APPLICATION OF pMOS DOSIMETERS IN LOW-FIELD MODE FOR RADIATION DOSE MEASUREMENTS WHICH COULD BE USED IN RADIOTHERAPY

by

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Scientific paper
DOI: 10.2298/NTRP1604349P

The pMOS dosimeters sensitivity (Tyndall National Institute, Cork, Ireland) to gamma and X-ray irradiation and 2000 h fading at room temperature is presented. The radiation fields were created using a ^{60}Co source for two dose ranges (1-5 Gy and 10-50 Gy) as well as for X-ray units of a 280 kV spectrum for a single dose range from 0.1 to 1 Gy. Irradiation was performed in low-field mode (no gate bias during irradiation, $V_{\mathrm{irr}} = 0$ V), sensitivity characterized by the threshold voltage shift as a function of the absorbed radiation dose and time after irradiation. Linear dependence between the threshold voltage shift and the absorbed radiation dose was only established for pMOS dosimeters which were irradiated by gamma rays in the dose range of 1 to 5 Gy. Obtained results show that the sensitivity of these components is much higher in case of X-ray radiation than in that of gamma ray radiation. Moreover, the fading of irradiated pMOS dosimeters with X-rays is higher than in the ones irradiated with gamma rays.

Key words: pMOS dosimeter, radiation dose, threshold voltage shift, fading, in vivo dosimetry

INTRODUCTION

External beam radiation is a well-accepted and established therapeutic modality for cancer treatment [1]. In this technique radiation beams generated by either a radiation source or linear accelerator are carefully directed at the patient's malignant tumor with the purpose of delivering a lethal dose to the cancerous cells without inducing significant damage to the healthy tissue. Dose precision in radiotherapy is expected to be of the order 5 %; however, ensuring that the expected dose is properly delivered to the correct spot with desirable intensity requires a robust and sophisticated radiation oncology quality assurance (QA) program [1, 2]. Also, the verification of the final dose delivered to the patient, which can only be carried out by *in vivo* dosimeters, is very important and should basically be used for all patients undergoing radiation treatments [3].

In vivo dosimetry can be measuerd by thermoluminescent dosimeters (TLD) [4, 5], diode dosimeters [6, 7], and metal-oxide-semiconductor field effect transistor (MOSFET) dosimeters [8, 9]. TLD are tissue-equivalent, small volume, accurate and cable-free. However, the reading procedure represents an important drawback of TLD because it occurs off-line, it is time consuming and information is lost during the reading. Although TLD requires a highly trained operator and the cost of the readout equipment is relatively high, it is the most popular dosimeter for QA in radiotherapy [1, 10, 11].

Diode dosimeters provide instantaneous readout, however, diodes must be connected to a cable for applied voltage during radiation. Even though diode dosimeters are sensitive to temperature and dependent on the energy of the radiation beam, the correction and calibration factors are generally well known [1, 10, 11].

MOSFET dosimeters are of small volume (the radiation sensitive region, the oxide film layer, is typically 1 m 200 m 200 m) and include more advantages as a non-destructive readout of information on the absorbed radiation dose, real-time reading, dose rate independence response, the ability of multiple readouts without erasing information on the accumulated dose, very low power consumption and a very competitive price [12, 13]. They are highly sensitive and can operate in low-field mode (without gate bias during irradiation)

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and show lower over-response at low energies than the diode dosimeter [14]. MOSFET dosimeter sensitivity can be adjusted, which makes them suitable for various applications in radiotherapy such as hadron therapy [15]. Also, MOSFET dosimeters have a limited life span because they respond linearly only within a certain range of the total accumulated dose, which depends on the dosimeter type and sensitivity. Once the upper limit of linearity is achieved, the MOSFET dosimeter needs to be replaced. However, recent studies have shown that such MOSFET dosimeters can be recovered for re-use by keeping them at room or elevated temperature for a sufficient time [16, 17] or by annealing using current [18].

BASIC MECHANISMS AND DOSIMETRIC PARAMETERS

It is known [19] that ionizing radiation creates positive charge in the MOSFET oxide which is stored near and at the SiO-Si interface, leading to a transistor's threshold voltage shift ΔV_T. The contributions of positive charge in the oxide ΔQ_{ot} and interface traps ΔQ_{it} to ΔV_T of MOSFET p-channel can be expressed as

$$\Delta V_T \quad \frac{\Delta Q_{ot} \quad \Delta Q_{it}}{C_{0x}} \tag{1}$$

where C_{0x} is the oxide capacitance. In MOSFET p-channel, both the positive charge in the oxide and interface traps contribute to the threshold voltage shift in the same direction. This is why MOSFET p-channel, instead of MOSFET n-channel, are usually used as radiation dosimeters. Thus, radiation sensitivity MOSFET p-channel are also known as pMOS dosimeters or radiation sensitive field effect transistors (RADFET).

In practical applications it is most convenient for MOSFET dosimeters to have a linear response to the threshold voltage shift regarding the absorbed radiation dose . It was shown that the response is linear for low doses and progressively saturates at a maximum value regarding gate bias [20]. Linear dependence is given by [21]

$$\Delta V_T \quad AD^n \tag{2}$$

where A is the constant and n is the degree of linearity. For $n = 1$, the constant A represents sensitivity S

$$S \quad \frac{\Delta V_T}{D} \tag{3}$$

The sensitivity of MOSFET dosimeters increases with gate voltage increase during irradiation [22, 23]. Namely, the number of created positive trapped charges in the oxide layer and interface traps rises with the number of holes which have avoided the re-combination with electrons. Low-field mode (when there is no gate bias during irradiation, $V_{irr} = 0$ V) corresponds to a small positive gate bias because of a work function difference between the gate and substrate which results in a low electric field in the oxide. As for gate bias during irradiation $V_{irr} > 0$, a large number of holes will escape the initial re-combination, further increasing the probability of an increase in positive trapped charge in the oxide and interface traps which, therefore, leads to the increase in ΔV_T. It is shown [24-26] that positive gate bias during irradiation leads to a more linear response of MOSFET dosimeters. Moreover, the sensitivity of MOSFET dosimeters can also be increased with the increase in oxide layer thickness [27, 28]. This is mostly due to the increase in the number of created positive trapped charges in the oxide with the increase in oxide layer thickness.

Long-term stability of irradiated MOSFET dosimeter threshold voltage is defined by the fading F which can be calculated as [28]

$$F \quad \frac{V_T(0) \quad V_T(t)}{V_T(0) \quad V_{T0}} \quad \frac{V_T(0) \quad V_T(t)}{\Delta V(0)} 100\% \tag{2}$$

where V_{T0} is the pre-irradiation threshold voltage, $V_T(0)$ – the threshold voltage immediately after irradiation, $V_T(t)$ – the threshold voltage after annealing time t, and $\Delta V_T(0)$ – the threshold voltage shift immediately after irradiation.

EXPERIMENTAL DETAILS

The devices used in this study were Al-gate p-channel enhanced MOSFET specifically designed for measuring the radiation dose (pMOS dosimeters, Tyndall National Institute, Cork, Ireland). The chip size is 1 mm 1 mm, and there are two 300/50 and 690/15 MOSFET on the chip. The numbers 300/50 and 690/15 represent the width and length of channels, respectively. One in each of the 300/50 and 690/15 devices have four terminals, bulks, drains, gates, and sources. These transistors can be treated as two terminal devices because their gates and drains, as well as their bulks and sources, are joined together and these MOSFET were used in our research (a detailed description can be found in [29]). Three transistors were used for each irradiation experiment condition. The differences between nominally identical samples were within 5 %.

The pMOS dosimeters were divided into three groups. The first group was irradiated with X-rays in the dose range from 0.1 to 1 Gy. Irradiation was performed using the X-ray generator MG320 (Philips, The Netherland) with a nominal tube voltage of 320 kVp. Beam quality used for the irradiation was generated using a tube voltage of 280 kV (140 keV), inherent filtration of 4 mm Al additional filtration of 3 mm Cu, which corresponds to the first half-value layer of 18 mm Al or 3.2 mm Cu. The second and third group was irradiated with gamma rays from ^{60}Co ranging from 1 to 5 Gy and 10 to 50 Gy, respectively. Irradiation was performed using teletherapy cobalt CIRUS-TS (CIS Alcyon, Biointernational, France) with 230 TBq activity (01.0.9.1999). Irradiation was carried out with an X or gamma ray beam incidenting normally to the oxide layer plane in low-field mode. The low-field mode is the simplest application of pMOS dosimeters, very important in the case of *in vivo* dosimetry. The irradiation was carried out at the Secondary Standard Dosimetry Laboratory of the Vinca Institute of Nuclear Sciences, Belgrade, Serbia (see Ref. [28] for more details).

The voltage V_{out} (fig. 1) was measured at 12 A readout current corresponding to the zero temperature coefficient (ZTC) point. The gate and drain of each pMOS dosimeter were short-circuited, as were the pMOS dosimeter's bulk and source. The technique for ZTC determination consisted of the following: readout current ranging from 1 to 150 A and output voltage V_{out} measured at temperature ranges from 25 to 100 °C. As can be seen from fig. 2, all of the curves intersected in the vicinity of 12 A. It can, thus, be concluded that a selection of this current would minimize the effect of temperature on threshold voltage. The voltage V_{out} measured for a drain current of 12 μA was taken as the threshold voltage V_T. The *I-V* characteristics and V_T were measured with a Keithly 4200 Semiconductor Characterization System. The threshold voltage shift ΔV_T is defined as V_T-V_{T0}, where V_{T0} and V_T are the threshold voltage measured before and after irradiation, respectively. Annealing represents the threshold voltage V_T changes of irradiation transistors at room temperature.

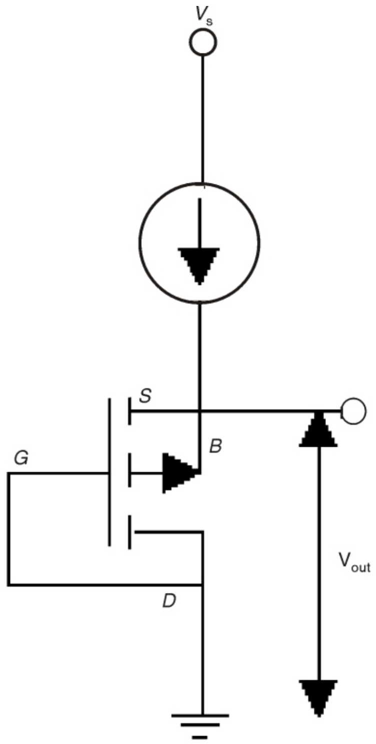

Figure 1. Threshold voltage VT measurement configuration

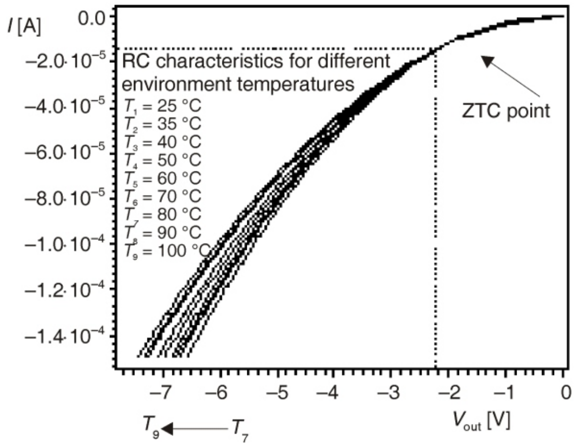

Figure 2. Current *I* as a function of output voltage V_{out}

RESULTS AND DISCUSSION

Irradiation

Figure 3 shows the threshold voltage shift ΔV_T of pMOS dosimeters for X-ray radiation dose *D* in the range from 0 to 1 Gy. It can be seen that the increase in the radiation dose within this range leads to an increase in ΔV_T from 0.11 do 0.66 V.

In figs. 4 and 5, the same dependences for gamma ray irradiation in the range from 0 to 5 Gy and that of 0 to 50 Gy are shown, respectively. The increase in the radiation dose in the range from 0 to 5 Gy leads to the increase in the ΔV_T value of 0.25 to 1.2 V, while the increase in the radiation dose in the range from 0 to 50 Gy leads to the increase of ΔV_T of 0.60 to 1.8 V.

For a practical application of pMOS dosimeters it is necessary to know the functional dependence between ΔV_T and *D* within the ranges of used radiation doses. This is why a fitting of experimental data with

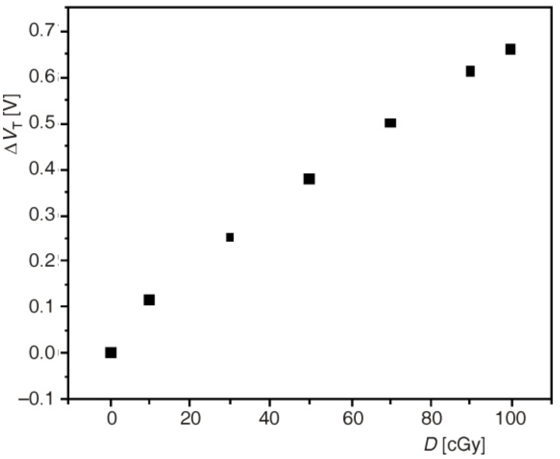

Figure 3. Threshold voltage shift ΔV_T as a function of X-ray radiation dose *D* in the range from 0 to 1 Gy

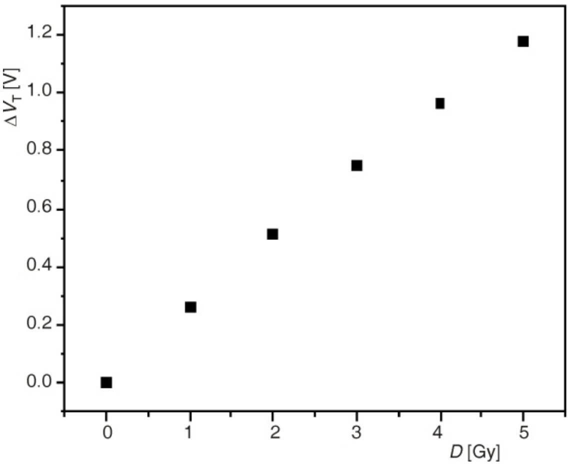

Figure 4. Threshold voltage shift ΔV_{T} as a function of gamma ray radiation dose *D* in the range of 0 to 5 Gy

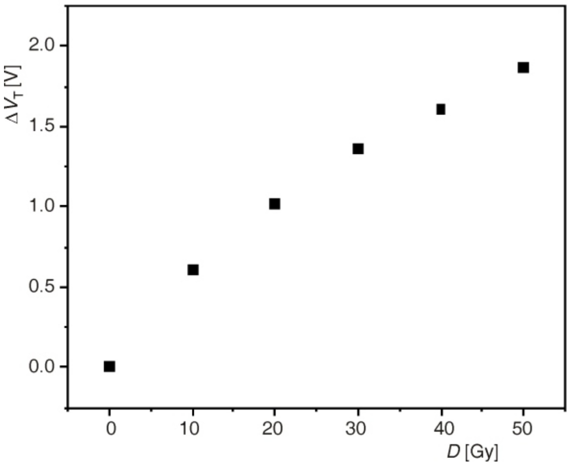

Figure 5. Threshold voltage shift ΔV_{T} as a function of gamma ray radiation dose *D* in the range of 0 to 5 Gy

expression (2) is necessary. The fitting of experimental results using this expression (2) can be applied in the case when there is a linear dependence between ΔV_{T} and *D*, when the fitting parameter $n = 1$. This expression can also be used when there is no linear dependence between ΔV_{T} and *D*, *i. e.*, when the fitting parameter *n* is not constant (power low). Experimental results from figs. 3, 4, and 5 were also fitted using the exponential function

$$\Delta V_{\mathrm{T}} \quad a(1 \quad \mathrm{e}^{\;bD}) \tag{4}$$

where *a* and *b* are constants. Values of correlation coefficients for these fittings are presented in tab. 1.

Table 1. Values of correlation coefficient R^2 for a single range X-ray radiation dose and two ranges of a gamma ray radiation dose

Radiation	Dose range [Gy]	R^2	Fit
X-ray	0 – 1	0.983	Linear
	0 – 1	0.998	Exponential
	0 – 1	0.999	Power low
Gama ray	0 – 5	0.998	Linear
	0 – 5	0.999	Exponential
	0 – 5	0.999	Power low
Gamma ray	0 – 50	0.947	Linear
	0 – 50	0.998	Exponential
	0 – 50	0.999	Power low

As can be seen from tab. 1, power-low fitting of experimental results is exceptional for the three dose ranges. Moreover, it can be seen that the experimental results are very well fitted with the exponential function. The linear fit can be used only when gamma ray radiation doses are in the range of 0 to 5 Gy (fig. 4) and when pMOS sensitivity is the same over the entire range, its value being 50 mV/Gy. However, having that the experimental data regarding the X-ray radiation dose is in the range from 0 to 1 Gy (fig. 3) and the gamma ray radiation dose in the range of 0 to 50 Gy (fig. 5), there is no linear dependence between ΔV_{T} and *D*, while $\Delta V_{\mathrm{T}}/D$ varies for every radiation dose. That is why the X-ray radiation dose of $D = 0.1$ Gy, $\Delta V_{\mathrm{T}}/D = 1150$ mV/Gy, while $D = 1$ Gy, $\Delta V_{\mathrm{T}}/D = 680$ mV/Gy. For a gamma ray radiation dose of $D = 10$ Gy, $\Delta V_{\mathrm{T}}/D = 60$ mV/Gy, $D = 50$ Gy, $\Delta V_{\mathrm{T}}/D = 37$ mV/Gy. According to these results, it can be concluded that the sensitivity of pMOS dosimeters to X-rays is significantly higher than to gamma rays. This is a consequence of different photon energies which lead to the ionization of gate-oxide molecules. Namely, X-ray photon energy of 140 keV leads to molecule ionization by both photo and Compton's effect, while gamma rays, which originate from ^{60}Co with energies of 1.17 and 1.33 MeV, lead to molecule ionization only by Compton's effect [30]. Since the probability for molecule ionization by photo effect is significantly higher than that of Compton's, during X-ray irradiation, a much larger number of positive trapped charges and interface traps are formed than during gamma ray irradiation, causing changes in ΔV_{T} values.

Fading

Fading of pMOS dosimeters which were previously irradiated with X-rays to a radiation dose of 1 Gy are shown in fig. 6. As can be seen, fading values after 24 h of annealing at room temperature are at about 13 %, from 24 to 80 h, fading increases for about 8 %, while for the time of 80 to 2000 h, it increases for about 2%. For pMOS dosimeters which were previously irradiated with gamma rays to the dose of 5 Gy (fig. 7), for the first 24 h of annealing at room temperature, fading is about 3.5 %, while for the annealing time of 24 to 800 h it increases up to 6 %. During further annealing, fading is minimal, *i. e.*, the value stable. The fading of pMOS dosimeters previously irradiated with gamma rays to 50 Gy is shown in fig. 8. It can be seen that for the first 24 h fading is 6 % and its value slightly increases up to the limit of 2000 h of annealing time. For

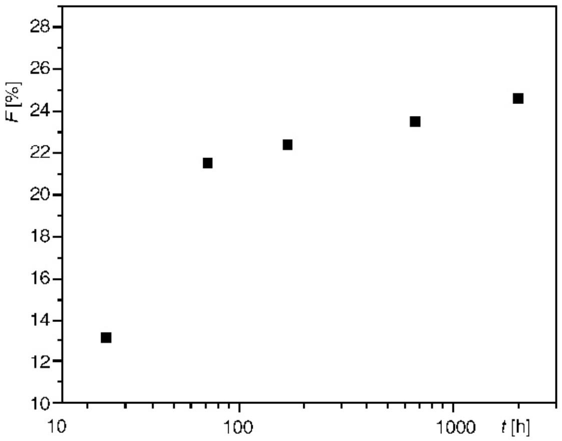

Figure 6. Fading *F* at room temperature for 2000 h of a pMOS dosimeter previously irradiated with X-ray radiation dose of 1 Gy

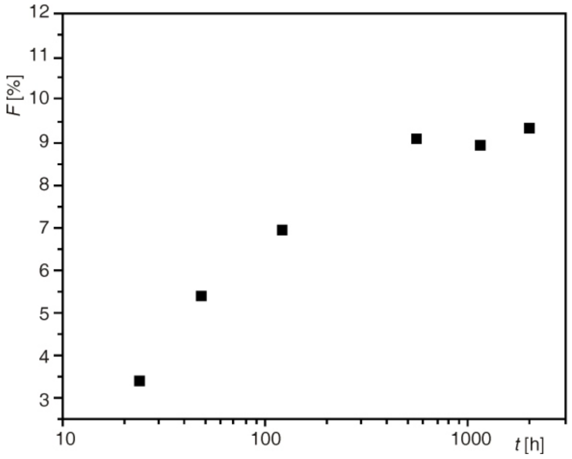

Figure 7. Fading *F* at room temperature for 2000 h of a pMOS dosimeter previously irradiated with a gamma ray radiation dose of 5 Gy

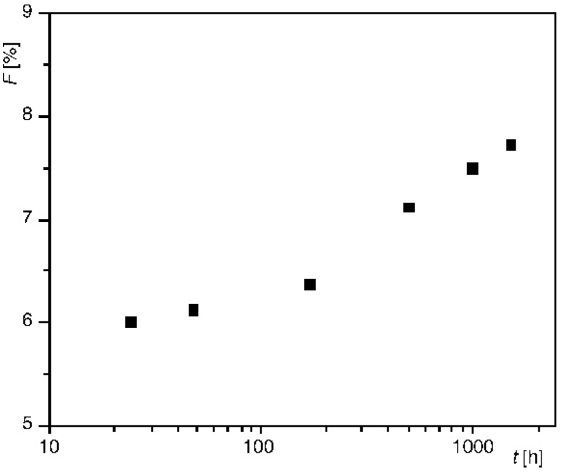

Figure 8. Fading *F* at room temperature for 2000 h of a pMOS dosimeter previously irradiated with a gamma ray radiation dose of 50 Gy

an annealing time longer than 2000 h, there is a slight increase in fading and, therefore, fading after 2000 h is approx. 2 % higher than after 2000 h. If we compare the results shown in figs. 6, 7, and 8, it can be concluded that at 2000 h of annealing at room temperature, the largest fading is to be detected in pMOS dosimeters previously irradiated with X-rays, amounting to 23 %. For pMOS dosimeters previously irradiated with gamma rays of 5 Gy to 50 Gy, the fading after 2000 h is about 8-9 %.

CONCLUSIONS

Threshold voltage shift ΔV_T as a function of the X-ray radiation dose *D* in the range from 0 to 1 Gy and gamma ray radiation doses ranging from 0 to 5 Gy and 0 to 50 Gy in the low-field mode have been investigated. In addition, fading results at room temperature for a 2000 h time period after irradiation are also presented. The results demonstrate a linear dependence between ΔV_T and *D* for pMOS dosimeters irradiated with gamma ray radiation doses in the range of 0 to 5 Gy. On the basis of such behavior, it was concluded that the sensitivity $\Delta V_T/D$ is the same over the entire range and that its value equals 50 mV/Gy. X-ray radiation doses within the range of 0 to 1 Gy and gamma-radiation doses in the range from 0 to 50 Gy can be well described by the exponential function. In this case, sensitivity depends on the radiation dose value. The results also show that the sensitivity of pMOS dosimeters is significantly higher in case of X-ray irradiation than when gamma-ray irradiation is concerned. Namely, for a X-ray radiation dose of 1 Gy, $\Delta V_T/D =$ $= 660$ mV/Gy, while for the same gamma ray radiation dose, $\Delta V_T/D = 47$ mV/Gy. These results show that the devices used are very sensitive detectors of gamma and, even more so, of X-ray radiation for doses applied in radiotherapy for a single fraction. However, the main disadvantage is a significant loss of dosimetric information (high fading value) in the first few days after irradiation, which is especially evident in pMOS dosimeters previously irradiated with X-rays. This is why they are not suitable for measuring the total radiation dose which the patient acquires during days or weeks of radiotherapy.

ACKNOWLEDGEMENT

This work was supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia under Contract no. 171007.

AUTHORS' CONTRIBUTIONS

Theoretical analysis was carried out by S. M. Pejović, M. M. Pejović, and D. Stojanov, the experiments carried out by S. M. Pejović and M. M. Pejović. All authors have analyzed and discussed the results. The manuscript was written by S. M. Pejović and M. M. Pejović. The figures were provided by S. M. Pejović.

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Received on September 9, 2016
Accepted on December 1, 2016

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ПРИМЕНА pMOS ДОЗИМЕТАРА У ПАСИВНОМ МОДУ ЗА МЕРЕЊЕ РАДИЈАЦИОНИХ ДОЗА КОЈЕ БИ СЕ МОГЛЕ КОРИСТИТИ У РАДИОТЕРАПИЈИ

У раду су приказани резултати осетљивости pMOS дозиметара (Tyndall National Institute, Cork, Ireland) на гама и X-зрачење као и њихов опоравак на собној температури у трајању од 2000 часова. Радијациона поља су реализована коришћењем ^{60}Co извора за два опсега доза (1-5 Gy и 10-50 Gy) и уређаја за добијање X-зрака спектра 280 kV за област доза 0.1-1 Gy. Озрачивање је обављено без поларизације на гејту. Карактеризација осетљивости рађена је на основу помераја напона прага у функцији апсорбоване дозе и времена после озрачивања. Линеарна зависност између помераја напона прага и апсорбоване дозе запажена је само у случају pMOS дозиметара озрачиваних гама-зрацима у опсегу 1-5 Gy. Показано је да је осетљивост ових компонената на X-зрачење знатно већа него на гама зрачење. Такође је показано да је фединг pMOS дозиметара који су претходно озрачивани X-зрацима знатно већи него дозиметара који су претходно озрачивани гама зрацима.

Кључне речи: pMOS дозиметар, радијациона доза, промена напона прага, фединг, in vivo дозиметрија