Threshold Voltage Distributions of Floating Gate Arrays Irradiated with Heavy Ions

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INTRODUCTION

Floating Gate (FG) memories are of great interest for the space community, due to their large capacity, low cost, and small power consumption. However, several issues exist concerning the radiation sensitivity of floating gate 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]. In recent years, though, FG cells have been aggressively scaled and, as a result of the dramatic decrease in stored charge, even they have begun to be 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 proved, and different models exist. Another open issue is the origin of the small threshold voltage (V_{th}) shifts of those cells whose V_{th} after heavy-ion exposure lays between the program distribution and the secondary peak, generated by the ions [5].

Understanding the generation of tails in the V_{th} distributions is of primary importance, because FG bit upsets, which are becoming more and more common as the feature size is scaled, are directly related to the part of the tails that lays below the read voltage.

In this paper, we will use a combination of experiments and MC simulations based on the Geant4 toolkit to gain new insight and provide original interpretations of the tails produced by heavy ions in FG devices.

EXPERIMENTS AND DEVICES

In this work we studied and simulated Multi-Level-Cell (MLC) 65-nm FG Flash memories with NOR architecture, manufactured by Numonyx. The erased level is the one with the lowest threshold voltage (V_{th}), and it is obtained by injecting holes into the FGs. The other three levels are programmed by injecting increasing numbers of electrons into the floating electrode. The neutral distribution, i.e., the distribution of the empty FG cells, with neither electrons nor holes, is between the erased and the lowest V_{th} program level.

The devices were irradiated with heavy ions at the SIRAD line of the INFN Legnaro National Laboratories (LNL) with LET in Si ranging from 2.85 to 28.4 MeV·cm²/mg and a fluence of 3·10⁷ ions/cm². Devices were also irradiated with 10-keV x-rays using a Seifert probe station at LNL.

The samples were programmed prior to irradiation and exposed unbiased.

RESULTS AND DISCUSSION

Figure 1 shows a typical V_{th} distribution before and after heavy-ion irradiation with a monochromatic heavy-ion beam (121-MeV Si) on a 65-nm MLC part, for the cells programmed at the highest V_{th} level. For ease of visualization, the other three V_{th} levels have been omitted in figure 1. Two additional regions besides the pre-rad peak can be observed after exposure to heavy ions: a secondary peak appears together with a transition zone between the main (resulting from the program operation) and the secondary peak.

Some features of these tails are well known in literature, in particular the electric field, ion fluence, and LET dependence. However, the shape and the transition area between the main peak and the secondary peak have not been thoroughly explained [5] and the exact physical mechanism leading to the discharge of FG cells has not been conclusively identified.

In the following, we will focus on the analysis of tails produced by monoenergetic beams. To this end, we have built an application based on the Geant4 toolkit to simulate the energy deposition by the ions in the memory cells. Fig. 2 shows the simulation of a heavy ion crossing a FG cell and injecting electrons in nearby cells, in a 65-nm part. For each event, the simulations provide the struck cell and the amount of energy deposition in the various regions we considered. A single ion can cause more than one event, corresponding to energy deposition in more than one cell.

From the point of view of the FG cells, we can distinguish two types of events arising in our simulations:

- Heavy ions crossing directly FGs (i.e. in which the center of the ion track goes through the FG), which we will call large events, and
- Secondary electrons crossing FGs, generated by ions passing nearby (but not through) FGs, which we will call small events.

The first ones deposit a large amount of energy in the FG and tunnel oxide. The second ones deposit only a tiny fraction (much less than 1/3) of the energy, in comparison with the events of the first type. We will now link these events to the tails observed after the exposure to heavy ions, discussing first the secondary peak and then the transition region.
The number of cells in the secondary peak, as obtained by experimental measurements, is roughly equal to the simulated number of large events. This figure is well correlated with the number of strikes occurring inside FGs, as it can be demonstrated by simple calculations on the FG vs cell area.

To obtain the threshold voltage tails from the Geant4 simulations of the deposited energy, we calculate a conversion factor ($\Delta V_{th}$/LET), dividing the experimentally measured average cell $\Delta V_{th}$ by the LET of the ions used in our experiments (considering the energy deposition in the FG, as opposed to the one in the tunnel oxide). Assuming a linear relationship between energy deposition in the FG and $\Delta V_{th}$ around the average value, we obtain the curves of the simulated large events shown in figure 3. The agreement between the experimental data and the simulation is satisfactory. It is clear from figure 3 that fluctuations in energy deposition are responsible for the shape of the secondary peak. The agreement between experiments and simulations of the secondary peak is worse if we consider energy deposition in the tunnel oxide rather than in the FG electrode. As expected, since the volume of the tunnel oxide is much smaller than that of the FG, the simulated energy deposition shows a broader distribution, which does not agree well with the experimental data.

Large events however do not allow one to explain the transition zone between the secondary and the primary peak, neither in terms of number of affected cells, nor in terms of $V_{th}$ shift. We then turn to the small events, i.e., those in which an ion deposits some energy in the FG, without going through the FG. If we consider the small events in terms of total dose, we obtain significant insight. We tested the same devices irradiated with heavy ions also with x rays. We calculate a conversion factor between TID and $V_{th}$ shift ($\Delta V_{th}$/TID) at low doses (< 30 krad) and find an approximately linear relationship between $\Delta V_{th}$ and dose, with a coefficient of 15.4 mV/krad. If we use these conversion coefficients extracted from x-ray experiments to turn the simulated deposited energy in the FG by small events to actual threshold voltage shifts, we obtain a very large number of events with a shape very similar to the transition zones. Small events in figure 3 are simulated with this method, which allows us to reproduce the transition regions.

CONCLUSIONS

In summary, with a combination of experiments and Geant4-based simulations, we have provided new insight, linking the $V_{th}$ shifts to two types of events: the first ones (large events), occurring when an ion goes through the FG, are responsible for the secondary peak; the second ones (small events) are due to ions passing by FGs, and are related to the transition zone.