Reducing Measurement Uncertainties Using Bias Cycled Measurement in MOS Dosimetry at Different Temperatures

José Lipovetzky, Eduardo Gabriel Redin, Mariano Andrés García Inza, Sebastián Carbonetto, and Adrián Faigón

***Abstract*—Temperature dependence of MOS dosimeters response used under the Bias Controlled Cycled Measurement technique is investigated. The use of the biasing technique allows the compensation of temperature-induced changes in the response of the sensors, and reduces at least ten times the dose measurement error caused by undesired threshold voltage shifts.**

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

I. INTRODUCTION

METAL OXIDE SEMICONDUCTOR (MOS) dosimeters are p-channel MOS transistors with a radiation-soft gate oxide. Usually, the dosimeters are irradiated holding a constant gate bias, leading to a negative shift in the threshold voltage ($\mathrm{V_T}$), which is used to quantify the absorbed dose [1].

Recently, a new biasing technique was proposed to extend the dose measurement range with MOS dosimeters. The technique, named Bias Controlled Cycled Measurement (BCCM), consists on changing the gate bias during irradiation to make the threshold voltage rebound through an effect known as Radiation Induced Charge Neutralization (RICN). The cyclic change in the gate bias maintains the threshold voltage in a convenient range, obtaining an almost constant sensitivity along very high doses [2].

This work investigates the effect of temperature variations in the response of MOS dosimeters when the BCCM technique is used. The main result is that the technique compensates for temperature effects. The following section reviews radiation effects on MOS transistors, explains what is the BCCM technique, and how temperature affects MOS dosimetry. Section III presents the experiments and results and Section IV reviews the results and presents conclusions.

II. PHYSICAL MECHANISMS AND BIAS CONTROLED CYCLED MEASUREMENTS

The irradiation of MOS transistors with ionizing radiation causes, among other effects, the shift of the threshold voltage ($\mathrm{V_T}$). This shift is originated in an increase in the interface traps density ($\mathrm{N_{IT}}$) and in the buildup or neutralization of electrical charge in the insulating gate oxide, and for a p-channel MOS transistor is given by [3]:

$$\mathrm{V_T} = -\frac{\mathrm{q}\Delta \mathrm{N_{IT}}}{\mathrm{C_{OX}}} + \mathrm{V_{OX}} + \mathrm{V_{T0}} \tag{1}$$

where:

$$\mathrm{V_{OX}} = -\frac{1}{\mathrm{C_{OX}}} \int_0^{\mathrm{t_{OX}}} \rho_{\mathrm{OX}}(\mathrm{x}) \frac{\mathrm{x}}{\mathrm{t_{OX}}} \mathrm{dx} \tag{2}$$

and q is the electron charge, $\mathrm{N_{IT}}$ the amount of interface traps per unit area, $\mathrm{C_{OX}}$ the oxide capacitance per unit area, x the distance from the gate to the location of trapped charge with density $\rho(\mathrm{x})$, and $\mathrm{t_{ox}}$ the gate oxide thickness. The term $\mathrm{V_{OX}}$ is the contribution of the oxide-trapped charge and $\mathrm{V_{T0}}$ is the pre-irradiation threshold voltage.

The physical mechanisms leading to the creation of interface traps and the buildup or neutralization of oxide charge have been studied for many years [3]–[5]. Radiation generates electron hole pairs in the oxide, and the fraction of them which escapes initial recombination is accelerated towards the electrodes. Under positive gate bias, electrons migrate towards the gate and holes begin a slower migration towards the oxide-semiconductor interface. During the migration some holes can be captured in defects of the $\mathrm{SiO_2}$ structure, which are mainly located near the $\mathrm{Si-SiO_2}$ interface, and behave as hole traps. The result is the buildup of a relatively stable positive charge density in the oxide. Probably as a result of the liberation of $\mathrm{H^+}$ species, interface traps are also created [3]. Both effects result in a negative shift of the threshold voltage of a p-channel MOS transistor.

However, if after irradiating the device with a positive gate bias, a smaller or negative bias is applied, the threshold voltage can rebound. This effect was observed by first time by A. Holmes-Siedle [6] and explained by D. M. Fleetwood [7], [8]. The inversion of the electrical field in the oxide makes the electrons accelerate towards the $\mathrm{Si-SiO_2}$ interface instead of moving towards the gate. A fraction of these electrons can

---

Manuscript received November 12, 2009; revised January 23, 2010 and January 23, 2010. Current version published April 14, 2010. This work was supported in part by the University of Buenos Aires under Grant I037 and by the CONICET. J. Lipovetzky holds a Peruilh Grant.

J. Lipovetzky, E. G. Redin, M. A. García Inza and S. Carbonetto are with the Departamento de Física, Device Physics Laboratory-Microelectronics, Facultad de Ingeniería, Universidad de Buenos Aires, C1063ACV, Buenos Aires, Argentina (e-mail: jlipove@fi.uba.ar; joselipo@gmail.com; eredin@fi.uba.ar; magarcia@fi.uba.ar; sebach@gmail.com).

A. Faigón is with the Departamento de Física, Device Physics Laboratory-Microelectronics, Facultad de Ingeniería, Universidad de Buenos Aires, C1063ACV, Buenos Aires, Argentina and also with CONICET, CP C1033AAJ Buenos Aires, Argentina (e-mail: afaigon@fi.uba.ar).

Digital Object Identifier 10.1109/TNS.2010.2042178

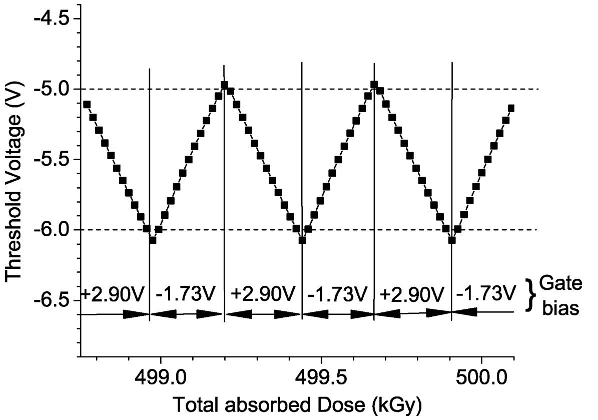


Fig. 1. The BCCM technique alternates stages of PCB under positive gate bias with stages of RICN under negative gate bias. When the measured value of the threshold voltage crosses a minimum preset value—in this case $V_{T\,\min} = -6$ V—the gate bias is switched to a negative voltage and a RICN stage begins. During this stage V_T increases, and the now positive shift in the threshold voltage is used to quantify the absorbed dose. When the threshold voltage crosses the maximum preset value, in this case $V_{T\,\max} = -5$ V, the gate bias is again positively switched, and a new PCB stage begins (After [2]).

recombine with the trapped holes, decreasing the net oxide trapped charge and making the threshold voltage to shift towards less negative values.

The rate of trapping or neutralization of oxide charge depends on the gate bias applied during the irradiation and the initial conditions, as was shown in [9].

A. BCCM Technique

In the usual way of biasing MOS dosimeters, a constant gate bias is applied during irradiation, resulting in a negative threshold voltage shift. However, after absorbing a high dose, the threshold voltage saturates or becomes too high, and the sensor needs to be replaced. To avoid this problem, and increase the dose measurement accuracy, we recently proposed a novel way to use MOS dosimeters, named BCCM technique [2].

The idea is to alternate stages in which the dosimeter is irradiated under a positive gate bias-in which the threshold voltage decreases-, with stages of negative bias irradiation—in which the threshold voltage rebounds. During positive gate bias irradiation, positive charge buildups in the oxide (PCB stage) and during negative bias irradiation the charge is neutralized (RICN stage). The negative and positive shifts in V_T caused by irradiation in both stages are used to continuously quantify the absorbed dose. The threshold voltage, which is periodically read, is kept within a convenient range of values in order to maintain a uniform sensitivity during the whole measurement. Fig. 1 shows the application of the BCCM technique extending more than one hundred times the measurement range of a sensor.

B. Temperature Effects on MOS Dosimeters

Several works have shown that the response of MOS dosimeters can be affected by temperature in several ways. One of them is that, even without irradiation, the threshold voltage depends on the temperature [10] as a result of the change of the built-in potential. This effect can be partially cancelled using the Zero Temperature Coefficient (ZTC) point of the current-voltage (I-V) characteristic of the device taking advantage of the fact that the carrier mobility in the channel has an opposite dependence with temperature [11]–[13]. However, the current level of the ZTC point can change with irradiation [14], limiting its applicability for temperature mitigation in radiation dose measurements. Another proposed way to compensate this effect is to take for dose indicator the difference between the threshold voltages of two identical transistors holding different gate bias during the irradiation, which is less dependent on the temperature and representative of the absorbed dose [15].

Temperature can also affect the rate of trapping of oxide charge or creation of interface traps during irradiation, even at room temperature, as was reported by [16] and [17]. At higher temperatures, thermal annealing of oxide trapped charge is observed, erasing the information of the accumulated dose. Thermal annealing was reported above temperatures ranging from 50°C [14] to 200°C [18], in different devices. High temperature annealing may happen during or after irradiation, and was proposed as a method to reuse MOS dosimeters by [19] and [18].

The described temperature-dependent effects introduce, therefore, unexpected shifts in the threshold volgate or changes in the sensitivity of the sensors which can cause dose measurement errors in MOS dosimeters.

III. EXPERIMENT AND RESULTS

To study the response of cycled biased MOS dosimeters at different temperatures, 70 nm oxide thick p-channel MOS transistors were irradiated holding the BCCM technique. The irradiation temperature ranged from −5°C to 97°C, controlled with an uncertainty smaller than 2°C. During the experiment the devices were biased holding a constant gate voltage with all the other terminals grounded. Every five seconds, the threshold voltage was read as the gate to source voltage required to sustain a drain current of $-40\ \mu$A, maintaining gate and drain shorted, and bulk and source grounded. Whenever the threshold voltage crossed a limit of the pre-defined window, the bias voltage was switched, according to the BCCM technique [2]. The reading of the threshold voltage required less than 70 ms, short enough to ensure that the change in the gate bias would not affect the overall response of the dosimeters. The devices were irradiated with a ^{60}Co gamma source at a dose rate of 9.1 Gy/s-all doses are referred to SiO_2. The response of the sensors using the BCCM technique showed to be dose rate insensitive as was reported in [2]. Before the experiments presented in this work, the dosimeters were irradiated to saturate interface traps, ensuring that all the shifts in the threshold voltage are due to oxide charge buildup and neutralization [2], [20] which was verified by the analysis of the I-V curves in the sub-threshold regime [21], [22]. All the measurements were simultaneously performed in at least two devices, obtaining always repetitive results.

The following experiments were done. First, the dosimeters were irradiated at different temperatures letting the threshold voltage to change along long transients to characterize the overall response of the sensors at different temperatures. Then, the devices were irradiated holding the BCCM technique to search an optimal V_T range in which temperature effects are compensated, reducing the dose measurement error. Finally,

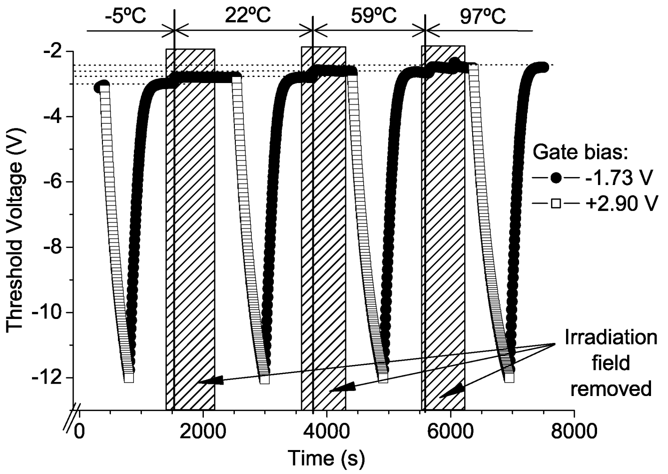


Fig. 2. Evolution of V_T in a MOS dosimeter irradiated at different temperatures. Solid circles represent the V_T during -1.73 V gate bias irradiation, whereas empty squares represent V_T during $+2.90$ V gate bias irradiation.

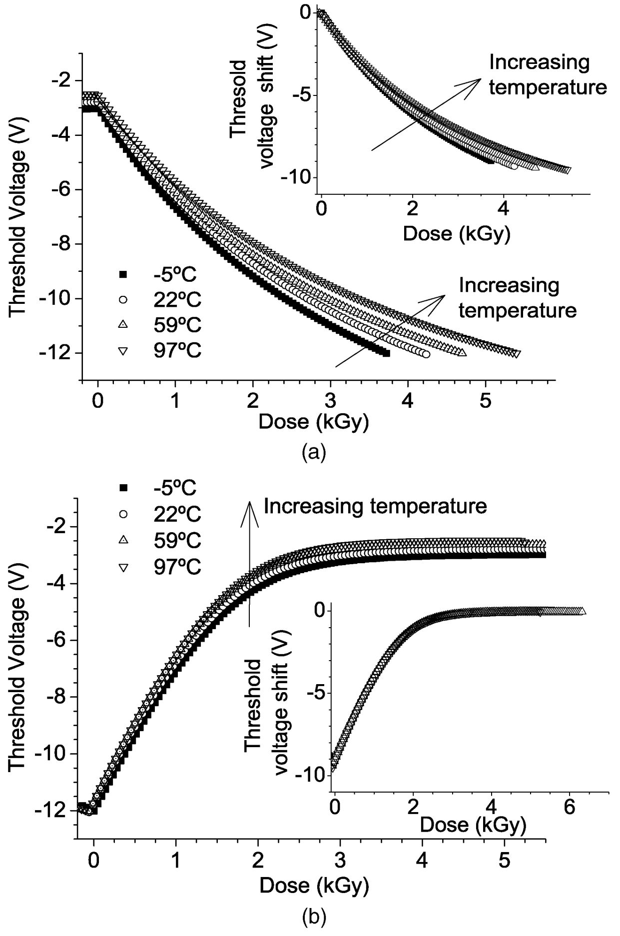
the dosimeters were irradiated changing the temperature during irradiation, in order to study dose measurement errors caused by temperature shifts.

A. *Response at Different Temperatures During PCB and RICN Transients*

A dosimeter was irradiated letting the threshold voltage shift through long transients at different temperatures, as is shown in Fig. 2. The device was initially cooled to a temperature of $-5°\mathrm{C}$, and irradiated holding a -1.73 V bias until it reached the steady level which corresponds to the first points in the figure. Then, while maintaining the irradiation field, the gate bias was changed to $+2.90$ V and the threshold voltage began to decrease. The response during positive bias irradiation is represented as empty squares in the figure. When the threshold voltage reached -12 V, the gate bias was again changed to -1.73 V. The response during negative bias irradiation is represented by solid circles. After the change in the gate bias, the threshold voltage rebounded and reached the same initial steady level.

After reaching the steady level, the irradiation field was removed during a period of time which is represented by lined regions in the figure. Within the first region, the temperature was raised to 22°C. As a result of the temperature change, the threshold voltage shifted as shown in the figure. That shift is caused by the change with temperature of the built-in potential, and has the same value of the shift observed in a device which has not been recently irradiated when the temperature is changed. This shift also showed to be reversible if the previous temperature is restored, showing that it is not a result of thermal annealing of oxide charge.

After changing the temperature, the irradiation field was restored. It is remarkable that when the irradiation started, the threshold voltage maintained the initial steady value, which was a saturation value for the gate bias. Then, the biasing scheme was repeated at the new temperature, 59°C and 97°C. For each temperature, the threshold voltage decreased with positive gate bias and with negative bias rebounded to the initial steady level. The steady levels for each temperature are marked with horizontal doted lines in the figure.



(a)

(b)

Fig. 3. Compared responses during (a) PCB and (b) RICN transients in the measurement of Fig. 3. The insets show the shift in V_T referenced to the steady value at each temperature.

Finally, the biasing cycle was repeated at the first temperature, and the response repeated, showing that no cumulative effects occurred during the whole experiment. As was shown in [2] and [20] interface traps saturation allowed to have repeated responses during consecutive oxide charge buildup and neutralization transients.

Figs. 3(a) and 3(b) show the compared responses of the sensor during the transients of Fig. 2 at the different temperatures. During positive bias irradiation the sensitivity decreased with temperature, whereas with negative bias irradiation the sensitivity increased. This effect, and the fact that the responses are not linear, will be used to compensate temperature effects in the BCCM technique in the next section.

The insets in Figs. 3(a) and 3(b) show the shifts in the threshold voltage relative to the steady level reached after -1.73 V gate bias irradiations at the different temperatures. The plotted shifts give information on the charge trapped in the oxide after switching the gate bias to $+2.90$ V.

For the positive bias irradiation of Fig. 3(a), the curves on the inset do not overlap. The threshold voltage shift became smaller as the temperature increased —as was observed by [16]—. This behavior might be a result of a dynamic balance between oxide

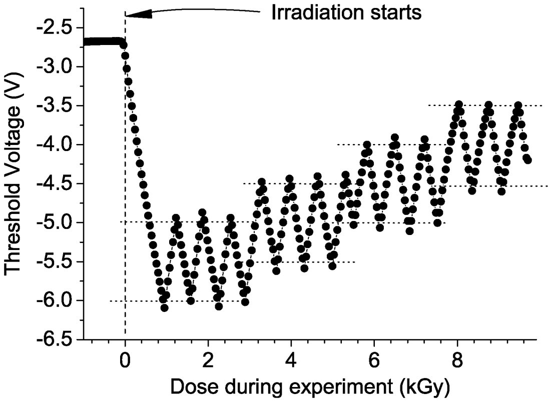


Fig. 4. A MOS dosimeter was irradiated at different temperatures following this biasing pattern, sweeping the limits of the 1 V V_T window. The measurement sequence of the figure was repeated at −5°C, 22°C, 52°C and 95°C.

charge trapping and an annealing activated by temperature. It might be also due to the temperature dependence of one or more of the fundamental mechanisms involved in oxide charge transport-trapping.

For the negative bias irradiation of Fig. 3(b), the curves in the inset overlap. This suggests that the different responses at the different temperatures are the same curves vertically shifted due to the contribution of the built-in potential which is temperature-dependent.

B. BCCM and Compensation at Different Temperatures

The results of Figs. 2 and 3 show that, for the devices used in this experiment, the sensitivity at a given threshold voltage value increases with temperature during RICN stages and decreases during PCB stages. This effect can introduce a dose measurement error in the reading of the dosimeters. However, using the BCCM technique, with the threshold voltage window properly chosen, the variation introduced in the PCB stage is compensated with the variation introduced during RICN stages, and it is possible to reduce the dose measurement error after a complete cycle, as shown below. The "properly choosen" threshold voltage window means to find optimal limits such that the lengthening in the PCB stages cancels the shortening of RICN stages as the temperature increases.

To find the optimal limits of the threshold voltage window, a dosimeter was irradiated holding the BCCM technique at −5°C, 22°C, 52°C and 95°C. At each temperature, the 1.00 V threshold voltage window position was swept from −6.00 V to −3.50 V in steps of 0.50 V as shown in Fig. 4. For each window and temperature, three complete RICN/PCB cycles were done. Fig. 4 shows the measurement scheme which was repeated at the four temperatures. From these measurements, the dose interval of the PCB and RICN stages, i. e. the dose required to cause a 1 V shift in the threshold voltage, during positive and negative bias irradiation, was obtained for all the temperatures.

Fig. 5(a) shows the dose interval of PCB and RICN stages for four different positions of a 1 Volt window. Fig. 5(b), shows the length of the complete cycle, i. e. the sum of the lengths of each stage. The compensation —total period invariant against temperature changes— occurs when the threshold voltage is allowed to shift between −5.50 V and −4.50 V. For this window, both stages change about 23% in the temperature range. However, due to the cancellation of the opposite effects, the variation in the complete cycle is smaller than a 2%.

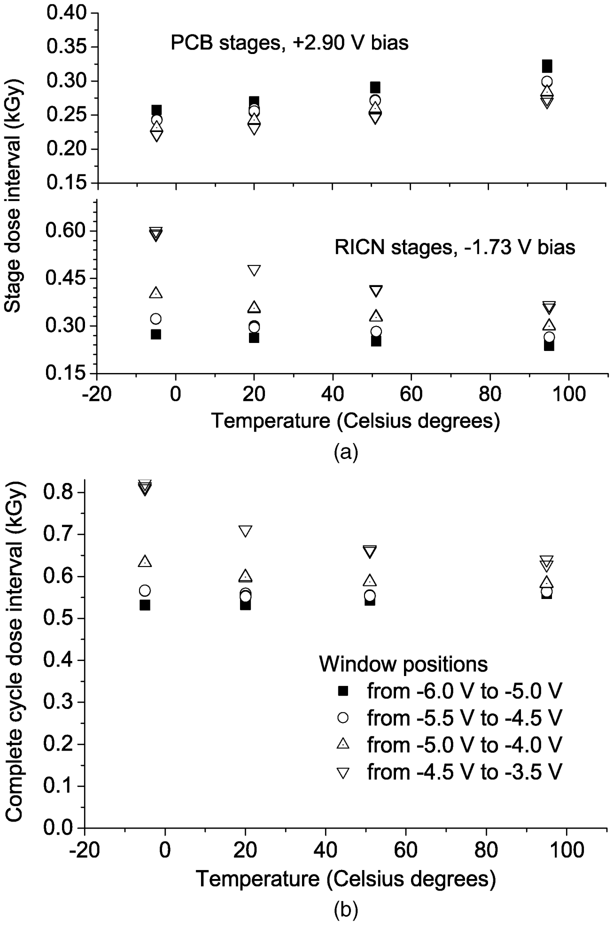


Fig. 5. Dose required (a) to cause a 1 V shift in V_T during PCB, RICN stages, and (b) to complete a measurement cycle.

C. Response at Non-Constant Temperatures

The observed change in the sensitivity with temperature is not the only thermal effect that can introduce errors in the dosimeter measurements. If the temperature changes during irradiation, the shift in the threshold voltage introduced by the built-in potential can be mistakenly confused with a radiation-induced shift. This unwanted effect will occur in MOS dosimeters even if the sensitivity does not depend on temperature.

The BCCM technique compensates in fact, at the end of each cycle, the threshold voltage drifts caused by whichever mechanism provided the drifts are at almost constant rate. A drift in the threshold voltage will underestimate the dose in one stage, but overestimate in the same amount the dose in the other stage.

To quantify this effect, the dosimeter used in the measurements of Figs. 2to 5 was irradiated holding the BCCM technique using the optimal threshold voltage window from −5.50 V to −4.50 V. During the irradiation the temperature was linearly swept from −5°C to 95°C and from 95°C to −5°C in a ramp of 2–3°C/sec. Fig. 6 shows the dose interval of both stages and of the complete cycles during the experiment. Although the dose interval of each separate stage shifted as much

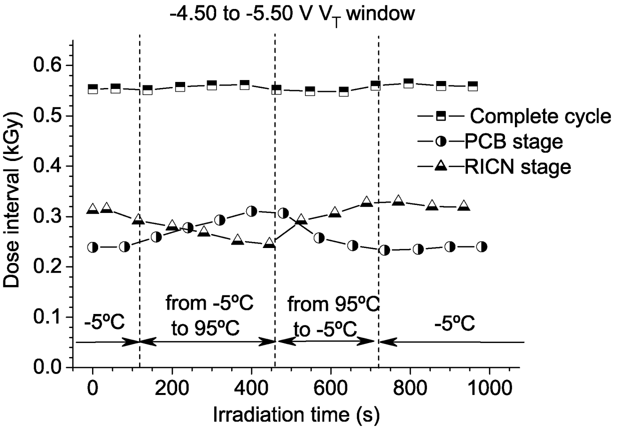


Fig. 6. A dosimeter was irradiated holding the BCCM technique. The temperature was changed from $-5^{\circ}\mathrm{C}$ to 95°C and restored to $-5^{\circ}\mathrm{C}$. During the temperature changes the dose interval of a complete cycle was almost constant, compensating for the temperature-induced $\mathrm{V_T}$ shift.

as 30%, the length of a complete cycle remains almost constant within a 2.5%.

IV. SUMMARY AND CONCLUSIONS

The response of MOS dosimeters using the BCCM technique at different temperatures was investigated. During positive gate bias irradiation, the sensitivity decreased with temperature, whereas during negative bias irradiation the sensitivity increased. This opposite behavior with temperature allows to design appropriate parameters in the BCCM technique which minimize the associated dose measurement error. Using the optimal window for our experimental conditions, the measurement error was reduced from a 23% for each stage to less than 2%, improving more than ten times the measurement accuracy after a complete PCB/RICN cycle, in a range of temperatures from −5°C to 95°.

The measurement error caused by temperature variations during irradiation can be also reduced with the BCCM technique. The measurement error was reduced from more than 30% for each stage to less than a 2.5% after a complete cycle after a change in temperature over 100°C.

As shown, the compensation technique depends only on the opposite change in the sensitivity for the two stages of a complete BCCM cycle, and not on the detailed mechanisms giving origin to these changes. This is to remark its applicability to thicker oxides for which—to our knowledge—, no thermal effects other than built-in voltage shift were reported in the literature [23]–[25].

The compensation of temperature effects is effective in environments in which the rate of change of temperature with time does not change significantly along complete cycles of the BCCM technique. For example a fast temperature change shorter than a single PCB or RICN stage, would only introduce a variation in the dose interval of one stage, and the compensation would not occur. The compensation would also fail in the measurement of a dose shorter than a complete PCB/RICN cycle. A strategy for compensating these fast temperature changes would be the reduction of the width of the threshold voltage window, shortening, thus, the dose and time required to complete a cycle. However, the window cannot be arbitrarily reduced. This is because every time the gate bias is switched at the end of PCB or RICN stages, the threshold voltage has a small shift as a result of the charging or discharging of border traps [2]–[4], also known as creep up effect [26]. If this shift is not negligible compared to the threshold voltage window, it would introduce significant dose measurement errors.

In summary, the BCCM technique involves a compensation mechanism against temperature dependent threshold voltage drifts that, properly tuned, provides high immunity against temperature changes from measurement to measurement and also within one measurement. In the studied range (−5°C, 95°C) the immunity gain is expressed by reducing in a factor ten the measurement error as compared with non compensated dose measurements.

The reading accuracy of the dosimeters can be improved even more using the BCCM technique in conjunction with other known temperature mitigation methods.

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 Eva Pawlak for her great assistance with the reference dosimetry.

REFERENCES

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

[2] A. Faigón, 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, Aug. 2008.

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

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

[5] H. L. Hughes and J. M. Benedetto, "Radiation effects and hardening of MOS technology: Devices and circuits," *IEEE Trans. Nucl. Sci.*, vol. 50, no. 3, pp. 500–520, Jun. 2003.

[6] W. J. Poch and A. G. Holmes-Siedle, "Long-term effects of radiation on complementary Mos logic networks," *IEEE Trans. Nucl. Sci.*, vol. NS-17, no. 6, pp. 33–40, Dec. 1970.

[7] D. M. Fleetwood, P. S. Winokur, and L. C. Riewe, "Predicting switched-bias response from steady-state irradiations MOS transistors," *IEEE Trans. Nucl. Sci.*, vol. 37, no. 6, pp. 1806–1817, Dec. 1990.

[8] D. M. Fleetwood, "Radiation-induced charge neutralization and interface-trap buildup in metal-oxide-semiconductor devices," *J. Appl. Phys.*, vol. 67, no. 1, pp. 580–583, 1990.

[9] A. Faigón, J. Lipovetzky, E. Redin, M. García Inza, M. Maestri, and A. Cedola, "Experimental evidence and modeling of non-monotonic responses in MOS dosimeters," *Radiat. Phys Chem.*, submitted for publication.

[10] S. M. Sze, *Physics of Semiconductor Devices*, 3rd ed. New York: Wiley, 2006, 978-0-471-14323-9.

[11] 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.

[12] N. Garry 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.

[13] A. Haran, A. Jaksic, N. Refaeli, 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.

[14] A. Haran, A. Jaksic, N. Refaeli, 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.

[15] M. Soubra and J. Cygler, "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.

[16] J. R. Schwank, F. W. Sexton, D. M. Fleetwood, R. V. Jones, R. S. Flores, M. S. Rodgers, and K. L. Hughes, "Temperature effects on the radiation response of MOS devices," *IEEE Trans. Nucl. Sci.*, vol. NS-35, no. 6, pp. 1432–1437, Dec. 1988.

[17] M. R. Shaneyfelt, J. R. Schwank, D. M. Fleetwood, and P. S. Winokur, "Effects of irradiation temperature on MOS radiation response," in *Proc. RADECS* , 1997, pp. 43–49.

[18] E. Yilmaza and R. Turan, "Temperature cycling of MOS-based radiation sensors," *Sens. Actuators A*, vol. 141, no. 1, pp. 1–5, 2008.

[19] A. Kelleher, N. McDonnell, B. O'Neill, W. Lane, and L. Adams, "Investigation into the re-use of PMOS dosimeters," *IEEE Trans. Nucl. Sci.*, vol. 41, no. 3, pp. 445–451, Jun. 1994.

[20] J. Lipovetzky, E. G. Redin, and A. Faigón, "Electrically erasable metal oxide semiconductor dosimeters," *IEEE Trans. Nucl. Sci*, vol. 54, no. 4, pp. 1244–1250, Aug. 2007.

[21] D. M. Fleetwood, M. R. Shaneyfelt, and J. Schwank, "Estimating oxide-trap, interface-trap, and border-trap charge densities in MOS transistors," *Appl. Phys. Lett.*, vol. 64, p. 1965, 1994.

[22] P. Antognetti, D. Caviglia, and E. Profumo, "CAD model for threshold and subthreshold conduction in MOSFET's," *J. Solid State Circuits*, vol. Sc-17, no. 3, pp. 454–458, 1982.

[23] P. G. Litovchenko, L. I. Barabash, and A. B. Rosenfeld *et al.*, "MOS structure for emergency gamma and proton dosimetry," *Radiat. Protect. Dos.*, vol. 33, no. 1/4, pp. 179–182, 1990.

[24] T. Cheung, M. J. Butson, and P. K. N. Yu, "Effects of temperature variation on MOSFET dosimetry," *Phys. Med. Biol.*, vol. 49, pp. N191–N196, 2004.

[25] A. B. Rosenfeld, "Electronic dosimetry in radiation therapy," *Radiat. Meas.*, vol. 41, pp. 134–153, 2006.

[26] A. B. Rosenfeld, "MOSFET dosimetry on modern radiation oncology modalities," *Radiat. Protect. Dos.*, vol. 101, no. 1, pp. 393–398, 2002.