Parasitic Conduction Response to X-ray Radiation in Unstrained and Strained Triple-Gate SOI MuGFETs

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ABSTRACT

In this work, the X-ray irradiation impact on the back gate conduction and drain current for Triple-Gate SOI FinFETs is investigated for strained and unstrained devices. Both types (P and N) of transistors were analyzed. Since X-rays promote trapped positive charges in the buried oxide, the second interface threshold voltage shifts to lower gate voltage. The performance of n-channel devices presented a strong degradation when submitted to X-rays, while for p-channel devices the opposite trend was observed. Two different dose rates were analyzed.

Index Terms: X-ray radiation, Multiple-Gate MOSFETs (MuGFETs), Parasitic back conduction.

I. INTRODUCTION

For radiation-harsh environments, a Silicon On Insulator (SOI) technology has presented several benefits over standard CMOS, due to its smaller active silicon area. However, the large buried oxide thickness of fully depleted (FD) SOI devices is responsible for the worse total ionization dose (TID) effects, which result in a larger variation of radiation-induced interface and oxide traps.

Gate leakage current and short channel effects become more noticeable as the scaling of devices advances. As a solution, the Multiple Gate Transistor (MuGFET) technology is often used to address these issues for the 22nm node or below due to its better control of charges in the channel [1]. Nevertheless, for narrower MuGFETs, a smaller effective carrier mobility occurs as the current flows mainly through the lateral sidewalls, so that strain-engineering techniques are applied to improve the mobility. Besides that, high dielectric constant (high-K) materials are also used in order to minimize the gate leakage current [2].

However, when considering the MuGFETs radiation hardness, even if fabricated in an SOI technology, a worse TID behavior was observed due to the presence of the buried oxide. In this paper, the X-ray radiation influence on the performance of strained and unstrained p- and n-channel MuGFET devices is investigated, focusing mainly on the back interface conduction.

II. DEVICE CHARACTERISTICS

The studied devices are triple-gate MuGFETs fabricated in imec, Belgium, and have the following characteristics: the gate dielectric consists of 1 nm SiO_2 covered by 2.3 nm HfSiON, resulting in an Equivalent Oxide Thickness (EOT) of 1.5 nm; the gate electrode is composed of 10 nm TiN, followed by 100 nm polysilicon. The buried oxide thickness and fin height are 145 nm and 65 nm, respectively. Two different splits were analyzed, one with unstrained silicon that is used as a reference, and a second uniaxially strained one using a dual Contact Etch Stop Layer (CESL) technique, generating tensile stress for nMuGFETs and compressive stress for pMuGFETs. The SiN_x cap is deposited over the gate stack and the processing parameters and hydrogen amount define the introduction of either a compressive or a tensile strain in the channel [3].The valence band structure of silicon is modified by uniaxial compressive stress to an extent that the transport direction's hole effective mass (typically <110> in a (100) plane) increases [4] and the tensile stressed modify the conduction band increase the eletron mobility [5]

Using an X-ray diffractometer XRD-7000 from Shimadzu Co. exposure rates of 15 krad(Si)/s and 300 rad(Si)/s at an effective energy of 10 keV were generated, which produce secondary electrons within a range of 500 nm, comparable to the typical thickness of the field (standard CMOS) and/or buried oxides

(SOI) [6]. By the photoelectric effect, electron-hole pairs are generated mainly inside the buried oxide, inducing TID effects similar to those produced by protons with energies between 20 and 200 MeV [6]. The Total Ionizing Dose accumulated in the device was 100 Mrad and 3 Mrad, respectively. The irradiation process was performed without polarization of the devices due to difficulty in polarizing non-encapsulated devices. The devices were measured using a HP 4156 Semiconductor Characterization System. The devices used in this work have a channel width of 870 nm and a length of channel 150 nm, once the devices with small dimensions have shown to be virtually immune to radiation.

III. RESULTS AND ANALYSIS

Figure 1 presents the experimental drain current (I_{DS}) as a function of gate voltage (V_{GF}), for both n-channel (A) and p-channel (B) MuGFETs, before and after X-ray radiation using 15 krad/s as a dose rate, considering both strained and unstrained splits.

For the strained and unstrained nMuGFET devices it is noticed that the charges generated in the gate and buried oxide [7] cause an increase of the subthreshold slope. Positive charges in the buried oxide cause a back interface threshold voltage reduction, inducing a back-gate leakage current and consequently a subthreshold swing (SS) degradation. This effect can be observed for both strained and unstrained devices.

In pMuGFETs (figure 1B) the opposite trend is observed. The positive charges in the buried oxide also cause a back interface threshold voltage shift to more negative gate voltage, but in case of pMuGFETs it results in a reduction of the parasitic back conduction, thus improving the switching performance. The subthreshold swing reduction makes this parameter close to ideal (60mV/dec).

Figure 2 shows the transconductance curves as a function of the gate voltage for nMuGFETs (Figure 2A) and pMuGFETs (Figure 2B). From figure 2A it can be seen that the radiation causes a transconductance increase in the subthreshold region. This effect is caused by the back conduction turn-on after radiation as explained before. Considering the maximum transconductance point (gm_{max}), one can observe a reduction after radiation for both splits. As the X-ray radiation is an electromagnetic radiation, the carrier mobility is

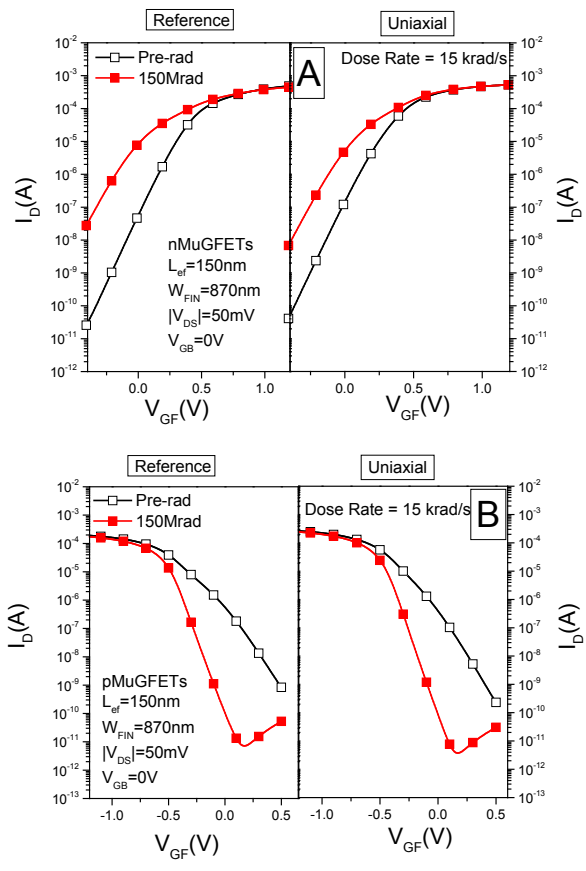

Figure 1. I_{DS} as a function of V_{GF}, for n-(A) and pMuGFETs (B), before and after radiation. (dose rate:15 krad/s)

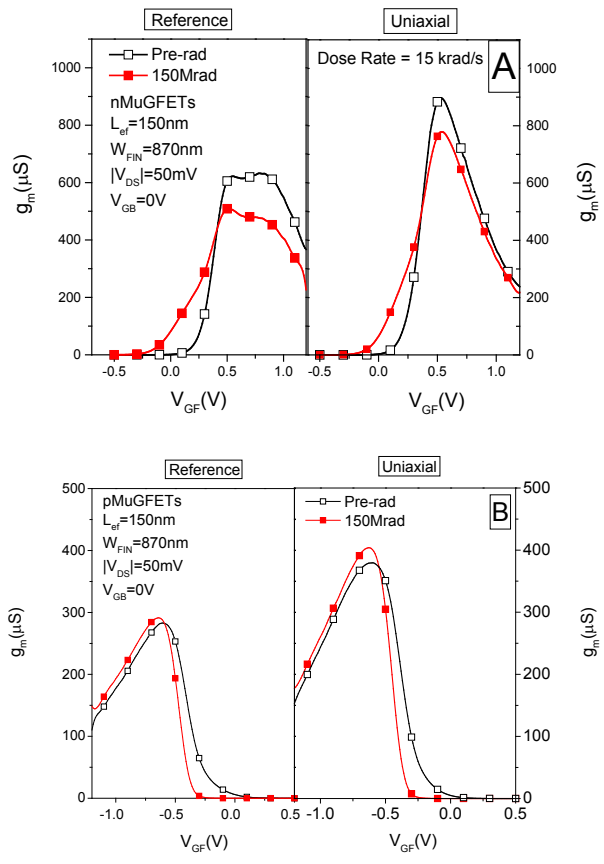

Figure 2. A) Transconductance as a function of gate voltage for nMOS transistor; B) Transconductance as a function of gate voltage for pMOS transistor.

not greatly affected. This effect is observed in radiation from heavy ions, protons and electrons. However, this reduction of gm_{max} cannot be only attributed to carrier's mobility degradation. Since the transconductance is the effectiveness of the drain current control by the gate voltage [8], when part of the drain current flows through the back interface the gm is also degraded.

Another interesting point is the plateau that appears in the gm behavior of unstrained devices. Its occurrence is caused by two different conduction channel and motilities (front and back interfaces) as observed in [9]. The presence of a plateau indicates that the back interface current occurs even before irradiation and it may start even before the front interface channel is on. The absence of the plateau in strained gm curves can be explained by the front threshold voltage reduction [10] that overrides the back one.

For pMuGFETs one can see a reduction of gm in the subthreshold region after radiation that occurs due to the positive trapped charge in the buried oxide that switches the back interface off. However, the maximum transconductance increases after X-ray radiation. This unexpected behavior can be explained by the competition between two factors: although the radiation reduces the carriers' mobility that usually degrades gm, the devices become more immune to back interface conduction, increasing the drain current control by the gate voltage and increasing gm.

As the analyzed devices present a back interface conduction even before radiation, it is no longer possible to associate the maximum transconductance value directly with the low field mobility value.

Aiming to better understand the behavior of the back leakage current, measurements of drain current as a function of gate voltage varying the back gate bias (V_{GB}) were performed (figures 3 and 5A).

The unstrained nMuGFETs were measured varying the back gate voltage from 0V to -15V, before (Fig. 3A) and after (Fig. 3B) X-ray irradiation. By reducing the back gate voltage, the back interface tends to accumulate, reducing the parasitic current at the back interface and the anomalous effect, caused by the competition between front and back conduction, cannot be observed anymore.

When the back interface tends to accumulate, the body potential is changed. When a substrate bias is applied, the current in the subthreshold region was eliminated. The negative substrate bias makes the back interface to turn off and the drain current flows only through the front interface.

Figure 4 shows the back transistor measurement while changing the V_{GB} from -2V to 16V and considering for the front gate voltage four different values 0V, -0.5V, -1V and -1.5V.

In case of even a wider fin transistor (W_{FIN}=1870nm), the worst short channel effect condition, for all analyzed V_{GF} no conduction through the front interface appears and all gm curves present just one peak and no anomalous plateau was observed before irradiation.

However, after radiation the effect of trapped charges is strong enough to produce two distinct peaks when V_{GF}=0V. These peaks show the conduction at each interface separately: the first peak is related to the

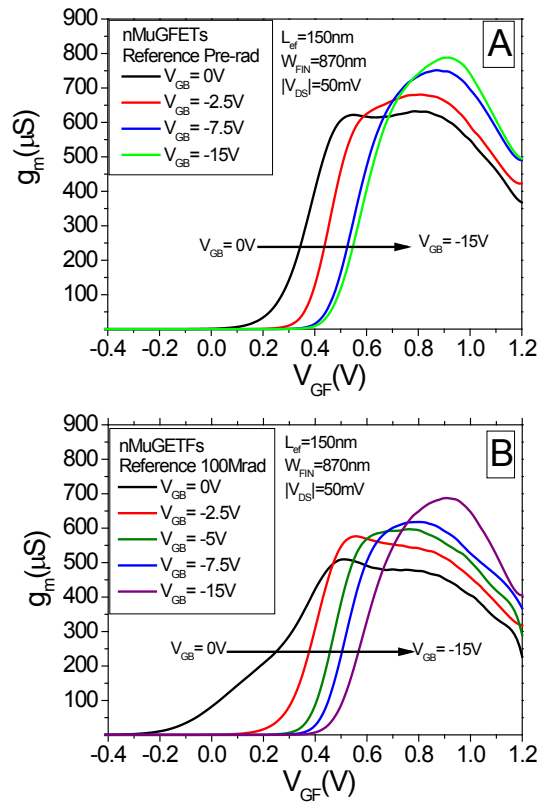

Figure 3. A) transconductance as a function of gate voltage for different V_{GB}, B) transconductance as a function of gate voltage for different V_{GB} for post radiation device.

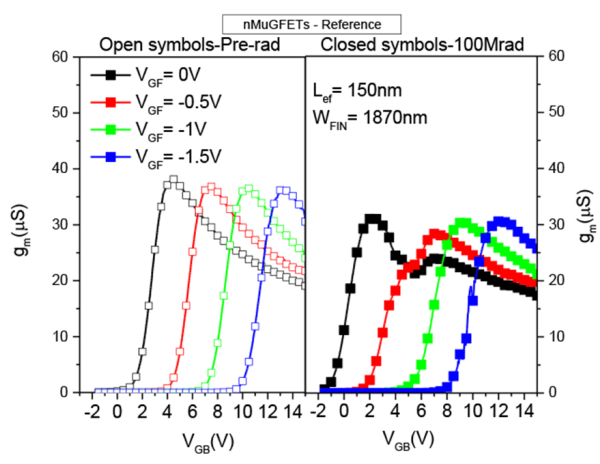

Figure 4. Transconductance as a function of back gate voltage for different V_{GF}.

back interface conduction and the second one to the front interface conduction. When V_{GF} = -0.5V, the back interface threshold voltage is shifted to higher back gate voltage due to the coupling between the front and back interfaces and as a consequence an anomalous gm behavior appears. For this gate bias, the two peaks are close to each other and it is impossible to distinguish them. Making the gate voltage even more negative, the front interface current turns off and tends to accumulate. After that, only one peak becomes visible in the transconductance curves.

The same analysis was performed for p-channel devices and is presented in figure 5. Since the radiation causes a reduction in parasitic current in pMuGFETs, the maximum transconductance tends to experience a slight increase after radiation. However, considering the results for V_{GB}=15V for which the back interface is turned off, it is possible to notice that the maximum transconductance keeps the same level before and after radiation, suggesting that the interface and oxide charge increase at the front interface is not enough to cause a significant degradation in hole mobility even for an 100 Mrad accumulated dose.

Looking at the transconductance as a function of back gate voltage for different values of front gate bias (Figure 5B), it can be seen that due to the thicker oxide, the back interface is more affected by radiation than the front one. For all V_{GF} values the gm_{max} was increased after radiation.

Figure 6A shows transconductance curves as function of front gate voltage for different substrate bias, before and after irradiation, for the strained nMuGFETs and pMuGFETs. In both devices (n and p-channel) the radiation-induced positive charges in the buried oxide shift the back interface threshold voltage towards more negative values. At V_{GF}=0V, for nMuGFETs the transconductance in the subthreshold region increases because the back leakage current was increased and for pMuGFETs it reduces as the back conduction turns off, as presented before (Fig. 2). However, varying the back gate bias (turning the devices to accumulation), for nMuGFETs, it is possible to observe a gm_{max}

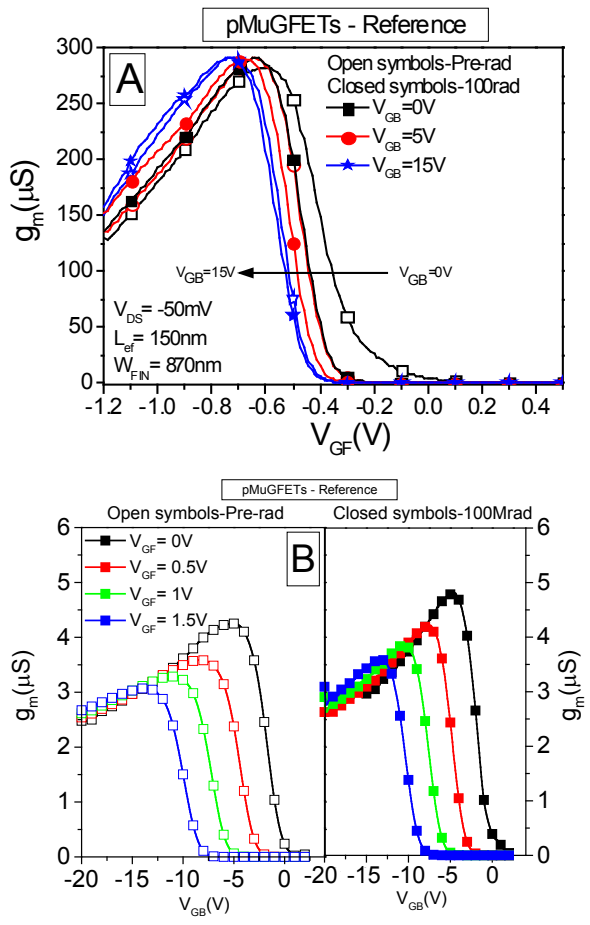

Figure 5. A) Transconductance as a function of front gate voltage for different V_{GB} for pre and post-irradiated devices; B) Transconductance as a function of back gate voltage for different V_{GF}.

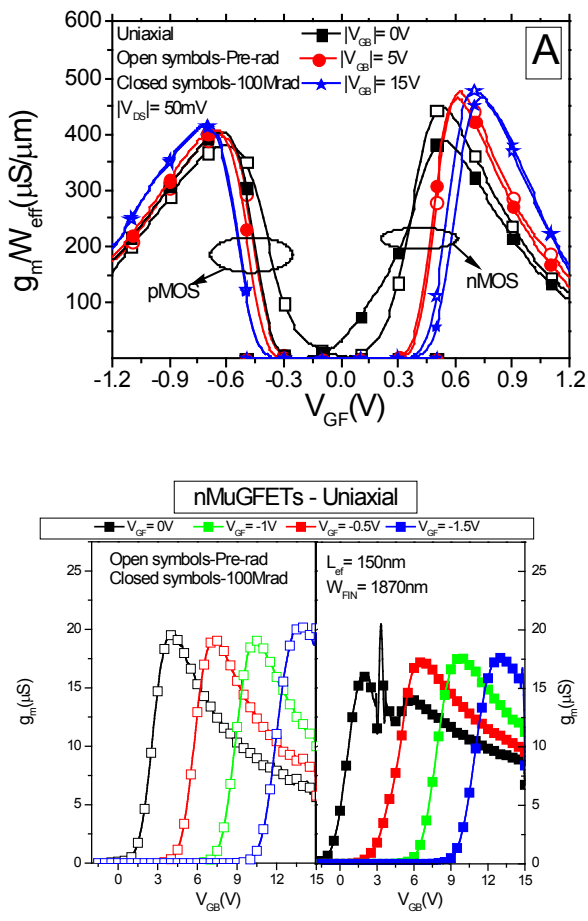

Figure 6. A) Transconductance as a function of front gate voltage for different V_{GB} before and after irradiation for n and p devices, B) Transconductance as a function of back-gate voltage for different V_{GF} .

reduction caused by the electron mobility degradation, while for p-channel devices, the front interface mobility seems to be not affected for this dose as also observed for the reference split.

When the transconductance as function of the back gate voltage for different V_{GF} values for uniaxial strained nMuGFETs was analyzed (Figure 6B), the same n-channel behavior as for the reference devices was obtained.

In order to analyze the devices response to different radiation dose rates, another set of devices was submitted to radiation using 300 rad/s as a dose rate. The maximum accumulated dose was 3 Mrad.

Figure 7 shows the drain current as function of the front gate voltage for strained and unstrained nMuGFET (A) and pMuGFET (B) devices. In Figure 7Aone can observe that for both applied dose rates the results are similar, even for very different TIDs. While for X-ray radiation using a dose rate of 15 krad/s the total ionization dose was 100 Mrad, reducing the dose rate to 300 rad/s (50 times) only 3 Mrad was enough to induce the same effect on the device behavior. It occurs because when the dose rate decreases, the exposure time becomes larger than for higher rates, increasing the amount of generated charges.

For pMuGFET devices (Figure 7B), considering X-ray radiation with a dose of 3 Mrad, it is also possible to see that the subthreshold region characteristics have been improved, even with a lower radiation dose, due to its higher charge trapping.

The values of the subthreshold swing are shown in Table I. For nMuGFETs devices, the subthreshold swing was increases because after X-Ray radiation these devices have increased the back interface current. For pMuGFETs devices, the subthreshold swing was decreases, duo to the reduction of the back interface current.

The same analysis was performed for the transconductance curve for n (Figure 8A) and p-channel (Figure 8B) devices. With a dose rate of 300 rad/s the same effect can be observed for both devices (n and p-channel). In nMuGFETs, the charges generated in the buried oxide increase the back parasitic current, degrad-

Table I. Value of subthreshold swing for devices.

TID	SS (mV/dec)			
	nMuGFETs		pMuGFETs	
	Pre	Post	Pre	Post
100Mrad	122	131	164	94
3Mrad	120	165	163	94

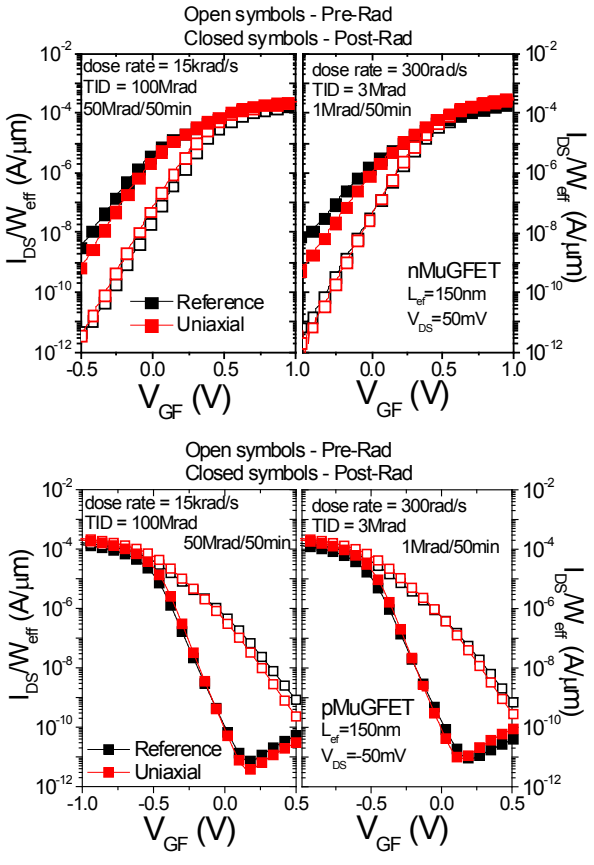

Figure 7. I_{DS} as a function of V_{GF}, for n-(A) and pMuGFETs (B), before and after radiation (dose rate: 300 rad/s).

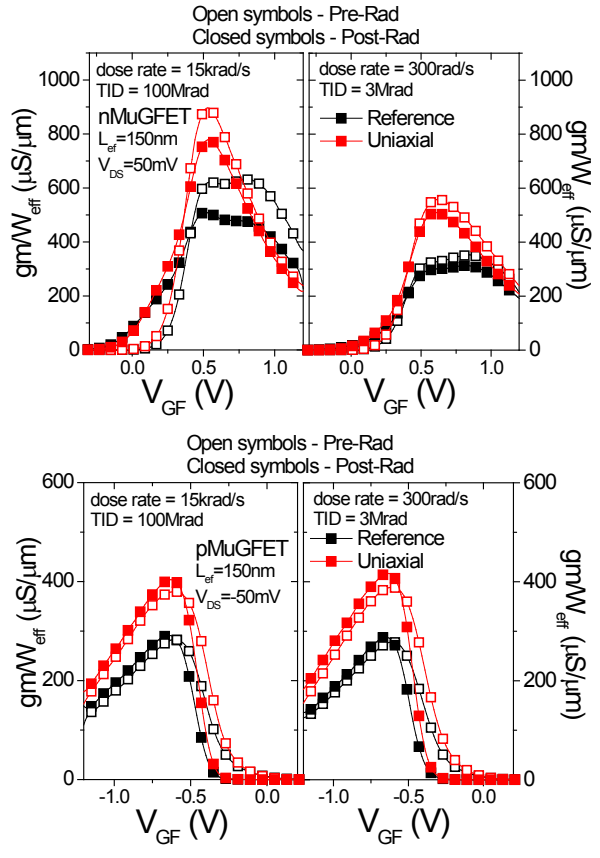

Figure 8. A) Transconductance as a function of front gate voltage for nMuGFETs (A) and pMuGFET (B) for 300 rad/s and 15 krad/s dose rate.

ing the transconductance characteristics. In pMuGETs, radiation has only a strong influence on the back interface conduction, reducing it by the positive charges created when submitted to radiation.

Comparing the two dose rates it was possible to observe the same effects as for 15 krad/s, but with a lower radiation dose. This is probably due to the exposure time, since when the devices spend more time under irradiation the probability to trap charges is increased.

IV. CONCLUSIONS

This paper presented the influence of X-ray exposure on the parasitic conduction in standard and uniaxially strained triple gate nMuGFETs and pMuGFETs for two different dose rates.

Irraadiation increases the parasitic current through the back interface significantly in nMuGFET devices, causing a degradation in performance.

In pMuGFETs, radiation causes a reduction of the parasitic current, improving its performance due to the creation of positive charges in the buried oxide, which turns off the parasite back conduction.

Comparing the two sets of radiation conditions, it was possible to note that for longer periods of exposure to radiation, greater variations in the device parameters occur. When using a lower dose rate, similar variations previously reported for 150 Mrad were observed, but using a total cumulative dose of only 3 Mrad.

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