Comparison of radiation degradation induced by x-ray and 3-MeV protons in 65-nm CMOS transistors

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The total ionizing dose (TID) response of 65-nm CMOS transistors is studied by 10-keV x-ray and 3-MeV protons up to 1 Grad (SiO_2) total dose. The degradation levels induced by the two radiation sources are different to some extent. The main reason is the interface dose enhancement due to the thin gate oxide and the low energy photons. The holes' recombination also contributes to the difference. Compared to these two mechanisms, the influence of the dose rate is negligible.

Keywords: total ionizing dose (TID) effects, grad dose, x-ray and protons, 65-nm CMOS transistors

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1. Introduction

For the electronics implemented in space or other radiation-related applications, it is mandatory for irradiation experiments to be performed under laboratory environments, such as Co-60 γ ray, 10-keV x-ray, low energy protons, low energy electrons, etc. One problem is that even with exposure to the same dose levels, the radiation damage in electronics induced by different radiation sources can be different to a great extent. The corresponding difference in CMOS technologies has been studied since the early 90 s.[1,2] The physical mechanisms were attributed to different fractional yields of the holes escaping the initial recombination,[1,3] different interface dose enhancement factors,[4] different track sizes,[5] different dose rates,[6] or not fully understood.[7]

One thing worth noting is that these studies correspond to thick gate oxide (>30 nm), where the physical processes of total ionizing dose (TID) can be divided into several independent processes, including the generation of electron/hole pairs, the transport of holes towards the Si/SiO_2 interface, the trapping of holes near the interface, and the accumulation of interface traps. Along with the scaling of CMOS technology, the charge trapping efficiency drops rapidly as the gate oxide is thinned to 5 nm and beyond, and these processes begin to interfere with each other. For state-of-the-art electronics, although there are some studies focusing on the radiation damage induced by different radiation sources, the research objects are mainly non-volatile memories or analog electronics.[8–10] Few studies have been done on state-of-the-art CMOS technologies.

For common space applications, the TID requirements for electronics are covered by several hundreds of kilorads. However, for the new Jovian missions, the hardening level of several megarads are mandatory to ensure the safe operation of the electronic systems. Besides the space applications, for the electronics implemented in the high-energy physics (HEP) environments, like in the LHC after upgrade (Super-LHC, SLHC), the target of radiation hardness has increased up to 1 Grad (SiO_2), which is the estimated deposited dose in 10 years of use.[11,12] In this work, we focus on the degradation of 65-nm CMOS technology irradiated up to 1 Grad (SiO_2) by 10-keV x-ray and 3-MeV protons. We aim to compare the dependence on radiation sources, concerning the vulnerability evaluation of a strong candidate for the LHC upgrade. The devices under investigation include thin-oxide core transistors (2.5 nm) and thick-oxide I/O transistors (5 nm), which help us explore the difference due to the technology scaling at the same time.

2. Experimental details

2.1. Test structures

The devices used in this study were bulk MOSFETs designed by CERN and fabricated in a commercially available 65-nm CMOS technology. For the I/O nMOS and pMOS transistors, the gate oxide is about 5 nm thick and the supply voltage is 2.5 V. For the core transistors, the gate oxide is about 2.5 nm thick and the supply voltage is 1.2 V. All the transistors feature the conventional open layout design.

2.2. Irradiation setup

After the wire bonding at INFN, Padova, we irradiated the transistors at room temperature using two radiation sources

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at the INFN-Laboratori Nazionali di Legnaro, Padova. The first one is 10-keV x-ray source with a dose rate of 1 krad·s^{-1} (SiO_2). Here we need almost 2 weeks to reach a 1 Grad (SiO_2) cumulative dose. The dose rate was measured by a square silicon diode calibrated in accordance to the ASTM recommendations, with an active area of $A = 5 \times 5$ mm^2 and thickness $d = 300$ μm, positioned on the chuck of a commercial semi-automatic probe station under the x-ray tube. During the x-ray dose rate measurements, the diode was reverse biased at full depletion and the active area was grounded, and the guard-ring contact was used to prevent border effects on the radiation-induced transient current.

The other one is the proton beam with a kinetic energy of 3 MeV and a maximum proton current of 1 μA. Before irradiation, the beam uniformity was checked by a Gafchromic radiology film which was exposed to the beam for a few seconds. Then the beam was carefully aligned to make sure that the sample could be placed in the uniform beam region. The beam intensity was measured with a Faraday cup before and after each exposure. During irradiation, the relative fluence was continuously monitored and adjusted by the current on the sample. A flux of 4×10^{10} p/(cm^2·s) was used up to 7×10^{13} p/cm^2. Here the dose rate was about 54 krad·s^{-1} (SiO_2). Then a higher flux of 4×10^{11} p/(cm^2·s) was used till 7×10^{14} p/cm^2 (950 Mrad (SiO_2)). Here the dose rate was about 540 krad·s^{-1} (SiO_2).

During irradiation, devices were de-lidded to make sure that the photons and protons can enter into the oxide region. The terminals of gate, drain, source, and n-well were connected together for pMOSFETs, whereas the gate contact was biased at the supply voltage for nMOSFETs, taking it as the "worst case" described in Ref. [13]. The irradiation was periodically interrupted to measure the transfer and output characteristics by using an HP4156 parameter analyzer.

3. Results and discussion

To quantitatively compare the radiation damage induced by the two radiation sources, statistics of the parameters were analyzed first. Figure 1 shows the variations of threshold voltage (V_{th}) and driving current (I_{ON}) of six groups of fresh core nMOS transistors. There are five transistors in each group, with the gate length (L) of 60 nm and the gate width (W) ranging from 120 nm to 600 nm. The average values and the standard deviations are also presented. From Fig. 1, the standard deviation of V_{th} was estimated to be 28 mV for 120/60 nm nMOSFETs, which is the largest variation among these five geometries and still within 5% of the average value. For the parameter I_{ON}, the ratios of average values to standard deviations are smaller than 6% for fresh core nMOSFETs with all the geometries. Figure 1 only shows the variations of fresh core nMOSFETs, and it is worth noting that this is also true for all other transistors, including core pMOS transistors, I/O nMOS and pMOS transistors: the standard deviation of V_{th} is smaller than 28 mV and the ratio of average value to standard deviation of I_{ON} is within 6%.

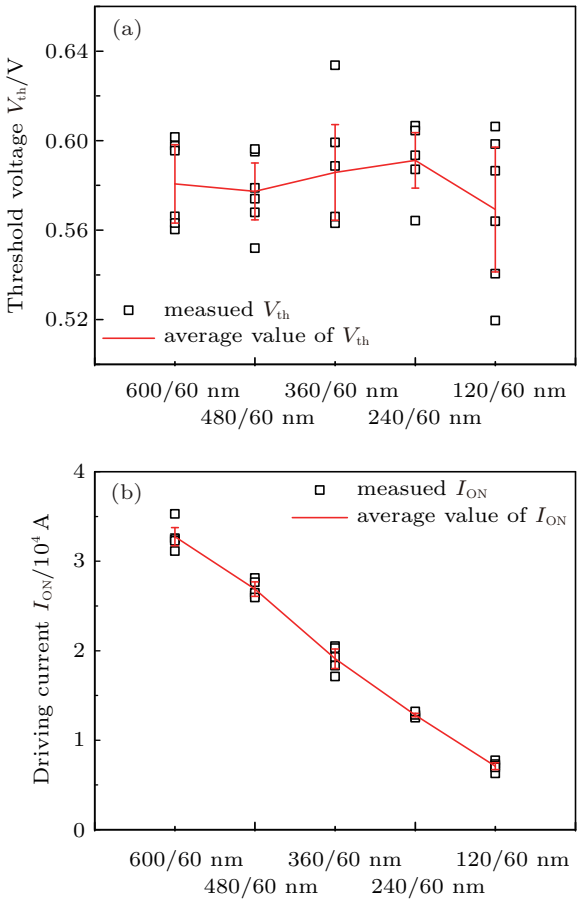


Fig. 1. (color online) (a) Variation of threshold voltage V_{th} at $V_{ds} = 0.1$ V for fresh nMOS core transistors featuring different geometries; (b) corresponding variation of driving current I_{ON} at $V_{gs} = V_{ds} = 1.2$ V.

Figure 2 shows the I_{ds}–V_{gs} curves of a 120/60 nm core nMOSFET before and after irradiation with the two radiation sources. The radiation degradation under both environments can be summarized as: i) the increase in drain leakage during the whole procedure from around 2 pA to around 20 pA, is visible but very limited compared to the 3 decades increase to almost 300 nA in the 130-nm nMOSFETs,[13] suggesting that the charge trapping in the STI oxide was modest; ii) V_{th} first decreases, and then increases; iii) I_{ON} first increases, and then decreases. For the 650-nm transistors in this study, the drain leakage increases towards one direction, so the charge trapping in the STI was unable to explain the shifts in the sub-threshold region, the charge trapping in the gate oxide contributed more evidently to the radiation-induced degradation.

Consistent phenomena were also observed for core nMOSFETs featuring other geometries. Although the trends of the degradations were similar, from Fig. 2, the degradation

levels in the drain leakage, V_{th} and I_{ON}, induced by the two sources were obviously different. A higher sensitivity could be observed under x-ray environment.

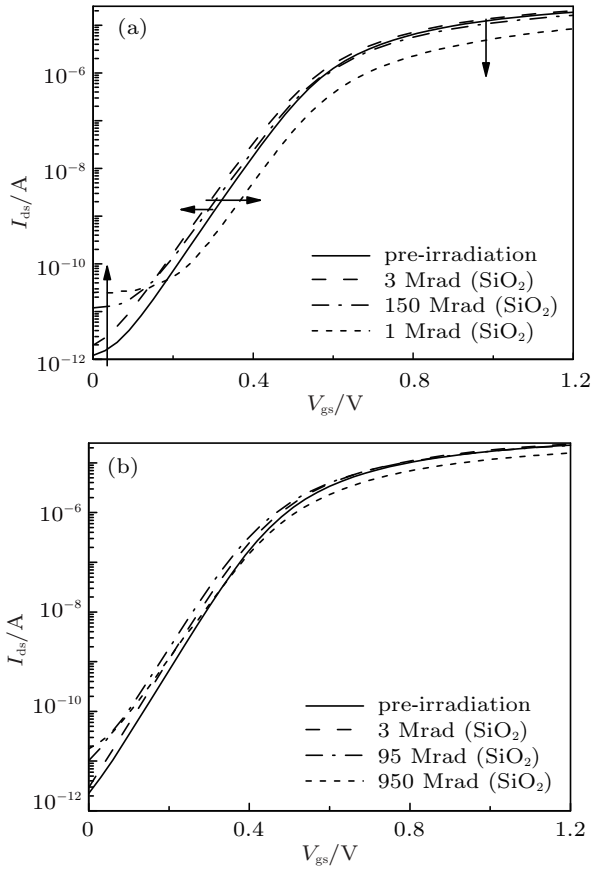


Fig. 2. (color online) (a) I_{ds}–V_{gs} curves of a 120/60 nm core nMOSFET before and after x-ray irradiation till 1 Grad (SiO_2) total dose, $V_{ds} = 0.1$ V; (b) similar evolution of I_{ds}–V_{gs} curves of a 120/60 nm core nMOSFET before and after proton irradiation.

To quantitatively compare the difference in radiation degradation induced by the two sources, figure 3 shows the comparison of the threshold voltage shift ΔV_{th} and the driving current degradation $\Delta I_{ON}/I_{ON,pre}$. From Fig. 3(a), the negative ΔV_{th} at the first stage of irradiation suggests a quick buildup of the oxide-trapped charge, and the value is small but visible. Then due to the competition with the slower buildup of the interface traps, ΔV_{th} started to increase and even turned to large positive values when irradiated with x-ray to Grad dose. Along with the evolution of V_{th}, I_{ON} changed correspondingly. From Fig. 3(b), I_{ON} lost 18% of the initial value under 1 Grad proton irradiation, whereas a loss of 38% was observed under 1 Grad x-ray irradiation.

Figure 4 shows the corresponding results of I/O nMOS transistors. For these transistors with thicker gate oxide (5 nm), radiation-induced ΔV_{th} and $\Delta I_{ON}/I_{ON,pre}$ were clearly much larger compared with the results of core nMOSFETs reported in Fig. 3, which was consistent with a stronger charge trapping in gate oxide, especially the buildup of the negative interface traps. Meanwhile, stronger degradation was induced by x-ray at lower than about 500 Mrad (SiO_2) total dose. Then at higher doses, it seems that proton-induced ΔV_{th} and $\Delta I_{ON}/I_{ON,pre}$ exceed the degradation induced by x-ray. However, after taking into account the statistical errors (standard deviation of 28 mV for ΔV_{th} and 6% for $\Delta I_{ON}/I_{ON,pre}$), the differences can be ignored and the degradations induced by the two sources were almost the same at 1 Grad.

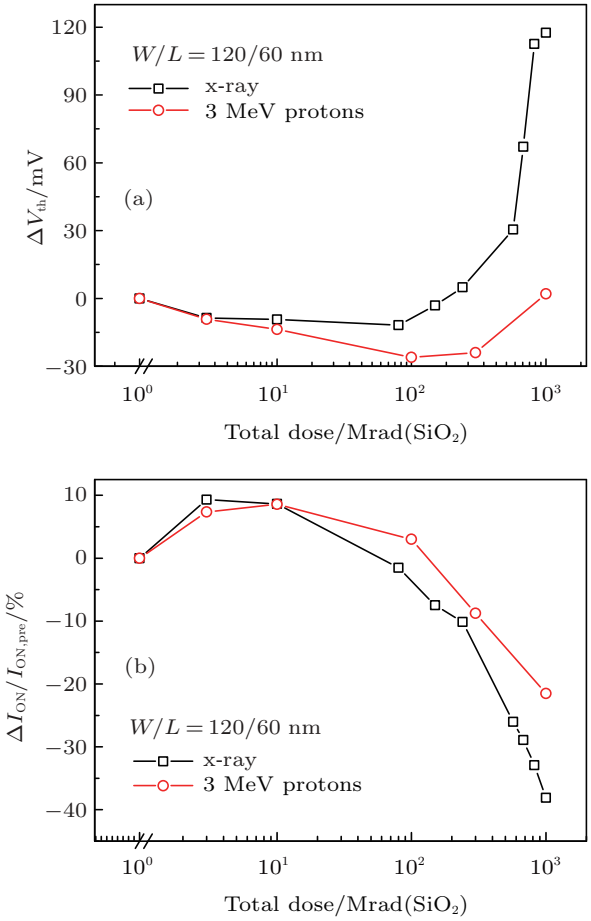


Fig. 3. (color online) (a) Comparison of threshold voltage shift (ΔV_{th}) of the 120/60 nm core nMOSFET induced by x-ray and protons, as a function of total dose; b): comparison of driving current degradation ($\Delta I_{ON}/I_{ON,pre}$) induced by the two sources.

To understand the origins of the degradation difference above, the differences from the two irradiation setups have to be considered. The factors possibly responsible for the degradation difference could be the interface dose enhancement, the fractional yield of holes, and the dose rate, which will be analyzed one by one.

Firstly, the interface dose enhancement effect is particular for low-energy source. From Fig. 5, when the gate oxide is thick enough, it is reasonable to ignore the dose enhancement effect. However, with a very thin gate oxide, the real dose deposited in the SiO_2 region can be much higher than the theoretical value. Some studies have already reported evident interface dose enhancement effect induced by x-ray.[9,14]

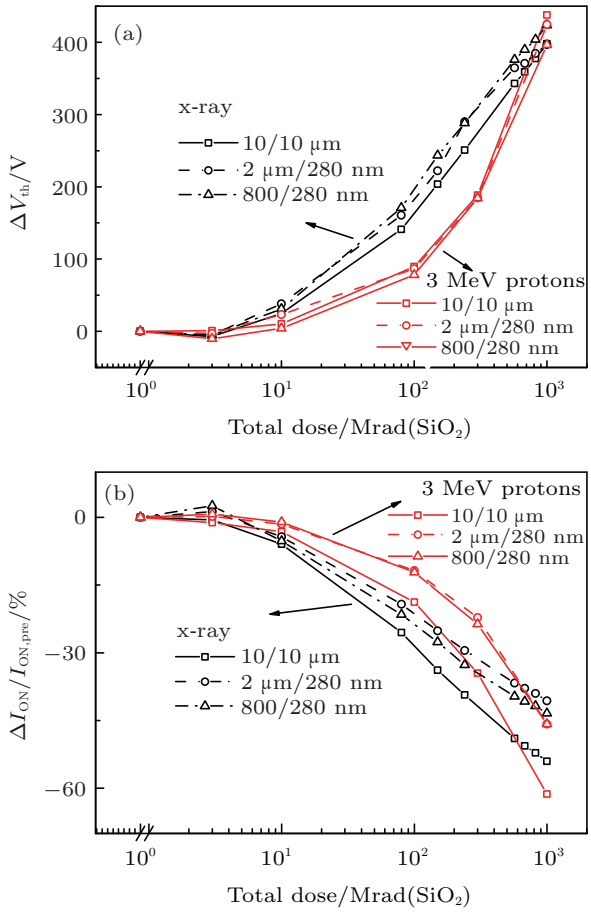


Fig. 4. (color online) (a) Comparison of $\Delta V_{\rm th}$ of three I/O nMOSFETs induced by x-ray and protons, as a function of total dose; (b) comparison of $\Delta I_{\rm ON}/I_{\rm ON,pre}$ induced by the two sources.

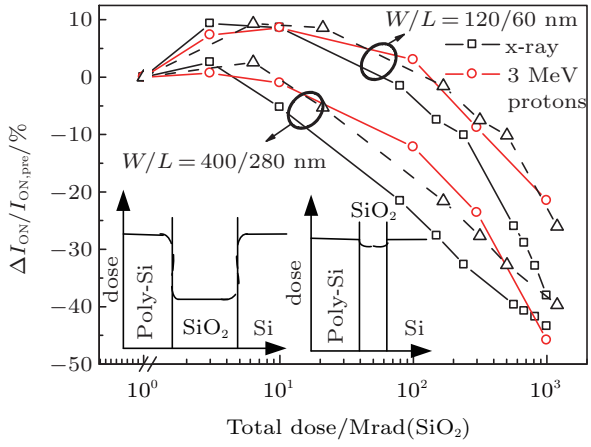


Fig. 5. (color online) Comparison of the proton-induced $\Delta I_{\rm ON}/I_{\rm ON,pre}$ values and the modified x-ray-induced $\Delta I_{\rm ON}/I_{\rm ON,pre}$ curves for the 120/60 nm core nMOSFET and the 400/280 I/O nMOSFET.

Assuming that the degradation difference was only due to the interface dose enhancement effect, figure 5 shows two series of curves from the $\Delta I_{\rm ON}/I_{\rm ON,pre}$ degradation: the first set (solid curves) are taken from Figs. 3(b) and 4(b), containing the degradation of the 120/60 nm core and 400/280 I/O nMOSFETs induced by the two radiation sources; the second set (dashed curves) contains the modified curves from the x-ray-induced $\Delta I_{\rm ON}/I_{\rm ON,pre}$ curves. The modification is to multiply the total dose under x-ray irradiation by a dose enhancement factor, which is the division of 1 Grad by the dose where the x-ray-induced $\Delta I_{\rm ON}/I_{\rm ON,pre}$ equals the protons-induced $\Delta I_{\rm ON}/I_{\rm ON,pre}$ at 1 Grad (factor: 2.1). From Fig. 5, it can be seen that the modified curve of the 120/60 nm core nMOSFET agrees very well with the proton-induced degradation curve. For the 400/280 nm I/O nMOSFET, the dose enhancement factor should be lower than the value of the core nMOSFET, but it is difficult to directly extract the factor since the x-ray-induced $\Delta I_{\rm ON}/I_{\rm ON,pre}$ is not always higher than the proton-induced $\Delta I_{\rm ON}/I_{\rm ON,pre}$. This is why we also use the enhancement factor of 2.1 to produce the modified curve. From the comparison results, the modified curve still shows some difference from the proton-induced degradation curve in the whole dose range. To summarize, results in Fig. 5 suggest that the interface dose enhancement effect can explain the degradation difference in the core nMOSFET very well, but cannot fully explain that in the I/O nMOSFET.

Secondly, the fractional yield of holes (or charge yield) is defined as the fraction of holes escaping the columnar or geminate recombination. There are experimentally measured values summarized in Refs. [1] and [3] for a number of particles. However, these studies were performed on MOS capacitors with very thick gate oxide ($>$ 100 nm), the preciseness of these values becomes questionable for modern CMOS technologies, due to the small shifts in parameters. In fact, results of floating gate cells with 10-nm tunneling oxide show similar degradation under Co-60 gamma ray and 27 MeV protons irradiation even though the charge yield values published before were quite different.[3,14] To provide more information, figure 6 shows the irradiation results from pMOSFETs: stronger x-ray-induced degradation can be seen in the core pMOSFET, whereas x-ray and protons induce similar degradation in $I_{\rm ON}$ for the I/O pMOFETs. Figure 6(a) also presents the modified curve (dashed one) after taking into account the dose enhancement factor of 2.5, and good agreement is achieved for the core pMOSFET, which is similar to the results reported in Fig. 5 for the core nMOSFET. However, for the I/O pMOSFETs, the behavior of the degradation difference is quite different from the I/O nMOSFETs and not consistent with the dose enhancement effect.

Under this circumstance, we further consider the contribution of the fractional yield of holes. For the nMOSFETs, the bias during irradiation guarantees that the electric field in the gate oxide is large (about 5 MV/cm) to enhance the charge trapping. For the pMOSFETs, all the terminals were connected together during irradiation, so the electric field in the gate oxide was much smaller than that of the nMOSFETs. Based on the mechanism of the interface dose enhancement

effect, it is irrelevant with the electric field. However, the fractional yield of holes is strongly dependent on the electric field in the oxide and increases with the value closely. Referring to Ref. [3], when the electric field is small, the yield differences between different sources are limited, and the yield differences cannot be ignored at high electric field (the yield for x-ray is stronger than that for 3 MeV protons).

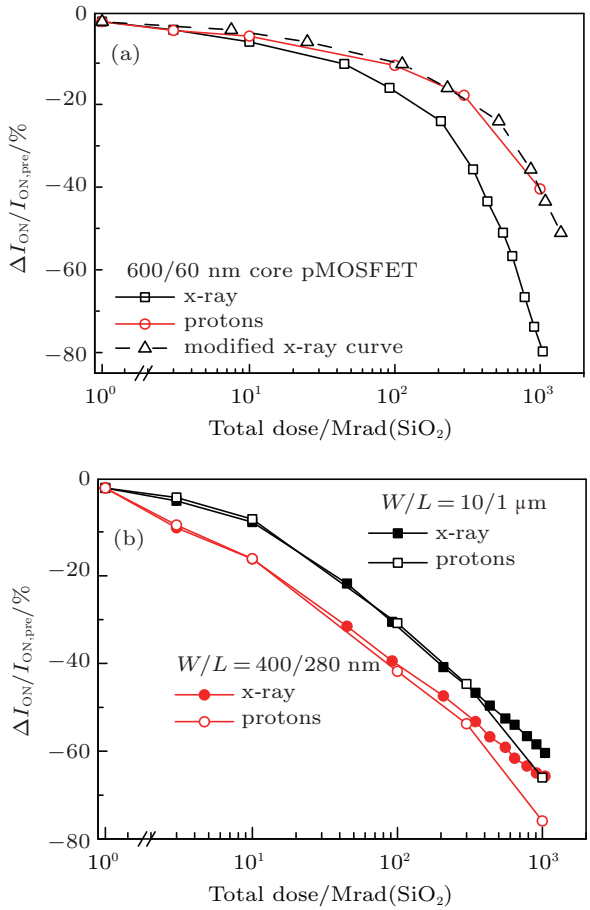


Fig. 6. (color online) (a) Comparison of the proton-induced $\Delta I_{ON}/I_{ON,pre}$ value and the modified x-ray-induced $\Delta I_{ON}/I_{ON,pre}$ curve for the 600/60 nm core pMOSFET; (b) comparison of $\Delta I_{ON}/I_{ON,pre}$ induced by the two sources for two I/O pMOSFETs.

Table 1 shows the relative contribution of the interface dose enhancement effect and the holes recombination to the difference in degradation induced by x-ray and 3-MeV protons, from a qualitative point of view. The arrows in the table represent the degrees of contribution. For the dose enhancement effect, the thinner the gate oxide is, the stronger the enhancement will be. Hence, the core transistors represent stronger enhancement. For the holes recombination, pMOSFETs are irradiated at low electric yield, so the fractional yields of holes are low and the contribution to the difference is negligible. To sum up, the core nMOSFETs feature the strongest degradation difference due to the two mechanisms, whereas the I/O pMOSFETs feature the weakest degradation difference, which can explain the negligible difference shown in Fig. 6(b).

Table 1. Analysis of the contribution of interface dose enhancement effect and the holes recombination to the difference in degradation induced by x-ray and 3-MeV protons.

	Contribution to the degradation difference			
	core nMOSFET	I/O nMOSFET	core pMOSFET	I/O pMOSFET
Dose enhancement under x-ray irradiation	strong enhancement ↑↑	strong enhancement ↑	strong enhancement ↑↑	strong enhancement ↑
fractional yield of holes	large yield big difference	large yield big difference	small yield negligible difference	small yield negligible difference
net contribution	↑↑↑	↑↑	↑↑	↑

Thirdly, the adopted dose rates corresponding to the two sources are 1 krad·s^{-1} (SiO_2) for x-ray, 54 krad·s^{-1} (SiO_2) and 540 krad·s^{-1} (SiO_2) for protons. From the conclusion in Ref. [15], at high dose rates, radiation-induced charge buildup in gate oxide is inclined to be suppressed. Considering that all the adopted dose rates are comparatively high, and the results in Fig. 6(b) suggest that the x-ray-induced degradation does not overwhelm the proton-induced degradation when the other two mechanisms contributed little, the influence of the dose rate is negligible in this study.

4. Conclusion

The TID effects induced by 10-keV x-ray and 3-MeV protons were studied in 65-nm CMOS transistors to irradiation up to 1 Grad (SiO_2). The degradation levels induced by the two radiation sources were different to some extent. Among all these transistors, core nMOSFETs and pMOSFETs showed the strongest differences where the x-ray-induced degradation was stronger. The degradation difference was also evident in the I/O nMOSFETs. For the I/O pMOSFETs, x-ray and protons almost induced the same level of degradation.

After taking the different radiation setups into account, three possible factors including the interface dose enhancement effect, the fractional yield of holes, and the dose rates are discussed in detail. The main reason for the degradation differences is the dose enhancement due to the thin gate oxide and the low energy photons. The holes' recombination also contributes to the difference. Compared to these two mechanisms, the influence of the dose rate is negligible.

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