Chapter 12

Application of pMOS Dosimeters in Radiotherapy

Momčilo M. Pejović and Milić M. Pejović

Additional information is available at the end of the chapter

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Abstract

The results of a study on pMOS dosimeters manufactured by Tyndall National Institute, Cork, Ireland and their sensitivity on radiation doses used in radiotherapy are presented. Firstly, we deal with analysis of defect precursors created by ionizing radiation, responsible for increase in fixed and switching traps, which are further responsible for threshold voltage shift as a dosimetric parameter. Secondly, influence of some parameters, such as gate bias during irradiation, gate oxide thickness and photons energies, on threshold voltage shift is presented. Fading of irradiated pMOS dosimeters and possible application of commercial MOSFETs in ionizing radiation dosimetry are also presented.

Keywords: fading, MOSFET, pMOS dosimeter, radiation dose, threshold voltage shift

1. Introduction

External radiotherapy is a well-accepted and established therapeutic modality for cancer treatment [1]. In this technique, radiation beams, generated by either radiation source or linear accelerator, are specifically optimized to cause the death of the tumor cells without having a greater impact on the healthy tissues. It is estimated that dose precision in radiotherapy is approximately ±5%. However, in order to ensure proper dose delivery to the designated area and appropriate intensity, a sophisticated radiation oncology Quality Assurance (QA) program is required [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 treatment [3].

In vivo dosimetry can be measured by thermoluminescent dosimeters (TLDs) [4, 5], diode dosimeters [6, 7] and MOSFET (Metal-Oxide-Semiconductor Field Effect Transistor) dosimeters [8, 9]. TLDs characteristics include the following: cable-free, accurate, small volume and tissue-equivalence. However, an important drawback of TLDs is the reading procedure because information is lost during the reading. Currently, TLDs are most popular dosimeters for QA radiotherapy despite the relatively high cost of the readout equipment and the requirement of a highly trained operator.

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

The concept of radiation sensitive MOSFETs as dosimeter is based on converting the threshold voltage shift as a dosimetric parameter into radiation dose. Ionizing radiation creates positive charge in the MOSFETs oxide and interface trap at silicon dioxide-silicon interface leading to a transistors threshold voltage shift. In p-channel MOSFETs, both the positive charge in the oxide and interface traps contributes to threshold voltage shift in the same direction. This is reason why p-channel MOSFETs instead n-channel MOSFETs are usually used as dosimeters. p-channel MOSFETs can be application in low-field mode (without gate bias during irradiation) and in high-field mode (with gate bias during irradiation). High-field mode leads to the sensitivity increase in MOSFET dosimeters.

The p-channel MOSFET as integrating dosimeters has been proposed in 1970 [10] and results being verified in 1974 [11]. This further leads to the production of radiation sensitive p-channel MOSFETs, also known as RADiation-sensitive Field Effect Transistor (RADFET) or pMOS dosimeter [12]. Besides, radiotherapy pMOS dosimeters could be used for radiation space monitoring [13, 14], irradiation of food plants [15] and in personal dosimetry [16].

A major advantage of the MOSFET as a radiation sensor is that the radiation-sensitive region, the oxide film, is very small [11]. The sensing volume is much smaller than competing integral dose measuring devices, such as the ionization chamber or TLD. The MOSFETs sensitive volume is typically 1 μm x 200 μm x 200 μm [17] implying that it could be used in vivo dosimetry [18]. This MOSFETs property also makes them attractive for measurements in the gradient radiation field where the gradient mostly depends on a single space coordinate, like resolving dose of X-ray micro beams or dept dose distribution [19]. The advantages of MOSFETs as dosimeters also include real time or delayed reading, non-destructive and immediate dosimetric information readout, wide dose range, accuracy, competitive price and possible integration with other sensors and/or electronics [20]. Moreover, another field where it is possible to explore their advantages is hadron therapy, which is one of the promising radiation modalities in radiotherapy [21]. On the other hand, an important disadvantage of MOSFETs as radiation sensors is the need to separate calibration in fields of different modalities and energies. Furthermore, MOSFET's total accumulated dose range depends on the dosimeter sensitivity and type. The MOSFET needs to be replaced when the upper limit of linearity is achieved. Although, recently, the possibility of MOSFET reuse after recovering for a certain period of time at room or elevated temperature [22] or by current annealing [23] has been studied.

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In radiotherapy, the radiation oncologist determines the radiation dose depending on many factors such as the type and size of tumor, location in the body, how close the tumor is to other radiation sensitive tissues, how deep into the body the radiation need to penetrate, the patient general health and medical history, whether the patient will have other type of cancer treatments (e.g., chemotherapy) and other factors such as patient age and medical conditions. Cumulative dose range used in radiotherapy ranges from 20 to 70 Gy [24], while typical radiation dose for one fraction is from 1 up to 5 Gy.

This chapter presents some of the results obtained in our laboratory, which considers the influence of some parameters to pMOS dosimeters sensitivity and fading. Dosimeters were manufactured in Tyndall National Institute, Cork, Ireland. Sensitivity results are also presented for commercial MOSFETs in order to investigate their possible application in radiotherapy.

2. Mechanisms responsible for threshold voltage shift during irradiation

The dosimetry of ionizing radiation using radiation-sensitive MOSFETs is based on the threshold voltage shift, conversion into absorbed radiation dose *D* [25, 26]. This shift originates in the radiation-induced electron-hole pairs formed during irradiation. Namely, gamma and X-rays interact with the electrons in SiO_2 molecules releasing secondary electrons and holes, that is, photons break $\equiv Si_o - ihSi_o \equiv$ and $\equiv Si_o - Si_o \equiv$ covalent bonds in the oxide [27] (the index $_o$ is used to denote silicon atom in the oxide). The released secondary electrons, which are highly energetic, may be recombined by holes at the place of production or may escape recombination. The secondary electrons that escape recombination pass through the oxide bulk, break covalent bonds and create $\equiv Si_o - O^{\bullet +} - Si_o \equiv$ complexes, where $^\bullet$ denotes the unpaired electron. This complex is energetically very shallow and trapped holes can easily escape it. It is obvious that secondary electrons play a more important role in the bond breaking than highly energetic photons, due to the difference in their effective masses, that is, in their effective cross section.

The $\equiv Si_o - O - Si_o \equiv$ mainly distributed near the Si/SiO_2 interface, can also the broken by passing secondary electrons, usually created by non-bridging oxygen (NBO) centers $\equiv Si_o - O$ and positively charged $E^{'}$ centers, $\equiv Si_o^+$ [28]. The main precursor of the traps in the oxide bulk and in interface regions is the NBO center, as an energetically deeper centre, and represents a more likely negative than positively charged amphoteric defect. Also, a secondary electron can also break $\equiv Si_o - Si_o \equiv$ bonds and create $E_\gamma^{'}$ centers, $\equiv Si_o^\bullet$ [27] by knocking out an electron.

Positive charge is formed in oxide by holes trapping, while electrons trapping lead to creation of negative charge. The concentration of positive charge in oxide is much higher since the hole trapping centers are more numerous compared to electron trapping centers. Moreover, trapped electrons and holes near Si/SiO_2 interface have the strongest impact on channel carriers, hence on MOSFET characteristics.

Amphoteric defects $Si_3 \equiv Si_s^\bullet$ (index $_s$ is used to indicate a silicon atom in substrate) are marked as true interface traps and represent defects at the Si/SiO_2 interface. At Si/SiO_2 interface, a silicon atom $\equiv Si_s^\bullet$ back bonds with three silicon atoms from the substrate $\equiv Si_s$ and is mostly marked as $\equiv Si_s^\bullet$ or $Si_s^\bullet$. Their creation can also originate from incident photons when they pass through the gate or substrate [27]; however, the amount can be neglected. Hydrogen released in the oxide (hydrogen-released species model H-model) [29, 30] is the main creator of interface traps. This model proposed that H ions released in the oxide by trapped holes at $\equiv Si_o - H$ and $\equiv Si_o - OH$ defects in the oxide drift toward the Si/SiO_2 interface under the positive electric field. When H^+ ions arrive at the interface, it picks up an electron from the substrate, becoming a highly reactive atom H^0 [31]. This atom reacts at the interface producing $Si_s^\bullet$ [32]. Dimerization of hydrogen atoms also exists near the Si/SiO_2 interface, what further leads to creation of H_2 molecule [31]. The increase in $Si_s^\bullet$ continues during annealing of irradiated MOSFETs for a long period of time [33].

Positive trapped charge in the oxide is called fixed traps (FT), and positive trapped charge near Si/SiO_2 interface is called switching traps (ST) [27], where FT represents traps in the oxide that without the ability to exchange the charge with the channel within the MOSFET transfer/subthreshold characteristic measurement time frame. On the other hand, ST represents traps created near and at Si/SiO_2 interface, and they do capture (communicate with) the carrier from the channel within the transfer/subthreshold characteristic measurement time frame. Furthermore, one can differentiate between slow switching traps (SST) created in the oxide near Si/SiO_2 interface and fast switching traps (FST) created at Si/SiO_2 interface also known as true interface traps ($Si_s^\bullet$).

Threshold voltage shift ΔV_T during irradiation is a consequence of the increase in concentration of FT, Q_{FT}, and the increase in the concentration ST, Q_{ST}. The threshold voltage V_T can be expressed as follows [33]

$$V_T = V_{T0} - \frac{Q_{FT} + Q_{ST}}{C_{ox}} = V_{T0} + \Delta V_T, \quad (1)$$

where V_{T0} is the value of V_T before irradiation and C_{ox} is the gate capacitance. In p-channel MOSFETs, both FT and ST are positive and they contribute to the threshold voltage shift in the same direction, i. e. both V_T and V_{T0} are negative. Also, the so-called rebound effect [34] is absent in p-channel MOSFETs: This phenomenon is due to the competitive effect of positive charge in the oxide and negative interface traps generated in n-channel MOSFETs leading to a positive or negative ΔV_T value dependence on the relative values of Q_{FT} and Q_{ST}. This is the reason why p-channel MOSFETs instead of n-channel MOSFETs are usually used in dosimetry of ionizing radiation.

3. Response of pMOS dosimeters to gamma and X-ray radiation

3.1. Important pMOS dosimetric parameters

The most important parameters that characterize the pMOS dosimetric radiation response are sensitivity, dose linearity and room temperature long-term stability [35, 36]. Sensitivity

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represents threshold voltage shift ΔV_T and radiation dose D ratio ($\Delta V_T/D$) and could be controlled by the gate bias during irradiation. It is well known [37, 38] that an increase in sensitivity could be achieved with increase in gate bias during irradiation. In the case of positive gate bias, the sensitivity is higher, than in the case of negative gate bias and the lowest sensitivity being for zero gate bias [20]. Moreover, sensitivity increase can be achieved by increasing the gate oxide thickness [36–39] and by processing conditions which determine the FT density, their capture cross section and their location as well as the ST density [40].

In practical applications, it is most convenient for pMOS dosimeters to have a linear response of threshold voltage shift ΔV_T regarding observed radiation dose D. In this case, the sensitivity is the same for considered dose interval. It was shown that the response is linear for low doses and progressively saturates at a maximum values which respect to gate bias [40]. The linear dependence is given by [36]

$$\Delta V_T = A \cdot D^n, \tag{2}$$

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

$$S = \Delta V_T / D. \tag{3}$$

Positive gate bias during irradiation reduces the recombination of produced electron-hole pairs in SiO_2 and as a consequence the pMOS dosimeters response becomes more linear and sensitive [33, 41].

Room-temperature long-tem stability of irradiated pMOS dosimeters can be observed by calculating fading F. The percent of fading can be calculated as follows [27]:

$$F = \frac{V_T(0) - V_T(t)}{V_T(0) - V_{T0}} = \frac{V_T(0) - V_T(t)}{\Delta V_T(0)}, \tag{4}$$

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

3.2. Influence of gate bias on threshold voltage shift during irradiation

Figures 1 and **2** show the threshold voltage shift ΔV_T of pMOS dosimeters with gate oxide thickness of 1 μm for X-ray (energy of 140 keV) as a function of radiation dose D in the range from 0 to 1 0 cGy and from 0 to 1 Gy, while gate bias during irradiation was 0 and 5 V [35], respectively. Experimental data fitting with Eq. (2) for $n = 1$ shows an almost linear response between ΔV_T and D. Namely, for gate bias during irradiation of $V_{irr} = 0$ V, correlation coefficient is $r^2 = 0.98$, whereas for $V_{irr} = 5$ V, correlation coefficient is $r^2 = 0.99$.

Figure 3 shows the threshold voltage shift ΔV_T of pMOS dosimeters with gate oxide thickness of 1 μm as a function of gamma-ray radiation dose D (gamma radiation originate from 60Co) in range from 0 to 1 Gy for gate bias during irradiation $V_{irr} = 0$ V and $V_{irr} = 5$ V [38]. The same dependence for gamma-ray radiation dose in range from 0 to 5 Gy is given in **Figure 4** [38].

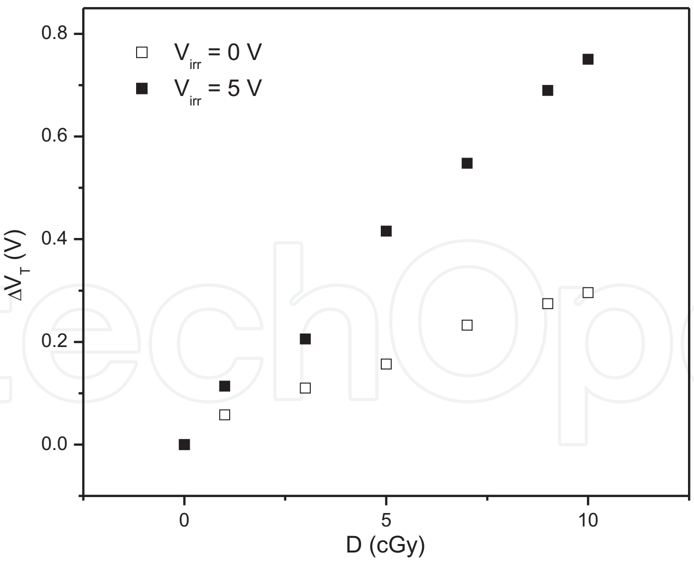

Figure 1. Threshold voltage shift ΔV_T in pMOS dosimeters with 1-μm-thick gate oxide as a function of X-ray radiation dose *D* in the 0–10 cGy range. Gate bias during irradiation V_{irr} was 0 or 5 V.

Experimental data fitting presented in these figures using Eq. (2) for $n = 1$ gives correlation coefficient $r^2 = 0.99$, so it is assumed that the linearity between ΔV_T and *D* is satisfactory for practical application.

Figure 5 shows the $\Delta V_T = f(D)$ dependence of pMOS dosimeters with gate oxide thickness of 1 μm for gamma-ray radiation dose in the range from 0 to 50 Gy [36]. During the irradiation, the gate biases V_{irr} were 0, 1.25, 2.50, 3.75 and 5 V. It can be seen that the threshold voltage shift for the same radiation dose increases with gate bias increase. The radiation dose up to 50 Gy did not significantly degrade the linearity of the pMOS dosimeters. Experimental data fitting

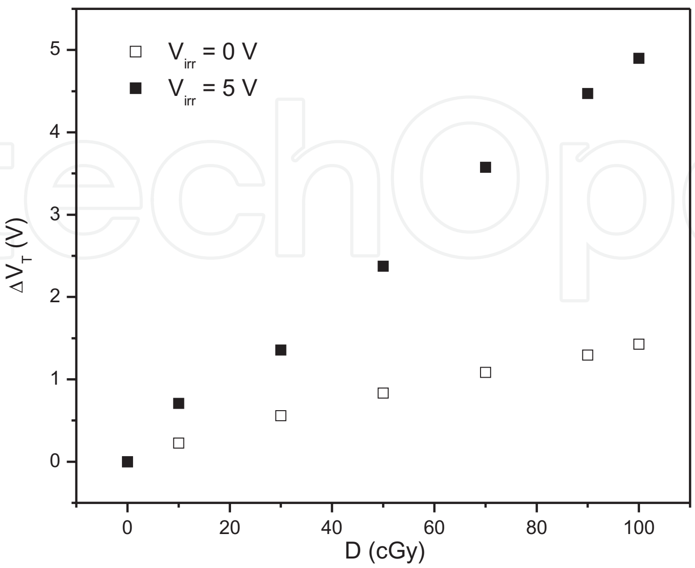

Figure 2. Threshold voltage shift ΔV_T in pMOS dosimeters with 1-μm-thick gate oxide as a function of X-ray radiation dose *D* in the 0–1 Gy range. Gate bias during irradiation V_{irr} was 0 or 5 V.

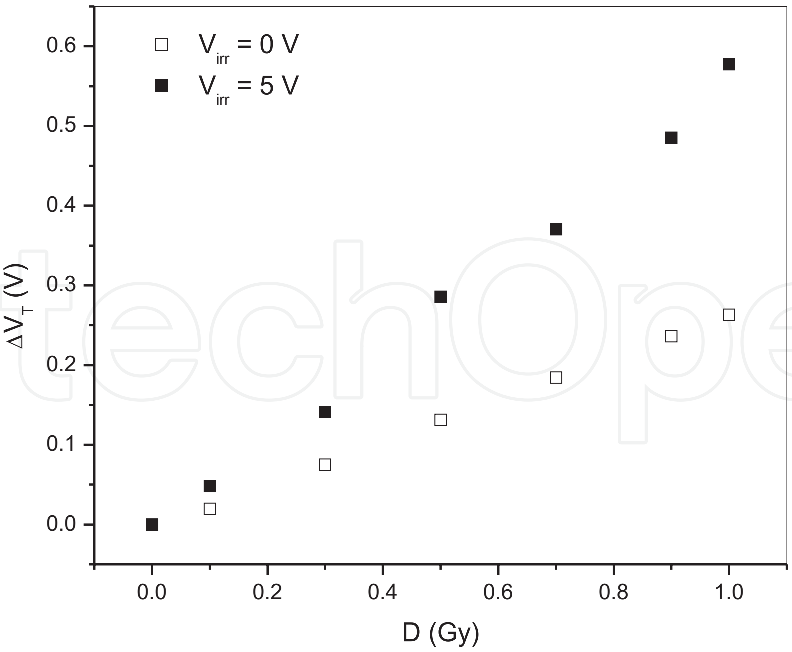

Figure 3. Threshold voltage shift ΔV_T in pMOS dosimeter with 1-μm-thick gate oxide as a function of gamma-ray radiation dose *D* in the 0–1 Gy range. Gate bias during irradiation V_{irr} was 0 or 5 V.

using Eq. (2) for $n = 1$ gives correlation coefficient, $r^2 = 0.98$. Having that r^2 are very close to one, it can be assumed that there is a linear dependence between ΔV_T and *D* and that the sensitivity of these devices for a given value of V_{irr} is the same in the range from 0 to 50 Gy.

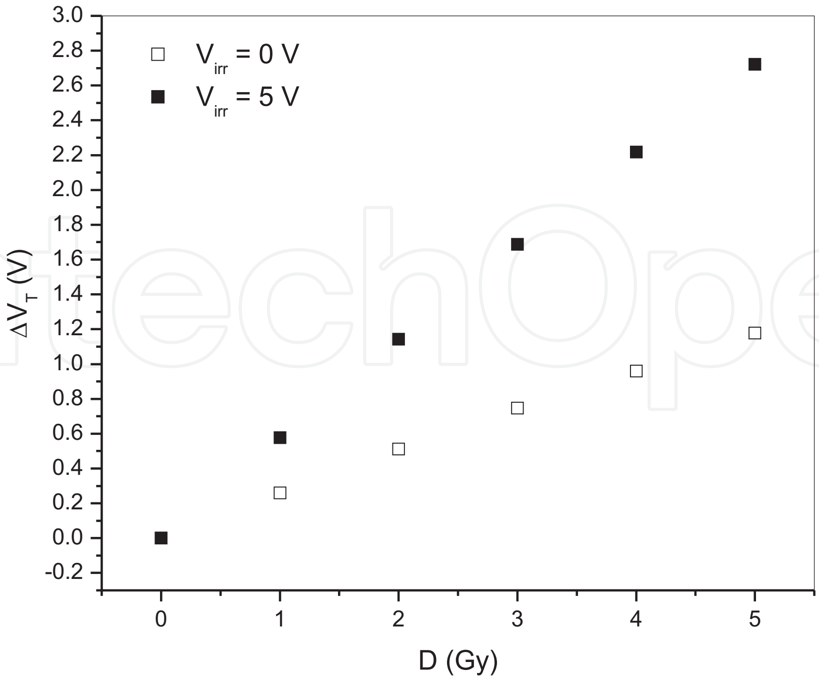

Figure 4. Threshold voltage shift ΔV_T in pMOS dosimeter with 1-μm-thick gate oxide as a function of gamma-ray radiation dose *D* in the 1–5 Gy range. Gate bias during irradiation V_{irr} was 0 or 5 V.

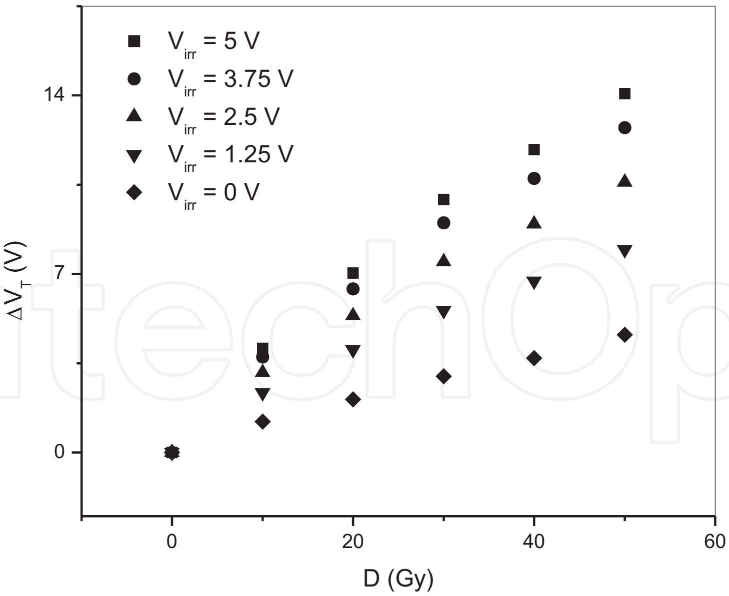

Figure 5. Threshold voltage shift ΔV_T in pMOS dosimeter with 1-μm-thick gate oxide as a function of gamma-ray radiation dose *D* in the 0–50 Gy range. Gate bias during irradiation V_{irr} was ranging from 0 to 5 V.

Figure 6 shows the sensitivity *S* as a function of gate bias V_{irr} during gamma-ray irradiation to 50 Gy of pMOS dosimeters with gate oxide thickness of 1 μm [36]. The symbols stand for experimental data, whereas the solid lines represent fits, which are exponential.

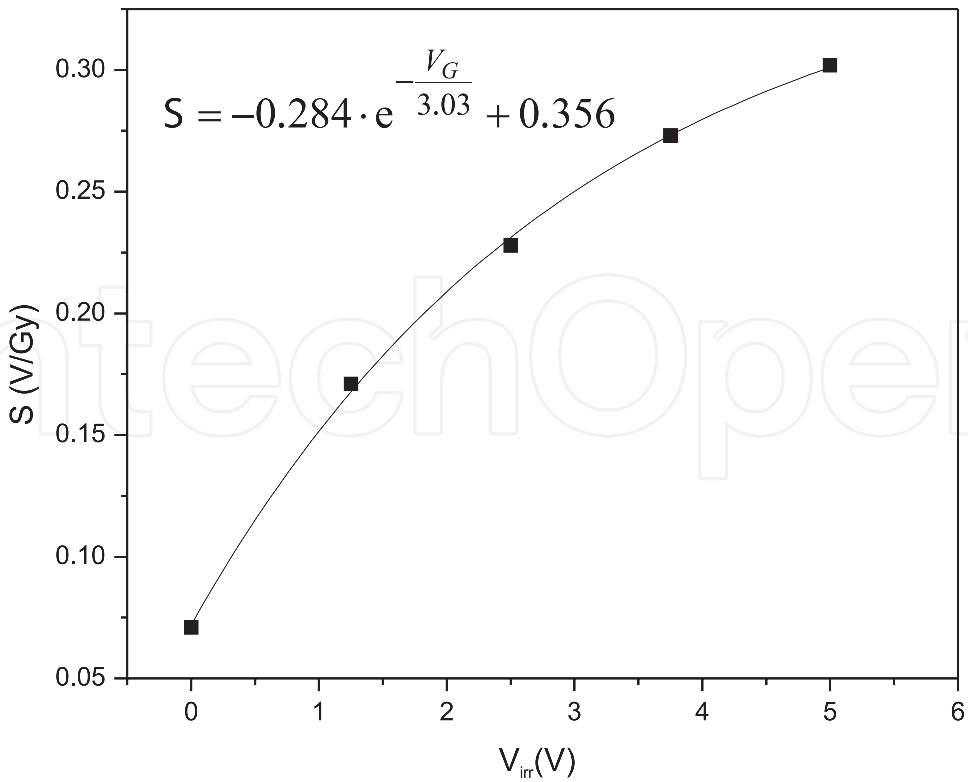

Figure 6. Sensitivity of pMOS dosimeter with 1-μm-thick gate oxide as a function of gate bias V_{irr} for 50 Gy gamma-ray irradiation.

The increase in ΔV_T with the increase in V_{irr} is due to the increase in FT and ST. It is well known that with the number of holes which have avoided the recombination with electrons, the number of created FT and ST increases. When $V_{irr} = 0$ V the electric field in the oxide is only due to work function difference between the gate and the substrate (zero bias conditions or dosimeter passive mode), so the probability for electron-hole recombination is higher than in the case when $V_{irr} > 0$ V. For higher value of V_{irr}, the large number of holes will escape the initial recombination, which further increase the probability for their capture at E', E'_γ and NBO centers and increase FT and SST which leads to increase in ΔV_T. Such conclusion is in agreement with results shown in **Figures 1–6**. It should be emphasized that during irradiation, the FT concentration is several times larger than ST concentration. This proves that the increase in ΔV_T value during irradiation is mainly due to increase in FT [42].

3.3. Influence of gate oxide thickness on threshold voltage shift during irradiation

Figure 7 shows the threshold voltage shift ΔV_T as a function of radiation dose D for pMOS dosimeters with gate oxide thicknesses of 400 nm and 1 μm [43]. Irradiation of these devices was performed with gamma-ray irradiation in the dose range from 0 to 5 Gy when gate bias during irradiation was $V_{irr} = 5$ V. It was shown that sensitivity $\Delta V_T/D$ increases with gate oxide thickness increase and that there is a linear dependence between ΔV_T and D (correlation coefficient $r^2 = 0.99$).

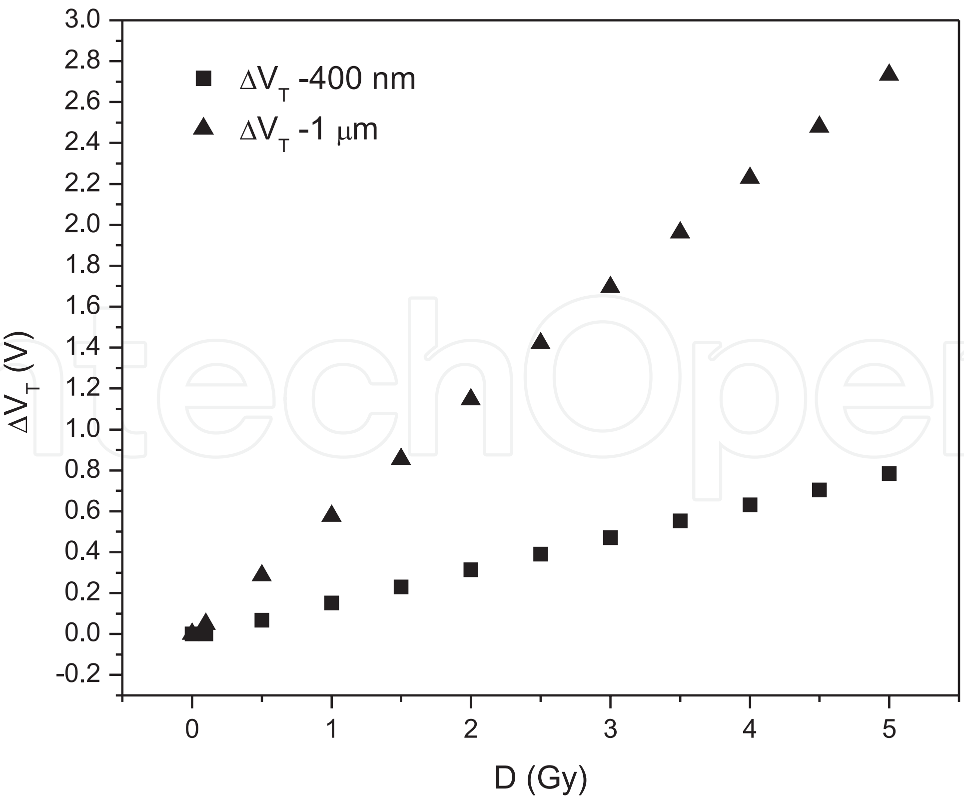

Figure 7. pMOS dosimeters threshold voltage shift ΔV_T as a function of gamma-ray dose in 0–5 Gy range. Gate bias during irradiation was $V_{irr} = 5$ V. Gate oxide thickness was 400 nm and 1 μm.

The $\Delta V_T = f(D)$ dependence for pMOS dosimeters with gate oxide layer thicknesses of 100 nm, 400 nm and 1 μm is shown in **Figure 8** [36]. The gamma-ray irradiation of these devices was performed in the dose range from 0 to 50 Gy, while the gate bias $V_{irr} = 5$ V. It can be seen that the increase in gate thickness leads to the increase in ΔV_T for the same radiation dose. It is mainly due to the increase in FT concentration [42]. Experimental data fitting using Eq. (2) for $n = 1$, gives the correlation coefficient values, for pMOS dosimeters with 100 nm, 400 nm and 1 μm gate oxide thickness 0.99, 0.99 and 0.98, respectively, what proves linear dependence between ΔV_T and D.

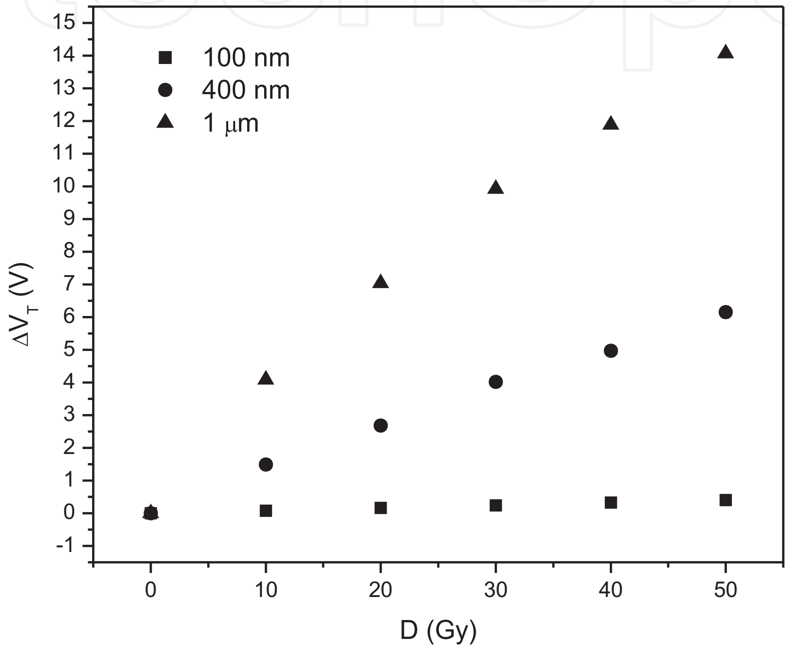

Figure 8. pMOS dosimeters threshold voltage shift ΔV_T as a function of gamma-ray dose in 0–50 Gy range. Gate bias during irradiation was $V_{irr} = 5$ V. Gate oxide thickness was 100 nm, 400 nm and 1 μm.

3.4. Influence of photon energy on pMOS dosimetry sensitivity

Figure 9 shows the threshold voltage shift ΔV_T as a function of radiation dose D for 1 μm gate oxide thickness pMOS dosimeters irradiated with gamma-rays which originates from 60Co and X-ray with energy 140 keV in dose range from 0 to 1 Gy for gate bias during irradiation $V_{irr} = 5$ V [35, 38]. Experimental results fitting using Eq. (2) for $n = 1$ gives the value of correlation coefficient $r^2 = 0.99$ assuming that there is linear dependence between ΔV_T and D, that is, sensitivity is the same for considered dose interval. It can be also seen from the figure that the sensitivity is much higher for X than for gamma radiation.

The $\Delta V_T = f(D)$ dependence for gamma and X-rays for pMOS dosimeters with gate oxide thickness of 1 μm in dose range from 0 to 5 Gy and $V_{irr} = 5$ V is shown in **Figure 10** [38]. Experimental results fitting using Eq. (2) for $n = 1$, gives correlation coefficient for gamma and X-rays 0.99 and 0.96, respectively. On the basis of these values, it can be concluded that for X-rays, there is no linear dependence between ΔV_T and D.

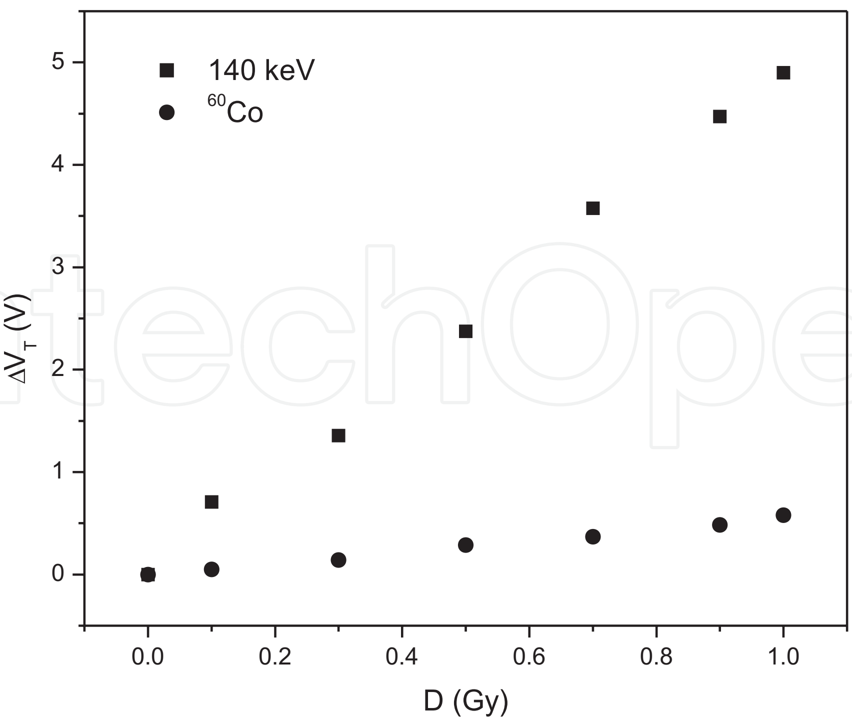

Figure 9. Threshold voltage shift ΔV_T in pMOS dosimeter with 1-μm-thick gate oxide as a function of gamma and X-ray radiation dose *D* in the 0–1 Gy range. Gate bias during irradiation V_{irr} was ranging from 0 to 5 V.

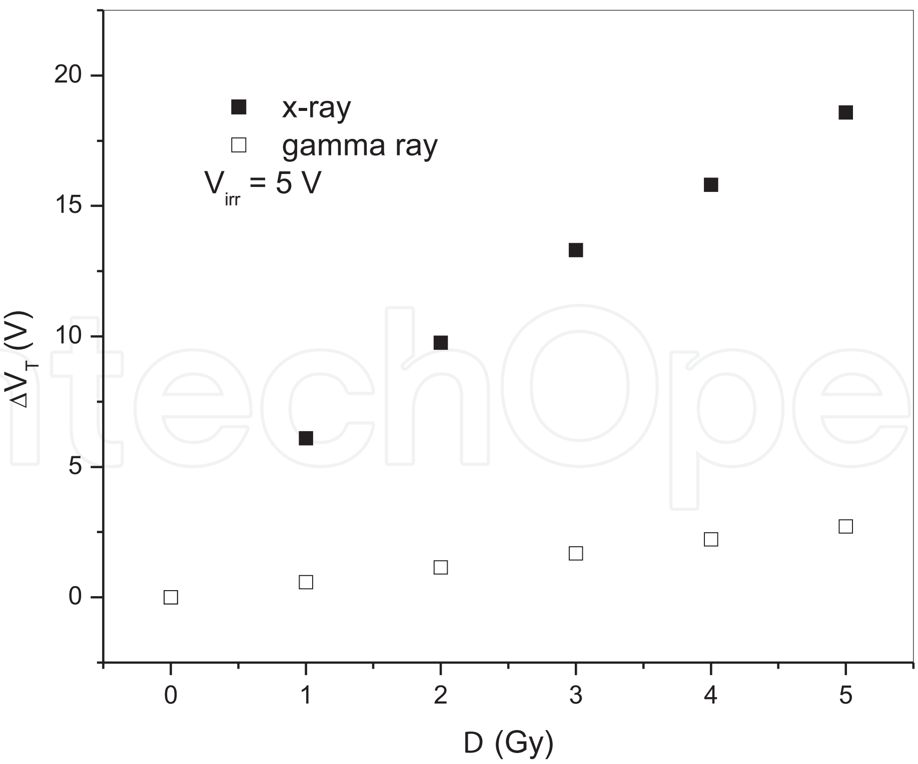

Figure 10. Threshold voltage shift ΔV_T in pMOS dosimeters as a function of gamma and X-ray radiation dose *D* in the 0–5 Gy range. Gate bias during irradiation was $V_{irr} = 5$ V.

From **Figures 9** and **10**, it can be seen that increasing in ΔV_T is much higher in the case when pMOS dosimeters are irradiated with X-rays (140 keV photon energy) than in the case of gamma-rays originating from ^{60}Co (energies of photons of 1.17 and 1.33 MeV). This is a consequence of different photon energies which lead to ionization of SiO_2 molecules. Namely, X-ray photons energy of 140 keV lead to molecule ionization by both photo effect and Compton's effect, while gamma-ray photons with energies of 1.17 and 1.33 MeV lead to SiO_2 molecules ionization only by Compton's effect [38]. A direct change in ΔV_T values is caused by a larger number of FT and ST, which are formed during X-ray irradiation compared to gamma-ray irradiation, the reason being the probability for molecule ionization by photoeffect is significantly higher than by Compton's effect.

4. Fading of irradiated pMOS dosimeters

As a dosimeter radiation sensitive MOSFET must satisfy a crucial demand, which implies compromising between sensitivity to irradiation and stability with time after irradiation. Stability represent insignificant change in ΔV_T of an irradiated MOSFET at room temperature for a long-time period (saved dosimetric information) [43]. Having that immediate dose readout is not always possible, also the exact moment of irradiation is often unknown as in the case of individual monitoring the radiation dose measurements must be performed periodically. Room temperature stability of irradiated pMOS dosimeters can be determined by calculating fading using Eq. (4).

Fading results for pMOS dosimeters with gate oxide thickness of 400 nm and 1 μm, at room temperature previously irradiated with X-ray (energy 140 keV) up to 1 Gy for $V_{irr} = 0$ V and $V_{irr} = 5$ V are presented in **Figures 11** and **12**, respectively [35]. It can be seen that fading of pMOS dosimeters with gate oxide thickness of 400 nm (**Figure 11**), which were irradiated with gate bias $V_{irr} = 5$ V, is about 40% in the first 7 days, whereas those of pMOS dosimeters irradiated without gate bias during irradiation have 22% fading also in the first 7 days. For the time period between 7 and 28 days, fading of pMOS dosimeters irradiated with gate bias 5 V increased for about 3%, whereas fading of pMOS dosimeters irradiated without gate bias during irradiation had a nearly constant value. Fading of 1 μm thick gate oxide pMOS dosimeter (**Figure 12**), which were irradiated up to 1 Gy with gate bias $V_{irr} = 5$ V, in the first 7 days was 14%, whereas for the time period between 7 and 28 days, it increases about 1%. pMOS dosimeters with the same gate oxide thickness, which were irradiated without gate bias the first 7 days, have fading increase for about 1%, and this value is kept up to 28 days. From **Figures 11** and **12**, it can be concluded that fading is lower when the gate oxide of pMOS dosimeters is thicker which in accordance with early study [44] showed that fading decreases with the increase in gate oxide thickness.

The decrease in the positive trapped charge causes fading of pMOS dosimeters. This decrease originates from electron tunneling from Si into SiO_2; once captured at positive oxide trapped charge, which lead to their neutralization/compensation and change in threshold voltage shift [45].

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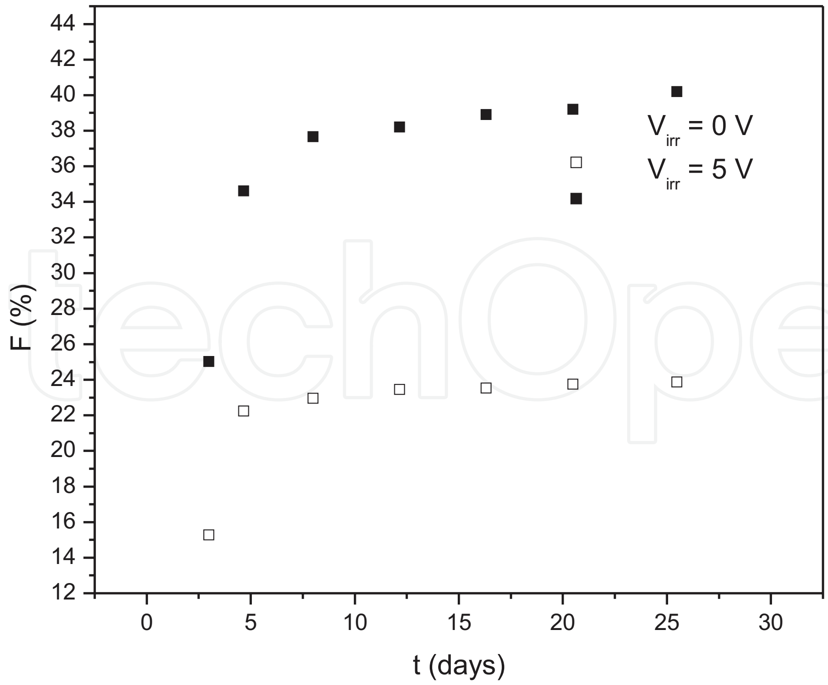

Figure 11. Fading *F* at room temperature for 30 days of pMOS dosimeter with 400 nm gate oxide thickness previously irradiated with X-ray (140 keV) radiation dose of 1 Gy. Gate bias during irradiation was $V_{\text{irr}} = 0\ \text{V}$ and $V_{\text{irr}} = 5\ \text{V}$.

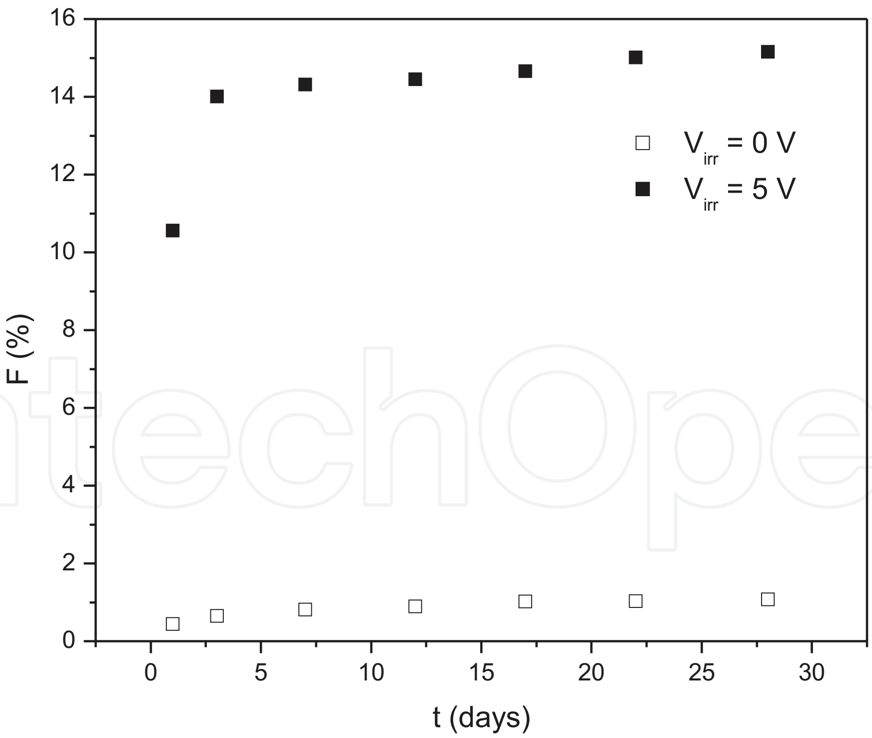

Figure 12. Fading *F* at room temperature for 30 days of pMOS dosimeter with 1 μm gate oxide thickness previously irradiated with X-ray (140 keV) radiation dose of 1 Gy. Gate bias during irradiation was $V_{\text{irr}} = 0\ \text{V}$ and $V_{\text{irr}} = 5\ \text{V}$.

5. pMOS dosimeter reuse

For a while, it was widely thought that pMOS dosimeters could not be used for subsequent determination of radiation dose. They were, namely, just used to determine the maximum radiation dose, after which they would be replaced. However, studies on the pMOS dosimeter reuse are given in [46] for radiation dose 400 Gy. Recent work has shown that irradiated pMOS dosimeters manufactured in Tyndall National Institute, Cork, Ireland, could be annealed at room and elevated temperature and reused for ionizing radiation measurements. **Figures 13** and **14** show the threshold voltage shift ΔV_T as a function of gamma radiation dose D for gate bias V_{irr} = 5 V and V_{irr} = 0 V, respectively, for both the first and second irradiation [47, 48]. After the first irradiation, the pMOS dosimeters were annealed at room temperature for 5232 h without gate bias. Latter, the annealing process was continued at 120° C without gate bias for 432 h. The pMOS dosimeters were then irradiated under the same conditions. It can be seen from **Figure 13** that the values of ΔV_T during the first and second irradiation are very close. For pMOS dosimeters irradiated with the gate bias V_{irr} = 0 V (**Figure 14**), the values of ΔV_T are higher for the second than for first irradiation. Such results are contradictory with earlier results [46] for pMOS dosimeters irradiated up to 400 Gy where it was shown that the values of ΔV_T during the first irradiation (for V_{irr} = 5 V and V_{irr} = 0 V) were higher than the values obtained during the second irradiation.

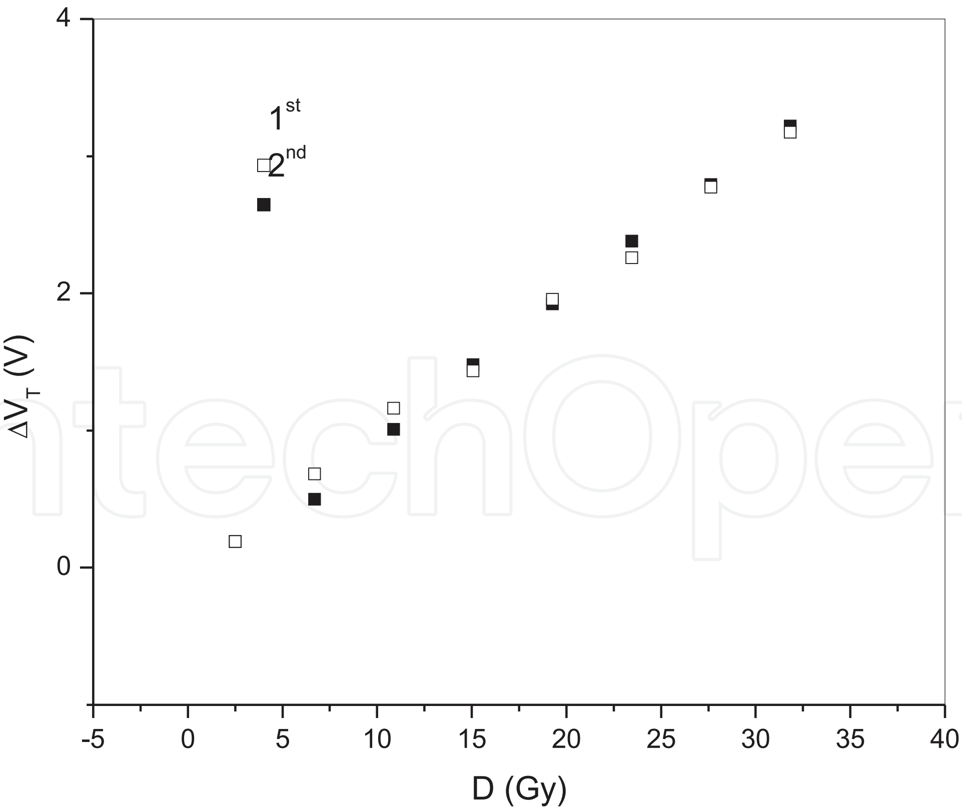

Figure 13. Dependence of the threshold voltage shift ΔV_T in pMOS dosimeters with 400 nm gate oxide thickness on the gamma-ray radiation dose D in the 0–35 Gy range during the first and second irradiation with gate bias V_{irr} = 5 V.

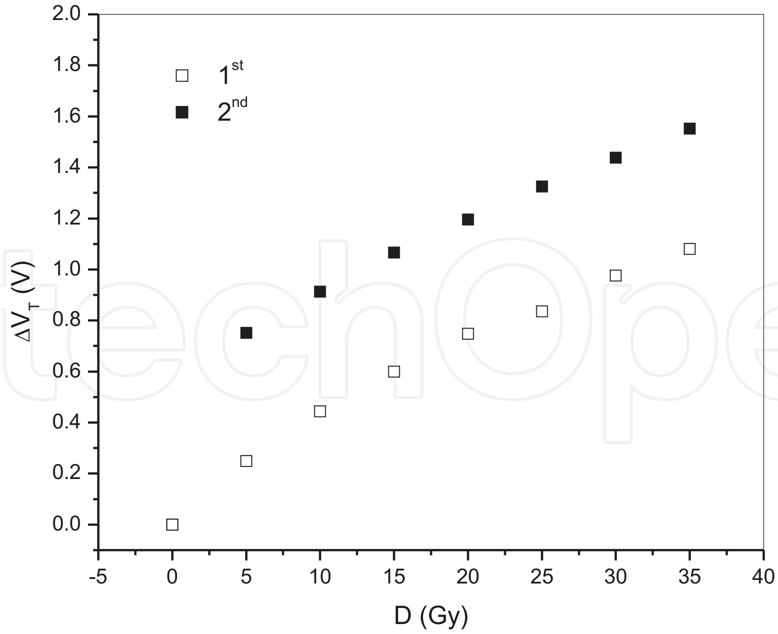

Figure 14. Dependence of the threshold voltage shift ΔV_T in pMOS dosimeters with 400 nm gate oxide thickness on the gamma-ray radiation dose D in the 0–35 Gy range during the first and second irradiation with gate bias $V_{irr} = 0$ V.

6. Low-cost commercial p-channel MOSFETs as pMOS dosimeters

In recent years, many investigations were driven toward application of low-cost commercial p-channel MOSFETs as a dosimeter in radiotherapy [49]. Asensio et al. [50] show results of some most important dosimetric parameters (sensitivity, linearity, reproducibility and angular dependence) for power p-channel MOSFETs 3N163. These transistors were irradiated by gamma-rays originating from ^{60}Co up to 55 Gy. These devices were irradiated without gate bias ($V_{irr} = 0$ V). **Figure 15** shows the $\Delta V_T = f(D)$ dependence for 15 devices. The data showed excellent linearity with a mean sensitivity value of 29.2 mV/Gy and reasonable good reproducibility. Moreover, the angular and dose rate dependencies are similar to those of other, more specialized pMOS dosimeters. The authors of this paper concluded that power p-channel MOSFET 3N163 would be an excellent candidate for low-cost system capable of measuring gamma-radiation dose.

The possibility of vertical diffusion MOS also called double-diffusion MOS transistor or simple DMOS as a sensor of electron beam was also investigated [51] These devices were DMOS BS250F, ZVP3306 and ZVP4525, manufactured by Diodes Incorporated (Plano, USA). The irradiation was performed by an electron beam of 6 MeV energy without gate bias. The same authors investigated the behavior of p-channel MOS transistors from integrated circuit CD4007 (Texas Instruments, Dallas, USA and NXP Semiconductor Eindhowen, Netherlands) under 6 MeV energy electron beam. In **Figure 16**, the ΔV_T versus D is plotted four samples of the ZVP3306 DMOS transistors. The results for other type DMOS transistors are similar. As it can be seen, there is a linear dependence between ΔV_T and D to radiation dose of 25 Gy. Values of sensitivity for BS250F, ZVP4525 and ZVP3306 are 3.1, 3.4 and 3.7 mV/Gy, respectively. It was also shown [51] that p-channel MOS

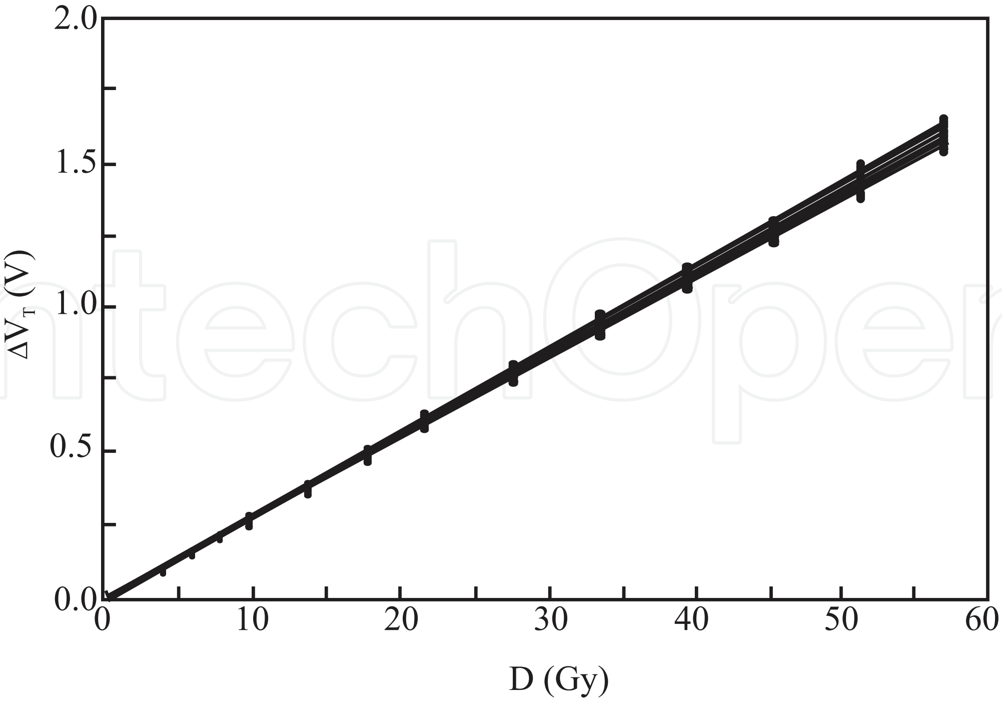

Figure 15. Threshold voltage shift ΔV_T in p-channel MOSFETs 3N163 as a function of gamma-ray radiation dose *D* in the 0–58 Gy range. Gate bias during irradiation was $V_{irr} = 0$ V.

transistors from integrating circuits CD4007 during irradiation without gate bias ($V_{irr} = 0$ V) presented the sensitivity 4.6 mV/Gy with a very good linear behavior of the threshold voltage shift compared to the radiation dose. Moreover, with the possibility of applying thermal compensation, this transistor may be a promising candidate in radiotherapy.

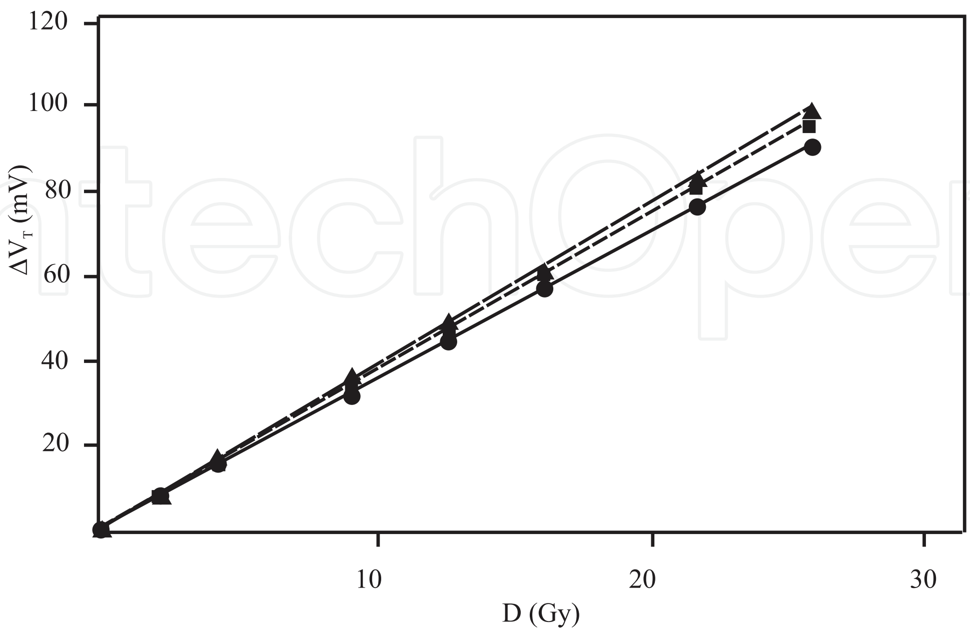

Figure 16. Threshold voltage shift ΔV_T in DMOS ZVP3306 as a function of 6 MeV electron beam radiation dose *D* in the 0–25 Gy range.

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7. Conclusion

The sensitivity of pMOS dosimeters manufactured in Tyndall National Institute, Cork, Ireland, with 100 nm, 400 nm and 1 μm thick gate oxide to gamma and X-ray irradiation, for radiation doses used in radiotherapy, has been investigated. It is shown that their sensitivity can be increased either by increase in gate bias during irradiation or by increasing the gate oxide thickness. The sensitivity increases with the decrease in ionizing radiation photon energy. Sensitivity of pMOS dosimeters with 1 μm thick gate oxide is satisfactory even for 1 cGy doses in low-field mode. Unfortunately, their major disadvantage is large fading immediately after irradiation. Investigations in a past few years have shown that some low-cost commercial p-channel MOSFETs could be good candidates for radiation dose measurements used in radiotherapy.

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Author details

Momčilo M. Pejović* and Milić M. Pejović

*Address all correspondence to: momcilo.pejovic@elfak.ni.ac.rs

Faculty of Electronic Engineering, University of Niš, Niš, Serbia

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