, Александар Б. ЈАКШИЋ, Ковиљка Ђ. СТАНКОВИЋ, Славољуб А. МАРКОВИЋ

СУКЦЕСИВНО ОЗРАЧИВАЊЕ ГАМА ЗРАЧЕЊЕМ И ОДГОВАРАЈУЋИ ОПОРАВАК pMOS ДОЗИМЕТАРА

Размотрена је могућност примене pMOS дозиметара за поновно мерење дозе гама зрачења. Ови дозиметри су озрачивани до дозе 35 Gy, потом опорављани на собној и повишеној температури и поново озрачивани до исте дозе. Праћене су промене напона прага током ових процеса и показано је да њихова поновна примена зависи од напона на гејту током зрачења. За напон на гејту од 5 V pMOS дозиметри се могу ефикасно применити за поновно мерење дозе после опоравка. Такође, pMOS дозиметри чија је поларизација на гејту 2.5 V могу се применити за поновно мерење дозе уз претходну калибрацију. За поновну примену pMOS дозиметара потребно је извршити опоравак тако да фединг буде већи од 50%.

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