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Proton-induced Upsets in 41-nm NAND Floating Gate Cells

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Abstract — **The corruption of the information stored in floating gate cells due to high-energy protons is analyzed in 41-nm single level NAND Flash memories. Proton-induced upsets are not negligible at this feature size. Experimental data and Geant4-based simulations show that the errors are related to a combination of direct and indirect ionization effects.**

Index Terms — **Flash memories, Radiation effects, Single event upset.**

I. Introduction

FLASH memories based on Floating Gate (FG) cells are of great interest for the space community, thanks to their large capacity, low cost, and small power consumption. The large size of these commercial devices is not available in any current rad-hard non-volatile memories, that are based on technologies such as nitride trapping, chalcogenides, magnetoresistive storage, and have feature sizes quite far from the state of the art in the mainstream market. However, several issues exist concerning the radiation sensitivity of FG memories in harsh environments [1]. In the past, radiation effects in FG memories were limited to the peripheral circuitry, especially the charge pumps [2],[3], where the large voltages necessary for the program and erase operations are generated on chip. In recent years, though, FG cells have been aggressively scaled and, as a result of the dramatic decrease in stored charge, they have become sensitive to single event effects (SEE) [4].

A considerable amount of experimental and theoretical work has been carried out to understand the response of FG cells to heavy-ion strikes [1]-[5], but many questions are still open. The exact physical mechanism leading to the discharge of floating gates has not been conclusively identified, and different models exist, with implications on the way error rate predictions are carried out.

Some investigations on Flash memories have used high-energy protons [5], but they are mainly focused on total ionizing dose effects, since the probability of proton-induced single event effects was extremely low. [6] considers this aspect but presents the irradiation results only in terms of threshold voltage shifts, which, at the time, were not large enough to cause upsets in cells hit by proton-induced secondaries.

In this paper we will use a combination of experiments (protons, x rays, heavy ions irradiations) and Monte Carlo simulations based on the Geant4 toolkit, to gain new insight on the response of FG memories to high-energy protons. This work brings several novelties. It discusses proton effects in devices with smaller feature sizes (41-nm) than those reported in the literature. As we will see, the increasing heavy-ion sensitivity of these devices significantly alters the response to protons: upsets do occur (especially at high energy) and are enhanced by total dose effects. This work also provides more detailed simulations, where the full device structure is simulated with Geant4, as opposed to the simplified approach used in [6].

II. Devices and Experimental Procedure

For this work we used commercial NAND Single-Level Cell Flash memories manufactured with a 41-nm feature size.

To have maximum visibility on the number of errors, all the measurements have been performed without any Error Correction Codes (ECC), which are required for the use of these memories. We will call 'raw bit errors' the bit errors detected without ECC.

Irradiations were done at the wafer level using the following radiation sources (Table I):

- protons (with energy 35.4, 105, and 498 MeV) at the TRIUMF Proton Irradiation Facility; for all proton energies, a dose of 30 krad has been reached.

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TABLE I
HEAVY-ION AND PROTON BEAMS USED IN THIS WORK

Ion species	Energy [MeV]	Surface LET [MeV · cm^2/mg]	Range in Si	Irradiation Facility
O	100.9	3	97 μm	LNL
Si	121	9.8	44 μm	LNL
Ni	212.8	29.5	36 μm	LNL
p	34.5	0.013	7 mm	TRIUMF
p	105	0.006	45 mm	TRIUMF
p	498	0.002	615 mm	TRIUMF

- 10-keV x rays at the INFN Legnaro National Laboratories (LNL), Italy. Dose steps from 0.1 to 30 krad(Si) have been delivered.
- heavy ions with LET ranging from 3 to 50 MeV·cm^2/mg at the SIRAD line of the TANDEM accelerator at the LNL. A fluence of $3 \cdot 10^7$ cm^{-2} has been delivered to the devices to assure good statistics and, at the same time, to avoid multiple strikes.

All irradiations have been performed at normal incidence, on unbiased samples at room temperature. Before the exposure, the devices were programmed with a checkerboard pattern. Before and after the irradiation, the memories have been read and, for a few blocks, the cell threshold voltage distributions have been measured.

For all samples and experimental points, several thousands of errors were collected in order to gain enough statistical accuracy. Annealing of FG errors after heavy-ion and x-ray irradiation [7] is not considered in this work, as all the samples were measured at about the same time after exposure, when annealing is practically over.

III. Experimental Results

It is worth to highlight that all the effects we are going to discuss are linked to phenomena occurring in the floating gate cells. In fact, all the devices have been irradiated in unbiased conditions (unpowered retention mode) with a total ionizing dose that does not cause malfunctions in the peripheral circuitry.

Fig. 1 shows the raw bit error cross section after irradiation with protons at different energies. For all proton energies, the total dose delivered during the tests was 30 krad(Si). Contrary to Flash memories with larger feature sizes tested in the past with the same beams and dose, raw bit errors do occur in these devices. The cross section sharply increases (about one order of magnitude) as we move from 34.5 MeV to 498 MeV. Upsets are prevalent in the programmed state, but the erased level is also affected, although the cross section is two orders of magnitude lower. Poisson error bars are smaller than the symbols in Fig. 1.

Fig. 2 presents the threshold voltage distributions for the programmed cells before irradiation and after exposure to protons with different energies. Two effects are apparent:

i) the whole distributions move towards lower threshold voltages;

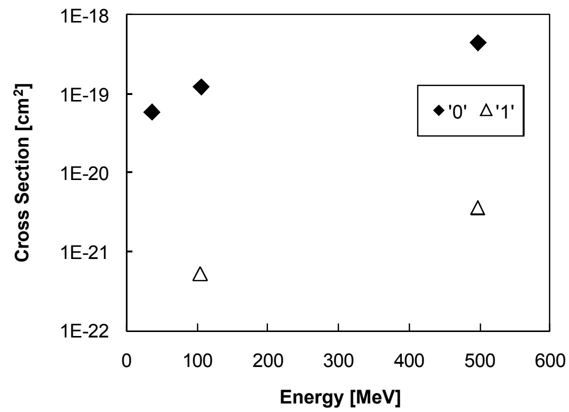

Fig. 1. Raw bit upset cross section as a function of impinging proton energy for programmed (‘0’) and erased (‘1’) floating gate cells.

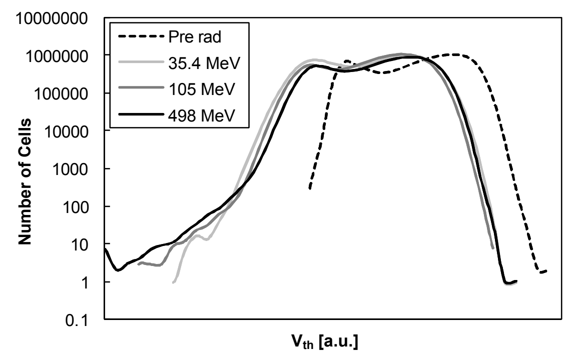

Fig. 2. Threshold voltage distributions before and after irradiation to protons at different energies.

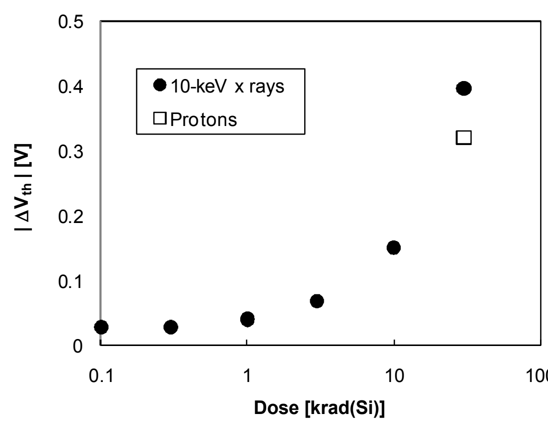

Fig. 3. Average threshold voltage shift as a function of dose after x-ray irradiation. The average shift induced by 30-krad protons is also shown.

ii) a tail becomes visible at low voltage, on the left-hand side of the irradiated distributions.

No tails appear exposing the same devices to x rays (not shown). It is worth to remark that one should not expect to find a perfect correlation between Figs. 1 and 2. Indeed, Fig. 1 was obtained measuring more than 10^{10} cells, whereas Fig. 2 refers to a small subset, consisting of 10^7 cells. Fig. 3 shows the average threshold voltage shift as a function of dose for devices irradiated with x rays. The x-ray data at 30 krad(Si) are consistent with the 30-krad(Si) proton irradiation: the slightly larger shift with x rays is attributable to dose enhancement effects.

Figs. 4-5 show the results of heavy-ion irradiations on the same samples. As seen in Fig. 4, the threshold LET for floating gate errors in these samples is below 10 MeV mg^{-1}·cm^2; this relatively low value means that we can certainly expect to have upsets generated by proton secondaries. Fig. 5 illustrates that the threshold voltage shift increases as the LET of impinging particles increases. In addition, the ion-induced shift depends on the cell program level, in agreement with previous results [7].

IV. Discussion

The global distribution shift (Fig. 2) is related to the total dose delivered to the components. No large variations are present in the devices irradiated up to the same dose with protons of different energies. As mentioned before, this global shift is in consistent with that observed after x rays (up to the same total dose).

On the contrary, the tails in the distributions, which contain just a subset of the irradiated bits (those that have experienced threshold voltage shifts much larger than the average cells), depend on the proton energy and are linked to proton-generated secondaries. To reach the same total dose for all irradiations, different proton fluences as a function of energy were used. Yet, this explains only in part the different tails observed in Fig. 2. In fact, the cross section in Fig. 1 is normalized by the proton fluence, implying that higher energy protons are more effective at generating errors. This may be due either to a larger nuclear interaction cross section with chip materials, but this is not supported by published data [8], or to a larger average energy of the secondaries, which increases their range and so the probability that they will deposit energy in sensitive parts of the memory array. In addition, the tails extends to lower V_{th} as the energy of protons increases.

Raw bit errors in floating gate cells occur when the threshold voltage of a programmed (erased) cell goes below (above) the reference voltage, which, in the case of SLC NAND, is 0 V. The total dose delivered to the parts by direct ionization does not shift enough the cell threshold voltage to cause errors, as clearly demonstrated by the absence of errors with 30-krad(Si) x-rays exposures. A higher TID, typically in the range of 100 krad(Si), is required to corrupt the state of FG cells [3]. However, at that dose point, degradation of the peripheral circuitry is likely to occur.

Errors in Fig. 1 must therefore be linked to the proton indirect ionization component. The shift needed to generate an upset in the average cell is about 2.5 V (corresponding to an LET of 10 MeV·cm^2/mg): this can be seen by comparing Figs. 4 and 5. At 30 krad(Si), the total dose induced shift is 0.3 V, well below that required to corrupt the information in the FGs, even considering large statistical variations. There are then two components in the threshold voltage shift of upset floating gate cells: one is related to total dose, the other one is linked to energy deposition of the generated secondary.

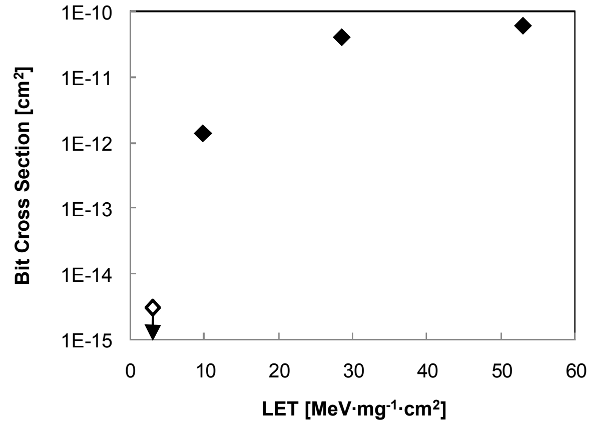

Fig. 4. Raw bit upset cross section as a function of heavy ion LET.

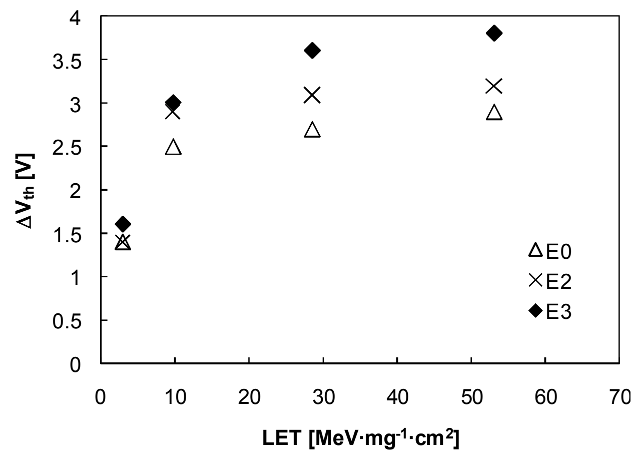

Fig. 5. Average threshold voltage shift as a function of LET at different tunnel oxide electric fields. E0 is the average electric field in the tunnel oxide of programmed cells, E2 > E1 > E0.

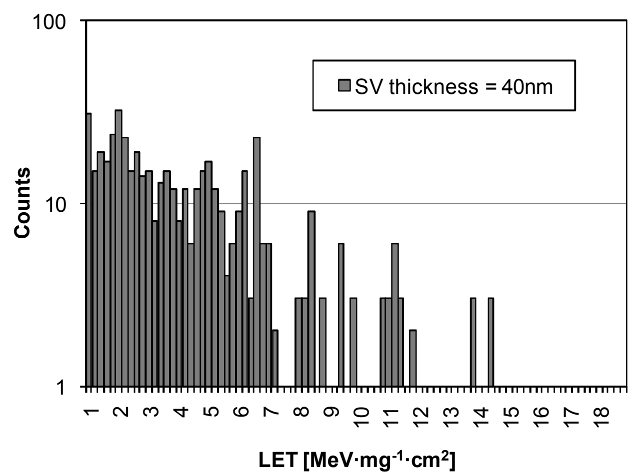

Fig. 6. Simulated distribution of energy deposition events in floating gate cells.

$$\Delta V_{th,upset\,cells} = \Delta V_{th,TID} + \Delta V_{th,HI} \qquad (1)$$

The basic mechanisms for $\Delta V_{th,TID}$ and $\Delta V_{th,HI}$ are likely different: the first one is due to FG injection of radiation-induced carriers generated in the tunnel and ONO stacks, photoemission of the stored FG carriers, and to small amount of charge trapping/interface state generation; the second one is still controversial: it may be related either to a transient conductive path triggered by the ion passage, or to a transient carrier flux. Published heavy-ion charge yield figures are too low to explain heavy-ion induced shifts in the same way as TID-induced shifts (although there is some controversy here as well).

Although $\Delta V_{th,TID}$ is smaller than $\Delta V_{th,HI}$, it cannot be neglected, as shown by the previous quantitative discussion. For instance, as previously illustrated [9], a small total dose (few 10's krad) delivered before heavy-ion irradiation can diminish the upset threshold LET, and increase the FG error cross section by a factor of 3.

Both $\Delta V_{th,TID}$ and $\Delta V_{th,HI}$ are a function of the electric fields in the cells. In turn, the electric field is determined by the amount of charge stored in the floating gate electrode. After each energy deposition, the amount of stored charge in the floating gate is decreased, because of direct or indirect ionization effects, leading to a corresponding decrease in the electric fields, which in turn causes a comparatively smaller threshold shift at the next energy deposition event. We can say that ΔV_{th} in upset cells is the result of several separate energy deposition events, each characterized by a different electric field, the majority due to direct ionization events, and at most one to indirect ionization event, due to the small cross section for proton nuclear interactions (the probability of double strikes by secondaries in our experimental conditions is almost zero):

$$\Delta V_{th,TID} = \Delta V_{th,HI}(E_{ox,t_{HI}}) + \sum \Delta V_{th,TID,i}(E_{ox,i}) \quad (2)$$

On top of this, if we want to model the post-rad threshold distributions (and the number of errors), we also need to consider cell-to-cell electric field variability, and the fact that there is a distribution of electric fields (even cells with the same initial threshold voltage do not necessarily have the same electric fields, due to the application of compaction algorithms that tighten the threshold voltage distribution). In summary, we must consider:

i) The pre-rad V_{th} and electric field of the FG cells

ii) The number and sequence of energy deposition events

iii) The variability in the individual energy deposition events

To account for iii) we have built an application based on the Geant4 toolkit to simulate the (direct and indirect) energy deposition by protons in the memory cells. We used technological information provided by the manufacturer to design a proper model, including details on the cell geometry and materials used in the front-end and back-end of the line. Realistic layouts have been used for the metallizations (word lines, bit lines, power and ground distribution, etc.) and the thicknesses of the various layers. Simulation speed was not a concern, whereas accuracy was. Electromagnetic interactions have been modeled using the low-energy Geant4 electromagnetic processes (Livermore library). For hadronic interactions, the Bertini and the parameterized models were used. Geant4 version 4.9.3 was utilized. This is a significant improvement over the approach used in [6], where the structure of the cells was not considered. We must also note that the samples in this work are much more sensitive than those in [6], so even nuclear reactions with silicon and oxygen can give rise to secondaries with high-enough LET to generate errors (as opposed to [6], where the focus was on tungsten).

Fig. 6 shows the energy deposition distribution of indirect ionization events generated by 498-MeV protons. The bottom 40-nm part of the floating gate was considered the sensitive volume, following the most recent results [10]. A similar histogram has been produced for direct ionization events (not shown).

The number of direct ionization energy deposition events (N_{ded}) in each cell is modeled as a random Poisson variable. For a statistically significant number of cells, N_{ded} events are picked from the direct ionization histogram generated with Geant4, together with one indirect ionization event (note that the energy deposition events are statistically uncorrelated, whereas the threshold voltage shifts are, because of the electric field reduction that each deposition causes). The sequence of N_{ded} +1 events is randomized, and the final threshold voltage is calculated on a cell, randomly picked from a gaussian pre-rad distribution. If the cell threshold goes below the read voltage (0 V), an upset is counted.

At the moment, we obtain an agreement between simulations and experimental data within a factor of about 2.5 with 498-MeV protons. We are working to improve this agreement, by more accurately defining the sensitive volume and the pre-rad statistical distribution of cell parameters.

V. Conclusion

We have shown that, in 41-nm single level NAND floating gate cells, high-energy protons can give rise to upsets. The relatively low threshold LET means that, in principle, no significant total dose must be accumulated on the device before an error can occur. However, the upset rate is significantly enhanced by the combination of direct and indirect ionization events generated by protons, as the total dose delivered to the component increases. A reasonable agreement, which we expect to improve in the coming months, has been found between experimental data and detailed simulations including variability in energy deposition, event sequence, and initial cell parameters.

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