Prediction of proton cross sections for SEU in SRAMs and SDRAMs using the METIS engineer tool

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Abstract

METIS, SIMPA and PROFIT are engineer tools based on heavy ion cross section for the assessment of Single Event Upsets induced by protons. Whereas SIMPA and PROFIT were based on analytical models; METIS has the particularity to rely on Monte-Carlo simulations of nuclear reactions and simple assumptions for upset triggering. Such tools are very useful for end-users because no information about the technology is needed to perform the sensitivity prediction, not even the feature size. The work presents the prediction results achieved on sub-100 nm technology SRAMs and SDRAMs with METIS and compares them with the ones obtained using SIMPA and PROFIT, widely applied for space radiation environment. METIS gives much more accurate results than the former analytical models.

1. Introduction

Single Event Upsets (SEUs) occur when a single ionizing radiation event produces a burst of hole–electron pairs that is large enough to change the state of a storage element, such as configuration memory cell, user memory, and register.

In space, SEUs are caused by charge collection at sensitive circuit nodes following a proton or a heavier ion strike. The heavy ions produce the effect directly while high energy protons induce upsets through ions emitted as a result of their nuclear interactions with the device matter. Furthermore, low energy protons may cause direct ionization SEU in very sensitive devices. Less than 1 proton in 10^5 will encounter a nuclear reaction in a silicon device. Although this seems like a very rare event, for low Earth orbits, the trapped proton fluxes are so high that they will contribute to more upsets than the heavy ion cosmic rays.

In order to reduce the cost and the number of radiation tests, it is interesting to develop bridges from one particle to another.

Among the large number of analytical predictions methods for SEU induced by protons based on heavy ion data, SIMPA [1] and PROFIT [2] are the most widely used by the European space community, as they are included in the OMERE package [3]. These models were developed in the middle of 90s, both require to specify the sensitive thickness and both rely on simplifications which have shown their limits for process technologies below 130 nm (see Table 1).

Monte Carlo codes based upon more physical triggering criteria compute the energy deposition by tracking all the secondary particles generated from nuclear interactions. Despite being more time consuming, they can be more accurate and detailed than analytical approximations [4].

Unfortunately, for an end-user, and so in space engineer working in radiations, technological data required for full physical simulations can be hardly obtained. An irradiation experiment often remains the only way to characterize the device sensitivity to radiation effects. The METIS (Monte-Carlo Engineering Tool for Ion-induced SEE) tool offers to extrapolate heavy ion data to proton or neutron cross section, which makes it therefore very close to the SIMPA and PROFIT approaches. Based on a nuclear database, and simple assumptions, it constitutes a relevant trade-off between accuracy and access to technological data. For SEU investigations in SRAMs, METIS is perfectly suitable for the end-user needs because no information about the technology is needed, not even the feature size, and the calculation is fast.

The tool has been extensively validated for SEU calculation on SRAM devices, bulk or SOI up to 45 nm [5]. We propose here to further validate the tool for very deep submicron SRAMs (45 and 28 nm) and to extend the validation to SEU in SDRAMs. Results are also compared with the ones achieved by SIMPA and PROFIT.
2. METIS overview

METIS relies on the same expression as the SIMPA methodology for a “gateway” tool between heavy ion and proton. The SEU proton cross section is given as a function of the heavy ion cross section by:

\[ \sigma_P(E_p) = \int \sigma_{HI}(E_d) \cdot P_{E_d}(E_d, V) \cdot dE_d \]

with \( E_p \) the incident proton energy, \( \sigma_{HI} \) the heavy ion cross section, and \( P_{E_d}(E_d, V) \), the probability to obtain a deposited energy \( E_d \) from the secondary ions in a given volume \( V \).

Based on the concept of sensitive sub-volumes having rectangular parallelepipeds (RPP) shape, an upset occurs when the energy deposited by the ions in the charge collection region exceeds the threshold energy. For the estimations performed in this paper, around 30 nested sensitive volumes were selected along a Weibull curve of the experimental heavy ion cross section. For each sensitive sub-volume, the threshold energy is the product of the heavy ion LET per the sensitive depth. In METIS, the probability for energy deposition is calculated using SRIM tables [6] and a Monte-Carlo selection of nuclear interactions from a pre-calculated database, which differs from the analytical expression used by the SIMPA method.

The nuclear database is constituted by listing the characteristic (type, energy and direction) of the secondary ions induced during elastic scattering and nuclear reactions. It was built using the MC-RED (Monte Carlo Recoil Energy Determination) code and was experimentally validated [7,8]. In this nuclear physics code, elastic reactions with silicon nuclei are studied with the ECIS [9] calculation code using the optical parameters from Koning and Delaroche [10]. Non-elastic reactions are simulated following, step by step, the nuclear decay. The pre-equilibrium stage is calculated using the 1D exciton model [11,12]. Equilibrium processes are simulated using the Hauser-Feshbach formulation [13]. The angular distributions are evaluated using the Kalbach systematics [14]. In the following studies, only nuclear reactions with silicon induced by protons are considered. Nuclear interactions with other elements than silicon used in the manufacturing process can be easily covered by including the proper database.

Table 1 presents a comparison between METIS and the former methodologies SIMPA and PROFIT.

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<thead>
<tr>
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<tbody>
<tr>
<td>Heavy ion cross section</td>
<td>Sensitive thickness only required for SEU in DRAM.</td>
<td>Sensitive thickness (default value 2 μm)</td>
<td>Average diffusion angle (default value 90°)</td>
</tr>
<tr>
<td>Collection Criteria</td>
<td>IRPP</td>
<td>Critical energy</td>
<td>Rectangular surface Critical LET</td>
</tr>
<tr>
<td>Nuclear data</td>
<td>Montecarlo selection</td>
<td>Experimental energy deposition in diodes</td>
<td>Analytical expressions for LET (Ea) and ( \sum_{m=1}^{nucl} )</td>
</tr>
<tr>
<td>Time-efficiency</td>
<td>~7 s/energy</td>
<td>&lt;1 s</td>
<td>&lt;1 s</td>
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</table>

3. SEU in SRAMs

For SEU studies in SRAMs with METIS, all input parameters are extracted from the measured heavy ion cross section. No technological data is required, and we assume that the heavy ion cross section fully characterizes the device sensitivity.

The sensitive areas are directly related to the measured heavy ion cross section curve. For submicron feature sizes, charge collection is mainly driven by diffusion mechanism and the sensitive thickness is therefore strongly linked to the sensitive surface (and is no more a constant value as it is in PROFIT and SIMPA). The sensitive thicknesses are then sized as half of the areal dimensions to approximate a hemisphere shape and are then increasing along the heavy ion cross section curve.

In order to achieve a good trade-off between computing time and accuracy, the nuclear interactions are generated in a silicon layer of 20 μm below the active surface and an upper layer of 5 μm, simulating the back end of line.

More details about the tool algorithms can be found in [5].

In [5], the METIS tool was validated for SEU simulation in SRAMs using a large number of commercial CMOS memories. For most of the devices, especially for deep submicron technologies, this tool gives more accurate predictions than SIMPA and PROFIT and the margin of 10 recommended in the ECSS Standard [15] when using SIMPA and PROFIT as a prediction tool could thus be reduced to about 3 when using METIS. Since then, new data are becoming available and this work investigates SEU in advanced SRAMs. Weibull fits, tabulated in Table 2, were made to all of the heavy ion data.

3.1. 45 nm SRAM

In [16], heavy ion (see Fig. 1) and proton (see Fig. 2) accelerator data are presented on 2 types of 45 nm SRAM from ST, with deep N-well layer (DNW) and without deep N-well structure. METIS simulations show fairly well accordance with experiments for both devices (see Figs. 2 and 3). SIMPA and PROFIT mainly underestimated the proton experiments when using 0.2 to 2 μm sensitive thicknesses and 90° of average diffusion angle for PROFIT.

3.2. 45 nm SRAM-based-FPGA

The susceptibility of a SRAM-based-FPGA based on a 45 nm technology was characterized under heavy ions and protons at UCL (see Fig. 4).
As expected, the CRAM cells were found slightly less sensitive than BRAM cells at low LET values. Predictions given by METIS, PROFIT and SIMPA are compared in Figs. 5 and 6 for BRAM and CRAM respectively. METIS results are in very good agreement with proton testing. As already highlighted, PROFIT and SIMPA underestimate the proton cross sections.

3.3. 28 nm SRAM-based-FPGA

The SEE response of the Xilinx 28 nm Kintex-7 FPGA under heavy ions is shown in Fig. 7 [17]. The Weibull curves illustrating the CRAM and the BRAM cross sections allow us, using the 3 predictions tools, to compute the proton sensitivity and to compare with proton data.
For BRAM cells (see Fig. 8), METIS gives an overestimation of a factor 2. For CRAM cells (see Fig. 9), METIS matches very correctly the experiments with a cross section value at 85% of the 63 MeV proton data.

### 3.4. 45 nm SOI

The P2010 is a microprocessor from the QorIQ family developed by Freescale manufactured on a 45 nm SOI (Silicon On Insulator) process. Figs. 10 and 11 provide the heavy ion and proton data obtained on the L2 cache memory [20].

The increase of the cross section measured below 10 MeV is probably due to the direct ionization of lower energy protons encountered in the beam. Direct ionization is also taken into account in METIS by calculating the sensitivity to protons having a LET of 0.54 MeV·cm²·mg⁻¹ (highest LET value of a proton given by SRIM) but no experimental data towards proton direct ionization was carried out.

METIS underestimates the proton cross section by a factor 3. We then adapt the METIS simulation in order to be closer to the SOI technology by limiting the sensitive thickness to the one corresponding to the SOI layer thickness. That means, if the thickness corresponding to a sensitive volume is lower than 150 nm, it remains unchanged. If this thickness is greater, we limit it to 150 nm. As shown in Fig. 11, this has no impact on cross sections predicted by METIS. As expected, the sensitivities estimated by PROFIT and SIMPA fall well below the accelerator data when using a 0.15 µm sensitive thickness.

### 4. SEU in SDRAMs

The experimental data on SDRAM are often more ambiguous than the one related to SRAMs. The sensitivity depends on the pattern and on the mode of operation, the effective LET used during a test at tilted angles is not adequate, the presence of error code correction is not always mentioned. This makes it difficult to validate METIS using bibliographical data. Moreover, some heavy ion data collected on very advanced SDRAMs show that the upset cross section does not reflect anymore the sensitivity at memory cell level [21]. In addition to the heavy ion curve, a SEU calculation in SDRAM by METIS involves one key parameter, the thickness of the sensitive volumes (as it would be for the PROFIT and SIMPA approaches). The diffusion model seems to be not applicable for DRAM due to the high level of doping and the presence of isolation well.

Since the METIS results strongly depend on the sensitive thickness for DRAM sensitivity and the limitations mentioned above, the use of METIS to predict SEU in this kind of devices is limited. Above all, the computation time is greatly increased in order to reach very low cross sections.

However, we conduct a study on two old generations of SDRAMs. Two 512 Mb SDRAMs (0.12 µm technology) were tested under heavy ions and protons [22]. METIS yields good result using a sensitive thickness of 0.5 µm (see Figs. 12 and 13). In the published data, most of the DDR2 and all the DDR3 SDRAMs tested under protons exhibit very low SEU saturation cross section, between $1E^{-20}$ and $1E^{-19}$ cm²/bit, which can probably not be imputed to discharge of the DRAM cell capacitor. In this case, METIS is not applicable.
5. Conclusion

In this paper, we have investigated the validity of METIS on 45 and 28 nm SRAMs and shown very good correlation with experimental values reported in the open literature on bulk CMOS technologies. For SOI process devices, the results are less accurate but still rather good and constitutes a significant improvement to the analytical methods that are SIMPA and PROFIT.

We have also performed a preliminary study to extend this tool for the SEU analyses in SDRAMs. The great dependence of the proton calculation on the sensitive thickness affects the capability of METIS when no technological data on the device is known, but, based on the results obtained on the 2 studied components, METIS seems to be also applicable for old technologies of SDRAMs for which the upset mechanism is attributed to charge collection in the memory cell capacitor. As proposed for the SET predictions in linear devices [23], one interesting way to use METIS tool studies could be to determine the sensitive thickness to consider based on the knowledge of both proton and heavy ion cross sections.

METIS can also handle the simulation of neutron environment for avionic applications, by replacing the proton-induced nuclear reactions by neutron nuclear data.

References