Switched Bias Differential MOSFET Dosimeter

M. Garcia-Inza, *Member, IEEE,* S. H. Carbonetto, *Student Member, IEEE,* J. Lipovetzky, *Member, IEEE*,
M. J. Carra, *Student Member, IEEE,* L. Sambuco Salomone, E. G. Redin, A. Faigon

***Abstract*—This paper presents a differential MOSFET sensor reading technique based on the bias controlled cycled measurement. The circuit was implemented, and tested with gamma radiation from a 60-cobalt source. Temperature rejection performance was assessed during the exposure in real-time measurements. The results show that in comparison with a single MOSFET dosimeter the thermal drift is 20 times smaller and the radiation sensitivity is approximately 10% higher. The switched biasing allows to extend the measurement range beyond MOSFET's threshold voltage saturation.**

***Index Terms*—MOSFET Dosimeter, Radiation Effects, MOS Sensors, Solid-State Detectors.**

I. INTRODUCTION

MOSFETs can be used to estimate ionizing radiation absorbed dose by measuring the shift in the threshold voltage (V_T) [1], [2]. Charge capture within the gate oxide (Positive Charge Build-up, PCB) and interface states creation are the main radiation effects in the Metal-Oxide-Semiconductor (MOS) structure [3], [4], [5]. Both phenomena, contribute to the variation of the threshold voltage which can be taken as the dosimetric signal.

Dose level control using MOSFETs has many applications: medical, space vehicles, and industrial irradiations, among others. One of their most relevant use is Quality Assurance (QA) in radiotherapy to verify if the prescribed and simulated dose by the system planning agrees with the actual dose delivered to the patient. In this field, MOSFETs have several advantages in comparison with other dosimeters, such as [6]: very small size (they allow unique spatial resolution), real-time reading, water equivalent response for MV accelerator beams, excellent surface behavior (if properly encapsulated [7]), dose rate independence up to $10^{10}\,rad/s$, and gate voltage controllable response. However, when using MOSFET dosimeters special care should be taken with respect to: dose measurement errors caused by temperature variations, energy dependent response in the range of low energy X-rays (due to the dose enhancement effect of the packaging), and angular dependence. MOSFETs intended for radiotherapy dosimetry should meet at least requirements on: sensitivity, linear measurement range and thermal stability.

The radiation sensitivity of MOSFETs increases approximately with the square of the gate oxide thickness [8]. Thick gate oxides are usually grown using ad-hoc fabrication processes to obtain high sensitivity dosimeters [9]. Nevertheless, this method has some disadvantages. One is the high V_T values due to the low capacitive coupling between the gate and the substrate. For the device to become useful it is needed to adjust V_T using ion implantation. This can affect the stability in the response of the dosimeters [10]. Another drawback of the ad-hoc processes is their economical cost, which results in expensive dosimeters.

In this work we use MOSFETs that overcome these issues since they were fabricated in a standard CMOS process with a special design technique that allows to obtain relatively thick gate oxide devices [11].

It is known that the linear measurement range of MOSFETs is limited by the trend to saturation of the threshold voltage shift with the accumulated dose [12]. This reduces the sensitivity of the dosimeter until it becomes useless. The saturation effect can be related to three factors: 1) the reduction of the radiation generated charge yield (pairs escaping the initial recombination) because of the screening effect in the oxide electric field by the positive trapped charge; 2) the decrease of trap cross section due to the increase of the local electric field in the region of the trapped charge; and 3) the reduction of the available traps.

In early works, some of the present authors developed two techniques to extend the measurement range of the MOSFET dosimeters. One is the electrical erasure by Fowler-Nordheim injection [13], [14]. The other is the Bias Cycled Controlled Measurement (BCCM) [15], which is based on the cycled application of PCB stages and Radiation Induced Charge Neutralization (RICN) [16] stages. This allows to keep the threshold voltage of the dosimeter within linear range by switching the gate bias during the irradiation. This method has been tested on different types of dosimeters obtaining very satisfactory results [15], [17], [18].

Temperature variations can induce dose reading errors because V_T is also temperature dependant. In case of medical applications, for example in *in-vivo* radiotherapy, the dosimeter has to be placed in contact with the patient's skin few minutes prior to the dose delivery. Thus, it may easily suffer a thermal drift of $\sim 20\,^oC$ (from ambient to body temperature). Since the stabilization of the dosimeter temperature could take several minutes, this means that during the radiotherapy session both, radiation and temperature can shift the threshold voltage. Thermal induced V_T variations in a regular MOSFET dosimeter might be large enough to introduce a dose measurement uncertainty greater than the tolerated.

To mitigate this unwanted effect it is possible to read V_T

Manuscript received XXXXX YYYth, 2013.

This work was supported by ANPCyT and UBA by the grants PICT Redes 2007 1907 and UBACyT Y064

Mariano Garcia-Inza (mariano.garciainza@ieee.org), Sebastián Carbonetto (scarbonetto@fi.uba.ar), José Lipovetzky (jose.lipovetzky@ieee.org), Martin Carrá, Gabriel Redin, Lucas Sambuco Salomone, and Adrian Faigon are with the Device Physics-Microelectronics Lab., INTECIN, Facultad de Ingeniería, Universidad de Buenos Aires, Av. Paseo Colón 850, C1063ACV, Ciudad Autónoma de Buenos Aires, Argentina. Phone +54 11 4343 0893. Jose Lipovetzky and Adrián Faigon are also with the CONICET. Sebastián Carbonetto holds a Peruilh grant.

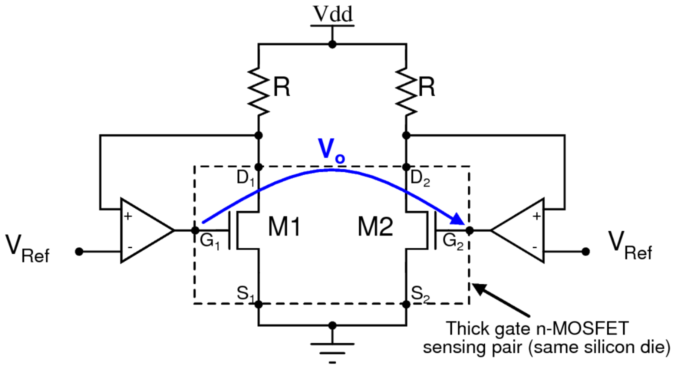

Fig. 1: Proposed differential circuit for reading mode. V_o, the difference between the gate voltages is the dosimetric signal.

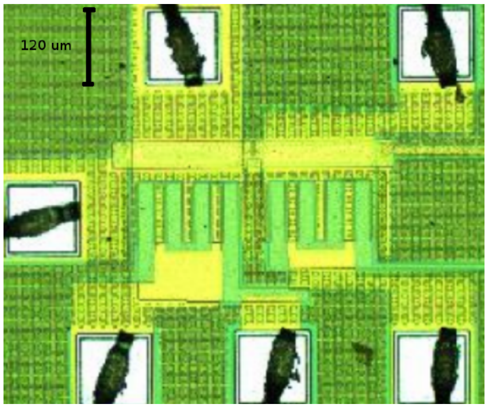

Fig. 2: Microphotograph of the n-MOSFET thick gate oxide sensing pair. Transistors fabricated using the Field OXide as gate insulator (FOXFETs). After [11].

using the Minimum Temperature Coefficient current (I_{MTC}) [19]. Although this is a useful method to reduce the thermal drifts, sometimes this reduction is not enough. Another disadvantage is that I_{MTC} changes with the accumulated dose, as it was reported in [20]. For high dose measurements, the BCCM technique can also help to reduce the dose uncertainty due to thermal drifts [21].

Another possible way to reduce the temperature dependence of these dosimeters is to use a pair of MOSFETs fabricated in the same silicon die. As both devices are expected to be at the same temperature, they will be affected by the same thermal drift. Instead of reading one single V_T, the difference between V_T of both transistors is taken as the dosimetric signal. It can be said that, at least at first approximation, that temperature affects the circuit in *common-mode* and its effect is rejected by the differential topology. To take advantage of this concept in a dosimeter, it is necessary to generate a dosimetric differential signal. This is achieved by applying different gate voltages to bias each MOSFET during the irradiation, modulating the response of both devices. This idea was proposed in [22] and developed by Soubra et al. in [23].

In this paper we propose, build and test a dosimeter based on the differential reading circuit shown in Fig. 1. The dosimetric signal is V_o, the difference between the gate voltages of transistors M2 and M1. Both thick gate devices used as the sensing pair were fabricated in the same chip [11]. A switched biasing technique is developed for this differential topology, based on the BCCM. Temperature rejection during irradiation is assessed in this work.

The paper is organized as follows. After this introduction, section II presents details on the MOSFET sensing pair; section III explains the differential BCCM technique and describes the circuit implementation; section IV presents the tests results; section V is the discussion; and section VI summarizes and concludes the work.

II. THE MOSFET SENSING PAIR

The proposed differential circuit is based on two thick gate oxide MOSFETs which behave as the radiation sensing pair. Both devices were fabricated in the same die in a standard $0.6\,\mu m$ CMOS process. The thick gate transistors were obtained by design using the Field OXide of the process as the gate insulator of the Field Effect Transistor (FOXFET). With this method an insulator layer ~40 times thicker than in the native MOSFET can be obtained. More details about these devices can be found in [11].

Fig. 2 shows a microphotograph of the FOXFETs. Each device was designed using 4 strips of polysilicon of $W = 100\,\mu m$ and $L = 25\,\mu m$. As they were fabricated on the p-substrate, using for Drain/Source diffusions the N-WELL layer of the process, the devices are n-channel transistors.

From the analysis of characteristic curves of Drain current I_D against V_{GS} and V_{DS} it can be verified that the devices behave as n-MOSFETs with negligible modulation of I_D with V_{DS}, result consistent with the high channel length.

The minimum temperature coefficient Drain current was determined using I_D vs. V_{GS} curves measured at different temperatures. The result was: $I_{MTC} \simeq 167\mu A$.

Along this paper the threshold voltage will be considered as the required V_{GS} voltage to sustain $I_D = I_{MTC}$. The *pre-irradiation* or *initial* threshold voltage of the device was $V_{T0} \approx 28.3\,V$.

Sampling V_T using the I_{MTC} as Drain current guarantees the minimum drift of V_T with temperature. Under this conditions a sensitivity of $2.58\,mV/^oC$ was measured.

A. Radiation response

The radiation response of the FOXFET device was completely assessed in [11]. Their sensitivity was $4.4\,mV/rad$ with $V_{BIAS} = 12\,V$ applied to the gate during the irradiation (doses in this paper are always referred to SiO_2) . The contribution to the threshold voltage shift of interface states creation was observed to be much lower than due to oxide trapped charge. This ensures a monotonic response and makes the devices suitable for dosimetric applications.

To be able to apply a switched bias technique as the BCCM, the oxide trapped charge needs to be removed during negative bias irradiation due to RICN. To evaluate if this was possible, a fresh FOXFET was irradiated biased initially with $V_{PCB} = 12\,V$ and after approximately $5.2\,krad$ the gate voltage was switched to $V_{RICN} = -6\,V$. The threshold voltage evolution was sampled every $11.4\,s$. The result of the experiment is shown in Fig. 3. When a negative gate bias is applied to the gate V_T recovers showing a typical

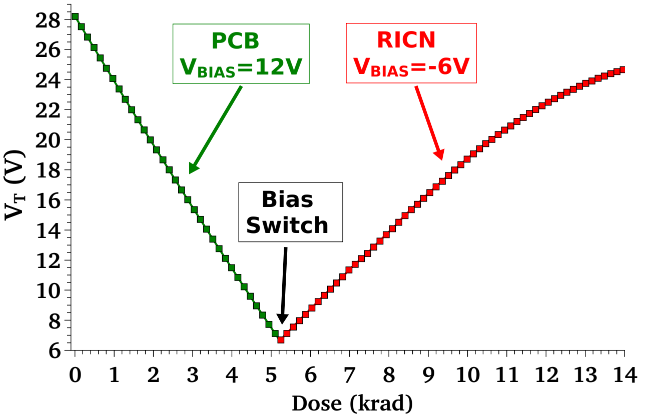

Fig. 3: Threshold voltage evolution with dose. PCB is observed with positive bias and RICN when the gate voltage is switched to a negative value (data decimated for clearer plotting).

RICN behavior. A recovery rate with dose of $2.4\,mV/rad$ was observed immediately after the switch due to oxide charge neutralization. When V_T approaches to the initial value this rate decreases due to the reduction of the positive trapped charge in the gate oxide.

B. Temperature and noise performance

To quantify the effects of temperature in a Single MOSFET (SM) dosimeter we define the Temperature Error Factor (*TEF*) as the ratio between the temperature sensitivity and the radiation sensitivity:

$$TEF_{SM} = \frac{S_T}{S_R} = \frac{2.58\,mV/^oC}{4.4\,mV/rad} \approx 0.59\,rad/^oC. \quad (1)$$

The units of *TEF* are $rad/^oC$. This means that *TEF* gives the absolute uncertainty in the dose measurement per unit of temperature change during the irradiation.

The noise performance of the dosimetric system (which includes the dosimeter, the connection cables and the measurement equipment) can be evaluated calculating the voltage RMS noise level (N_{RMS}) in V_T, in this case $50\,\mu V$. Knowing the radiation sensitivity, it is possible to calculate de Noise Equivalent Dose (NED) as:

$$NED_{SM} = \frac{N_{RMS}}{S_R} = \frac{50\,\mu V}{4.4\,mV/rad} \approx 12\,mrad. \quad (2)$$

According to eqs. (1) and (2), the temperature variation required to induce a dose uncertainty equivalent to the noise level, is: $\Delta T = 0.02\,^oC$. This small temperature variation indicates that to be able to fully exploit the dosimetric capability of the system it should work under strongly controlled conditions of temperature stabilization. Otherwise the thermal drifts will be the limiting factor of the dose resolution.

III. DIFFERENTIAL BCCM TECHNIQUE

The aim of the differential BCCM is to reduce reading errors caused by temperature variations, to enhance the radiation sensitivity, and to extend the measurement range of the dosimeter, by applying a switched bias technique to a pair of MOSFETs sensors.

During the exposure to radiation, the circuit is configured in *biasing mode*, in which an independent voltage is applied to each gate. Periodically, the circuit is commuted to the *reading mode* of Fig. 1 to read the differential signal V_o. This operation takes $\sim 100\,ms$ and after it, the circuit is restored back to the *biasing mode*. This procedure is repeated every $11.4\,s$ to track the evolution of the dosimetric signal.

A. Differential biasing and reading circuit

The reading circuit is shown in Fig. 1. The sensing pair is comprised of two thick gate n-FOXFETs fabricated in the same die using a standard CMOS process. The circuit has two identical branches, each composed of one n-FOXFET, one resistor (R) and one Operational Amplifier (OA). A reference voltage (V_{ref}) is applied to the inverting input of the OA which forces through the feedback loop connection the same voltage in the Drain of the FOXFET. The current flowing into the transistor is thus controlled by the ratio V_{ref}/R and can be adjusted to be I_{MTC}. The output signal is V_o, the difference between the gate voltages of the FOXFETs.

The differential topology allows to reject *common-mode* drifts such as temperature variations. To obtain a differential signal from the radiation one transistor is biased with a positive voltage (PCB), while the other one is biased with a negative voltage (RICN), as shown in Fig. 4. In this manner, the shift in V_T of each transistor is opposite, and the dosimetric signal turns out to be a differential signal.

The output voltage V_o can be kept within a predefined window by switching the bias of the FOXFETs. Both gate voltages are switched simultaneously to change the direction of the radiation-induced threshold voltage shifts, and thus the direction of the differential signal.

The FOXFET's biasing voltages are chosen to obtain equivalent sensitivities in the PCB and in the RICN stages. As consequence of this, the switched technique keeps also each single threshold voltage confined between a maximum and a minimum value. This allows an extended measurement range since both threshold voltages are kept far from the saturation region along the irradiation.

During the evaluation of the RICN behavior of the FOXFET device, the maximum neutralization rate was $2.4\,mV/rad$ with $V_{RICN} = -6\,V$. This limits the biasing voltage of the PCB stage to $V_{PCB} = 4\,V$.

It must be observed that this method requires the pre-irradiation of the MOSFET sensing pair. There must exist a minimum amount of positive trapped charge within the gate oxide to properly apply RICN.

B. Circuit implementation

The circuit was built in an experimental board using the following components: $30\,k\Omega$ ($1\,\%$) discrete resistors, a reference voltage $V_{REF} = 31\,V$ generated by a stabilized voltage reference, and LF442 OAs. The FOXFET sensing pair is contained in a silicon die wire-bonded to a DIP 40 package. An external voltage source of $36\,V$ is used as V_{DD}. To commute

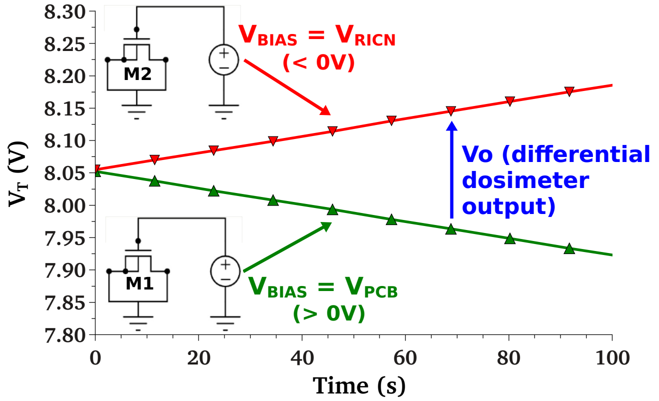

Fig. 4: Proposed differential circuit for biasing mode. While one MOSFET is biased with positive voltage the other is biased with a negative value, obtaining opposite evolutions in V_T due to PCB and RICN effects respectively.

the circuit from biasing mode to reading mode, MAX4533CPP solid state switches are used.

The experimental board was connected through a shielded cable to the acquisition unit Agilent 34970. A PC commanded the measurement and logged the data. The sampling period was $11.4\,s$. The acquisition unit tracks the signals: V_o, V_{T1}, V_{T2}, V_{ref}, the dosimeter temperature (using a thermistor), and also generates both biasing voltages for the FOXFETs.

IV. PERFORMANCE OF THE DIFFERENTIAL BCCM DOSIMETER

A. Radiation response

The radiation tests were carried out using a 60-cobalt source from a Theratron 780 teletherapy unit. The field size was $20\,cm$ x $20\,cm$ and the distance from source $80\,cm$. The dosimeter was placed on the acrylic area of the Theratron's stretcher. The acquisition system remained outside the bunker in the control room.

A Scanditronix-Wellhöfer FC 65 ionizing chamber was used for control dosimetry. The dose rate in the experiments was $\sim 32\,rad/min$.

The required pre-irradiation of the sensing pair shifted both V_T's from $\sim 28\,V$ to $\sim 8\,V$, quiescent point where the highest RICN sensibility was observed.

Fig. 5 shows the result of applying the switched bias differential technique with $V_{PCB} = 4\,V$ and $V_{RICN} = -5\,V$. The output voltage V_o was kept within the window $(-0.1\,V,\ 0.1\,V)$. The radiation sensitivity of the measurement was $\sim 4.8\,mV/rad$.

The RMS noise level in V_o was $N_{RMS} = 92\,\mu V$. Thus, the noise equivalent dose of the Differential MOSFET (DM) dosimeter is:

$$NED_{DM} = \frac{92\,\mu V}{4.8\,mV/rad} \approx 20\,mrad. \qquad (3)$$

To study the precision of the switched technique the repeatability of the measurement of Fig. 5 was evaluated. The positive-shift and the negative-shift stages of V_o were grouped in two separated plots, as illustrated in Fig. 6. In both cases, the deviation in the slope was below $2\,\%$.

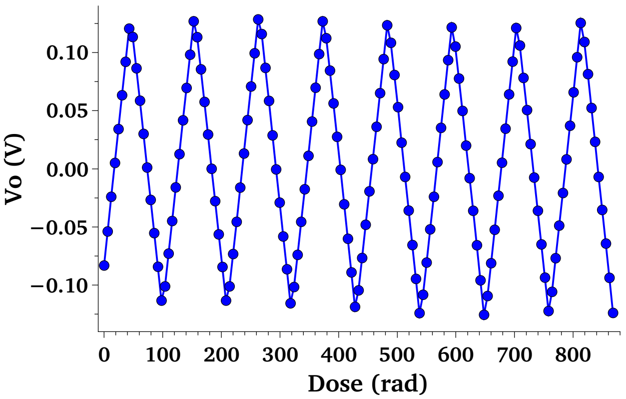

Fig. 5: Differential output evolution under commuted biasing irradiation.

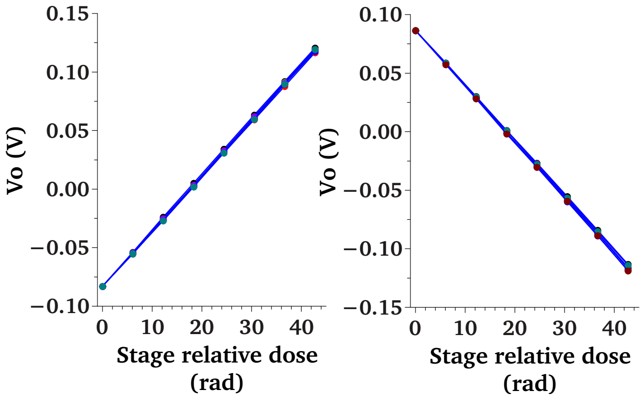

Fig. 6: Repeatability evaluation of the differential response.

B. Temperature tests

In order to evaluate the thermal sensitivity of the system, we also tested the dosimeter behavior against temperature. With this purpose, temperature was swept while sampling the output voltage V_o. The result is shown in Fig. 7, where ΔV_o and ΔV_T are plotted against temperature. The thermal sensitivity of the differential dosimeter is $S_T = 0.13 mV/^oC$.

The temperature error factor of the differential dosimeter can now be calculated:

$$TEF_{DM} = \frac{S_T}{S_R} = \frac{0.13\,mV/^oC}{4.8\,mV/rad} \approx 0.027\,rad/^oC. \qquad (4)$$

C. Combined temperature and radiation tests

To complete the thermal study a temperature pulse was applied during the irradiation. The results of this experiment are shown as function of irradiation time in Fig. 8, where chart (a) shows the temperature applied to the dosimeter; chart (b) shows the dosimetric signal V_o; and chart (c) plots the individual V_T's of each MOSFET in the sensing pair. It can be clearly observed that the evolution of V_T of each transistor is modulated by the pulse of temperature. Despite this modulation, the output voltage V_o does not seem to be affected by the pulse.

For a better understanding on the effects of temperature in the dose measurement, the evolution of the instant sensitivities of V_o, V_{T1}, and V_{T2} are plotted in Fig. 9 using the data from

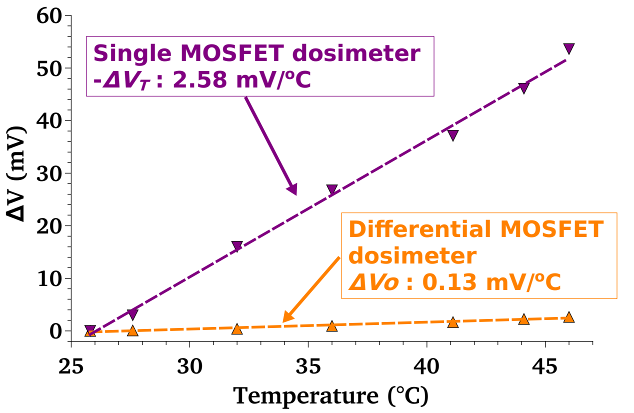

Fig. 7: Thermal response of the differential output (dosimetric signal) compared with threshold voltage of the single MOSFET.

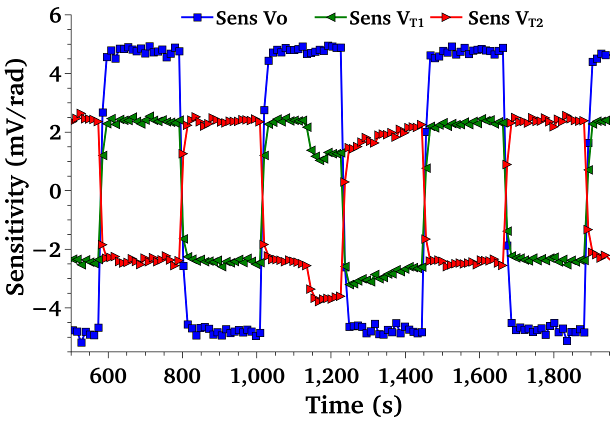

Fig. 9: Sensitivity of the circuit during the temperature pulse.

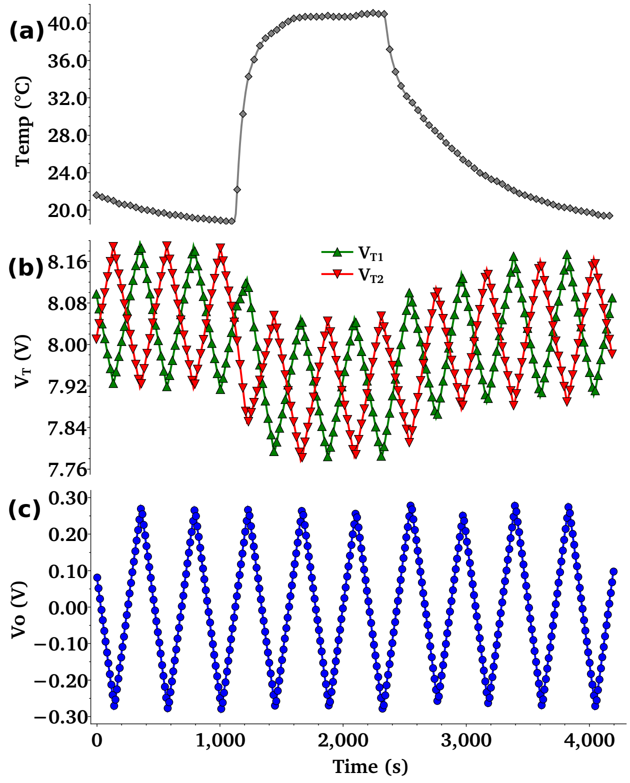

Fig. 8: Temperature pulse applied during the irradiation.

Fig. 8. It can be seen that the sensitivity of each transistor is affected in the same way. Near the instant $t = 1150\,s$, the temperature rise induces a negative shift in both V_T's. The sensitivity of M1 suddenly decreases since the thermal drift is opposite to the radiation induced shift. For transistor M2, the thermal drift and the radiation shift are both negative, increasing the absolute value of the sensitivity. The thermal drifts in both devices have the same amplitude, explaining why the sensitivity of V_o remains constant (within the measurement error) along the measurement.

V. DISCUSSION

Table I shows the most important results of this paper, comparing the single and the differential MOSFET dosimeters. The target of this comparison is to highlight the advantages of the switched differential method regardless of the characteristics of the MOSFET sensing pair used. Moreover, p-channel transistors could easily be used with few modifications in the reading circuit.

Radiation sensitivity of the differential dosimeter with extended measurement range is $\sim 10\,\%$ higher. In other approaches [23] both MOSFETs were biased with different positive voltages, thus both working under PCB. In this case, the differential dosimeter will always have less sensitivity than the single one. For the technique we are presenting, there is always one of the devices working under RICN, generating opposite directions in the radiation-induced V_T shifts. This allowed to reach higher sensitivities than the single MOSFET dosimeter.

If the extended measurement condition is not required, the maximum achievable sensitivity for the differential dosimeter could be $\sim 54\,\%$ higher (using $V_{PCB} = 12\,V$). In this case, the threshold voltage evolution of each MOSFET could not be bounded, as it was explained in section III.A. The repeatability and the linearity range under this conditions will be investigated future works.

Temperature sensitivity of the differential dosimeter is $\sim$20 times lower, and this rejection was observed to work properly during the irradiation.

As a result of the rejection of the thermal drifts and the enhancement of the radiation sensitivity, the measurement uncertainty with the differential dosimeter is more than 21 times smaller. This means that, for example, in dose control for *in-vivo* radiotherapy, assuming a typical dose session of $100\,rad$ and a thermal drift of $20\,^oC$ during the irradiation due to the ambient-body temperature difference, the uncertainty of the proposed dosimeter will be $0.5\,rad$. In the case of the single MOSFET, the uncertainty would rise to $12\,rad$ (not tolerable for medical applications).

The noise equivalent dose of the differential technique is worse than the single MOSFET dosimeter. This is due to the increment of the noise level in the dosimetric signal introduced by the addition of a second sensor. Even the NED grew 66%, this is not a critical issue for the radiotherapy application since it represents less than the 0.02% of a $100\,rad$ session. The temperature variation that now equates the noise level is $\Delta T = 0.74\,^oC$, result which is reasonable for a system that

TABLE I: Comparison between the single and the differential MOSFET dosimeters: radiation sensitivity, thermal sensitivity, temperature error factor and noise equivalent dose.

Dosimeter	S_R (mV/rad)	S_T $(mV/^oC)$	TEF $(rad/^oC)$	NED $(mrad)$
Single	4.4	2.58	0.586	12
Differential	4.8	0.13	0.027	20

is not intended to work under thermal stabilized conditions.

Another advantage of the proposed reading circuit is that V_T is measured under constant V_{DS} voltage, instead of the usual diode configuration (Gate-Drain connected). In this configuration, the radiation-induced threshold voltage shift appears also in the Drain-Source voltage: $\Delta\ V_T\ =\ \Delta\ V_{DS}$. This causes the increment of the current due to the channel length modulation, reducing the effective current through transistor. The measurement error because of the diode connection depends on the output resistance of the device and the magnitude of the shift $\Delta\ V_{DS}$. However, this uncertainty is completely removed using the constant V_{DS} reading circuit of Fig 1.

Finally, an advantage to be remarked of the dosimeter proposed in this work is the extended measurement range. This is a heritage from the BCCM technique. During the tests carried out in this work a total dose of several $krad$ were accumulated by the devices and no effects of wearing-out or aging were observed.

VI. SUMMARY

In this work a switched bias differential MOSFET dosimeter was presented. The device was conceptually introduced, its construction was fully depicted and its behavior was assessed experimentally in real-time measurements.

The main experimental results are:

- The enhancement of the thermal rejection which leads to a reduction in more than 21 times of the uncertainty when measuring in non-stabilized conditions, as it can occur for *in-vivo* radiotherapy.
- The extension of the measurement range.

Based on these results, further work aim to the design and fabrication of a monolithic CMOS circuit for system-on-chip dosimeters. It is expected that the integrated approach would improve several aspects of the current differential proposal such as thermal rejection and size. Moreover, the integration would also allow to include other devices in the circuit to increase the gain in the dosimetric signal and thus achieving better resolution. But for this, it will be necessary to overcome some design issues such as the high voltages involved and the negative bias for RICN.

ACKNOWLEDGMENT

The authors want to thank to the Prof. Angel Roffo Institute (University of Buenos Aires) for the access to irradiation facilities and Diana Feld for her help with dosimetry and use of the radiation source.

REFERENCES

[1] A. Holmes-Siedle, “The space-charge dosimeter: General principles of a new method of radiation detection,” *Nuclear Instruments and Methods*, vol. 121, no. 1, pp. 169–179, 1974.

[2] G. Sarrabayrouse and S. Siskos, “Radiation dose measurment using mosfets,” *Instrumentation and Measurement Magazine*, vol. 1, no. 2, pp. 26–34, 1998.

[3] T. Oldham and F. McLean, “Total ionizing dose effects in MOS oxides and devices,” *IEEE Trans. Nucl. Sci.*, vol. 50, no. 3, pp. 483–499, 2003.

[4] H. J. Barnaby, “Total-ionizing-dose effects in modern CMOS technologies,” *IEEE Trans. Nucl. Sci.*, vol. 53, no. 6, pp. 3103–3121, 2006.

[5] J. R. Schwank, M. R. Shaneyfelt, D. M. Fleetwood, J. A. Felix, P. E. Dodd, P. Paillet, and V. Ferlet-Cavrois, “Radiation effects in MOS oxides,” *IEEE Trans. Nucl. Sci.*, vol. 55, no. 4, pp. 1833 –1853, aug. 2008.

[6] A. B. Rosenfeld, “Electronic dosimetry in radiation therapy,” *Radiation measurements*, vol. 41, pp. S134–S153, 2006.

[7] A. B. Rosenfeld, M. G. Carolan, G. I. Kaplan, B. J. Allen, and V. I. Khivrich, “Mosfet dosimeters: the role of encapsulation on dosimetric characteristics in mixed gamma-neutron and megavoltage x-ray fields,” *Nuclear Science, IEEE Transactions on*, vol. 42, no. 6, pp. 1870–1877, 1995.

[8] N. S. Saks, M. G. Ancona, and J. A. Modolo, “Radiation effects in mos capacitors with very thin oxides at 80k,” *Nuclear Science, IEEE Transactions on*, vol. 31, no. 6, pp. 1249–1255, 1984.

[9] G. Sarrabayrouse and S. Siskos, “Low dose measurement with thick gate oxide mosfets,” *Radiation Physics and Chemistry*, vol. 81, no. 3, pp. 339 – 344, 2012.

[10] A. Haran and A. Jaksic, “The role of fixed and switching traps in long-term fading of implanted and unimplanted gate oxide RADFETs,” *IEEE Trans. Nucl. Sci.*, vol. 52, no. 6, pp. 2570–2577, 2005.

[11] J. Lipovetzky, M. Garcia-Inza, S. Carbonetto, M. J. Carra, E. G. Redin, L. Sambuco Salomone, and A. Faigon, “Field oxide n-channel mos dosimeters fabricated in cmos processes,” *Nuclear Science, IEEE Transactions on*, vol. PP, no. 99, pp. 1–9, 2013.

[12] H. E. Boesch, F. B. McLean, J. M. Benedetto, J. M. McGarrity, and W. E. Bailey, “Saturation of threshold voltage shift in MOSFET’s at high total dose,” *IEEE Trans. Nucl. Sci.*, vol. 33, no. 6, pp. 1191–1197, 1986.

[13] J. Lipovetzky, E. G. Redin, and A. Faigon, “Electrically erasable metal–oxide–semiconductor dosimeters,” *IEEE Trans. Nucl. Sci.*, vol. 54, no. 4, pp. 1244–1250, 2007.

[14] A. Faigon and E. Redin, “Dosimetro mos de borrado electrico,” 2007, ”Patent P020100113AR (AR045294B1)”. [Online]. Available: http://www.patentesonline.com.co/dosimetro-mos-de-borrado-electrico-para-medir-de-modo-no-destructivo-dosis-de-energia-1381ar.html

[15] A. Faigon, J. Lipovetzky, E. Redin, and G. Krusczenski, “Extension of the measurement range of MOS dosimeters using radiation induced charge neutralization,” *IEEE Trans. Nucl. Sci.*, vol. 55, no. 4, pp. 2141–2147, 2008.

[16] D. M. Fleetwood, “Radiation induced charge neutralization and interface trap buildup in metal oxide semiconductor devices,” *Journal of Applied Physics*, vol. 67, no. 1, pp. 580–583, 1990.

[17] J. Lipovetzky, A. Siedle, M. Garcia-Inza, S. Carbonetto, E. Redin, and A. Faigon, “New Fowler-Nordheim Injection, charge neutralization, and gamma tests on the REM RFT300 RADFET dosimeter,” *IEEE Trans. Nucl. Sci.*, vol. 59, no. 6, pp. 3133–3140, 2012.

[18] M. Garcia Inza, J. Lipovetzky, E. G. Redin, S. Carbonetto, and A. Faigon, “Floating gate PMOS dosimeters under bias controlled cycled measurement,” *IEEE Trans. Nucl. Sci.*, vol. 58, no. 3, pp. 808–812, 2011.

[19] G. Sarrabayrouse and S. Siskos, “Behaviour of high sensitivity mos radiation dosimeters biased in the mtc current region,” in *Proc. 9th WSEAS Int. Conf. on Instrumentation, Measurement, Circuits and Systems*. WSEAS, 2010, pp. 38–41.

[20] S. H. Carbonetto, M. Garcia-Inza, J. Lipovetzky, E. G. Redin, L. Salomone, and A. Faigon, “Zero temperature coefficient bias in MOS devices. dependence on interface traps density, application to MOS dosimetry,” *IEEE Trans. Nucl. Sci.*, vol. 58, no. 6, pp. 3348–3353, 2011.

[21] J. Lipovetzky, E. Redin, M. Garcia-Inza, S. Carbonetto, and A. Faigon, “Reducing measurement uncertainties using bias cycled measurement in MOS dosimetry at different temperatures,” *IEEE Trans. Nucl. Sci.*, vol. 57, no. 2, pp. 848–853, 2010.

[22] M. Brown, G. MacKay, and I. Thomson, “Direct reading dosimeter,” May 26 1992, ”US Patent 5,117,113”. [Online]. Available: http://www.google.com.br/patents/US5117113

[23] M. Soubra, J. Cygler, and G. Mackay, “Evaluation of a dual bias dual metal oxide-silicon semiconductor field effect transistor detector as radiation dosimeter,” *Med. Phys.*, vol. 21, no. 4, pp. 567–572, 1994.