Floating Gate PMOS Dosimeters Under Bias Controlled Cycled Measurement

M. García Inza, José Lipovetzky, Eduardo Gabriel Redin, Sebastián Carbonetto, and Adrián Faigón

***Abstract*—Floating Gate Metal Oxide Semiconductor (FG-MOS) structures, designed and fabricated in a CMOS process, were irradiated under the Bias Controlled Cycled Measurement (BCCM) novel technique conditions. Results presented in this work show the possibility of using such structures with the BCCM technique to measure ionizing radiation absorbed dose over a range of several kGy without significant loss of sensitivity. Transients observed after the bias switch are related to the evolution of the charge distribution between the floating gate and oxide traps near the semiconductor.**

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

I. Introduction

MOS dosimeters are p-channel transistors in which the radiation-induced shift of the threshold voltage [1]–[4] is used to measure absorbed dose of ionizing radiation [5]–[8]. The shift in the threshold voltage is a consequence of charge trapping in the oxide and the creation of interface states during irradiation:

$$V_T = V_{T0} - \frac{Q_{OX}}{C_{OX}} - \frac{qN_{IT}}{C_{OX}} \tag{1}$$

with V_{T0} the initial threshold voltage due to constructive factors of the device, q the elementary charge; N_{IT} the interface state density; C_{OX} the SiO_2 capacitance per unit of area and Q_{OX},

$$Q_{OX} = \int_0^{t_{OX}} \rho(x)\left(1 - \frac{x}{t_{ox}}\right) dx \tag{2}$$

where x the distance measured from the Si–SiO_2 interface to the location of trapped charge with density $\rho(x)$, and t_{ox} the gate oxide thickness.

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

A. Faigón is with the National Research Council of Argentina (CONICET), 1033 Ciudad de Buenos Aires, Argentina and also with the Device Physics-Microelectronics Laboratory, Departamento de Física, INTECIN, Facultad de Ingeniería, Universidad de Buenos Aires, C1063ACV Ciudad Autónoma de Buenos Aires, Argentina (e-mail: afaigón@fi.uba.ar).

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Given negligible interface states creation, radiation-induced shifts in V_T are caused by the trapping and neutralization of electrical charge in oxide traps. The manner in which the charge is trapped or neutralized depends on the preexisting trapped charge and on the bias applied on the gate during irradiation [9]. When a device is irradiated under positive gate bias, positive charge is trapped and V_T decreases. However, if during irradiation the gate bias is switched to a less positive or negative value; the oxide charge may decrease and V_T rebounds. The recovery found after switching the gate bias is known as Radiation Induced Charge Neutralization (RICN) [10].

A measurement technique was recently proposed allowing to extend the measurement range of MOS dosimeters by taking advantage of RICN. The idea is to alternate stages of charge trapping in the oxide or Positive Charge Build-up (PCB) with stages of RICN, maintaining V_T in a convenient range. The technique, named Bias Controlled Cycled Measurement (BCCM) [11] consists of the following steps :

- During the PCB stage, the device is irradiated holding a positive gate bias. As a result, positive charge is trapped in the oxide and V_T decreases. The shift in V_T, which is periodically monitored, is used to quantify the absorbed dose. When V_T reaches a predefined minimum value $V_{T\,\min}$, the RICN stage begins by switching the gate bias.
- The RICN stage begins after V_T crosses the minimum value and the gate bias is switched to a negative voltage. With the negative gate bias, RICN begins to occur and V_T increases. During this stage, V_T continues to be periodically monitored, and the now positive shift in V_T is used to quantify the absorbed dose. When V_T crosses a maximum value, the gate bias is switched again to a positive value, and a new charge buildup stage begins.

The window within which V_T is maintained, i. e. the range between $V_{T\,\min}$ and $V_{T\,\max}$, is chosen to keep similar sensitivities during positive charge buildup and RICN stages.

The use of the BCCM technique allows to extend the dose measurement range of MOS dosimeters [11] and to mitigate unwanted V_T drifts during the irradiation. It was shown in previous works [12], [13] that the technique is dose-rate independent over three orders of magnitude; drifts due to temperature effects and interface states creation are mitigated; and there is an improvement regarding fading when the irradiation ends with negative bias applied to the dosimeter gate.

Floating gate transistors have been proposed as MOS dosimeters for the possibility they give to control the geometry of the stored charge and to electrically modify its amount [14]–[16]; because they can be easily adapted to different strategies to improve their radiation sensitivity and stability [17]–[19]; and

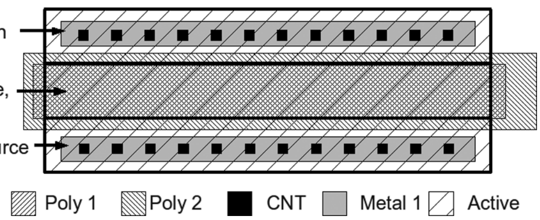

Fig. 1. Floating gate PMOS dosimeter physical layout.

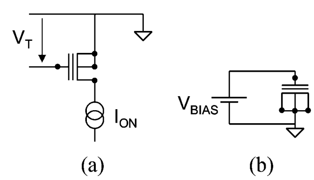

Fig. 2. Device possible configurations in BCCM technique (a) Measurement mode (b) Biasing mode.

because they provide an indirect way to obtain thicker oxides under the control gate in standard processes in which the gate oxide thickness is defined by the technology.

In this work, we explore the possibility of implementing the BCCM technique on floating gate structures. In the following section experimental details of the measurement set up are presented. In Section III measurement results are shown. Discussion and conclusions about the results are presented in Sections IV and V.

II. Experimental Details

A standard $1.5\ \mu\mathrm{m}$ Complementary MOS (CMOS) technology that provides two polysilicon layers was used to design and fabricate p-channel floating gate transistors. Fig. 1 shows the device physical layout. The thicknesses of gate and interpoly oxides are approximately 30 nm and 57 nm. The width and length of the floating gate is $W/L = 64\ \mu\mathrm{m}/6\ \mu\mathrm{m}$, while the control gate is 9 μm length.

The floating gate devices contained in a die were wire-bonded to a DIP-40 ceramic package, connected to a real time acquisition system and placed in the control room shielded from the radiation field.

The irradiation source was a high activity $^{60}\mathrm{Cobalt}$ source used for commercial sterilization purposes. The chip was located at a convenient distance from the source receiving a constant dose rate. The total dose was obtained through a silver dichromate sample [20] used for control dose measurement.

The BCCM technique was applied while the devices were exposed to a gamma ray source. The gate biasing and the V_T acquisition of the floating gate device was accomplished by a specially dedicated system. Its functions are to bias the gate of the device (Fig. 2(b)) and periodically switch it into measurement mode (Fig. 2(a)). In measurement mode, the system acquires the V_T value by forcing a reference current I_{ON} of 40 μA to flow between Source and Drain terminals. The acquisition occurs 20 ms after switching into measurement mode. When this measured V_T value crosses the limits of the predefined BCCM window, the bias is switched.

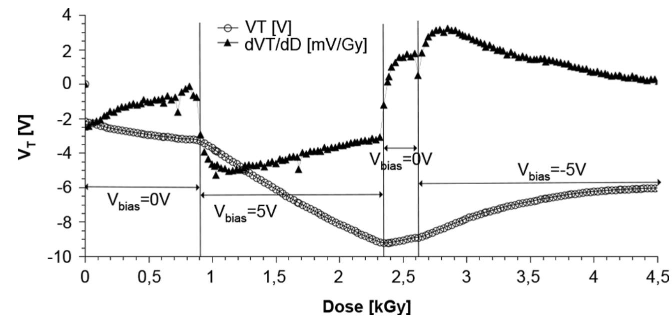

Fig. 3. Empty circles V_T evolution for irradiation under the gate bias sequence: 0 V, 5 V, 0 V, -5 V. Solid triangles: Device instant sensitivity $(dV_T/dDose)$.

III. Results

We present the results of two irradiations separated in three parts. The target of the first irradiation (parts A and B) was to test the response of the device under different gate bias and to apply the BCCM technique. After this, a new irradiation (part C) took place for an identical device aiming to study the V_T response to the gate bias switch.

A. Gate Bias Response

The first irradiation results are shown in Fig. 3. The evolution of the threshold voltage when the device is irradiated under different gate bias is shown together with its associated sensitivity (taken as the instant variation of V_T per unit of dose). The exposure dose rate was 20.8 kGy/h.

The response of device (Fig. 3) shows that it is possible to apply the BCCM technique due to its expected behavior: PCB and RICN for the chosen positive and negative bias respectively. The sensitivity of the device $(dV_T/dDose)$ is not constant showing dependence on the biasing and on the accumulated dose, and its magnitude is suitable for high dose estimation.

B. BCCM

When the device reached an accumulated dose of approximately 5 kGy the BCCM technique was started. V_T was kept between -8 and -9 V, and the gate bias voltages were 5 V for PCB stages and -5 V for RICN stages. The measurements finished at a total dose of 25 kGy. Fig. 4 shows the first and the last 3 complete (PCB-RICN) stages of the BCCM technique in a broken axis graph.

To facilitate the understanding of the BCCM properties, the six stages of PCB and RICN are plotted in separated figures as shown in Figs. 5 and 6. This allows comparison device responses as a function of total accumulated dose.

C. Transients After Switching

Figs. 5 and 6 show the detailed PCB and RICN stages of the complete BCCM irradiation. It can be seen a transient behavior at the beginning of the curves. This transient response occurs after switching the gate bias and lasts approximately 100–200 Gy. After the transients, the response is approximately linear until the next bias switch.

The transients, which do not affect the large dose estimations for which these devices would be suitable, were investigated

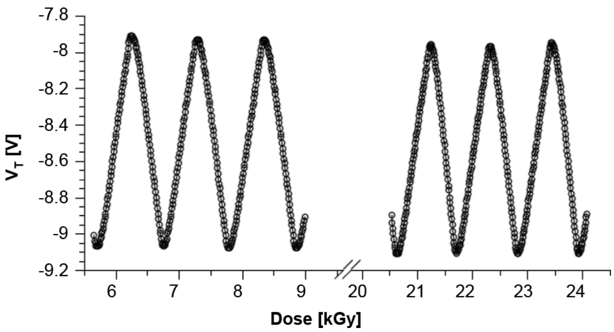

Fig. 4. Six complete cycles of the BCCM technique applied to a FG-MOS transistor. For the last three cycles a previous 20 kGy dose was accumulated.

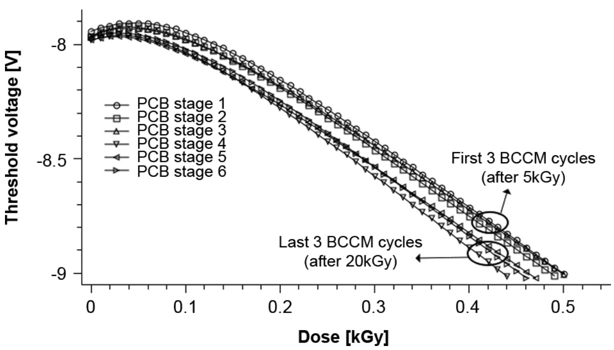

Fig. 5. PCB stages of the BCCM measurement. The dose accumulated between the first 3 stages and the last 3 stages is approximately 15 kGy.

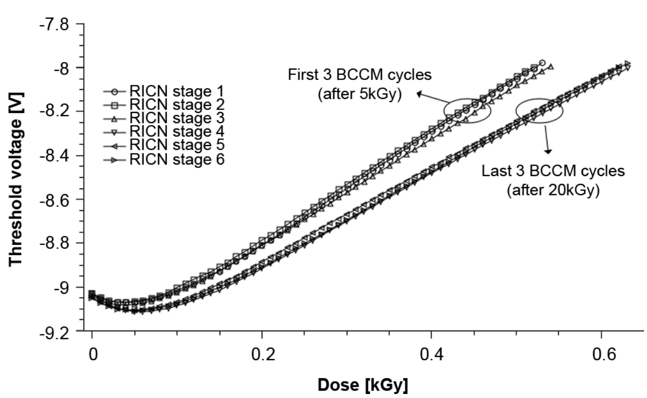

Fig. 6. RICN stages of the BCCM measurement. The dose accumulated between the first 3 stages and the last 3 stages is approximately 15 kGy.

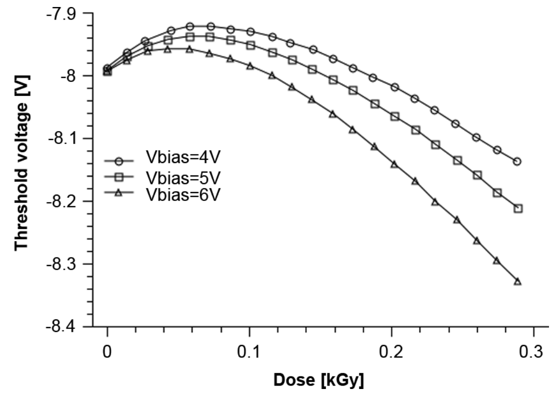

Fig. 7. Details of the transient behavior when the gate bias is switched from -5 V to Vbias during the irradiation with a 60Co source at a dose rate of 10.4 kGy/h.

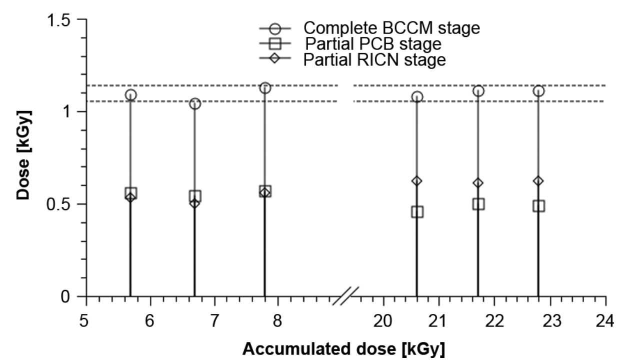

Fig. 8. Squares: required dose to complete a PCB stage. Diamonds: required dose to complete a RICN stage. Circles: required dose to complete a BCCM cycle (sum of RICN and PCB stages).

since they provide information about an (apriori) unexpected charge distribution in the insulator; first results follow.

To study the dependence of the transient response with gate bias, the device was irradiated under BCCM conditions, maintaining V_T between two reference values, and using different bias voltages in succesive charge buildup or charge neutralization stages. Fig. 7 shows three transient responses when switching from a negative bias of -5 V to three different positive biases of 4 V; 5 V; and 6 V. As the bias voltage is increased, the transients become shorter. Similar results showing attenuated overshoot transients when switching to higher absolute values of $V_{\rm bias}$ were seen also in the "valleys" i.e., switching in the opposite direction.

IV. Discussion

The main property of the BCCM technique is to extend the dose measurement range. In addition it provides a compensation mechanism for cases in which unwanted V_T variations affect the measurements. An example is the slow V_T drift towards negative values due to the creation of interface states during the irradiation. It shifts downwards the entire response V_T vs dose if repeated after a significant amount of dose received by the device. Being this response non linear, as can be seen in Fig. 3, the result is a change in the slopes of those parts of the response curve appearing within the BCCM window. Fig. 8 shows, for each cycle of Fig. 4, the necessary dose to complete half cycle corresponding to a RICN or PCB stage, and the sum of them, which is the dose required to complete one BCCM cycle. It can be seen from Fig. 8 that, due to the change in slopes (Fig. 5), the PCB stage doses for the last 3 cycles are less (by about a 15%) than PCB doses for the first three cycles. However, it is also apparent that the RICN stage doses for the last three stages are greater (than RICN doses for the first three stages) by about the same amount, thereby keeping the dose for each complete cycle of the BCCM within the same dispersion range for the first three and the last three cycles. Thus, at the end of each cycle possible deviations from original calibration are compensated.

The application of the BCCM technique showed that when the gate bias of the device is switched, the V_T evolution presents

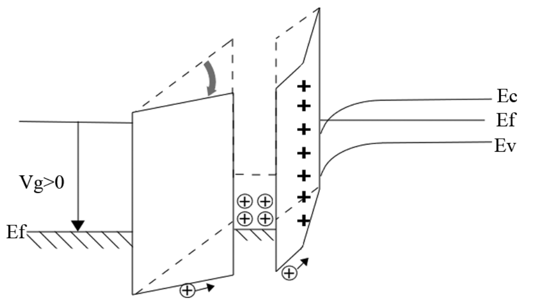

Fig. 9. Energy band diagram of a FG MOS device irradiated with positive bias. From left to right, control gate, interpoly oxide, gate oxide, silicon substrate. Dashed lines show the preirraditaion condition, without charge captured. Solid lines show the the effect of the radiation-induced trapped charge in the oxide close to the substrate and in the FG.

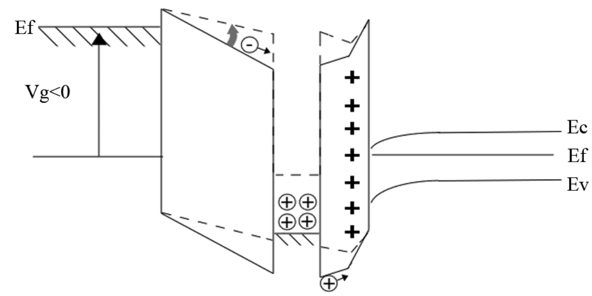

Fig. 10. Energy band diagram of a FG MOS device while irradiated with negative bias. Solid lines show the state of charge and the field distribution immediately after switching from a positive to a negative bias. It can be seen that the sense of the electric field between the FG and oxide trapped charge remains unchanged as is the current of positive charge in this region to the traps close to the interface where the positive charge might be captured. The floating gate neutralizes its accumulated positive charge with electrons generated mainly in the interpoly oxide. Dashed lines show the state of the device after the transient. In this situation, both positive charge in the FG and in the oxide are neutralized by electron currents from the interpoly oxide and the gate oxide, respectively.

a transient behavior. Fig. 7 shows that the behavior of V_T depends on the bias after switching. It also suggest that for higher absolute values of the bias voltages, the transient response is shorter.

As said, the transients can be a tool to investigate the evolution of the charge distribution in the oxide, and in particular, the role played by traps near the interface even in floating gate devices. A qualitative description follows.

Radiation induced V_T shifts in FG devices are due to the contribution of charge captured in different zones: i) at the FG, ii) in the oxide near the Si–SiO_2 interface, iii) between the gate and the FG, and interface traps creation. The results shown can be explained if the predominant effects are the trapping of charge in the FG and in the oxide near the Si–SiO_2 interface.

If enough charge is collected in the FG while a positive bias is applied (Fig. 9), the associated electric field discontinuity may be such that, after a bias switch to negative values, the field does not invert its sign along the whole oxide (Fig. 10). Instead, the oxide field below the floating gate may retain its sign, and, with it, the process of charging existent traps close to the Si interface may continue. This could be the origin of the "inertia", the slow change in the slope of V_T vs dose after the bias switch instead of an abrupt one. The process of trapping of positive charge in the oxide proceeds together with the discharge of the FG due to the large amount of electrons contributed from the thicker oxide between it and the control gate. Consequently the fields evolve in the way of slowing the first and reinforcing the second with the final result of inverting the sense in the evolution of V_T to the expected one.

This is consistent with the observation (Fig. 7) that switching to a higher absolute value of $V_{\rm bias}$ shortens the transient. The stronger external field weakens the resultant field in that region of the oxide where the built-in field is opposite to the external one, which is the responsible for the existence of the transient.

The uncertainty in the BCCM technique for high dose range applications should be tolerable when replacing the reading during the previously discussed transient by an estimation based in the precedent stable readings. This requires the assumption that the irradiation proceeds with its immediately precedent dose rate. Even so, a possible way to circumvent this uncertainty is to use two FG PMOS sensors simultaneously under the BCCM conditions with a phase difference of a quarter cycle. This could be easily implemented since many devices can be integrated in a small silicon area. In this way when the switch condition arrives for one sensor, the reading of V_T shift is taken from the other one, and the accumulated dose could always be read with a sensor in the stabilized sensitivity region.

V. Summary and Conclusion

This work tested the possibility of applying the Bias Controlled Cycled Measurement (BCCM) technique on a floating gate device designed and fabricated in a standard CMOS process. The presented results show the applicability of the technique to such structures to sense absorbed dose of ionizing radiation.

It was also shown that the dose required to complete a BCCM cycle is approximately constant regardless the previous accumulated dose mitigating the effect of slow V_T drifts.

Transients in the evolution of the threshold voltage after the bias switch were observed during the application of the BCCM technique. Complementary measurements show they depend on biasing voltage. The observed behavior is attributed to the evolution of the inner charge distribution between the FG and the traps in the oxide near the substrate.

The studied FG device in the BCCM technique showed to be particularly useful for measuring in a high dose range, where standard techniques of MOS dosimetry fail due to the saturation of the response.

Two lines remain open for further investigation. One is to study other geometries of these versatile structures for improving the sensitivity and implement them with the BCCM technique ensuring higher dose range without sensitivity loss. The other (which complements the first one) is to measure and model charge and field evolutions in FG devices subjected to irradiation under bias in order to gain in the understanding of the basic processes, and to predict with better accuracy its response under switched bias irradiations.

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