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6MV LINAC characterization of a MOSFET dosimeter fabricated in a CMOS process

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ABSTRACT

This paper presents the characterization of a thick gate oxide MOSFET for radiotherapy in-vivo dosimetry. The device is an N-channel transistor fabricated in a standard CMOS process using the Field Oxide as gate insulator. Sensitivity, fading, gate bias voltage dependence, percentage depth dose and angular response were assessed using a 6 MV LINAC. Experimental results showed that it is possible to estimate dose with a 3% uncertainty in a range up to 85 Gy with an average sensitivity of 62 mV/Gy. The measurement system noise equivalent dose is 3 mGy.

1. Intro

In-vivo dosimetry (IVD) is a recommended practice for safety and quality assurance (QA) in radiotherapy applications (Purdy et al., 2006). Independent dose measurements are necessary to prevent radiotherapy accidents and for early detection of deviations from the planned treatment. Hence, IVD allows to introduce corrections along the treatment avoiding under- or over-exposure which can result in the reduction of the treatment efficiency or the damage of healthy tissue.

Following recommendations of international medical and radio-protection organizations (AAPM, 1994), (ICRP, 2000) several countries have IVD as a mandatory practice. Until the year 2012, the members in this group were (Patient Safety N5, 2014): France, Norway, Sweden, Finland, Austria, Denmark and Czech Republic. In others countries as Belgium and the United Kingdom consider IVD was considered a good practice. This regulation is expected to spread to other countries in a near future.

Over the last years several publications have shown that MOSFET dosimeters are suitable for clinical applications (Ramani et al., 1997; Quach et al., 2000; Dybek et al., 2005; Cherpak et al., 2008; Qi et al., 2009). Recently, different MOS devices were proposed as sensors for dosimetry (Hardcastle, 2008; Lipovetzky, 2013; Siebel et al., 2015; Villani et al., 2016; Garcia-Inza et al., 2016a; Faigon et al., 2017). MOS-based sensors are attractive for dosimetry since they present many advantages in comparison with other dosimeters: small size, mechanical robustness, dose rate independent response, excellent surface response, and adequate dose depth profile for energies in the range of radiotherapy applications (Rosenfeld, 2006). The dosimetric signal is a voltage signal whose response to ionizing radiation is accumulative with dose and can be read once the exposure has finished, thus wiring is not needed during the irradiation.

However, an accurate dose estimation with MOSFET requires to address three main considerations. First of all, the dosimetric signal is temperature dependent and special care should be taken to avoid mistaken dose estimations (Carbonetto, 2011; Sarrabayrouse, 2012). Secondly, the radiation sensitivity reduces as dose is accumulated. This can limit the sensor accuracy and in consequence its measurement range (Boesch et al., 1986; Faigon et al., 2014). And in third place, the response is dependent with the angle of incidence of radiation beam (Rosenfeld, 2006).

According to ICRU report (ICRU, 1976) the required accuracy in the measurement of the delivered dose along the treatment is 5%. Taking into account the complexity of the radiotherapy procedure the AAPM recommends 3% accuracy in each session to achieve the overall 5% (AAPM, 1994).

The operating principle of the MOSFET dosimeter can be briefly described as follows (Schwank et al., 2008). When the device is exposed to ionizing radiation electron-hole pairs are generated within the gate oxide. In presence of electric field electrons and holes drift in opposite directions through the insulator. Electrons are rapidly swept out, but

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holes can be trapped in defects within the oxide. It is usually accepted that these traps are oxygen vacancies due to an incomplete oxidation process during the fabrication (Nicklaw et al., 2002). These trapped holes are positive charge that is relatively stable in time. Its presence within the gate oxide modify the electrical characteristics of the MOSFET by shifting its threshold voltage (V_T). This change in V_T can be used as a dosimetric signal to quantify the absorbed dose (Holmes Siedle, 1974).

MOSFETs for dosimetry are usually fabricated using ad hoc processes. The reason for this relies in the fact that radiation sensitivity increases with gate oxide thickness. In standard CMOS processes the gate insulator thickness is not a design parameter and is usually too thin for dosimetric purposes. Ad hoc processes allow to fabricate MOSFETs with the required gate thickness for the intended application. Nevertheless, thicker oxides can entail some disadvantages for dosimetry, as instabilities in the dosimetric signal (Haran et al., 2004).

In this paper we present the characterization of a thick gate MOSFET dosimeter fabricated in a CMOS standard process (Lipovetzky, 2013). The proposed device is an N type transistor in which the gate insulator is the Field OXide of the CMOS process (FOXFET). The gate is a polysilicon strip deposited over the field oxide of ~600 nm thickness. Drain/source are N-Well diffusions in a P-substrate. The methodology description to fabricate these type of thick gate transistors can be found in (Lipovetzky, 2013). The advantages of this approach are: the reproducibility of this type of processes, the reduced cost in case of massive fabrication, and the possibility to integrate the sensor with other circuits to improve its performance.

2. Materials and methods

2.1. FOXFET

CMOS chips containing field oxide transistors were designed and fabricated in a standard 0.6 μm technology. These chips also integrate other devices and structures for dosimetry as it was presented in (Garcia-Inza, 2016b). FOXFET fabricated for this project have the same layout (physical design) as the one published in (Lipovetzky, 2013). The resulting chip has 3.16 mm side.

2.2. Dosimeter

The chip was mounted on a printed circuit board (PCB) and the leads of the FOXFET were wire-bonded to the copper tracks to provide electrical connection (Fig. 1a). The PCB, of dimensions 18 mm × 12 mm is compatible with a type-A USB socket.

To protect the gold bond-wires, a case was fabricated in a 3D printer using ABS plastic of dimensions 9 mm × 12 mm x 5 mm with wall thickness of 1 mm. Fig. 1 b is a photograph of the complete dosimeter.

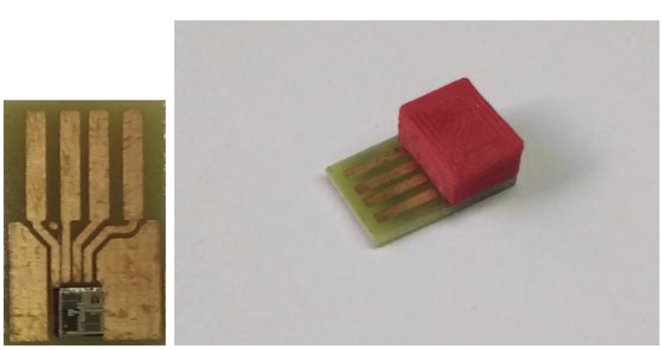

Fig. 1. a (left): chip mounted on PCB. Fig. 1 b (right): complete dosimeter with protecting case.

2.3. Measurement method and experimental setup

For in-vivo radiotherapy dose control, the dosimeter should be placed on the skin of the patient to measure the incident dose. The threshold voltage (V_T) must be sampled before and after the exposure using a dedicated hardware. The radiation-induced shift in V_T is used to estimate the absorbed dose. This procedure does not require wires connected to the dosimeter when it is placed on the patient, during irradiation. It has to be plugged into the USB socket of the reader instrument before and after the treatment session in order to sample the pre and post irradiation V_T.

The measurement setup used in this work was as follows. The dosimeter was wired to the reading system to avoid entering the irradiation room between exposures to take out the dosimeter for its reading. The threshold voltage was sampled immediately before and after the radiation pulse. To obtain proper backscatter radiation, the dosimeters were placed on a stack of 10 cm solid water as can be seen in the photographs of Fig. 2. The radiotherapy unit used for the irradiations was a LINAC VARIAN UNIQUE 6 MV (photons). It was configured to deliver a dose rate of 3 Gy/min in all the measurements. The monitor units were set to obtain the desired dose in a water depth of 1.5 cm. The irradiation field used throughout the experiments was 20 cm × 20 cm.

The instrument used to read the FOXFET dosimeters is a dedicated microcontroller-based hardware designed for this application. The acquisition instrument switches between two operation modes, shown in Fig. 3. For most of the time, the FOXFET is connected in biasing mode (Fig. 3a) where the system sets a fixed voltage to the gate of the FOXFET (V_{BIAS}). This is the default state of the system, and it only switches to reading mode (Fig. 3b) when a sample of V_T is requested by the user. To read V_T the circuit forces I_{REF} into the drain of the diode-connected FOXFET and samples V_{GS} which we will take as V_T in this work. The current I_{REF} was fixed to the MTC (minimum temperature coefficient) of the transistor, in this case 170 μA. The reading procedure lasts barely 100 ms and then the device returns to the biasing mode.

3. Results

In this section we present the results of the experiments carried out to characterize the proposed dosimeter.

3.1. Gate bias response

To obtain the initial sensitivity dependence with the applied gate bias voltage, a fresh device was exposed for several radiation pulses of 1 Gy changing the voltage applied to the gate (V_{BIAS}) in each pulse. The experiment was repeated twice for V_{BIAS}: 0, 6, 12, 18 and 24 V.

Fig. 4 shows that for 0 V gate bias, the sensitivity is 74 mV/Gy, and for higher gate biasing voltage the sensitivity monotonically increases, reaching 270 mV/Gy when V_{BIAS} = 24 V. The repetition of the experiment shows that, within the error of the sensitivity values in successive measurements, the response of the FOXFET was not substantially affected by the short irradiations (and corresponding small V_T shifts) used for their determination.

3.2. Calibration

As radiation is absorbed by the dosimeter the value of V_T reduces due to positive charge trapped within the gate oxide. Considering the radiotherapy application, it is of interest to characterize the sensitivity variation as a function of V_T. With this calibration, the reading system can calculate the sensitivity of the dosimeter for each measurement without requiring the information of the total accumulated dose.

To characterize the loss of sensitivity of the proposed dosimeter, the following experiment was carried out. A fresh device was irradiated using the following sequence: 3 pulses of 1 Gy (V_{BIAS} = 0 V), 1 pulse of 8 Gy (V_{BIAS} = 20 V), 3 pulses of 1 Gy (V_{BIAS} = 0 V), 1 pulse of 12 Gy

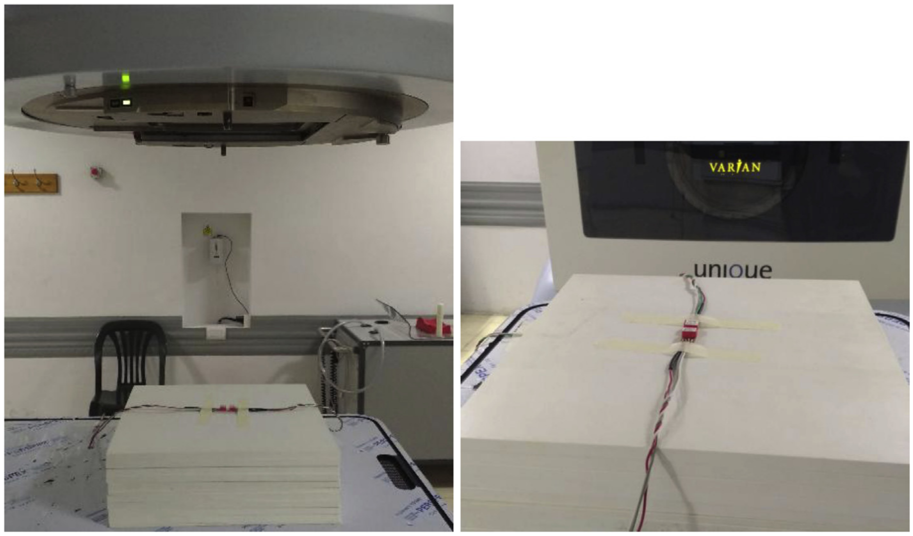

Fig. 2. Measurement setup showing the wired dosimeters placed on solid water phantoms.

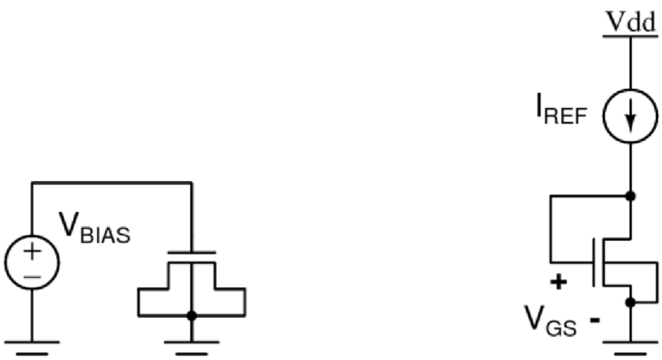

Fig. 3. a (left): biasing mode circuit. Fig. 3 b (right): reading mode circuit (simplified schematics).

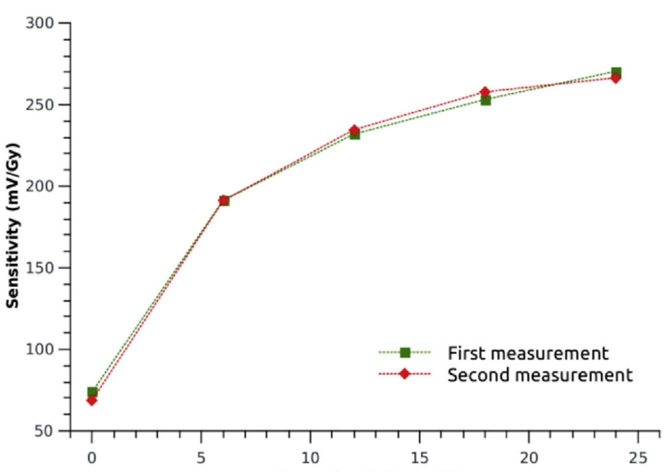

Fig. 4. Response of the FOXFET dosimeter to different gate voltages applied during the exposure to radiation.

(V_{BIAS} = 20 V), 3 pulses of 1 Gy (V_{BIAS} = 0 V), 1 pulse of 12 Gy (V_{BIAS} = 20 V), 3 pulses of 1 Gy (V_{BIAS} = 0 V). The longer pulses involving more dose with higher bias voltage were performed for a faster reduction of V_T.

For the calibration plotted in Fig. 5, only the pulses of 1 Gy were considered. The sensitivity was calculated from the average of 3 consecutive 1 Gy radiation pulses. The first group corresponds to V_T ~ 28.8 V with sensitivity of 74 mV/Gy. As V_T reduces as a consequence of the absorbed dose, the sensitivity also reduces. The error bars are the standard deviation in sensitivity and V_T for each group of samples.

3.3. Fading

After the irradiation of a MOS dosimeter, a fraction of the oxide trapped charge can be neutralized due to a thermal annealing effect. As a consequence, the V_T signal exhibits a recovery with time called fading. It is important to characterize this effect since it can affect the reproducibility and accuracy of the dose estimations.

In order to study the fading effect of the proposed dosimeter, V_T was sampled instantly after the exposure and again 1, 2 and 3 min after it. This experiment was carried out simultaneously with the previous calibration (section 3.2), at room temperature.

Fig. 6 shows the evolution of V_T due to the fading effect. Measurements were presented in subplots which correspond to the groups of measurements shown in Fig. 5. When comparing the responses It can be seen that groups with higher accumulated dose exhibit higher recovery of V_T.

Within each group, the first measurement has the highest fading, and it decreases for the following 1 Gy irradiations. This expected behavior can be related to the annealing of the large amount of charge trapped during the long irradiation pulse with higher gate bias. Further in time from the end of these long radiation pulses, the fading effect is attenuated. Taking into account its application to in-vivo dosimetry, the device will never be irradiated with gate voltage different to zero. We consider that the fading effect of the device after the third pulse in each group is the most representative behavior of the device.

3.4. PDD

The depth response of the dosimeter was studied by measuring the percentage depth dose (PDD). Measurements were performed in a solid water phantom (RW3), manufactured by PTW. For this experiment a fretwork in a solid water plate was made to insert the dosimeter in its center. The results were compared with measurements performed with a parallel plate ionization chamber (PTW 34045 Advanced Markus). The results are shown in Fig. 7.

Fig. 7 shows that for the depth of 0.2 cm the PDD measured with the FOXFET is 84% while for the ionization chamber is 62%. The maximum value is reached for both devices at the same depth of 1,3 cm. Then, both responses evolve in a similar way (differences bellow 1%) until

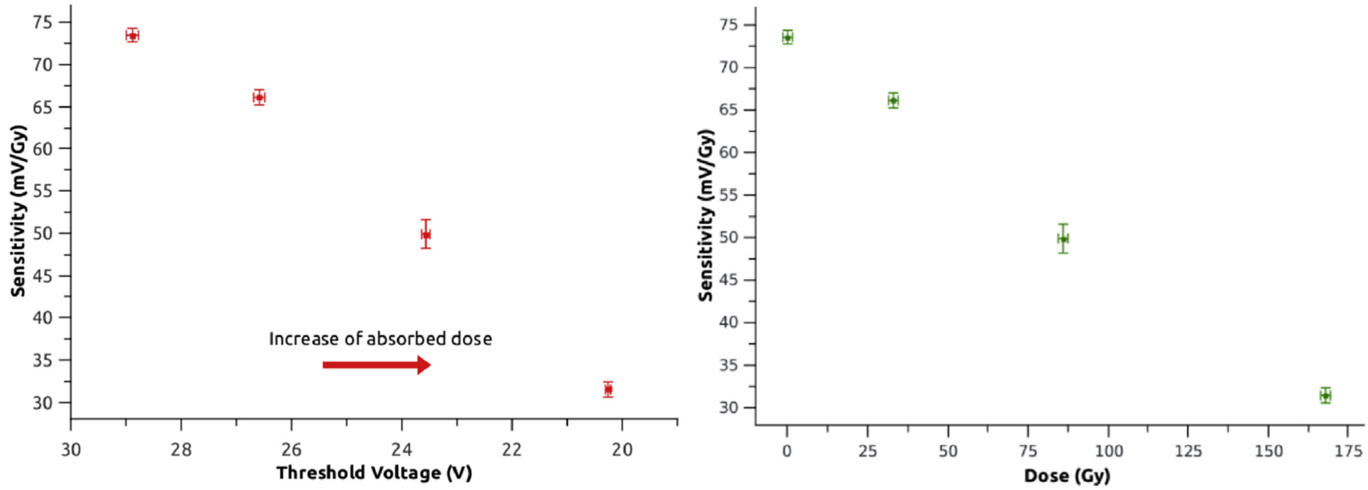

Fig. 5. (Left) Response of the FOXFET for different V_T corresponding to different accumulated doses, and (right) response plotted as a function of absorbed dose (equivalent dose for $V_{BIAS} = 0$ V).

depth 15 cm in which the FOXFET is 2.2% below the chamber.

3.5. Angular response

In order to study the angular dependence of the FOXFET, it was placed in the isocenter of the LINAC mounted on a thin acrylic stick to reduce the surrounding material. Special care was taken to position the chip exactly on the rotational axis of the LINAC which was parallel to the longitudinal axis of the dosimeter (inset Fig. 8). Then, several 1 Gy pulses were executed at different angles by rotating the gantry of the LINAC.

The relative sensitivity was plotted as a function of the angle in Fig. 8. It shows two peaks in the angular response corresponding to 60° and −60°. Considering an angle of ± 30° respect the normal incidence the response variation keeps within 3%. Measurements for angles: 150°, 180° and −150° (back side of the device) shown a lower variation of

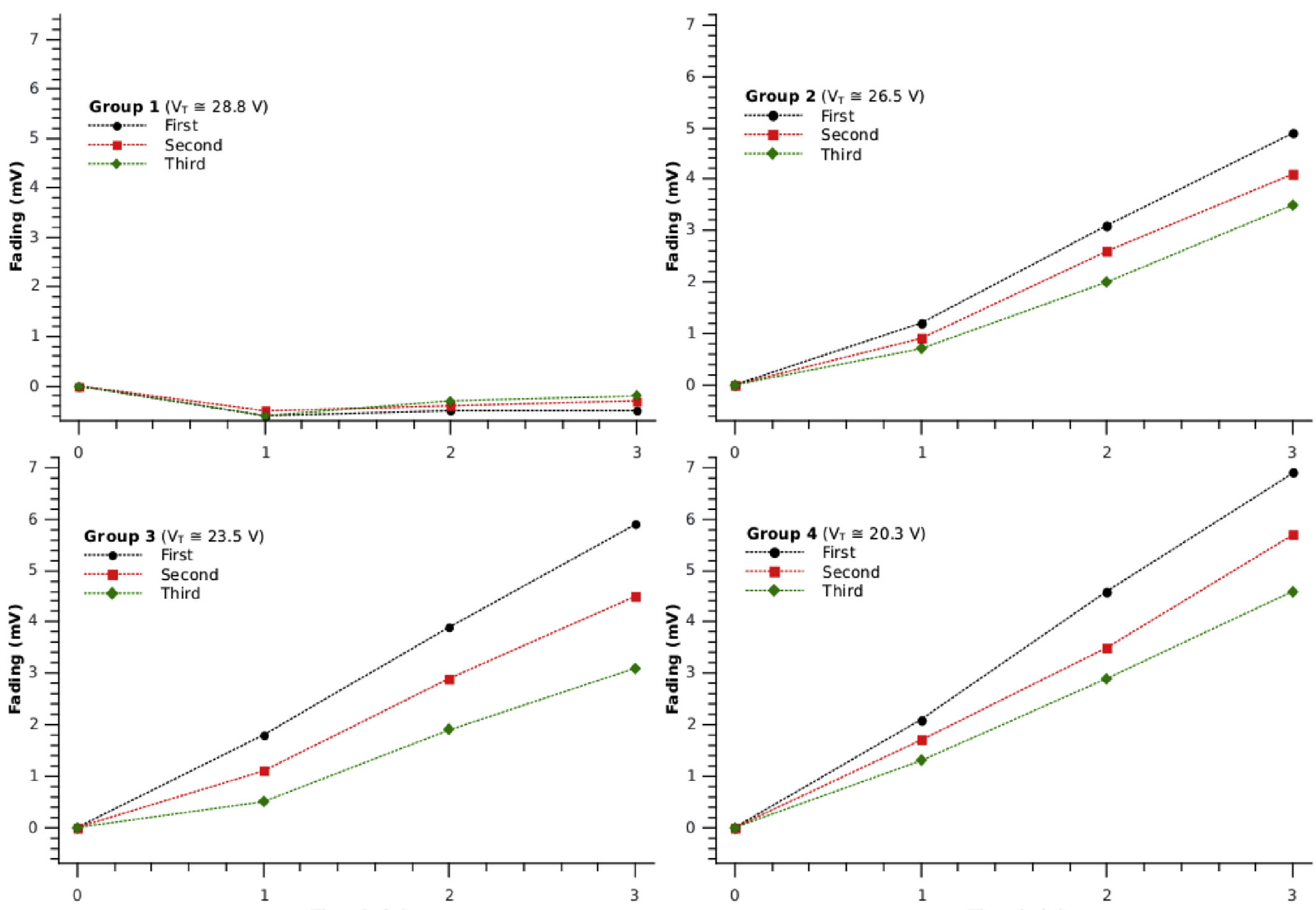

Fig. 6. Detailed fading evolution grouped by initial V_T.

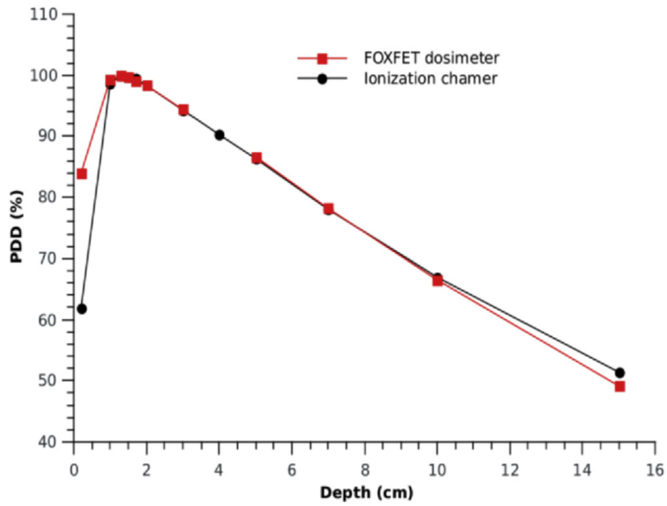

Fig. 7. PDD in solid water.

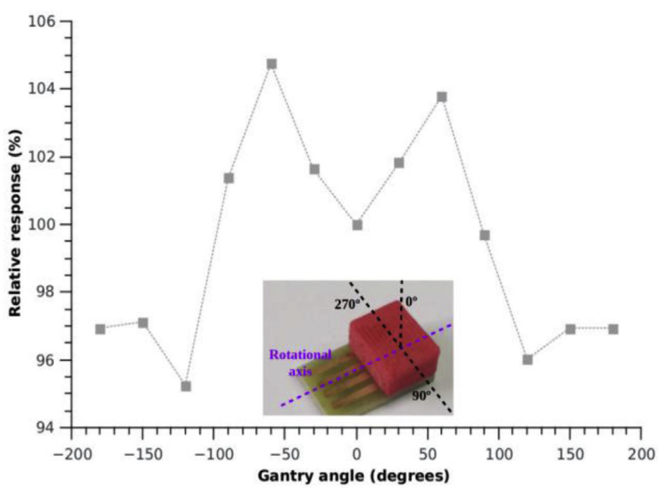

Fig. 8. Angular response of the FOXFET dosimeter. Relative sensitivity as a function of the gantry angle.

less than 1%.

3.6. Temperature coefficient

When the dosimeter is placed in contact with the body of the patient it can change its temperature. Since V_T is temperature dependent, it is important to obtain the temperature coefficient (TC) of the device. For this purpose, the V_T shift due to thermal variations was measured by changing the temperature of the device with a peltier plate. This procedure was carried out for a non irradiated FOXFET and repeated for an irradiated FOXFET with V_T near 20 V.

Results of temperature characterization are presented in Fig. 9. From the linear adjust of the measurements TCs of −0.5 and −3,4 mV/°C were obtained for the non irradiated and the irradiated device respectively.

4. Discussion

The behavior of gate bias response of the FOXFET dosimeter shown in Fig. 4 is consistent with previous reports of MOSFETs irradiated with gamma radiation (Shwank et al., 2008; Lipovetzky, 2013; Faigon et al., 2014). The bias voltage controls the oxide electric field. For higher fields more radiation-induced electron-hole pairs can escape initial recombination (charge yield). The increase of the holes density moving through the oxide increases the probability of charge trapping, which results in a higher sensitivity.

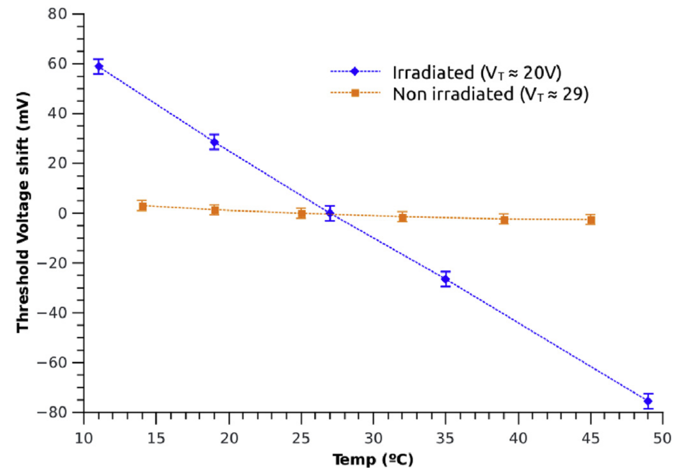

Fig. 9. Temperature response of FOXFETs dosimeters.

From the calibration of Fig. 5 it can be observed a reduction of the sensitivity as the dosimeter accumulates dose and V_T decreases. This effect is consistent with the modulation of the oxide electric field by the trapped positive charge. For lower electric field in the gate oxide, the initial recombination of electron-holes pairs increases, and the sensitivity decreases.

The sensitivity was calculated considering the dose delivered at D_{MAX} (depth for maximum dose). The measurements carried out for the calibration were made with the dosimeter placed on the surface of the solid water phantom. The actual absorbed dose in this case is a lower value because the packaging does not provide the complete build-up required for charged particle equilibrium (CPE). As a result, the sensitivity presented in this work is lower than the one at D_{MAX} under CPE conditions.

The growth of fading when V_T reduces with the absorbed dose can be related to the creation of border traps close to the silicon-oxide interface (Fleetwood et al., 1993). Since this effect implies the neutralization of positive trapped charge, it can be considered as a loss of information of the dosimeter. This undesired behavior can limit the range of operation of the dosimeter.

Fig. 10 shows the increment of the fading effect after 1 min calculated as the average of the measurements of Fig. 6. Using this information combined with the sensitivity of Fig. 5 and considering an exposure of 1 Gy, the uncertainty in the dose estimation due to this

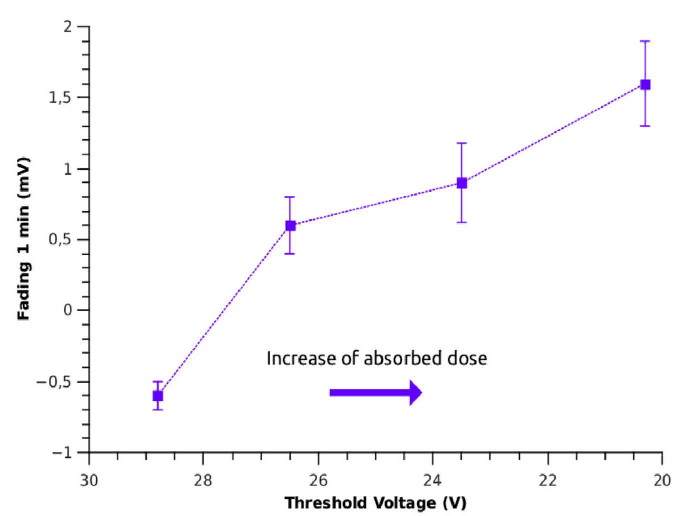

Fig. 10. Fading evolution with the reduction of V_T.

fading effect is for group 1: 0.7%; group 2: 1%; group 3: 1.8%; and for group 4: 3.2%.

Radiotherapy applications demand a measurement uncertainty of 3%. For this dosimeter the measurements of group 1, 2 and 3 meet this requirement within the range of V_T form 28.8 to 25.3 V. Taking into account an average sensitivity of 62 mV/Gy the measurement range is ~85 Gy.

The PDD experiment verifies the good surface performance of the MOSFET in comparison with the ionization chamber whose response is 26% lower. The depth for the maximum response is 1.3 cm while it is known that for this photon energy should be 1.5 cm. This difference can be attributed to the build-up produced by the plastic case and the chip layers deposited over the sensitive volume of the FOXFET.

Regarding the angular dependence of the dosimeter, the non-constant response is a consequence of the lack of symmetry of the device. This could be improved with a new design of the packaging case, using a semi cylindrical geometry for example. Since the MOSFET is not a symmetrical device this problem can not be eliminated, but a careful design of the package would reduce its impact.

The experimental results obtained with this package suggest that it would be convenient to use it with its back side up (180°). In this position, the sensitivity varies less than 1% in an angular range of 60°.

Thermal variations are of concern since the contact with the patient's body can change the temperature of the dosimeter. Considering a session of 1 Gy and the measured TC of −3.4 mV/°C with sensitivity 62 mV/Gy, if we take for example 2 °C as the difference between the readings of V_T, the dose error introduced is 11% which is far above the tolerance of 3%.

Fig. 9 shows that the TC of the device changes when it is irradiated. This effect was already observed in other work and attributed to the creation of interface states (Carbonetto, 2011). The variation of the TC with dose invalidates the implementation of an error correction method by measuring the device temperature.

With the aim of keeping the temperature error bounded an active control of temperature should be implemented. This could be accomplished by measuring the chip's temperature, and including a peltier plate in the reader's hardware to set the reference temperature of the dosimeter to 37 °C for every measurement of V_T. The temperature can be measured with a PN diode on the same chip (for example the Drain/Source - Bulk junction of the MOSFET). With this method it would be possible to measure ΔV_T with a difference below 0.2 °C, resulting in an error in the threshold voltage difference of approximately 1%.

5. Conclusion

This work has presented experimental results for the characterization of a MOSFET dosimeter in a 6 MV photon LINAC. The device is a FOXFET fabricated in a CMOS standard process. The resulting chip was wire-bonded to a PCB and covered with a plastic case.

The experiments carried out in a radiotherapy unit allowed to measure: sensitivity, gate bias dependence, fading, angular dependence and temperature coefficient. From the analysis of these data the main limitations of the device regarding its dosimetric performance were addressed and the operational dose range was estimated.

Results showed that the uncertainty in dose estimation increases as the device is irradiated due to the reduction of sensitivity and the growing of the fading effect. This uncertainty can be kept below 1.4% if the accumulated dose is below 85 Gy. In this range the sensitivity changes from 74 to 50 mV/Gy. Considering the 3% uncertainty tolerated for radiotherapy applications the other two main sources of dispersion, which are temperature and angle, should be kept below 1.6%. To achieve this goal it is necessary: 1) to implement an active control of the chip's temperature at the moment of its reading, and 2) to carefully position the dosimeter to ensure normal incidence of the radiation beam.

We can mention the following future work related to this dosimetry project. Inter chip dispersion: it will be necessary to evaluate if the chips have to be calibrated separately or if a batch characterization would be enough to accomplish the required tolerance. Package: a new semi cylindrical encapsulation will be tested with the aim of reducing the angular dependence. Finally, once these issues were addressed, we expect to start a new stage of the project which involves the clinical application of the dosimeters.

Acknowledgement

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References

AAPM, 1994. Comprehensive QA for Radiation Oncology. AAPM report NO. 46,1994. .

Boesch, H.E., McLean, F.B., Benedetto, J.M., McGarrity, J.M., Dec. 1986. Saturation of threshold voltage shift in MOSFET's at High total dose. IEEE Trans. Nucl. Sci. NS-33 (No. 6).

Carbonetto, S., Garcia Inza, M., Lipovetzky, J., Redin, G., Sambuco Salomone, L., Faigón, A., 2011. Zero Temperature Coefficient bias in MOS devices. Dependence on interface traps density, application to MOS dosimetry. IEEE Trans. Nucl. Sci.(0018-9499) 58 (6).

Cherpak, Studinski, Cygler, 2008. MOSFET detectors in quality assurance of tomotherapy treatments. Radiother. Oncol. 86, 242–250.

Dybek, Marcin, Lobodziec, Wlodzimierz, Kawa-Iwanicka, Aneta, Iwanicki, Tomasz, 2005. MOSFET detectors as a tool for the verification of therapeutic doses of electron beams in radiotherapy. Rep. Practical Oncol. Radiother. 10 (6), 301–306.

Faigon, A., Garcia Inza, M., Lipovetzky, J., Redin, E., Carbonetto, S., Sambuco Salomone, L., Berbeglia, F., 2014. Experimental evidence and modeling of non-monotonic responses in MOS dosimeters. Radiat. Phys. Chem. 95, 44–46. ISSN 0969-806X. https://doi.org/10.1016/j.radphyschem.2013.04.029.

Faigon, A., Martinez Vazquez, I., Carbonetto, S., Garcia Inza, M., 2017. Floating Gate sensor for in-vivo dosimetry in radiation therapies. Design and first characterization. In: VIII International Congress of Engineering Physics IOP Conf. Series: Journal of Physics: Conf. Series. 792, 012057. https://doi.org/10.1088/1742-6596/792/1/012057. IOP Publishing.

Fleetwood, D.M., Shaneyfelt, M.R., Winokur, P.S., Reber, R.A., Meisenheimer, T.L., Riewe, L.C., May 1993. Effects of oxide traps, interface traps, and border traps on metal-oxide-semiconductor devices. J. Appt. Phys. 73 (lo), 15.

Garcia-Inza, M., Carbonetto, S.H., Lipovetzky, J., Faigon, A., 2016a. Radiation sensor based on MOSFETs mismatch amplification for radiotherapy applications. In: IEEE Transactions on Nuclear Science. 63. pp. 1784–1789. https://doi.org/10.1109/TNS.2016.2560172. June 2016, no. 3.

Garcia-Inza, M., Carbonetto, S., Salaya, G., Martinez Vazquez, I., Faigon, A., 2016b. Integration of structures and circuits for dosimetry in a single CMOS chip. In: Proceedings Paper at Radiation Effects on Components and Systems Conference (RADECS) IEEE, 19-23 Sep, 2016, Bremen, Germany.

Haran, Avner, Jaksic, Aleksandar, Refaeli, Nati, Eliyahu, Avraham, David, David, Joseph, Barak, 2004. Temperature effects and long term fading of implanted and unimplanted gate oxide RADFETs. IEEE Trans. Nucl. Sci. 51 (NO. 5) Oct.

Hardcastle, Emilie Soisson, Metcalfe, Peter, Anatoly, B., Rosenfeld, Wolfgang A., Med, Tomé, 2008. Dosimetric verification of helical tomotherapy for total scalp irradiation. Phys 35 11 November.

Holmes-Siedle, A., 1974. The space charge dosimeter: general principles of a new method of radiation dosimety". Nucl. Instrum. Methods 121, 169–179.

ICRP, 2000. Prevention of accidents to patients undergoing radiation therapy", ICRP publication 86, ann. ICRP 30 (3), 2000.

ICRU, 1976. Int. Commisson radiation units and measurement (ICRU), determination of absorbed dose in a patient irradiated by beams of X- or gamma-rays in radiotherapy procedures. IRep 24, 1976.

Lipovetzky, J., Garcia-Inza, M., Carbonetto, S., Carra, M., Redin, E., Sambuco Salomone, L., Faigon, A., 2013. Field oxide n-channel MOS dosimeters fabricated in CMOS processes. IEEE Trans. Nucl. Sci. 60 (6), 4683–4691.

Nicklaw, C.J., Lu, Z.-Y., Fleetwood, D.M., Schrimpf, R.D., Pantelides, S.T., 2002. The structure, properties, and dynamics of oxygen vacancies in amorphous SiO2. IEEE Trans. Nucl. Sci. 49 (6), 2667–2673. https://doi.org/10.1109/TNS.2002.805408.

Patient Safety N5, 2014. Patient Safety N5 - In-vivo Dosimetry. ASN january 2014.

Purdy, J.A., Klein, E., Vijayakumar, S., Perez, C.A., Levitt, S.H., 2006. Quality assurance in radiation oncology. In: Perez, C.A., Levitt, S.H., Purdy, J.A., Vijayakumar, S. (Eds.), Technical Basis of Radiation Therapy: Practical Clinical Applications. Springer-Verlag, Berlin 395e422.

Qi, Deng, Huang, Zhang, He, Li, Kwan, Lerch, Cutajar, Metcalfe, Rosenfeld, 2009. In vivo verification of superficial dose for head and neck treatments using intensity-modulated techniques. Med. Phys. 36 (1), 59–70.

Quach, K.Y., Morales, J., Butson, M.J., Rosenfeld, A.B., Metcalfe, P.E., 2000. Measurement of radiotherapy x-ray skin dose on a chest wall phantom. Med. Phys. 27 (7), 1676–1680.

Ramani, Ramaseshan, Russell, Stephen, O'Brien, Peter, 1997. Clinical dosimetry using mosfets. Int. J. Radiat. Oncol. Biol. Phys. (0360-3016) 37 (Issue 4), 959–964. https://

doi.org/10.1016/S0360-3016(96)00600-1.

Rosenfeld, Anatoly B., 2006. Electronic dosimetry in radiation therapy. Radiat. Meas. 41 (Suppl. 1), S134–S153. ISSN 1350-4487. https://doi.org/10.1016/j.radmeas.2007.01.005.

Sarrabarouse, Siskos, 2012. Low dose measurement with thick gate oxide MOSFETs. Radiat. Phys. Chem. 81, 339–344.

Schwank, James R., Shaneyfelt, Marty R., Fleetwood, Daniel M., Felix, James A., Dodd, Paul E., Paillet, Philippe, Ferlet-Cavrois, Véronique, 2008. Radiation effects in MOS oxides. IEEE Trans. Nucl. Sci. 55 (NO. 4) Aug.

Siebel, O.F., Pereira, J.G., Souza, R.S., Ramirez-Fernandez, F.J., Schneider, M.C., Galup-Montoro, C., 2015. A very-low-cost dosimeter based on the off-the-shelf CD4007 MOSFET array for in vivo radiotherapy applications. Radiat. Meas. 75, 53–63 ISSN 1350-4487.

Villani, E.G., Crepaldi, M., DeMarchi, D., Gabrielli, A., Khan, A., Pikhay, E., Roizin, Y., Rosenfeld, A., Zhang, Z., 2016. A monolithic 180 nm CMOS dosimeter for wireless in Vivo Dosimetry. Radiat. Meas. 84, 55–64 ISSN 1350-4487.