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Field Oxide n-channel MOS Dosimeters Fabricated in CMOS Processes

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***Abstract*—This paper presents a new technique to build MOS dosimeters using unmodified standard CMOS processes. The devices are n-channel MOS transistors built with the regular Field Oxide as a thick radiation-sensitive gate. The devices were fabricated in two different commercial $0.6\ \mu$m CMOS processes, gate oxide thicknesses of ~ 600 nm and ~ 400 nm. Responsivities up to 4.4 mV/rad with positive bias, and 1.7 mV/rad with zero gate bias were obtained in the thicker oxides. The effect of charge trapped in the oxide and interface states on the shift in the threshold voltage are analyzed.**

***Index Terms*—Dosimeters, MOS devices, radiation effects, solid-state detectors.**

I. Introduction

METAL OXIDE SEMICONDUCTOR (MOS) dosimeters are MOS transistors, usually with p-type channel, in which the accumulative radiation-induced shift in the threshold voltage (V_T) is used to quantify the absorbed dose [1]. MOS dosimeters allow the electronic and automatic reading of doses in real time, with an extremely low power consumption, and due to their very small size can be put in catheters or measure with high spatial resolution irradiation fields in medical applications [2], [3], [4], [5].

The responsivity of a MOS transistor to total doses of ionizing radiation, defined as the absolute value of the V_T shift per unit dose, increases with gate oxide thickness (t_{ox}) [6]. In order to achieve high responsivities, the dosimeters are usually built with oxide thicknesses of several hundreds of nanometers, or even a few micrometers [7], [2], [8], [9], [10]. These oxides are much thicker than the regular gate oxides available in standard CMOS processes, thus, ad-hoc processes are needed to fabricate the devices.

Several authors proposed the fabrication of MOS dosimeters using standard CMOS processes. The fabrication of MOS dosimeters in standard CMOS process would reduce the manufacturing cost, and have all the advantages of using very stable and repeatable fabrication processes [11]. Also, it opens the possibility of integrating in the same die the readout electronics and control circuits, with the potential fabrication of a dosimetry system on a single chip [12], [13]. One of the proposals was done by Tarr *et al.*, who presented a transistor with an extended floating gate which collects charge generated in its surroundings. This MOS dosimeter had a high responsivity thanks to its large area [14], [15], [16]. In [17] Martin *et al.* proposed the use of regular floating gate transistors as dosimeters, and in [18] some of the present authors studied the response of floating gate dosimeters under switched bias irradiation. Other approach explored in [19] and [20] was to follow the discharge of floating gate transistors in a commercial memory cell.

In [13] García Moreno *et al.* presented a radiation sensor using regular transistors integrated in a CMOS process. The sensor takes advantage of the fact that the radiation-induced V_T shifts of n-channel and p-channel transistors are different. Their circuit provides an output signal which changes frequency with dose. Using Tarr's floating gate transistors, a much higher resolution was reported by the same group in [21]. In [22] some of the present authors proposed to use the shift with dose of the frequency of ring oscillators as a dosimetric parameter. A small increase in resolution was obtained, but high uncertainties were introduced by temperature. In [23] an integrated dosimetric system on chip based on the threshold voltage of a buried oxide in a Silicon On Insulator (SOI) process was proposed.

In this work, we propose a new strategy for fabricating MOS dosimeters in unmodified standard CMOS processes. The idea is to use the thick Field Oxide (FOX) which is used to isolate non-active areas in the chip [11], as gate oxide for the sensors. We found convenient the use of n-channel transistors instead of the traditional approach which uses p-channel devices. Discrete or thick Al gate N-channel MOS transistors fabricated in a special process have already been used as dosimeters in [24], [25], [26], [27].

The following section describes the design of the proposed Field Oxide dosimeter and the fabrication of the sensors in two CMOS standard processes. Section III presents experimental results obtained with the irradiation of the fabricated sensors with a ^{60}Co gamma-rays source. In Section IV the results are discussed and Section V presents the conclusions of the work.

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II. Design of the Field Oxide Dosimeters

To fabricate in a standard CMOS process high sensitive dosimeters, we propose to use as a sensor a MOS transistor built with a Field Oxide as its gate oxide. Field Oxides are used to isolate components in CMOS circuits [11]. Usually, FOX devices have very high absolute values of V_T—frequently higher than 20 V. This is to fulfil its isolation function avoiding accidental induction of a conductive channel in the underlying silicon by the operating voltages at the conductive lines which lie on the thick oxide [28].

A. Total Ionizing Dose Effects in Field Oxides

Due to their high thicknesses—usually greater than 300 nm—FOX are very sensitive to Total Ionizing Doses (TID) [29]. The high responsivity to radiation of FOX is very well known, since it causes one of the most important TID effects in CMOS circuits, which is the increase of the off-current in n-channel devices. The trapping of electrical charge in the FOX [30], [31], [32], [33] can turn on two parasitic transistors which are in parallel with the "drawn" device, situated in the "birds beak" of the LOCOS process. If the V_T of the parasitic transistors decreases too much, they can turn on, creating current paths beside the n-channel "drawn" device. Also, parasitic current paths between n-wells and n-plus implants might appear [34] for example in inverters. These effects can be avoided if special layout techniques are used [35].

The shift in V_T caused by TID in MOS devices—including FOX transistors—is the result of two main effects, the trapping of positive oxide charge, and the creation of interface traps [29]. Both effects are the result of a complex series of mechanisms described in detail for example in [36], [29]. The way in which these effects modify V_T can be summarized as follows. The trapping of positive oxide charge causes negative shifts in the flat-band voltage (V_{FB}), and thus adds a negative contribution to the shift of V_T. The creation of interface traps modifies V_T because the new states are filled with electrons in V_T biased n-channel devices, and, oppositely, are voided in p-channel ones. This causes a negative contribution for V_T shift in the p-channel device which adds to the contribution originated in the trapped charge, and a negative contribution in the n-channel device which opposes to that from the trapped charge. As a result of both effects, the total shift in V_T of p-channel MOS transistors is always negative. In n-channel devices, the opposite sign of both contributions can lead to a smaller response, or even to a non monotonic response observed when the rates in which both defects grow change differently with time. If the response is initially dominated by the trapping of positive oxide charge, and then by negative charged interface traps, a "rebound" or "superrecovery" effect is observed [6], [29]. Since p-channel devices always have larger and monotonic responses, p-channel transistors are usually used as dosimeters [1].

The use of p-channel FOXFETs as dosimeters presents the practical difficulty that after irradiation the absolute value of V_T, which is initially high, would further increase, adding complexity of to the reading electronics.

On the other hand, the high initial value of V_T in a n-channel FOXFET is convenient because if charge trapping dominates the response of the device during irradiation, V_T will decrease with dose, making easier the reading process. We will show that in the two CMOS processes in which we fabricated the devices, the oxide trapped charge contribution is higher than the interface traps contribution to the V_T-shift, and the resulting n-channel dosimeters have monotonic responses.

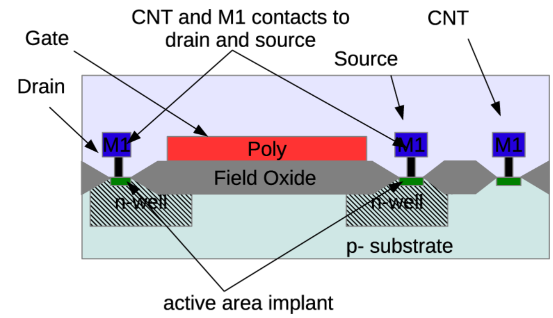

Fig. 1. Cross section of the FOXFET dosimeter proposed in this paper.

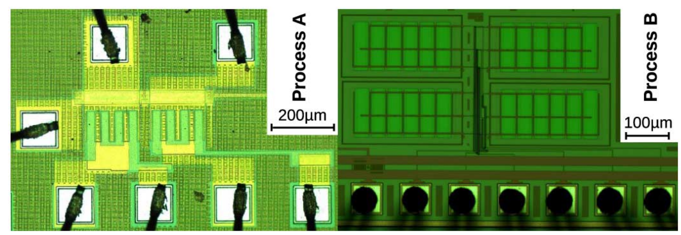

Fig. 2. Micrography of the fabricated sensors.

B. Design and Fabrication of FOXFET Dosimeters

FOXFET dosimeters were fabricated in two CMOS processes from different vendors. One of the processes, to which we will refer as process A, has a FOX thickness of $\sim$ 600 nm. The other process, to which we will refer as B, has a FOX oxide thickness of $\sim$ 400 nm—estimated from MOS capacitor measurements. Both processes use Local Oxidation of Silicon (LOCOS) to create the isolation areas.

The Drain and Source regions of the n-channel FOXFET were fabricated using the N-WELL implants which have lower doping concentrations than the ACTIVE-NPLUS regions, increasing the maximum admissible Drain voltage, as in high voltage transistors in standard CMOS processes [28]. Also a good overlapping of source and drain N-wells with a gate FOX can been obtained. Fig. 1 presents a cross section of the device.

In each die, two identical FOXFETs were placed. Each FOXFET has individual contacts to drain, source, and gate. The bulk contact is shared between both devices placed on the same p^- substrate. In Fig. 2 a micrograph of each integrated circuit is shown.

To minimize the modulation of I_D with the drain voltage, and obtain a good capacitive coupling between gate and the channel, relatively long channels were used. The transistors from process A had a channel lenght (L) of 25 μm and transistors from process B had a channel length of 22 μm.

For the FOXFETs to be able to manage currents in the range of hundreds of microamperes, each FOXFET consisted of several fingers in parallel. Devices from process A are formed by four fingers of $W = 110$ μm, leading to

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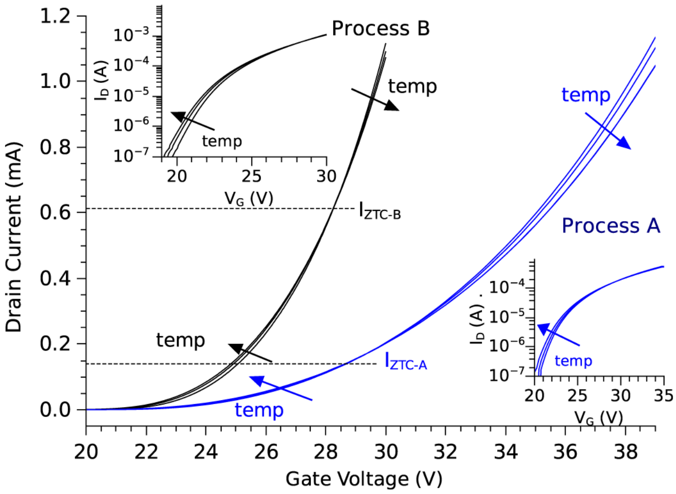

Fig. 3. I_D vs V_{GS} curves of unirradiated FOXFETs at different temperatures. For process A, curves shown correspond to temperatures of 5°C, 30 °C, and 45°C; and for process B 15 °C, 30 °C, and 45 °C. The insets show the same curves plotting I_D in a logarithmic scale.

$W_{eq} = 440$ μm. FOXFETs built in process B consisted of 12 fingers of $W = 110\,\mu$m, and a $W_{eq} = 1200$ μm. Each of the two transistors fabricated in process B were designed in such a way that they shared a common centroid. Dies from both packages were wire-bonded in open cavity DIP40 packages.

III. Measurements

This section presents experimental results. Initially, I_D vs. V_{GS} curves of the devices were measured to characterize the devices before irradiation. Then, the devices were irradiated under different gate biases to characterize their dosimetric performance. Oxide trapped charge and interface traps creation was monitored through the change in current-voltage curves.

A. Electrical Characterization of FOXFET Devices

Before irradiation, the effect of temperature on the I_D vs V_{GS} current-voltage characteristic was studied. Fig. 3 shows the I-V curves, i.e. the I_D V_{GS} characteristics of the FOXFETs from both processes. Several curves measured at different temperatures are shown in the plot. It can be observed that I_D has approximately the expected quadratic dependence with the gate voltage (V_{GS}) over $\simeq$ 23 V for process A, and $\simeq$ 21.5 V for process B.

The expected behavior with temperature is also observed, for low currents I_D increases with temperature, whereas for high currents I_D decreases with temperature. There is a certain I_D for each device where the I-V curve has a very small dependence with temperature. This I_D is called the Zero Temperature Coefficient current (I_{ZTC}) [7], [37]. In MOS dosimetry, in order to minimize errors introduced by temperature on the reading, the shift in the V_{GS} required to obtain the I_{ZTC} is frequently used to quantify the absorbed dose. Thus, in this work we will consider the dosimetric threshold voltage (V_T) as the gate to source voltage required to sustain the I_{ZTC}, instead of the traditional threshold voltage definition of minimum V_{GS} required to generate strong inversion under the gate [38]. The zero temperature coefficient current was 170 μA and 610 μA for devices fabricated in a process A and B respectively.

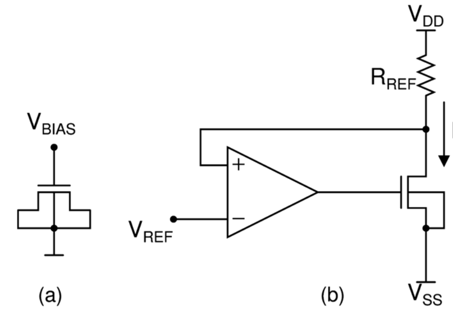

Fig. 4. "Bias" configuration (a), and "Read" configuration used to measure V_T (b). The resistor R_{REF} and the reference voltage V_{REF} are chosen to force the I_{ZTC} current through the drain in saturation mode.

Due to the long channel of the devices, I_D has a negligible dependence with the drain to source voltage (V_{DS}) in the range from 0 V to 30 V. The I_D vs V_{GS} characteristics of the pair of FOXFETs placed in the same die were almost similar. There was only a very small difference in V_T between the two neighbouring transistors. This small difference between the two dosimeters from the same die was of 65 mV for process A and 25 mV for process B, and repeated in all the samples from the same process as a systematic offset [28].

B. Response to Radiation of the FOXFETs

The devices were irradiated using ^{60}Co gamma rays at dose rates from 35 to 70 rads/min. During irradiation the gates of both devices were positively biased while other pins were grounded. FOXFET were readout within 20 ms each 20 seconds with the I_{ZTC} current through the drain determined by resistor R_{REF} and V_{DS} bias 31 V by switching from "Bias" to "Read" mode as on a Fig. 4. Short readout time did not effect essentially the radiation response of the MOSFETs. In the "Read" mode V_T was measured forcing the I_{ZTC} current through the drain, with a fixed $V_{DS} = 31$ V.

Fig. 5 shows the response to irradiation, i.e. the evolution of V_T with dose, of two sensors from the same die fabricated in process A. During the irradiation one of the devices was biased with $V_{\text{BIAS}} = +9$ V, and the other with $V_{\text{BIAS}} = 0$ V. It can be seen that the responsivity of the dosimeter was higher for +9 V bias irradiation, with an initial maximum responsivity of 3.95 mV/rad. The initial responsivity with $V_{\text{BIAS}} = 0$ V was 1.74 mV/rad. The inset shows how the responsivity changed with total dose. The response was monotonic and no "rebound" effects were observed [29] in these n-channel FOXFETs.

The dash lines on Fig. 5 show radiation response of the devices assuming initial response 3.95 mV /rad and 1.74 mV/rad for A devices under +9 V and zero gate biases respectively. The reduction of the sensitivity with dose is a well known effect explained by the field collapse effect [39], [40] leading to stronger recombination of e-h pairs in the gate oxide; and partially modulation of the trapping cross section with the local electric field [36].

The response curves of dosimeters from process B are shown in Fig. 6. A much lower responsivity of 0.50 mV/rad

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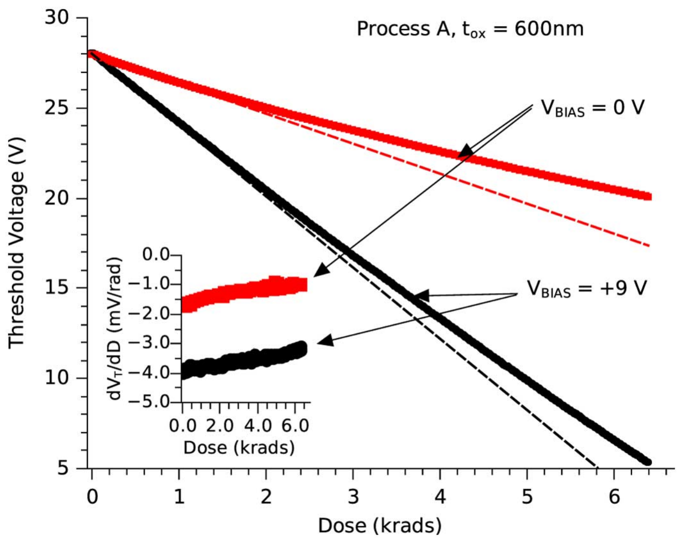

Fig. 5. Response of FOXFET dosimeters from process A under +9 V and 0 V of gate bias. The inset shows the responsivity of the sensors vs dose.

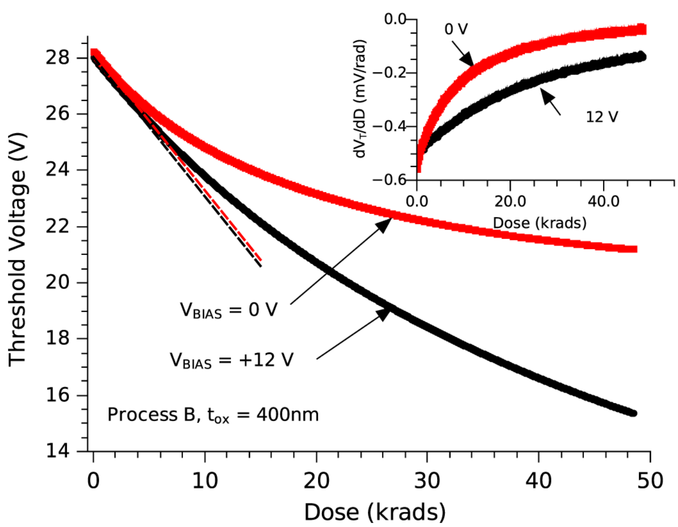

Fig. 6. Response of FOXFET dosimeters from process B under +12 V and 0 V of gate bias. The inset shows the responsivity of the sensors vs dose.

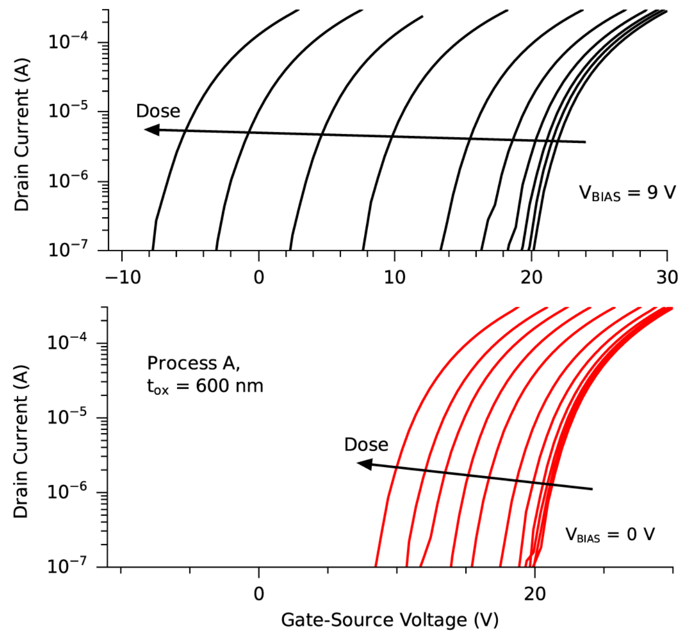

Fig. 7. I-V curves of FOXFET dosimeters from process A after 0.1; 0.2; 0.4, 0.8; 1.6; 3.2; 6.4; 8.2 and 9.6 krads.

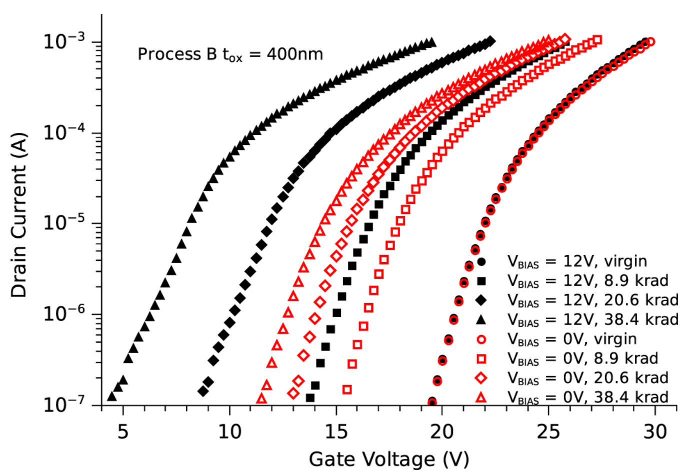

Fig. 8. I-V curves of FOXFET dosimeters after 8.9, 20.6 and 38.4 krads.

was observed in this dosimeter for both $V_{\mathrm{BIAS}} = +12$ V and $V_{\mathrm{BIAS}} = 0$ V. After a few krads the responsivity for $V_{\mathrm{BIAS}} = 0$ V decreased rapidly, as can be observed comparing the experimental points with the extrapolation of the first krad plotted as straight lines for both FOXFETs. The responsivity with $V_{\mathrm{BIAS}} = +12$ V also decreased but at a lower rate. No "rebound" effect was observed in the response of the sensors fabricated in a process B similar to the sensors fabricated in a process A.

C. Oxide Charge Buildup and Interface Traps Creation

To study the charge trapping in the oxide and the creation of interface traps, devices from both processes were irradiated in steps of incremental doses followed by measuring an I-V curve after each irradiation step.

Devices from process A were irradiated with $V_{\mathrm{BIAS}} = +9$ V and $V_{\mathrm{BIAS}} = 0$ V to up to a dose of 9.6 krads. Fig. 7 shows the I-V curves after each irradiation step. Parallel shift of I-V characteristics with dose without changing of their shapes is suggesting that their shift is determined mostly by build up positive charge in the gate oxide while creation of interface traps under these doses is minimal [29].

Fig. 8 shows I-V curves after irradiation steps in devices from process B, holding $V_{\mathrm{BIAS}} = +12$ V in one transistor and $V_{\mathrm{BIAS}} = 0$ V in the other of the same die. The curves also shift towards the left—suggesting the charge trapping in the oxide—, with a small stretchout which suggests a small increase in interface traps density.

From the sub-threshold swing the increase in interface traps density ΔD_{IT}, and its contribution ΔV_{IT} to the V_T shift were estimated [41]. In Fig. 9 the ΔV_{IT}, the oxide trapped charge contribution ΔV_{OT} and the V_T shift ΔV_T are plotted. For process A, ΔV_{OT} is always from five to ten times greater than ΔV_{IT}. For process B and zero volts bias the ratio between

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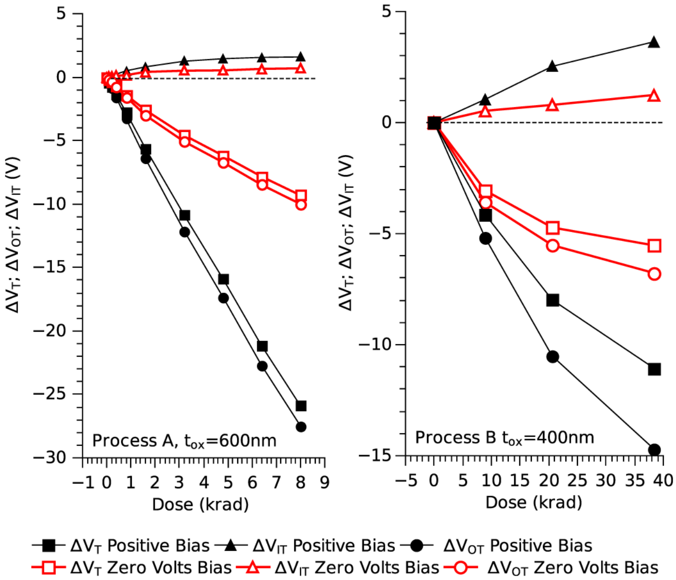

Fig. 9. Evolution of ΔV_T, ΔV_{IT}, and ΔV_{OT} as a function of dose for processes A and B.

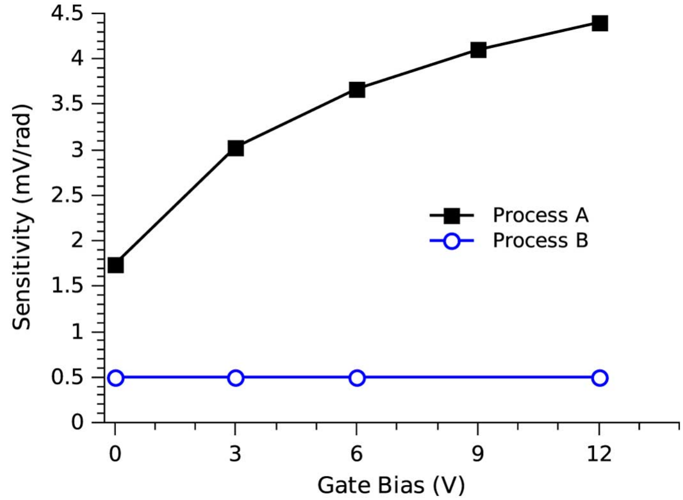

Fig. 10. Initial responsivity vs gate bias for FOXFET dosimeters from processes A and B.

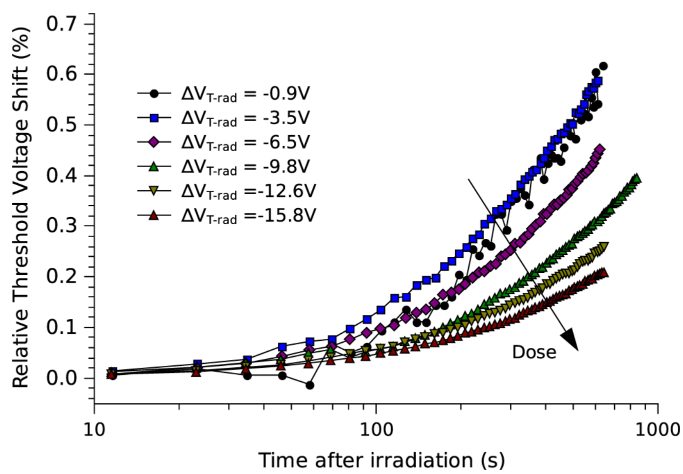

Fig. 11. Fading in a FOXFET dosimeter from process A. The ratio between the post irradiation shift and the radiation induced shift is plotted, giving an idea of how much relative error is introduced by fading in the dose measurements.

ΔV_{OT} and ΔV_{IT} is also always greater than five, whereas for positive bias irradiation the ratio is slightly smaller but always larger than 3.6.

Besides, at the end of the irradiation, ΔD_{IT} for zero volts irradiation in process A was 8.26×10^{10} eV^{-1} cm^{-2} and for positive bias 1.90×10^{11} eV^{-1} cm^{-2}. For process B the figures were 7.7×10^{10} eV^{-1} cm^{-2} and 2.25×10^{11} eV^{-1} cm^{-2}.

D. Dependence of the Responsivity With the Gate Bias and Fading

In order to investigate the bias dependence of the responsivity, a fresh FOXFET dosimeter from each process was irradiated in small steps of 100 rads, applying different positive $V_{\rm BIAS}$ during each step. The V_T shifts after each step were small enough to disregard the variation of responsivity with dose and consider that the shift is independent of the history of the sensor. From those small irradiation increments, the responsivity for each gate bias voltage was estimated. Fig. 10 shows the responsivity as a function of gate bias for FOXFETs from processes A and B. In process A, the responsivity increases with $V_{\rm BIAS}$. An unusual behavior is observed in devices from process B, where the responsivity is independent of the gate bias for voltages from zero to +12 V for small dose increments. However sensitivity for +12 V is higher than for unbiased device (Fig. 9) for large doses. It could be explained by minimal effect of the initial external electrical field on the overall oxide field, affecting recombination of e-h pairs.

The evolution after irradiation of V_T in FOXFET dosimeters from process A, was tracked during many of the experiments shown in previous figures. To quantify the effect of fading on the reading of the absorbed dose, we plot in Fig. 11 the shift caused by post irradiation annealling [10], [36] normalized to the magnitude of the radiation-induced V_T shift. This ratio is a measure of the relative error introduced by annealing in the measurement of the total dose. It can be seen that in the worst case—between 10 and 100 seconds after irradiation—a 0.5% error per decade of annealing time is observed. Although the results are limited, this response is comparable to fading observed in other devices with oxides specially grown for its use in dosimetry [10]. At least for radiotherapy, where irradiation times are similar to the length of our experiments, it can be concluded that the post irradiation performance of the FOXFET dosimeters from process A is acceptable.

In FOXFET dosimeters from process B the post irradiation annealing was not systematically studied, but in general similar results were observed, e.g. a shift of a 0.2% after 10 minutes of annealing, which introduces a negligible dose measurement error in case of V_T read out is within this time interval.

IV. Discussion

This paper presents a novel method to fabricate MOS dosimeters in regular CMOS processes. N-channel MOS transistors using the thick Field Oxide of the process as its gate oxide, were fabricated. The gate is built using a polysilicon strip—POLY1—, leading to a stack of field oxide covered by polysilicon over the p^- substrate. We made other attempts using Metal strips—METAL1 or METAL2 layers—as gates, but the resulting devices were unstable, probably because the gate oxide might have been formed by stacks of thermal Field Oxide covered by layers of BPSG [11], [28].

In our FOXFETs dosimeters with polysilicon gates, the initial V_T was greater than 20 V, and reduced with dose. We can perform dosimetry using the negative and accumulative shifts in V_T.

A. Interface Traps and Their Effect in the Response

One relevant result of the work is that at least for the two processes tested, the response of the sensor is monotonic, not showing the "rebound" reported on many n-channel MOSFETs. The "rebound" is observed when at the beginning of the irradiation the interface traps contribution to the shift in V_T is greater than the oxide charge contribution, but then slows down, and the oxide charge buildup begins to dominate the response [6]. That behavior is not seen in our FOXFETs, where the interface traps creation is always slower than oxide charge buildup, ensuring a monotonic response of the dosimeters.

However, the slow creation of interface traps diminishes the responsivity of the sensor with respect to what would exhibit a p-channel MOS dosimeter with the same rate of oxide charge buildup and interface traps creation. At the end of irradiations of Fig. 9, for process A this reduction would have been 13% for $V_B = 9$ V and 12% for $V_B = 0$ V; and for process B a 40% for $V_B = 0$ V and 30% for $V_B = 0$ V.

B. Bias Dependence of Oxide Trapping and Internal Field Effects

The dependence of responsivity with $V_{\rm BIAS}$ of FOXFET dosimeters from process A is similar to what is observed in state of the art MOS dosimeters [7]. At low electric fields as the one used in this work, the responsivity of the sensor increases with the electric field. This is caused by the increase in the generation yield [6], i.e. the fraction of holes which escape from immediate recombination after being generated by the incident secondary electrons [29]. These higher number of holes is then drifted by the electrical field towards the $\rm Si-SiO_2$ interface. During their transport, a fraction of these holes can be trapped in oxide traps. Since the flux of holes increases with electric field due to a higher yield, the responsivity—at the fields used in this work—is expected to grow.

As an example, the following is an estimation of how much of the charge generated by ionization is finally trapped in FOXFETs from process A with $V_{\rm BIAS} = 12$ V. Knowing that the pair generation rate in $\rm SiO_2$ during ^{60}Co gamma irradiation is $g_0 = 8.10^{12}$ pairs cm^{-3} rad^{-1} [6], and given a fractional generation yield of $\simeq 60\%$ for an electric field in the oxide of 0.2 MV/cm—i.e. 12 V applied in our 600 nm oxides—, an equivalent flux of $\sim 2.9 \times 10^8$ holes/cm^2/rad migrate towards the $Si - SiO_2$ interface. Only a fraction of these holes is finally trapped in the oxide. From the responsivity measured for 12 V irradiation—Fig. 10—, and assuming that the oxide traps are located very close to the semiconductor [6], the rate of hole trapping is $\sim 1.6 \times 10^8$ holes/cm^2/rad, which means that only $\simeq 55\%$ of the holes which escape initial recombination are finally captured.

Probably, the responsivity would further increase if $V_{\rm BIAS}$ is increased. It has been reported that the product of the generation yield with oxide trap cross section has a maximum at electric fields of $\simeq 1$ MV/cm, thus it is expected that applying higher bias voltages higher sensitivities should be achieved in the FOXFETs of process A. Future work with a modified version of our V_T tracker will be done in order to fully characterize the bias dependence of the responsivity.

On the other hand, FOXFET dosimeters from process B had a completely different behavior. Their responsivity was $\simeq 0.50$ mV/rad, much lower than the FOXFET dosimeters from process A, and it remained almost constant for gate biases from 0 to 12 V. Only for -0.5 V biased irradiation the responsivity of the sensor could be reduced to a few tens of microvolts per rad, probably due to the inversion of the electric field in the oxide, forcing generated holes to migrate to the gate instead of the $Si - SiO_2$ interface, where most oxide traps are supposed to be located [39]. This unusual behavior, will continue being investigated. However, due to the incomplete information given by foundries about their fabrication process, the explanation of this observed dependence might not be found.

An effect observed in Figs 5 and 6 is the decrease in the responsivity with the dose increase. This gradual decrease of the responsivity with dose is smaller for 9 V irradiation than for 0 V, and might lead to a saturation of the response of the sensor with very high doses [39]. This gradual decrease in the responsivity can be the explained by the "Field Collapse effect" [39]. The idea is that the electrical field generated by the positive charge trapped in the oxide screens the external field applied on the oxide. The reduction of the field in most of the oxide, causes a decrease in the fractional yield, with a reduction in the amount of holes and in the hole flux, leading to a smaller rate of charge buildup.

An advantage of using the n-channel FOXFET dosimeters is that the reading of V_T involves a positive V_{GS}. Positive V_{GS} usually provide high responsivities, making it possible to use the device continuously in the "read" mode of Fig. 4, avoiding the unnecessary switch to "bias" mode. This simplifies the V_T reader electronics, and eliminates the uncertainities introduced by V_T drifts caused by slow traps charging after switch [2].

C. Comparison With Other Reported Responses

Many works have dealt with TID effects on different thick oxides, ad-hoc processes optimized to build MOS dosimeters, thick Field or Shallow Trench Issolation (STI) oxides in CMOS processes, or even oxides in Commercial Of The Shelf (COTS) transistors. In Table I the responsivities of different thick oxides reported in different papers are compared with the results from this paper.

Several groups and companies have their own fabrication processes to build MOS dosimeters based on p-channel devices [7], [42], [43], [44], [45], [46]. The responsivities of these dosimeters with oxide thickness of several hundred nanometres do not vary too much from the responsivities we obtained on our n-channel devices from process A, but are usually higher than the poor responsivity of our FOXFETs from process B.

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TABLE I
RESPONSIVITIES OF DIFFERENT THICK OXIDES

Device	t_{ox} (nm)	Bias (V)	External Field (MV/cm)	resp. (mV rad^{-1})	$\hat{R}$ (mV rad^{-1} μm^{-2})
This paper:					
Process A nMOS	600	0 / +12	0 / 0.2	1.6 / 4.4	4.4 / 12.2
Process B nMOS	400	0 to +12	0 to 0.3	0.4	2.5
REM Oxford LTD					
RFT 300 pMOS [42]	300	0 / +9 / +18	0 / 0.3 / 0.6	0.20 / 1.25 / 1.75	2.2 / 13.9 / 19.4
TOT 501C "R" pMOS[7]	850	0V	0	0.91	1.26
TOT 504 "R" pMOS[7]	1230	0 / +20	0 / .16	2.3/20	1.5 / 13.2
Tyndall dosimeter pMOS[43]	400	+2.5 / +5V	0.0625 / 0.125	∼0.8/∼1.0	∼5.0 / ∼6.2
Best Medical 502RD pMOS[44] [45]	500	+5 / +15	0.1 / 0.3	1 / 3	4 / 12
LAAS PMOS dosimeter [46]	1600	0	0	4.2	1.65
3N163 MOSFET COTS pMOS [47]	∼200	0	0	0.3	7.5
STI–FOX [48] [49] [50] [51]					
STI TSMC 180 pMOS @20krad	425	+1	0.02	1.38	7.64
ASU FOXCAP nMOS @20krad	320	+1.38	0.043	0.325	3.27
SOI Dosimeter SANDIA CMOS7 SOI [23]	200	0	0	0.125	3.125
Ukranian n-MOSFET n-channel dosimeter [27]	1000	0	0	1.80	1.80

The oxide of some MOS dosimeters is sometimes optimized to obtain very low fading [42]. The post irradiation response of our FOXFET was not as good as in these dosimeters, but was comparable to most of the other reported shifts, compatible with medical applications.

Other works present TID effects on STI and thermal thick oxides. Sanchez Esqueda *et al.* [48], [49] irradiated 425 nm STI oxides and applying a small 1 V bias voltage. After $\simeq$ 20 krads they found an increase in oxide charge and interface traps which would lead to a $\Delta V_{OT} \simeq -17.8$ V and $\Delta V_{IT} \simeq 9.9$ V. In comparison, in our 400 nm thick gate oxide, with $V_B = 12$ V, lower shifts of $\Delta V_{OT} \simeq -10.5$ V and $\Delta V_{IT} \simeq 2.5$ V were observed—the values are even lower for zero volts irradiation. The 600 nm oxides were not irradiated to such high doses, but after 8 krad irradiation with zero bias, the figure from Fig 9 is $\Delta V_{OT} \simeq -10$ V not too far from the values obtained by Sanchez Esqueda. Lower responsivities were reported by the same group irradiating 200 nm oxides [50].

Another work proposes to measure the shift in V_T in a backgate parasitic transistor built in a Silicon On Insulator (SOI) process [23] to quantify the dose. The thick oxide used for dosimetry is the buried oxide from the SOI wafer, which seems to be more soft to radiation than regular thermal oxides because the high temperature steps used in processing of SOI wafers increases the number of oxygen vacancies, and thus, the number of hole traps. The responsivity r in this 200 nm oxide was not far from the responsivity found in process A with zero volts bias.

The response of a thick gate commercial transistor was studied and modeled in [47], obtaining a responsivity close to 0.3 mV/rad in the p-MOS switch 3N163 with an estimated thickness of $\sim$ 200 nm.

To allow a normalized comparison of the sensitivities of the different oxides, in Table I we also show the electric field at which each responsivity is obtained, and a normalized responsivity $\hat{R} = r/t_{ox}^2$ similar to the parameter analyzed in [51]. The idea is that since the V_{FB} shift in thick oxides is approximately proportional to t_{ox}^2 [52] this normalized responsivity gives an idea of how "rad soft" an oxide is, and allows a comparison of our FOXFET dosimeters with other devices. We find reasonable to use this figure of merit to compare the responses of different devices irradiated applying the same electric field, i. e. under similar generation yield and hole transport conditions.

From the comparison for electric fields in the range from 0.2 to 0.3 MV/cm, it can be concluded that oxides from process A are have comparable characteristics to other dosimetric oxides fabricated in ad-hoc processes. On the other hand, oxides from process B appear to be much more "radiation hard", being less convenient for MOS dosimetry. The comparison of the normalized response of different devices at zero electric field is quite difficult, because at zero volts of gate bias, the real electric field in the oxide is not zero because of the built in potential. The built in potential is different in different devices and adds an electric field which cannot be neglected compared with the external bias. Despite this observation, the results suggest that oxides from process B also present at zero bias a good response compared to other oxides with different thicknesses.

The high dispersion in responsivities suggests that probably not all CMOS processes can provide sensors with sufficient sensitivity, and that a characterization of different processes is required to choose a convenient one. This dispersion in responsivities has been reported many times e.g. in [32], [51], [53].

V. CONCLUSION

MOS dosimeters were fabricated in two CMOS processes. The devices are n-channel MOS transistors built with the regular thick FOX, which makes them softer to TID. The devices were fabricated in two different commercial CMOS processes with minimum channel lengths of 0.6 μm, obtaining gate oxide thicknesses of $\sim$ 600 nm and $\sim$ 400 nm and sensitivities of 4.40 mV/rad and 0.50 mV/rad with positive bias, and 1.74 mV/rad and 0.50 mV/rad with zero gate bias respectively.

Despite the fact that the FOXFET dosimeters were not fabricated in an ad-hoc process, with special conditions to grow the gate oxide, their performance is comparable to specially manufactured dosimeters. Particularly in process A, a very high responsivity compatible with radiotherapy dosimetry [2] was obtained.

Temperature induced uncertainties can be reduced if V_T is measured at the ZTC current, which exists at practical voltages at values between 28 and 30 V. These voltages are compatible with some high voltage CMOS processes, which might allow, in the future, the integration in the same chip of the reading electronics of the dosimeter.

From the results of the two processes tested in this work, it can be concluded that fabricating FOXFET dosimeters is possible with a practical applicability in radiotherapy applications.

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