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SOME ADVANCES IN DOSE MEASUREMENT WITH MOSFET FOR PORTABLE INSTRUMENTATION

Abstract: *This paper revises some of the methods for extracting the dosimetric information from irradiated MOSFETs and their implementations using electronic circuits suitable for portable instrumentation. Issues such as thermal compensation and linear range improvement in dose measurements will be discussed.*

Key words: dosimetry, MOSFET, electronic instrumentation, thermal compensation.

INTRODUCTION

In-vivo dosimetry during radiotherapy treatments can be carried out with different types of sensors, such as ionization chambers, thermoluminescent crystals, or semiconductor detectors, mainly diodes or MOSFETs (Metal-Oxide-Semiconductor Field Effect Transistor). The use of MOSFET dosimeters has been extended in the last few decades due to some advantages such us immediate and non-destructive readouts, low power consumption, easy calibration, and reasonable sensitivity and reproducibility [1, 2, 3, 4].

Previous works showed an approximately linear dependence between the threshold voltage shift, ΔV_T, and the absorbed dose in the oxide for p-channel MOSFETs (pMOS) [2, 3 , 5]. Basically, the sensitivity *S*, defined as ΔV_T per dose unit, depends on the radiation energy, the electric field in the oxide, the encapsulation of the transistor, and the incidence direction of the radiation beam during irradiation. Indeed, a transistor in biased mode (with the appropriate external polarization) has greater sensitivity and a wider linear range than the same transistor in unbiased mode (terminals short-circuited altogether, without external polarization) due to more efficient charge transport and storage in the oxide. Moreover, the positive charge generated during irradiation can recombine during storage periods. It is well known that the bulk electrons can jump into the oxide by the tunnel effect and neutralize some charge in the oxide, reducing ΔV_T[5]. This is known as fading effect, avoiding to use MOSFET dosimeters as dose accumulator sensors over long periods of time. Just after irradiation, the reordering of charges in the MOSFET can change the threshold voltage, which could falsify the dose reading. Therefore, the fading effect should be studied in depth in these dosimetry systems.

On the other hand, the encapsulation affects the absorbed dose in the oxide of the pMOS dosimeter. As it is well known, the dose depends on the path covered by the radiation beam. The maximum dose is reached a few millimetres from the surface of the dosimeter, where the charged particle equilibrium is reached, and this distance depends on the type of radiation and its energy. To reduce the angular dependence of the dosimeter, charged particle equilibrium must be achieved [6], but this depends, critically, on the shape, composition, and thickness of the device encapsulation [7, 8]. One possibility to solve this problem is to add build-up caps, thus producing a reduction in the angular dependence [7, 8, 9].

The shift in threshold voltage with the dose has been commonly used as the dosimetric parameter. It can be obtained by extracting the complete current-voltage characteristic curves of the device [10]. Simpler methods, based on constant current measurements, require measuring the drain-source voltage while the transistor remains biased by a constant drain current and the gate and drain terminals are short-circuited. Under this configuration, the source-drain voltage shift is approximately equal to ΔV_T [9, 10]. The monitoring of the drain-source voltage can be done continuously during irradiation. However, if measurements are made just before and after irradiation, the dosimeter can be operated without connections during the radiation treatment, thereby increasing patient comfort.

Most commercial dosimetry systems based on MOSFETs measure increments of the drain-source voltage at constant drain current [11, 12]. Usually, in order to minimize thermal drift, the drain current selected is the Zero Temperature Coefficient current, I_{ZTC}, where the thermal dependence of the drain-source voltage cancels out. Nevertheless, the dosimetric parameter used is the difference between the drain-source voltage of two transistors polarized at the same drain current, but with different source-gate voltages and, as a consequence, with different dose sensitivities. Using this arrangement, a wide linear range and thermal compensation are achieved in the biased mode [11]. There is another commercial system based on transistors in the unbiased mode, but the linear range is up to 5 Gy and its use is limited to only one irradiation session [12, 13]. Although the dosimetry systems based on MOSFETs developed so far now show remarkable specifications and performances, there are certain

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issues that can be improved upon, such as cost, range of use, and technology of the sensor, together with a reader unit able to extract the corresponding parameters with suitable measurement algorithms. The aim of this work is to exploit the possibilities in this direction.

In previous works, we showed the feasibility of using a general-purpose low-cost pMOS as a dosimeter, irradiated in unbiased mode, with a significant increase in linear range and reduced thermal drift compared to similar systems [9, 10, 14]. Moreover, its radiation response has been numerically modelled by the Monte Carlo method, showing very good agreement between experimental data and numerical results [6].

MATERIAL AND METHODS

Measurement algorithms

The pMOS used in the dosimetry system developed here was irradiated in unbiased mode, and the transistor was connected to the reader unit only during the readout process, which allowed us to calculate the V_T and obtain the dose. The theoretical basis of these calculations has been reported in previous works [11, 17] and here we present a brief summary. As done by other authors [6, 14], during the readout process, the gate and the drain terminals of the MOSFET are short-circuited and grounded, and the bulk and the source are also inter-connected. In this configuration, the transistor operates in the saturation region, where I_D-V_S can be modelled for pMOS as [15]:

$$I_{\mathrm{D}} = \frac{\beta}{2}\left(V_{\mathrm{S}} - |V_{\mathrm{T}}|\right)^2 , \quad (1)$$

where I_D is the drain current, V_S is the source voltage and V_T is the threshold voltage. Using equation (1) before (pre) and after (post) irradiation, we have

$$\Delta|V_{\mathrm{T}}| \equiv V_{\mathrm{T}}^{\mathrm{post}} - V_{\mathrm{T}}^{\mathrm{pre}} = \Delta V_{\mathrm{S}} - \sqrt{2I_{\mathrm{D}}}\left(\sqrt{\frac{1}{\beta^{\mathrm{post}}}} - \sqrt{\frac{1}{\beta^{\mathrm{pre}}}}\right), \quad (2)$$

where

$$\Delta V_{\mathrm{S}} \equiv V_{\mathrm{S}}^{\mathrm{post}} - V_{\mathrm{S}}^{\mathrm{pre}} . \quad (3)$$

Measuring ΔV_T at two different drain currents, I_{D1} and I_{D2}, one obtains [9]:

$$\Delta|V_{\mathrm{T}}| = \Delta V_{\mathrm{S1}} + \frac{\Delta V_{\mathrm{S2}} - \Delta V_{\mathrm{S1}}}{1 - \sqrt{\dfrac{I_{\mathrm{D2}}}{I_{\mathrm{D1}}}}} , \quad (4)$$

where ΔV_{Si} is the source voltage shift measured at constant drain current I_{Di}. Equation (4) allows one to extract the exact value of ΔV_T using two currents only and not considering the increase in the source-voltage due to $\Delta\beta$. As a consequence, the linear range of pMOS dosimeters in unbiased mode is enhanced. In addition, if a third drain current, I_C, is considered, both the thermal compensation and the linear range enhancement can be obtained simultaneously. In fact, this is done by sequentially applying the following expressions [14]:

$$\Delta V_{\mathrm{S1}}^{0} = \Delta V_{\mathrm{S1}} + \left(\Delta V_{\mathrm{SC}} - \Delta V_{\mathrm{S1}}\right)\frac{\sqrt{I_{\mathrm{D1}}} - \sqrt{I_{\mathrm{ZTC}}}}{\sqrt{I_{\mathrm{D1}}} - \sqrt{I_{\mathrm{C}}}},$$
$$\Delta V_{\mathrm{S2}}^{0} = \Delta V_{\mathrm{S2}} + \left(\Delta V_{\mathrm{SC}} - \Delta V_{\mathrm{S2}}\right)\frac{\sqrt{I_{\mathrm{D2}}} - \sqrt{I_{\mathrm{ZTC}}}}{\sqrt{I_{\mathrm{D2}}} - \sqrt{I_{\mathrm{C}}}}, \quad (5)$$

and

$$\Delta|V_{\mathrm{T}}^{0}| = \Delta V_{\mathrm{S1}}^{0} + \frac{\Delta V_{\mathrm{S2}}^{0} - \Delta V_{\mathrm{S1}}^{0}}{1 - \sqrt{\dfrac{I_{\mathrm{D2}}}{I_{\mathrm{D1}}}}} . \quad (6)$$

It is worth noting that the application of this method requires a knowledge of I_{ZTC} only. In addition, equations (5) are simplified if I_{D1} or I_{D2} is equal to I_{ZTC}. For example, if $I_{D2}=I_{ZTC}$, the source voltage shifts for I_{D2} are thermally compensated, and then only ΔV^{0}_{S1} must be calculated, using the first of equations (5) to evaluate equation (6).

Experimental evidence of a reduction in the 1/f noise and an enhancement of the linear range appeared when the drain currents are pulsed during biasing, as reported in a previous work [9]. Therefore, the optimum simplified algorithm to obtain ΔV_T proposed in this work is to measure the source voltage for three drain pulsed currents and to apply equations (5) and (6).

Description of the dosimetry system

A dosimetry system that implements the measurement method described above has been designed, built, and tested. This electronic measurement system consists of a reader unit and a set of wireless sensor modules whose block diagrams are shown in Figure 1.

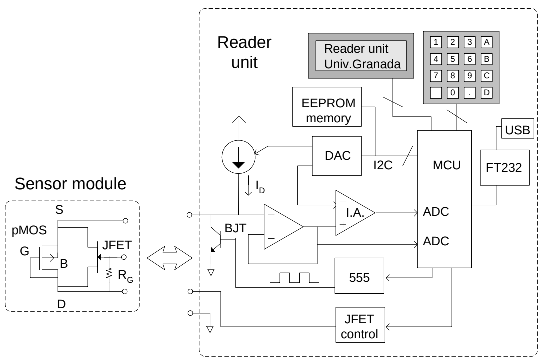

Figure 1. *Block diagrams of the reader unit and the sensor module*

The sensor module is based on the general-purpose pMOS transitor 3N163, which is soldered onto a printed circuit board (PCB) with additional elements that are described below. This transistor is a lateral enhanced pMOS without any protection against accidental electrostatic charge injection. Therefore, an n-channel JFET (see Figures 1 and 2), with a surface-mounted-device (SMD) case element that maintains the terminal of the source connected to bulk, and the drain connected to the gate, short-circuited during irradiation and storage periods, has been included in the sensor module. We used the MMBF4391 of NXP Semiconductor (Eindhoven, Netherlands), with a cut-off voltage of -10V and ON resistance of 30 Ω, welded in the bottom layer of the PCB. This transistor is normally on and keeps the source and bulk terminals connected to the drain and gate. However, during the readout process, the connection between the source and drain must be interrupted by the polarization of the JFET gate to at least -10V. The JFET gate capacitance discharges through R_G, and all of the pMOS transistor terminals become connected again, when the sensor module is removed from the reader unit.

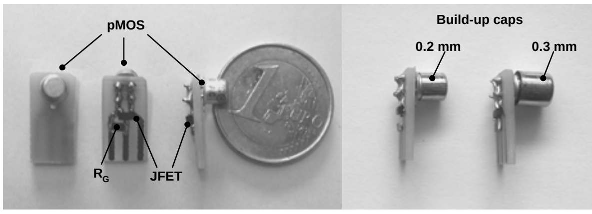

Figure 2 *(a) Sensor module, (b) Sensor modules with different built-up caps*

As mentioned above, the absorbed dose in the oxide of the pMOS transistor depends on the encapsulation and this affects the angular dependence of the sensor response [8]. The transistor 3N163 used in this work is encapsulated in a nickel casing with a thickness of 0.26 mm. The sensor is used as a dosimeter with different photon beams. In our tests, we have considered those produced by a Theratron-780 from ^{60}Co and the 6 and 18 MV beams generated by a LINAC Siemens Mevatron KDS. The WET corresponding to the nickel housing of the 3N163 transistor is 0.23 cm. Thus, we can consider that, in the case of the ^{60}Co source, electron equilibrium conditions are met.

However, for LINAC photon beams, the situation is quite different. The PDD measured for 6 and 18 MV beams with a radiation field of 10x10 cm^2 showed that maximum doses were reached at 1.6 cm for 6 MV and at 2.8 cm for 18 MV. At the WET of the 3N163 nickel housing, the dose percentage did not exceed 65% for 6 MV and 51% for 18 MV of the maximum dose. This fact produces an angular dependence of the dosimeter radiation response [8] and a lower dose sensitivity. To prevent these effects, additional build-up caps are required. We used two types of caps made of brass with thicknesses of 0.2 and 0.3 mm (see Figure 2). In actual irradiations, two different build-up caps were used for 6 MV, one of 0.3 mm and another of 0.5 mm, made stacking the 0.2 and 0.3 mm caps. The second type of cap of 0.5 mm was also used for 18 MV. With these build-up caps, the dose reaches values above 75% of the maximum dose for an irradiation field of 10x10 cm^2.

The reader unit (see the block diagram in Figure 1) consists of three functional blocks: the user interface, the microcontroller central unit (MCU) with an external memory, and the analog circuitry. The user interface includes an LCD screen, a keypad, and the circuitry necessary for computer connection via a USB port. An EEPROM memory is included in order to store different parameters of up to 256 different sensor modules each. Each sensor module must be identified by entering its identification number (ID) using the keypad for zeroing and for dose measurements.

As can be seen in Figure 1, the MOSFET bias is provided by a programmable current source. Its output current is controlled by the MCU with a digital-to-analog converter (DAC). In addition, as mentioned above, drain currents can be applied in the switching mode to reduce the 1/f noise and improve linearity. To do so, the current is diverted by a bipolar transistor (BJT) controlled by a pulsed signal generated by a 555 timer.

The source voltage is connected to the non-inverting input of an instrumentation amplifier (IA) with a buffer stage for impedance decoupling. The second channel of the DAC is connected to the inverting input of the IA to increase system resolution (see Figure 1). For each drain current, the calculation of the source voltage shifts needed for the evaluation of equations (3) and (4) is as follows:

1. Before irradiation, for the zeroing step, the pre-irradiation source voltage is detected and the microcontroller calculates the DAC output voltage necessary to reduce the IA output down to tens of millivolts. The digitized source voltages and the DAC words are stored in the EEPROM, which is mapped depending on the sensor module ID.
2. After irradiation and charge stabilization in the pMOS transistor (see below), the dose can be measured. The sensor ID is introduced on the keypad and then the post-irradiation source voltage is measured and subtracted from the DAC word stored in the zeroing step. Subsequently, it is amplified with a factor *G* (the gain of the IA).
3. Subtracting digitalized IA outputs from the two steps, the source voltage shift can be calculated with an amplification factor of *G*. The preset current values and the calibration parameters are loaded from the EEPROM and the dose is calculated. Finally the results are shown on the display or can be downloaded to a computer.

Given the dose sensitivity *S*, the system resolution δ is given as:

$$\delta = \frac{\Delta}{G\,S}, \qquad (7)$$

where Δ is the ADC resolution in volts. Obviously, a better resolution is achieved if *G* and *S* increase and Δ reduces. In our case, with a 10-bit ADC (powered to 5 V), with an IA gain of 20 and a minimum sensitivity of

20 mV/Gy, a resolution of 2 cGy is obtained. Electronic noise has also been kept lower than the ADC resolution (0.1 % in this case) by the averaging of 512 replicas for each source voltage measurement. Therefore, this noise has a negligible contribution to the final total error where another factors will be much more relevant as we will show below.

Experimental setup

Dosimeters were irradiated with a Theratron-780, which includes a ^{60}Co source, and a LINAC (Siemens KDS Mevatron) with 6 and 18 MV photon beams, both operating at the University Hospital San Cecilio (Granada, Spain). Dosimeters were situated at the isocentre of the sources (80 cm for the Theratron-780 and 100 cm for the Siemens KDS), and the irradiation fields used were 25x25 cm^2 for the first one and 10x10 cm^2 for the LINAC. The transistors irradiated in the LINAC were provided with the build-up caps described above to approach charged particle equilibrium. To control the stability of the photon source, an ionization chamber (PTW23332) was used in every irradiation sessions. The various analyses were performed with groups of dosimeters. Fading was analysed with a group of 5 transistors. To study the linearity and perform the calibration for ^{60}Co, we used 6. The response to the 6 MV photon beam was investigated with 14 sensors: 4 for the angular response (with a 0.5 mm build-up cap) and two sets of 5 MOSFETs, with caps of 0.3 and 0.5 mm, respectively, to study linearity and determine sensitivity. For the 18 MV beam, we used 5 dosimeters, with a 0.5 mm cap.

The reader unit was configured to measure the source voltage at 30, 120, and 270 μA and to calculate the threshold voltage shifts, considering that I_{ZTC}=225 μA, according to our previous work [14]. In order to evaluate the thermal drift of the dosimetry system, the reader unit with a dosimeter connected was introduced in a thermal chamber that can produce temperature variations from 20 to 36 ºC with an uncertainty of 0.5 ºC. The threshold voltage was determined at different temperatures for 10 additional sensor modules connected to the reader unit.

RESULTS AND DISCUSSION

Thermal drift and fading effect

The thermal drift of the entire dosimetry system was analysed by introducing the reader unit and the dosimeter inside the thermal chamber. Figure 3 shows the thermal drift of V_T for one of the dosimeters, with and without thermal compensation. The average thermal coefficient for the set of 10 sensor modules studied was (65±5) μV/ºC (coverage factor k=2) with thermal compensation. This result is in agreement with data previously reported [14]. Therefore, applying our thermal compensation method, we can consider a maximum thermal coefficient of 70 μV/ºC . If the minimum sensitivity of the sensor is considered, which is 20 mV/Gy, the maximum thermal drift of V_T is 3.5 mGy/ºC, suitable for typical radiotherapy treatments.

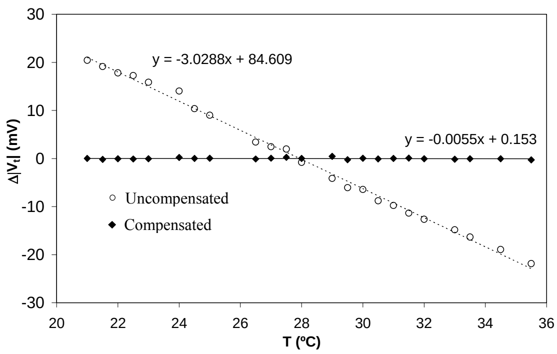

Figure 3. *Typical thermal drift of a dosimeter with and without applying the thermal compensation method*

For the short-term fading, the threshold voltage transient (in mV) was measured as a function of time elapsed, in 30 s intervals, from the moment of the connection of the sensor module to the reader unit. The time between the end of irradiation and the connection of the sensor module to the reader unit was approximately 30 s. Our results indicate that, after the first 120 s, V_T can be considered as stable. The long-term post-irradiation fading was measured every 12 hours for two sensors with an accumulated dose of 27 Gy. The threshold voltage long-term recovery showed an exponential dependence with the time elapsed since irradiation. This is in agreement with the behaviour expected due to the charge cancellation by the tunnel effect [5]. The decay time constant is about a week and, therefore, dose measurements must be done within a few hours to ensure that this recovery effect is negligible. We have set a delay time of 3 minutes from the end of irradiation to ensure reliable measurements without short- or long-term fading effects.

Linearity study and calibration

The linear response of the sensor for the ^{60}Co photon beam was shown in previous works, where it was concluded that an individual calibration for each transistor is needed for reliable in-vivo dose measurements [9, 10]. In this study, we have established the dose measurement and sensor calibration protocol. After a pre-irradiation of 23 Gy, two irradiation sessions of 3 Gy were provided per day up to a total of 70 Gy. The accumulated V_T shift versus the dose is plotted in Figure 4 for various dosimeters. As can be seen, it shows a clear linear dependence.

To set a limit for sensor usage before recalibration, we have considered that the linear range of the sensor ends with the dose necessary to produce a reduction of 5% in sensitivity in comparison to the initial sensitivity of the calibration session. The first irradiation session after pre-irradiation was considered as the first calibration.

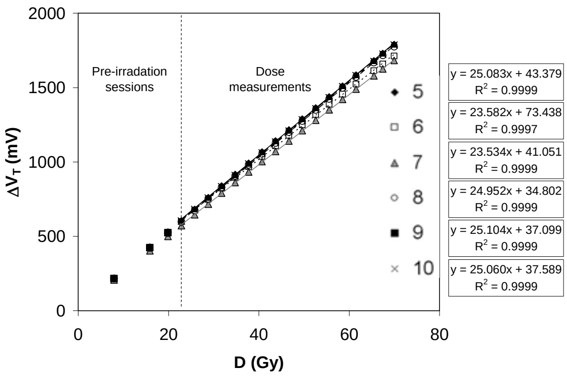

Figure 4. *Voltage threshold shift as a function of the dose accumulated for various dosimeters*

Of all the sensors studied, the worst situation corresponded to transistor 6, for which the sensitivity reduction reached 5% when the accumulated dose was four times the dose used in the calibration. All transistors withstood at least four times the calibration dose. Therefore, we have established that the usage range of the sensors is four times the calibration dose, considering sessions of around 2–3 Gy, typically used in radiotherapy treatments. The enhancement of the range of use is due to the algorithm of linear range extension developed in a previous work [9] and discussed briefly above. When the usage range is completed, a new calibration should be carried out. In our study, the recalibration was made at 44 Gy. After the second calibration, the sensitivity of the sensor modules again remains below 5% at up to eight times the calibration dose. This means that sensors can be reused, resulting in a significant cost savings for monitoring radiotherapy treatment. The calibration dose and the measurement configuration can be updated using either the reader unit or the computer.

Table 1. *Average global sensitivity (coverage factor k=2) of the dosimeters for different radiation sources*

Energy	Build-up	Sensitivity (mV/Gy)
^{60}Co	None	24.3±1.8
6 MV	0.3 mm	20.8±1.6
6 MV	0.5 mm	20.7±3.6
18 MV	0.5 mm	21.4±2.8

The linearity was studied for the 6 and 18 MV LINAC beams, with three sets of five sensors. After a pre-irradiation of 20 Gy, the dosimeters were irradiated with up to 70 Gy, with a maximum of 8 Gy per day, obtaining similar results as for the ^{60}Co beam. The average sensitivity of each dosimeter was considered as the slope of the linear fit to the accumulated ΔV_T as a function of the dose, without considering the pre-irradiation sessions. Global sensitivity can be calculated as the mean value of the average sensitivities for each dosimeter set. This global sensitivity is summarized in Table 1. It can be seen that the studied dosimeters do not show energy dependence for the LINAC, but the sensitivity for the ^{60}Co photon beam is higher due to the well-known dose sensitivity dependence with photon energy [8].

To determine the maximum accumulated dose that can be handled by our dosimetry system, sensor modules were irradiated until the source voltage measured at the highest bias current (270 μA, in our case) reached approximately 5V. This voltage is the limit of the source current of the reader unit. In this experiment, no sensor module suffered extra damage and all of them survived for the entire experiment. For the ^{60}Co beam, the dosimeters were irradiated with doses of up to 84 Gy, and for the LINAC with 6 and 18 MV, the sensor modules were irradiated with doses of up to 86 Gy.

Angular dependence

In a previous work, the angular dependence was studied by comparing experimental results with those found in a Monte Carlo simulation of the irradiation of the MOSFETs at various incidence angles. Therein, specific laboratory instrumentation was used to polarize the pMOS transistor and to measure the threshold voltage shifts [6]. The results showed that, for a 75º incidence, the experimental response of the dosimeters was 5% (7%) less than the simulated one for dosimeters with a 0.5 mm (0.3 mm) build-up cap in the case of the 18 MV (6 MV) beam. Consequently, thicker build-up caps were needed to reduce the angular response dependence.

In the present work, we have reproduced and extended the previous study in order to validate our reader unit. Four sensor modules were pre-irradiated with a dose of 20 Gy. To obtain the angular response, the dosimeters were calibrated just prior to irradiation for incidence angles of 15, 30, 45, 60, 75, and 90º. The angular response of the sensor module with a 0.5 mm build-up cap was calculated for a photon beam of 6 MV and an irradiation field of 10x10 cm^2. With 0.5 mm of brass, the dose in the transistor oxide reached 91.1% of the experimental value for 6 MV photon beams. The results were in agreement with the previous ones [6]. For ^{60}Co, no angular dependence was found, but in the case of the LINAC and for angles greater than 75º, sensitivity increased by up to 15%. Therefore, the sensor module should be used with a maximum incidence angle of 75º, where the dosimeter sensitivity varies down to 5% with a build-up cap of 0.5 mm of brass for energies of 6 and 18MV.

CONCLUSION

In this work, the development of a dosimetry system based on commercial MOSFETs operating in unbiased mode is presented. Its characterization for ^{60}Co and LINAC photon beams has also been carried out. The three drain currents algorithm has been implemented in the portable read out unit, achieving thermal compensation and extension of the linear range up to four times the dose used for the calibration. Several recalibrations can be made up to a maximum dose of 84 Gy for ^{60}Co and 86 Gy for the LINAC photon beam of 6 and 18 MV. In addition, the reader unit amplifies the increase in drain-source voltage to increase resolution, achieving an accuracy of ±3%. The dosimeters must be pre-irradiated with at least 20 Gy to homogenize the oxide charge. Therefore, a useful maximum dose of 60 Gy can be reached, including recalibration sessions that would be enough for monitoring the most common radiotherapy treatments. We consider our dosimetric system very suitable for low-cost in-vivo dosimetry.

REFERENCES

[1] M. Soubra, J. Cygler, and G. Mackay, "Evaluation of A Dual Bias Dual Metal-Oxide-Silicon Semiconductor Field-Effect Transistor Detector As Radiation Dosimeter", Medical Physics, vol. 21, pp. 567-572, 1994, http://dx.doi.org/10.1118/1.597314

[2] A. Holmes-Siedle and L. Adams, "Radfet - A Review of the Use of Metal-Oxide Silicon Devices As Integrating Dosimeters", Radiation Physics and Chemistry, vol. 28, pp. 235-244, 1986.

[3] R. C. Hughes, D. Huffman, J. V. Snelling, T. E. Zipperian, A. J. Ricco, and C. A. Kelsey, "Miniature Radiation Dosimeter for Invivo Radiation Measurements", International Journal of Radiation Oncology Biology Physics, vol. 14, pp. 963-967, 1988, http://dx.doi.org/10.1016/0360-3016(88)90019-3

[4] R. A. Price, C. Benson, M. J. Joyce, and K. Rodgers, "Development of a RadFET Linear Array for Intracavitary in Vivo Dosimetry During External Beam Radiotherapy and Brachytherapy", Ieee Transactions on Nuclear Science, vol. 51, pp. 1420-1426, August 2004, http://dx.doi.org/10.1109/TNS.2004.832570

[5] T. P. Ma and P. V. Dressendorfer, "Ionizing Radiation Effects In MOS Devices and Circuits", John Wiley & Sons, New York, 1989.

[6] M. A. Carvajal, S. Garcia-Pareja, D. Guirado, M. Vilches, M. Anguiano, A. J. Palma, and A. M. Lallena, "Monte Carlo Simulation Using the PENELOPE Code With an Ant Colony Algorithm to Study MOSFET Detectors", Physics in Medicine and Biology, vol. 54, pp. 6263-6276, October 2009, http://dx.doi.org/10.1088/0031-9155/54/20/015, PMid:19794247

[7] D. Georg, B. De Ost, M. T. Hoornaert, P. Pilette, J. Van Dam, M. Van Dycke, and D. Huyskens, "Build-Up Modification of Commercial Diodes for Entrance Dose Measurements in 'Higher Energy' Photon Beams", Radiotherapy and Oncology, vol. 51, pp. 249-256, June 1999, http://dx.doi.org/10.1016/S0167-8140(99)00058-4

[8] V. Panettieri, M. A. Duch, N. Jornet, M. Ginjaume, P. Carrasco, A. Badal, X. Ortega, and M. Ribas, "Monte Carlo Simulation of MOSFET Detectors for High-Energy Photon Beams Using the PENELOPE Code", Physics in Medicine and Biology, vol. 52, pp. 303-316, 2007, http://dx.doi.org/10.1088/0031-9155/52/1/020, PMid:17183143

[9] M. A. Carvajal, M. Vilches, D. Guirado, A. M. Lallena, J. Banqueri, and A. J. Palma, "Readout Techniques for Linearity and Resolution Improvements in MOSFET Dosimeters", Sensors and Actuators A-Physical, vol. 157, pp. 178-184, February 2010, http://dx.doi.org/10.1016/j.sna.2009.11.034

[10] L. J. Asensio, M. A. Carvajal, J. A. Lopez-Villanueva, M. Vilches, A. M. Lallena, and A. J. Palma, "Evaluation of a Low-Cost Commercial Mosfet As Radiation Dosimeter", Sensors and Actuators A-Physical, vol. 125, pp. 288-295, January 2006, http://dx.doi.org/10.1016/j.sna.2005.08.020

[11] I. Thomson, "Direct Reading Dosimeter", European Office Patent, EP 0471957A2, EP 0471957A2, July 1991.

[12] S. Best, A. Ralston, and N. Suchowerska, "Clinical Application of the OneDose (TM) Patient Dosimetry System for Total Body Irradiation", Physics in Medicine and Biology, vol. 50, pp. 5909-5919, December 2005, http://dx.doi.org/10.1088/0031-9155/50/24/010, PMid:16333163

[13] P. H. Halvorsen, "Dosimetric Evaluation of a New Design MOSFET in Vivo Dosimeter", Medical Physics, vol. 32, pp. 110-117, January 2005, http://dx.doi.org/10.1118/1.1827771 PMid:15719961

[14] M. A. Carvajal, A. Martinez-Olmos, D. P. Morales, J. A. Lopez-Villanueva, A. M. Lallena, and A. J. Palma, "Thermal Drift Reduction With Multiple Bias Current for MOSFET Dosimeters", Physics in Medicine and Biology, vol. 56, pp. 3535-3550, June 2011, http://dx.doi.org/10.1088/0031-9155/56/12/006, PMid:21606552

[15] S. M. Sze, "Physics of Semiconductor Devices", 2nd, John Wiley & Sons, New York, 1981.

BIOGRAPHY

Alberto J. Palma was born in Granada (Spain) in 1968. He received the BS and MSc degrees in physics in 1991 and the PhD degree in 1995 from the University of Granada, Granada, Spain. He is currently a Full Professor at the University of Granada in the Department of Electronics and Computer Technology. Since 1992, he has been working on trapping of carriers in different electronic devices (diodes and MOS transistors) including characterisation and simulation of capture cross sections, random telegraph noise, and generation-recombination noise in devices. From 2000 in the interdisciplinary group ECsens, his current research interests are devoted to design, development and fabrication of sensors and portable electronic instrumentation.

NEKE PREDNOSTI PRI DOZNOM MERENJU SA PRENOSNIM INSTRUMENTIMA SA MOSFETOM

Alberto J. Palma, Miguel A. Carvajal

Rezime: *U ovom radu je prikazan kritički pregled određenih metoda za dobijanje dozimetrijske informacije iz MOSFET-ova izloženih radijaciji i njihova primena u elektičnim kolima koja se koriste u prenosnim mernim instrumentima. Razmatrana su pitanja termičke kompenzacije i poboljšanja linearizacije opsegu pri merenja doza..*

Ključne reči: dozimetrija jonizujućeg zračenja, MOSFET, elektronski instrumenti, termička kompenzacija.