The influence of the proton irradiation on nFinFET inverter.

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***Abstract*—In this work, the influence of proton irradiation on main basic parameters of FinFET transistors were analyzed. This evaluation was performed focusing on the subthreshold swing, threshold voltage and transconductance behavior considering two different fin widths. Studying as well the effects of these changes in a nMOS inverter designed with FinFETs.**

***Keywords*—FinFET, nMOS inverter, proton irradiation**

I. INTRODUCTION

With the constant evolution of transistors, the need to use increasingly smaller devices is a necessity to have a more significant performance increase in the same silicon area. For a very small scale (<= 32 nm) the planar transistors were no longer a good alternative and therefore, the traditional 2D transistors began to be replaced by multiple gate vertical transistors [1]. Currently the FinFET is widely used, several companies such as Intel use this technology to produce their latest nodes processors [2,3].

The multiple gate structure combined with a SOI substrate presents a very good performance when operating at harsh environments. Nevertheless, SOI technology is well known for its high immunity to the transient effects of radiation, it is also known that the presence of buried oxide can impair the device's behavior when considering the total ionization dose effects [4,5].

In this work, the impact of total ionization dose (TID) of proton irradiation on the basic parameters of triple gate SOI FinFETs is studied and its application in the simplest digital circuit (nMOS inverter) is evaluated.

II. DEVICES CHARACTERISTICS

The studied FinFETs were fabricated at Imec on SOI substrates with a 150-nm-thick buried oxide. The gate oxide is composed by 1nm of interfacial SiO_2 and 2nm of HfSiON on top and it is covered by 10 nm of TiN followed by 100 nm of poly-silicon. The measured device has the following characteristics: channel length of 150 nm, fin height (H_{fin}) of 65 nm and three different fin widths (W_{fin}) were studied (20 nm, 120 nm and 870 nm). A selective epitaxial growth (SEG) process was used to elevate source and drain (S/D) regions, in order to reduce parasitic series resistance.

Since the FinFET is a triple gate device, the effective channel width is calculated by equation (1):

$$W_{ef} = W_{fin} + 2 * H_{fin}$$

Figure 1 shows a schematic view of FinFET transistor.

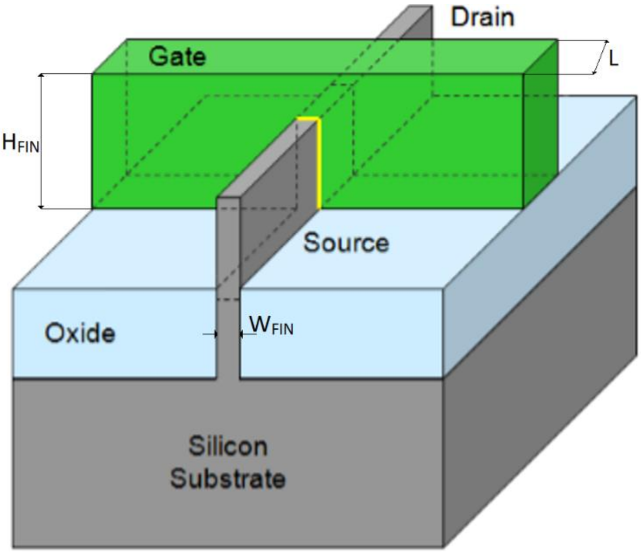

Fig. 1. Schematic of a FinFET transistor

Proton irradiation was performed at the Cyclone facility in Louvain-la-Neuve (Belgium) with 60-MeV and a fluence of 10^{12} p/cm^2, at room temperature. The devices were irradiated without biasing.

The measurements were performed at wafer level using the the Semiconductor Device Analyzer (B1500A) from Keysight at USP through an agreement between USP and UNESP universities. The analyzed wafers were irradiated in 2010, that means only the permanent effects will be investigated.

After the analysis of the radiation influence on DC basic parameters, some simulations, using Atlas simulator, were performed in order to study how the radiation affects the nFinFET inverter. The simulations were calibrated with experimental measurements.

III. RESULTS AND DISCUSSIONS

Before starting to analyze the results, it is important to keep in mind that the ionizing radiation occurs when an energy particle incident on the device can ionize atoms, i.e., remove one electron from an atom. When this happens in semiconductors devices like the SOI FinFET, the energy particle leaves a trail of electrons/holes in its path [6]. This phenomenon results mainly [7] in TID (Total Ionizing Dose) effects, that in turns cause a charge trapping in oxides and the increase of interface state density. These two characteristics were implemented in the simulation in order to consider the radiation effects as occurs in experimental devices.

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Another important note is the relation between fin width (W_{fin}) and effective channel width (W_{ef}). Considering that the fin height is 65nm, the studied effective channel widths are:

Wfin = 20 nm → Wef = 150 nm

Wfin = 120 nm → Wef = 250 nm

Wfin = 870 nm → Wef = 1000 nm

Although FinFETs usually have narrow Wfin in order to improve the electrostatic coupling between gates, aiming to evaluate the radiation effects on FinFETs in this work large Wfins were also considered.

A. *Radiation impact on basic parameters*

Figure 2 shows the experimental drain current (A) and transconductance (B) curves as a function of gate voltage for nFinFETs with two different fin widths before and after proton irradiation.

The transistor with smaller W_{FIN} (20 nm) was not showed in the figure 2, because it is almost immune to the effects of the ionizing radiation (TID effects) due to the strong electrostatic coupling between the gate and channel. So, no variation in electrical parameters is expected.

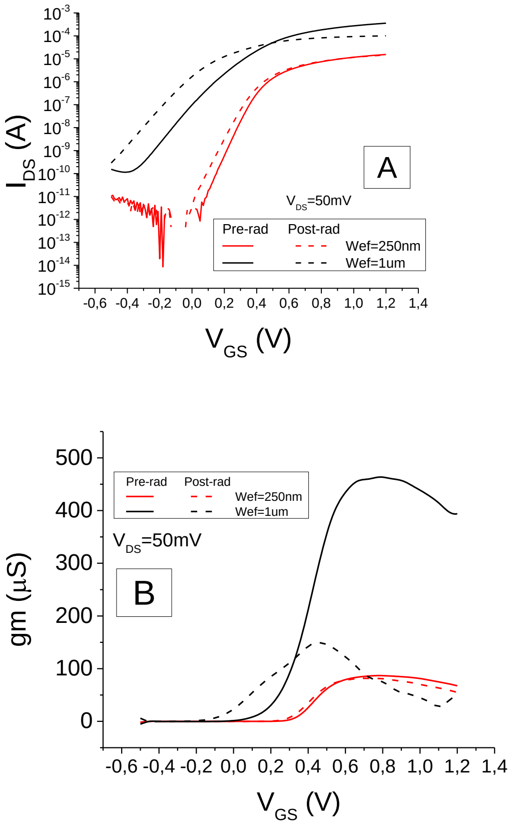

Fig. 2. Experimental drain current (A) and transconductance (B) for N-type FinFETs with two different channel widths before and after radiation.

From figure 2 it's possible to see that the FinFETS starts the conduction with a lower gate voltage after radiation, i.e. V_T reduces, mainly because of the trapped charges in the oxide that reduces the voltage needed to start the conduction. Besides that, when the subthreshold region is analyzed, it can be observed a degradation in the subthreshold swing (SS) that is caused by the traps at interface between the gate oxide and silicon layer, that in turns generates a parasitic capacitance.

Analyzing the g_m X V_{GS} curves it is noticed that after the radiation g_{mMAX} reduces because the proton radiation damages the silicon lattice, reducing the carriers mobility causing the reduction of the maximum transconductance [7]. Besides the carrier mobility degradation, the strong reduction of g_m observed for the widest device is caused by the strong influence of the second interface leakage current that means the loss of control on the charges into the channel.

Table 1 presents the extracted values of the subthreshold Swing (SS), Threshold Voltage (V_T) and maximum transconductance (g_{mMAX}) of the FinFETs before and after the radiation.

To extract V_T, the method of the second derivative of the curve I_{DS}/V_{GS} was used, which was obtained experimentally [8].

TABLE I. ELETRIC PARAMATERS OF N-TYPE FINFETS

W_{ef} (µm)	*SS* [mV/dec]	V_T [V]	g_{mMAX} [µS]
1 (pre-rad)	115.8	0.42	463.5
1 (post-rad)	126.8	0.35	149.3
0,25 (pre-rad)	65	0.43	21.9
0,25 (post-rad)	77	0.41	20.7

In Table I is possible to see how the radiation affects the wide FinFETs. The threshold voltage shift is much smaller for FinFET with W_{fin}=120 nm due to the better electric coupling between lateral gates than for FinFET with W_{FIN}=870 nm. This gate coupling avoid that the accumulated charges, at the interface and oxide, interfere on the transistor behavior.

Besides the V_T shift, it is also possible to observe a strong degradation of SS and g_{mMAX} values when wide devices are submitted to the radiation. Although the g_{mMAX} is affected by two different factors (the mobility degradation and the loss of gate control over the total drain current), the changes in SS and g_{mMAX} for wide transistor are mainly caused by the second interface leakage current that is worsened after proton radiation.

For the P-type transistor with the same dimensions, the same measurements were performed resulting in the following results shown in Figure 3.

It's noticed that the *SS* after the radiation in PMOS FinFET was improved. This occurred because with larger devices, the electrostatic coupling is weak and it causes a current flowing through the second interface of the FinFET. The radiation causes a shift in the threshold voltage in the negative gate voltage direction. It occurs for both first and second interfaces, however, as the buried oxide is thicker than the gate one, the variation of V_T of second interface is more pronounced and it turns off the leakage current and improves the I_{DS} characteristic.

The transconductance is also affected and although the mobility is slightly degraded, the g_{mMAX} raises after the radiation, because of the better second interface behavior (turns off the leakage current) that results in a better control of the charges of the channel.

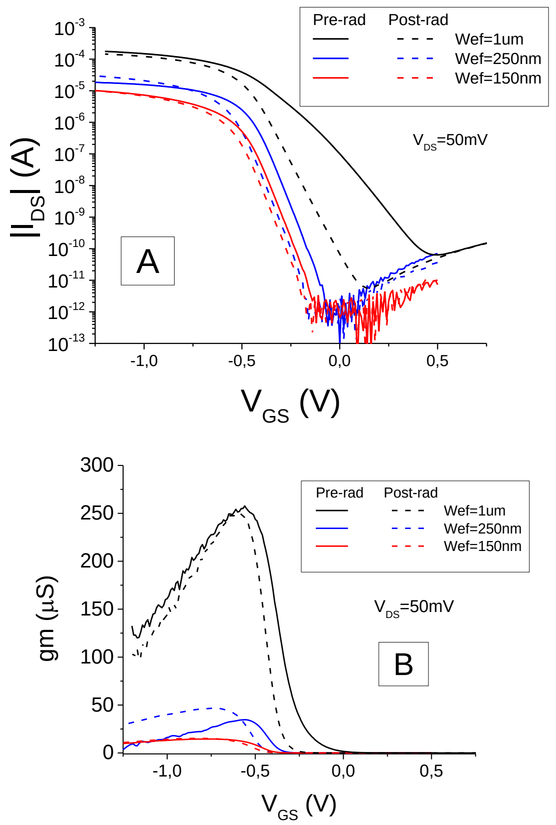

Fig. 3. Drain current – I_{DS} (A) and transconductance - g_m (B) as a function of the gate voltage for P-type transistors with two different channel widths before and after radiation.

Table II presents the results of the electrical parameters of the P-type FinFET for W_{FIN} 870 nm, 120 nm and 20 nm.

TABLE II. ELETRIC PARAMATERS OF P-TYPE FINFETS

Wef (µm)	*SS* [mV/déc]	V_T [V]	g_{mMAX} [µS]
1 (pre-rad)	131	-0.38	257
1 (post-rad)	92	-0.44	251
0,25 (pre-rad)	66	-0.43	34.6
0,25 (post-rad)	62	-0.52	46.7
0,15 (pre-rad)	64	-0.46	14.5
0,15 (post-rad)	62	-0.51	15.2

Comparing tables 1 and 2, for P-type transistor, the threshold voltage decreases (becomes more negative) more than for N-type transistor. The possible explanation for that is for pFinFETs the two types of trapped charges, N_{IT} and N_{OT}, contribute to the V_T decrease, while for N-type transistor N_{IT} tends to increase V_T and N_{OT} takes V_T in the opposite direction.

Analyzing the experimental SS values its possible to see an improvement of these characteristics after the radiation. Although the radiation induces the N_{IT} increase, with tends to degrade the SS behavior, the positive trapped charges in the buried oxide reduces the threshold voltage of the second interface and consequently turning off the second interface leakage current, that in turns, causes a SS improvement.

Focusing on maximum transconductance we have a competition between two factors: the carrier mobility degradation and the better control of the channel charges caused by second interface turn off.

B. *NMOS Inverter*

Knowing the FinFET transistor behavior when it is submitted to radiation, the NMOS inverter designed with FinFET was simulated using Atlas simulator from Silvaco.

For the narrowest device (W_{fin}=20 nm), in figure 4, it is shown that the radiation almost did not affect the transfer characteristic of nMOS inverter (very small shift in V_{INV}). The strong coupling between lateral gates of the FinFET suppress the effects of the trapped charges in the interface and oxide, better controlling the charges into the channel, which means that the proximity of the lateral gates shields the device against the radiation effects, as can be seen in figure 4.

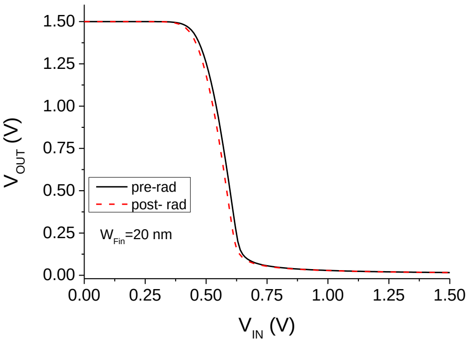

Fig. 4. NMOS Inverter for W_{FIN} = 20 nm (W_{ef}=150 nm)

In figures 5 and 6 the results of an NMOS inverter before and after the radiation of W_{FIN} 120 nm and 870 nm are presented, respectively.

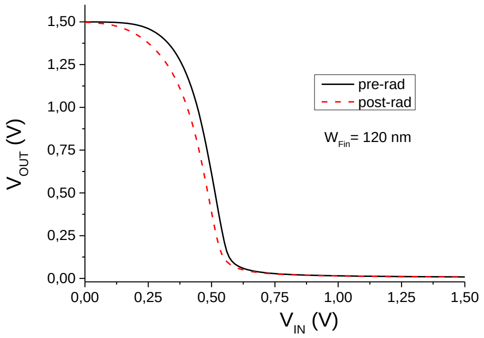

Fig. 5. NMOS Inverter for W_{FIN} = 120 nm

In Fig. 5 its visible that after the radiation the inversion voltage occurs early (for smaller input voltage) due to the threshold voltage reduction.

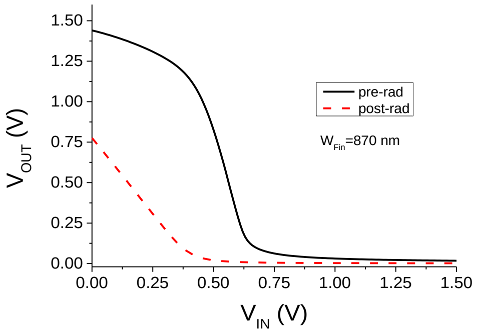

Fig. 6. NMOS Inverter for W_{FIN} = 870 nm

In Fig. 6 we can clearly to see that even before the radiation the transfer curves are already degraded due to the leakage current that flows at second interface and prevent that the out voltage reaches the supply voltage (V_{DD}) value. After the radiation the inverter designed with the wider FinFET is not usable anymore, because the circuit lost its switching properties after proton irradiation. Since the trapped charges into the buried oxide reduce the second interface threshold voltage, increasing the second interface leakage current, the switch property is lost.

IV. CONCLUSIONS

Studying the effects of geometry and the radiation impact on FinFET behavior, it was possible to explain the response in basic logic circuits. The analyzed device's parameters were SS, V_T and g_{mMAX}.

The SS is affected by the interface traps that generates a parasitic capacitance and difficults the switching of the device. The transconductance of the transistor is affected by the degradation of the mobility caused by the damage suffered by the silicon structure and for the loss of control of the channel charges. While the V_T is affected mainly due to the trapped charges in the oxide. However, a special attention should be given to the interface traps which tends to shift V_T in opposite directions depending on the type of transistor.

Analyzing the results, it is notable that the FinFET is almost immune to radiation effects when a narrow device is considered due to the strong electrostatic coupling between the side walls. Its seen that the FinFET with 20 nm shows the best results, and it is basically immune to total ionization dose effects, while larger devices are susceptible to these effects.

The results of the NMOS FinFET was very realistic since the simulations are calibrated with experimental results and it shows that the narrow FinFET works very well even on radiated environments. However, for wide FinFETs, or quasi-planar FinFETs, the response of the inverter was not suitable even before of the radiation, mainly caused by the interference of the second interface leakage current.

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REFERENCES

[1] KATARIA, S.; BENIWAL, P. FinFET Technology: A Review Paper. IJTR, Vol. 5, Issue 2, Pág 35-36, July-Aug 2016.

[2] BOHR, M.; MISTRY, K. Intel's Revolutionary 22 nm Transistor Technology. May, 2011.

[3] Tsmc.com. 2020. TSMC 2019 Annual Report. [online] Available at: <https://www.tsmc.com/download/ir/annualReports/2019/english/ebook/index.html> [Accessed 20 July 2020].

[4] COLINGE, Jean-pierre. FinFETs and Other Multi-Gate Transistors. Cork, Ireland: Springer, 2008. 350 p.

[5] COLINGE, Jean-pierre. SILICON-ON-INSULATOR TECHNOLOGY: MATERIALS TO VLSI. 3. ed. California: Springer, 2004. 374 p.

[6] SCHWANK, James R. et al. Radiation Effects in MOS Oxides. Ieee Transactions On Nuclear Science, [s.l.], v. 55, n. 4, p.1833-1853, ago. 2008. Institute of Electrical and Electronics Engineers (IEEE). http://dx.doi.org/10.1109/tns.2008.2001040.

[7] AGOPIAN, Paula G. D. et al. Influence of 60-MeV Proton-Irradiation on Standard and Strained n- and p-Channel MuGFETs. Ieee Transactions On Nuclear Science, [s.l.], v. 59, n. 4, p.707-713, ago. 2012. Institute of Electrical and Electronics Engineers (IEEE). http://dx.doi.org/10.1109/tns.2012.2187070..

[8] MARTINO, J. A.; PAVANELLO, M. A.; VERDONCK, P. B.. Caracterização elétrica de tecnologia e dispositivos MOS. Sao Paulo: Thomson Learning, 2003.