Zero Temperature Coefficient Bias in MOS Devices. Dependence on Interface Traps Density, Application to MOS Dosimetry

Sebastián H. Carbonetto, Mariano A. García Inza, José Lipovetzky, *Member, IEEE*, Eduardo G. Redin,
Lucas Sambuco Salomone, and Adrián Faigón

***Abstract*—In this paper the influence of temperature fluctuations on the response of thick gate oxide metal oxide semiconductor dosimeters is reviewed and the zero temperature coefficient (ZTC) method is evaluated for error compensation. The response of the ZTC current to irradiation is studied showing that the error compensation impoverishes with absorbed dose. Finally, an explanation and analytic expression for the shifts in the ZTC current with irradiation based on the interface traps creation is proposed and verified with experimental data.**

***Index Terms*—Dosimetry, ionizing radiation sensors, MOS devices, radiation effects, temperature.**

I. INTRODUCTION

MOS dosimeters are p-channel metal-oxide-semiconductor field effect transistors (MOSFETs) where the shift in the threshold voltage (V_T) is used to estimate the absorbed dose [1], [2]. This shift in V_T is mainly a consequence of positive charge build-up caused by the interaction between ionizing radiation and the gate oxide [3], [4].

One difficulty associated with MOS dosimetry is that the accuracy of the sensor is determined by temperature variations during measurements, as the read out voltage is temperature dependent [2], [5]–[7]. In high dose measurements, these fluctuations may be negligible, whereas in low dose measurements, such as radiotherapy sessions, the MOSFET temperature sensitivity may introduce significant errors in the dose evaluation. To reduce the temperature error, four techniques are proposed in the literature [6], [8]:

- Characterize the sensor response to temperature for later correction [9].
- Integrate a temperature sensor whose reading automatically corrects the MOSFET reading [5].
- Perform differential measurements using two MOS sensors [9]–[11].
- Fix the measurement current to the minimum temperature sensitivity current, known as the *zero temperature coefficient* current (I_{ZTC}) [6], [12].

In this paper we investigate the performance of the zero temperature coefficient (ZTC) technique in dose measurements. The error minimization is studied as well as the robustness of the technique against radiation since the I_{ZTC} exhibits a non-negligible dependence on the total accumulated dose. An explanation for these shifts in I_{ZTC} with irradiation is proposed, which shows to be consistent with the presented measurements.

II. STANDARD MEASUREMENT TECHNIQUE AND TEMPERATURE AS AN ERROR SOURCE

The exposure of a MOSFET to ionizing radiation affects a number of physical parameters of the device. The threshold voltage shift [13]

$$\Delta V_T = -\frac{1}{C_{OX}} \int_o^{t_{OX}} \Delta\rho_{OX}(x)\frac{x}{t_{OX}}dx - q\frac{\Delta N_{IT}}{C_{OX}} \qquad (1)$$

where C_{OX} is the oxide capacitance per unit area, x is the distance from the gate electrode to the $Si\text{-}SiO_2$ interface, t_{OX} is the oxide thickness, $\Delta\rho_{OX}(x)$ is the trapped charge density within the gate oxide, and ΔN_{IT} is the interface traps density creation; and the carrier mobility (μ) [4]

$$\mu = \frac{\mu_0}{1+\alpha\Delta N_{IT}} \qquad (2)$$

where μ_0 is the pre-irradiation carrier mobility, and α is a technology dependent parameter; these are the main effects to be considered in this study as they correlate with the oxide charge density and the interface traps, respectively.

The positive charge build-up (PCB) is related to hole trapping in the oxide bulk [3], and the interface trap creation (ΔN_{IT}) may be a consequence of hydrogen ions release during hole trapping [14]. For p-channel MOS transistors (pMOSFETs), both phenomena cause a negative shift in the threshold voltage. This shift in V_T allows the use of MOS transistors as total ionizing radiation dose sensors.

Manuscript received April 19, 2011; revised September 19, 2011; accepted September 21, 2011. Date of publication November 01, 2011; date of current version December 14, 2011. This work was supported in part by the University of Buenos Aires under Grant I037, in part by ANPCYT PICT 2007-01907, and in part by CONICET. S. Carbonetto and M. A. García Inza hold a Peruilh Grant, and L. Sambuco Salomone holds a UBACyT Grant.

S. H. Carbonetto, M. A. García Inza, J. Lipovetzky, E. G. Redin, and L. Sambuco Salomone are with the Device Physics-Microelectronics Laboratory, Departamento de Física, Facultad de Ingeniería, Universidad de Buenos Aires, C1063 ACV, Ciudad Autónoma de Buenos Aires, Argentina (e-mail: scarbonetto@fi.uba.ar; magarcia@fi.uba.ar; jlipove@fi.uba.ar; eredin@fi.uba.ar; lsambuco@fi.uba.ar).

A. Faigón is with the Device Physics-Microelectronics Laboratory, Departamento de Física, and INTECIN, Facultad de Ingeniería, Universidad de Buenos Aires, C1063 ACV, Ciudad Autónoma de Buenos Aires, Argentina, and also with the National Research Council of Argentina (CONICET), CP C1033 AAJ, Ciudad de Buenos Aires, Argentina (e-mail: afaigon@fi.uba.ar).

Digital Object Identifier 10.1109/TNS.2011.2170430

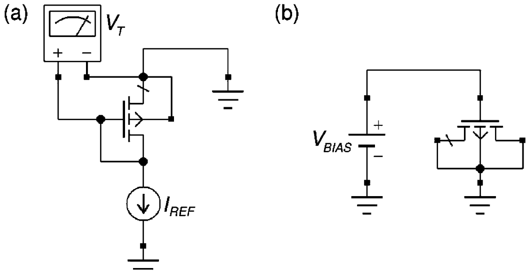

Fig. 1. Schematic circuit of (a) "Measurement Configuration" used to read V_T and (b) "Bias Configuration".

A. Standard Measurement Technique

The standard use of MOS dosimeters consists in tracking V_T shifts during or between irradiations. For this purpose, a constant reference current (I_{REF}) is usually injected in the device channel and the gate-to-source voltage read is used as the value of V_T [2], [15]. I_{REF} is chosen so that the device should work in the transition between the weak inversion (or subthreshold) and strong inversion regime. In order to improve the sensitivity to radiation, a constant positive gate bias (V_{BIAS}) is applied during irradiations [2] and between V_T readings. The dosimeter electronics switches the sensor between "Measurement" and "Bias Configurations" (see Fig. 1).

The sensitivity of the sensor to radiation (S_R) is the variation in V_T with the dose, and for low dose measurements can be considered constant [5]. Then

$$S_R = \frac{\Delta V_T}{\Delta D} \tag{3}$$

where ΔD is the absorbed dose.

B. Temperature Effects on MOSFETs and Dose Measurement Error

Temperature fluctuations affect several physical parameters of the MOS transistor, which impact on the electrical behavior of the device [6], [16], [17]. Experimental measurements show that the threshold voltage varies linearly with the temperature as [16], [17]

$$V_T(T) = V_T(T_0) + \theta_T(T - T_0) \tag{4}$$

where θ_T is the threshold voltage temperature coefficient, which is constant and positive for pMOSFETs.

The carrier mobility, in turn, decreases with increasing temperatures

$$\mu(T) = \mu(T_0)\left(\frac{T}{T_0}\right)^{-n} \tag{5}$$

where n is an exponent which varies from 1.6 to 2.4 [6], [17].

For a given drain current (I_D), the gate to source voltage of a pMOSFET is given by

$$V_{GS}(I_D, T) = V_T(T) - \sqrt{2\frac{|I_D|}{\mu(T)C_{OX}}\frac{L}{W}} \tag{6}$$

which is temperature dependent. The temperature coefficient (or temperature sensitivity, S_T) can be defined as [12], [16]

$$\begin{aligned} S_T(I_D, T) &= \frac{\partial V_{GS}(I_D, T)}{\partial T} = \\ &= \frac{\partial V_T}{\partial T} + \frac{1}{2\mu(T)}\sqrt{2\frac{|I_D|}{\mu(T)C_{OX}}\frac{L}{W}}\frac{\partial \mu}{\partial T}. \end{aligned} \tag{7}$$

When using MOS dosimeters in a non-controlled temperature environment, the slightest temperature variation may induce a shift in V_T [5], [18]; hence, a measurement error is introduced. As explained in the earlier section, the measured V_T is defined as the gate to source voltage at a reference drain Current

$$V_T \equiv V_{GS}(I_{REF}) = V_T^{(0)} + \Delta V_T^{(rad)} + \Delta V_T^{(temp)} \tag{8}$$

where $V_T^{(0)}$ is the value of the threshold voltage before irradiation, $\Delta V_T^{(rad)}$ and $\Delta V_T^{(temp)}$ are the radiation and temperature induced shifts in the threshold voltage, respectively. Then, the absorbed dose would be mis-estimated

$$\hat{D} = \frac{\Delta V_T}{S_R} = \Delta D + \frac{S_T}{S_R}\Delta T \tag{9}$$

where the ratio S_T/S_R gives some insight of the temperature induced estimation error. According to (9), to minimize this error, it is necessary for the device to be as insensitive to temperature as possible. The ZTC method was studied in this regard.

C. ZTC Reference Current

The ZTC reference current is defined as the drain current for which the temperature sensitivity of the MOS transistor is zero [12], [16]. From (7)

$$S_T(I_{ZTC}) = 0 \tag{10}$$

implies

$$I_{ZTC} = -\frac{\mu(T)C_{OX}}{2}\frac{W}{L}\left(2\mu(T)\frac{\frac{\partial V_T}{\partial T}}{\frac{\partial \mu}{\partial T}}\right)^2. \tag{11}$$

Differentiating and replacing (4) and (5) into (11)

$$I_{ZTC} = -\frac{\mu(T_0)C_{OX}}{2}\frac{W}{L}\left(\frac{T}{T_0}\right)^{2-n}\left(2\frac{\theta_T T_0}{n}\right)^2. \tag{12}$$

Equation (12) shows that the I_{ZTC} is temperature dependent; hence, a constant I_{ZTC} does not strictly exist. Nevertheless, since the n parameter is approximately 2, the temperature dependent factor $(T/T_0)^{2-n}$ is very close to 1, and the I_{ZTC} is quasi-constant in a limited temperature range. Conversely, when the current-voltage (I–V) curves are closely examined near the ZTC condition, it can be seen that there is a bounded range of currents for which the temperature sensitivity is minimum. For this reason, some authors call it the minimum temperature coefficient (MTC) current.

III. EXPERIMENT, RESULTS, AND MODELING

To study the efficiency of the ZTC method as a temperature compensation technique, the radiation and temperature response of three 140 nm oxide thick pMOSFETs were characterized.

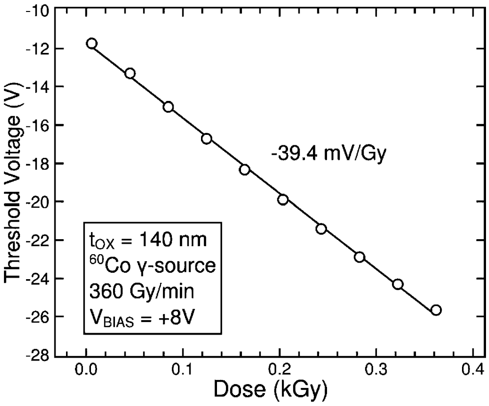

Fig. 2. Response of the sensor under test to radiation. The 140 nm dosimeter was exposed to a ^{60}Co γ-source with a dose rate of 360 Gy/min for characterization.

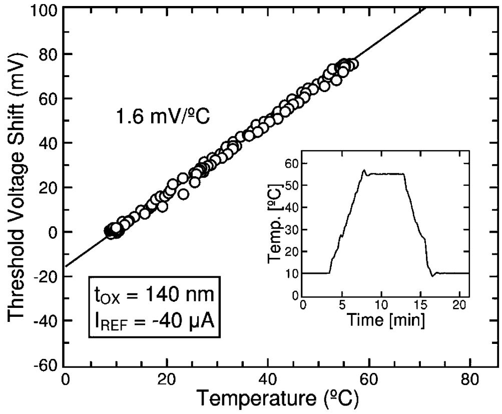

Fig. 3. Response of the sensor under test to temperature at an arbitrary reference current of $-40\ \mu$A. The inset shows the temperature pulse used for characterization.

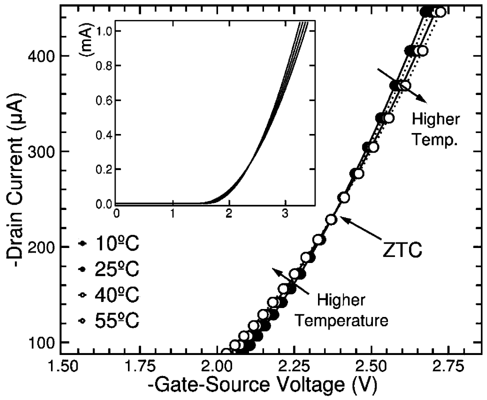

Fig. 4. Close view of the Current-Voltage characteristic at different temperatures of a pMOSFET used as dosimeter. The existence of a ZTC biasing current is revealed. The inset shows the complete I–V curves.

First of all, the sensors were exposed to a ^{60}Co γ-source with a dose rate of 360 Gy/min, in order to study their sensitivity to radiation. During irradiation, the transistors were connected in Bias Configuration [as in Fig. 1(b)] holding an 8 V gate voltage. The threshold voltage evolution was tracked every five seconds switching to Measurement Configuration [as in Fig. 1(a)] for less than 100 ms, with an arbitrary reference current of $-40\ \mu$A.

The temperature dependence of the samples was investigated recording I–V curves at different temperatures (from 10°C to 55°C in steps of 15°C) for later recognition of the ZTC current. The devices were heated or cooled with a Peltier Cell and a dedicated temperature control equipment with an uncertainty of 0.2°C. The shift in V_T with temperature was also tracked connecting the sensors as in Fig. 1(a) while changing the temperature of the devices. The experiment was performed repeatedly with different I_{REF} to study how the sensitivity to temperature of the devices changes. These experiments were performed without exposure to radiation.

Finally, several irradiations were performed exposing the samples to a ^{60}Co γ-source with a dose rate of 0.5 Gy/min holding the gate bias at 8 V to track the shift in I_{ZTC} with the absorbed dose. The ZTC current was determined between the radiation sessions repeating the I–V measurements at different temperatures.

A. ZTC Reference and Error Minimization

Fig. 2 shows the response of one of the devices under test to radiation. For low dose measurements, a constant sensitivity of 39.4 mV/Gy is obtained. On the other hand, the same device shows a temperature sensitivity of 1.6 mV/°C, at an arbitrary I_{REF} of $-40\ \mu$A, as shown in Fig. 3. Under these circumstances, the sensitivity ratio S_T/S_R results in an error of 40.6 mGy/°C, which can be unacceptable in strict low dose applications such as radiotherapy.

Fig. 4 shows the I_{ZTC} determination and the advantage of choosing $-236\ \mu$A for the reference current. The dependence of the temperature induced error on the chosen value of I_{REF} is plotted in Fig. 5. This error changes about 5 μV/°C per μA of change in I_{REF}. As expected, reference currents lower than I_{ZTC} result in a positive temperature coefficient, whereas higher currents result in a negative temperature coefficient. When the device is working in the ZTC condition, i.e., $I_{REF} = -236\ \mu$A, the temperature sensitivity is zero over the whole measured interval, but it exhibits very small oscillations with a local maximum value of 83 μV/°C, hence the maximum dose estimation error extending for no more than a few °C is reduced to 2.1 mGy/°C.

B. Radiation Effects on I_{ZTC} and Its Impact on the Measurement Error

In the previous subsection, it was shown that the ZTC method achieves temperature error compensation. But is it a radiation-hard technique? It has been reported in [5], [6], [12], and [18] that radiation affects the ZTC current, but there is no information about the magnitude of this effect.

To study how the I_{ZTC} changes with the absorbed dose, the dosimeters where irradiated in short sessions until the total absorbed dose was 1 Gy, 2 Gy, 10 Gy, and 20 Gy. The irradiation conditions were explained earlier in this section. Before and after each irradiation session, the I_{ZTC} was determined as in Fig. 4.

Fig. 6 shows the ZTC current shift with the dose, where the error bars indicate the difficulty in the determination of the I_{ZTC}. This indeterminacy is a consequence of the temperature

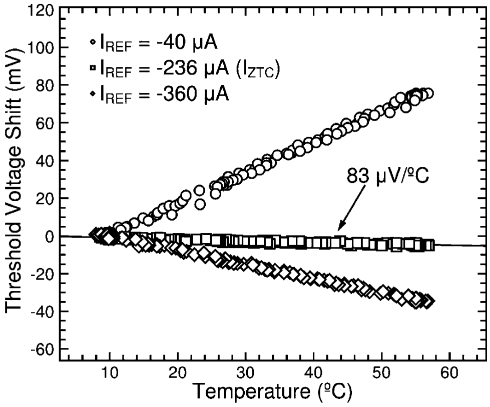

Fig. 5. Response of the sensor under test to temperature at different reference currents. It is shown that when the reference current coincide with the ZTC current, the change of V_T with temperature is minimum.

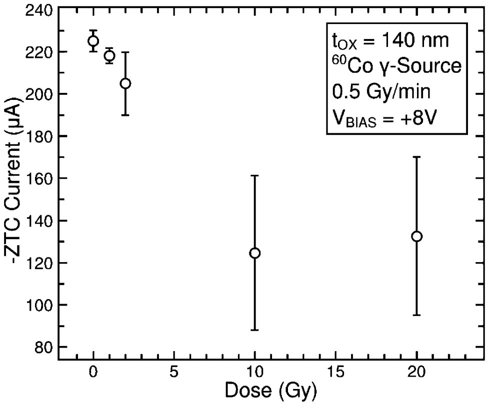

Fig. 6. ZTC current variation with absorbed dose. The error bars represent the minimum and maximum current for which the I–V curves at different temperatures cross each other, whereas the circles represent the mean value between these two quantities.

dependent factor in (12) and it is exhibited as multiple crossing points of the I–V curves at different temperatures. The error bars boundaries represent the higher and lower current for which these curves cross and the circles in the figure are the mean value of these currents. It can be seen that the I_{ZTC} decreases with the absorbed dose, but not at a constant rate. A rapid decrease in the first few Grays is followed by a slow recovery after approximately 10 Gy. In addition, the ZTC current indeterminacy increases with the absorbed dose. This behavior was exhibited in the three samples under test. All of them had a similar pre-irradiation I_{ZTC}, with inner sample dispersion lower than 3%, and an analogous response to irradiation, but at different scales.

This decrement in the ZTC current intensity impacts on the temperature induced error increasing it. During the threshold voltage measurement, the reference current remains constant, whereas the ZTC current is affected by radiation. Therefore, the temperature sensitivity increases as the device is irradiated, along with the temperature measurement error. For the sensor under test, the I_{ZTC} is reduced in almost 50% of its initial value. Fig. 7 shows a close view of the I–V curves at different temperatures after 20 Gy of absorbed dose. The initial and the

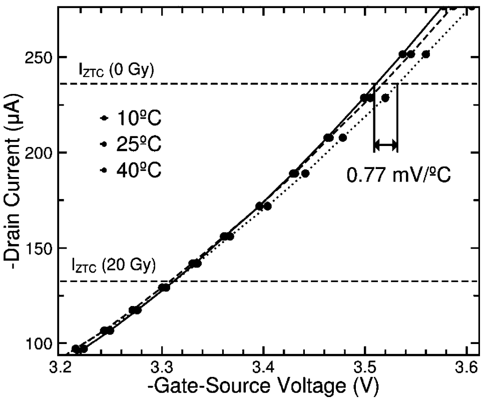

Fig. 7. Close view of the Current-Voltage characteristic at different temperatures of the sensor under test after 20 Gy of absorbed dose. It is shown how the ZTC current changes with radiation and its impact in the temperature sensitivity if the reference current is not updated.

ZTC current after radiation are marked, showing the temperature sensitivity increment. If the reference current is not periodically calibrated, the temperature sensitivity increases up to 0.77 mV/°C, and the measurement error to 19.5 mGy/°C, more than one order of magnitude larger than the corresponding value before irradiation.

C. Modeling the I_{ZTC} Radiation Induced Shifts

Equation (12) can be simplified assuming that $n = 2$

$$I_{ZTC} \approx -\frac{\mu(T_0)C_{OX}}{2}\frac{W}{L}(\alpha_T T_0)^2. \tag{13}$$

The only parameter in (13) that is affected by irradiation is the charge carrier mobility in the transistor channel, as it has not been reported that α_T is radiation sensitive. The interface traps creation lowers the carrier mobility according to (2), which is consistent with the ZTC current decrement. Replacing (2) in (13), a mathematical expression for the dependence of the ZTC current with the ΔN_{IT} is obtained:

$$I_{ZTC} = \frac{I_{ZTC}^{(0)}}{1 + \alpha\Delta N_{IT}} \tag{14}$$

where $I_{ZTC}^{(0)}$ is the pre-irradiation ZTC current.

To verify (14), the N_{IT} build-up was measured after each irradiation session using the Subthreshold Swing Method [4]. The method correlates N_{IT} generation with the variations in the Subthreshold Slope of the I–V curves of the device

$$\Delta N_{IT} = \frac{C_{OX}}{kT\ln(10)}\Delta S \tag{15}$$

where k is the Boltzmann constant, T is the temperature, and ΔS is the change in the Subthreshold Slope.

As the measurement of the I–V curves of the sensors takes several seconds, it is possible for border traps to affect them [19]. Taking this into account, the estimated values for ΔN_{IT} should be considered effective values for all traps near the interface.

Fig. 8 shows the N_{IT} build-up with dose at 25°C. The error bars represent the uncertainty of the Subthreshold Slope determination.

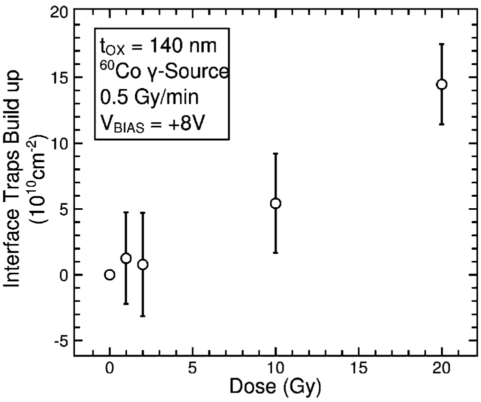

Fig. 8. Interface traps creation with absorbed dose calculated with the Subthreshold Swing Method. The error bars represent the uncertainty in the determination of the Subthreshold Slope.

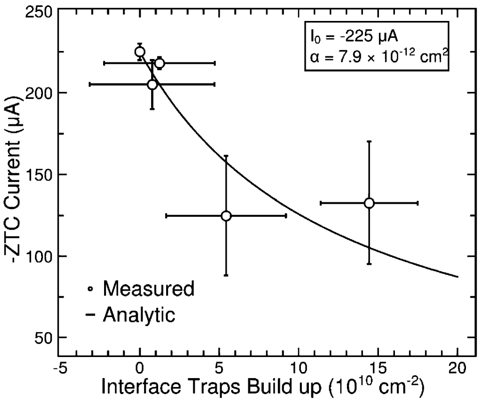

Fig. 9. Correlation between the ZTC current variations and the ΔN_{IT}. Circles represent the measured values whereas the solid line is the fitted expression with parameters I_0 and α.

Finally, the variation of the I_{ZTC} after each radiation session was plotted against the corresponding N_{IT} build-up, and fitted with (14). The results are shown in Fig. 9, where it can be seen that the analytic expression proposed fits the measurements, within the determination error of both variables.

IV. DISCUSSION AND CONCLUSION

The ZTC method for temperature error compensation in MOS dosimeters was studied. In particular, its robustness against radiation was investigated. The method is based in the opposite response to temperature of the build-in potential and the carrier mobility in the transistor channel. When applied to MOS dosimeters, it showed to successfully mitigate the temperature induced error.

When the sensor is exposed to radiation, a shift in the ZTC current is observed. As a consequence of this shift in I_{ZTC} with irradiation, the reference current during V_T measurement is no longer the optimal for temperature error compensation, and the temperature sensitivity of the device increases along with the measurement error. Measurements show that after 20 Gy of absorbed dose, if I_{REF} is maintained constant, the error per °C increases one order of magnitude. This confirms the results presented by [5], [6], [12], and [20].

Not only the ZTC current shifts with irradiation, but also does the uncertainty of its determination. In the previous section, it was proposed that the factor $(T/T_0)^{2-n}$ was responsible for the indeterminacy of the I_{ZTC}—(12) and (13). Sarrabayrouse *et al.* suggested that the parameter n decreases with radiation [6]. This is consistent with the results obtained in the present work, as a lower n means that the factor $(T/T_0)^{2-n}$ is more sensitive to temperature variations; thus, the ZTC working point is more unstable. The build-up of border traps may also have some responsibility for the I_{ZTC} indeterminacy increment.

An explanation for the shift in the ZTC current with irradiation was proposed. Analyzing both the I_{ZTC} evolution with the absorbed dose and its analytic expression given by (13), it was concluded that the most possible and simple explanation leading to this behavior, i.e., lowering the ZTC working point and the saturation, should be the ΔN_{IT}. Equation (14) is proposed to model this behavior which reasonably fits the measurements.

The measured dependence of ZTC current with ΔN_{IT} is consistent with (14) giving the change in mobility due to interface states increase. Nevertheless, it would be useful to have an expression linking I_{ZTC} versus Dose, but the latter requires an analytical expression for ΔN_{IT} versus Dose. Reference [21] empirically proposed that for low dose, the N_{IT} increases linearly with dose, result that in our measurements is observed, within the measurement uncertainty, in Fig. 8. Thus, a possible dose dependence of the I_{ZTC} is

$$I_{ZTC} = \frac{I_{ZTC}^{(0)}}{1+\kappa\Delta D} \tag{16}$$

where κ is a constant and ΔD is the absorbed dose. This expression should be tested in order to determine the conditions for its validity.

Taking into account that in fact the I_{ZTC} does not remain constant as the sensor is irradiated, two strategies are suggested to enhance the robustness of the ZTC method as a temperature compensation technique. The first one is to periodically calibrate the sensor. Assuming that the dosimeter is used in low dose irradiations, i.e., 1 Gy, the shift in I_{ZTC} should not be significant, and the temperature sensitivity after irradiation should remain negligible. Nevertheless, to avoid further increment of S_T, the measurement current should be updated after each irradiation to the "new" I_{ZTC}. The second technique takes advantage of the possible correlation of the ZTC shifts with the ΔN_{IT}. As the ΔN_{IT} saturates after sufficient absorbed dose, the shifts in the ZTC current should saturate as well. Therefore, it would be advisable to pre-irradiate the sensor with enough dose to saturate the ΔN_{IT}. Once the ΔN_{IT} ceases, the dosimeter should be ready to use and no shift in the ZTC current should be expected. This technique was suggested and successfully tested in [22].

In summary, the ZTC method is very efficient compensating temperature induced threshold voltage shifts. Nevertheless, the temperature sensitivity of the dosimeter increases with the total absorbed dose. In this paper, we suggest that this variation of the ZTC bias point is linked to ΔN_{IT}; thus, to prevent I_{ZTC} shifts with radiation, it is recommended that the ΔN_{IT} be saturated with a pre-irradiation of the sensor.

ACKNOWLEDGMENT

The authors would like to thank the Planta Semi Industrial de Irradiaciones, Centro Atómico Ezeiza, Comisión Nacional de Energía Atómica, for the access to irradiation facilities, and E. Pawlak for her assistance with dosimetry.

REFERENCES

[1] A. G. Holmes-Siedle and L. Adams, "RADFETs: A review of the use of metal-oxide-silicon devices as integrating dosimeters," *Radiat. Phys. Chem.*, vol. 28, no. 2, pp. 235–244, 1986.

[2] G. Sarrabayrouse and S. Siskos, "Radiation dose measurment using MOSFETs," *IEEE Instrum. Meas. Mag.*, vol. 1, no. 2, pp. 26–34, 1998.

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

[4] T. P. Ma and P. V. Dressendorfer*, Ionizing Radiation Effects in MOS Devices and Circuits*. New York: Wiley, 1989.

[5] A. Holmes-Siedle, F. Ravotti, and M. Glaser, "The dosimetric performance of RADFETs in radiation test beams," in *Proc. 2007 IEEE Radiation Effects Data Workshop*, 2007, pp. 42–57.

[6] G. Sarrabayrouse and S. Siskos, "Temperature effects and accuracy of MOS radiation dosimeters," in *Proc. 7th WSEAS Int. Conf. Microelectronics, Nanoelectronics, Optoelectronics*, 2008, pp. 26–30.

[7] J. Lipovetzky, E. G. Redin, M. A. G. Inza, S. H. Carbonetto, and A. Faigón, "Reducing measurements uncertainties using bias controlled cycled measurements in MOS dosimetry at different temperatures," *IEEE Trans. Nucl. Sci.*, vol. 57, no. 2, pp. 848–853, Apr. 2010.

[8] A. Haran, A. Jaksic, N. Rafaeli, A. Eliyahu, D. David, and J. Barak, "Temperature effects and long term fading of implanted and unimplanted gate oxide RADFETS," *IEEE Trans. Nucl. Sci.*, vol. 51, no. 5, pp. 2917–2921, Oct. 2004.

[9] N. G. Tarr, K. Shortt, Y. Wang, and I. Thomson, "A sensitive, temperature-compensated, zero bias, floating gate MOSFET dosimeter," *IEEE Trans. Nucl. Sci.*, vol. 51, no. 3, pp. 1277–1282, Jun. 2004.

[10] 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. 257–272, 1994.

[11] N. G. Tarr, G. F. Mackay, K. Shortt, and I. Thomson, "A floating gate MOSFET dosimeter requiring no external bias supply," *IEEE Trans. Nucl. Sci.*, vol. 45, no. 3, pp. 1470–1474, Jun, 1998.

[12] G. Sarrabayrouse and S. Siskos, "Behaviour of high sensitivity MOS radiation dosimeters biased in the MTC current region," in *Proc. 9th WSEAS Int. Conf. Instrumentation, Measurement, Circuits and Systems*, 2010, pp. 38–41.

[13] T. R. Oldham, "Ionizing Radiation Effects in MOS Oxides," in *International Series on Advances in Solid State Electronics and Technology*. Singapore: World Scientific, 1999.

[14] M. R. Shaneyfelt, J. R. Schwank, D. M. Fleetwood, P. S. Winokur, K. L. Hughes, and F. W. Sexton, "Field dependence of interface-trap buildup in polysilicon and metal gate MOS devices," *IEEE Trans. Nucl. Sci.*, vol. 37, no. 6, pp. 1632–1640, Dec. 1990.

[15] A. B. Rosenfeld, "Electronic dosimetry in radiation therapy," *Radiat. Meas.*, vol. 41, pp. 134–153, 2007.

[16] I. M. Filanovsky and S. T. Lim, "Interaction of threshold voltage and mobility temperature dependencies applied to stabilization of current and voltage," in *Proc. IEEE Midwest Symp. Circuits and System*, 2000, vol. 43, pp. 1022–1025.

[17] S. M. Sze*, Physics of Semiconductor Devices*, 2nd ed. New York: Wiley, 1981.

[18] G. Sarrabayrouse and F. Gessinn, "Thick oxide MOS transistors for ionizing radiation dose measurement," *Radioprotection*, vol. 29, no. 4, pp. 557–572, 1994.

[19] D. M. Fleetwood, M. R. Shaneyfelt, W. L. Warren, J. R. Schwank, T. L. Meisenheimer, and P. S. Winokur, "Border traps: Issues for MOS radiation response and long-term reliability," *Microelectron. Reliab.*, vol. 35, no. 3, pp. 403–428, 1995.

[20] G. Sarrabayrouse, M. Gavelle, and S. Siskos, "Influence of border traps on the determination of the minimum temperature coefficient current in high sensitivity MOS radiation dosimeters," in *Proc. 3rd Int. Conf. Signals, Circuits and Systems*, 2009, pp. 1–5.

[21] J. M. Benedetto, H. E. Boesch Jr., and F. B. McLean, "Dose and energy dependence of interface trap formation in Cobalt-60 and X-Ray environments," *IEEE Trans. Nucl. Sci.*, vol. 35, no. 6, pp. 1260–1264, Dec. 1988.

[22] A. Faigón, J. Lipovetzky, E. Redin, and G. Krusczenski, "Extension of MOS dosimeters using radiation induced charge neutralization," *IEEE Trans. Nucl. Sci.*, vol. 55, no. 4, pp. 2141–2147, Aug. 2008.