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MC-ORACLE: A tool for predicting Soft Error Rate

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ABSTRACT

Natural radiation is known to be a source of microelectronics failure. For instance, neutrons, protons, heavy ions, and alpha particles have all been implicated in the occurrence of soft errors in memory devices. To predict the reliability of electronics devices we developed a tool called MC-ORACLE. This Monte Carlo application is based on the common empirical soft error criterion for a critical charge deposited in a parallelepiped sensitive volume. MC-ORACLE is able to deal with complex structures composed of various materials. It provides single and multiple error cross sections as well as the soft error rate.

1. Introduction and context

Radiation-induced failure in microelectronics is a crucial issue in the aerospace and avionic communities [1,2]. Incident radiation acting on these devices is mainly due to cosmic rays and their secondary particles produced in the Earth atmosphere. These particles induce various dysfunctions through their interaction with the electronic device materials. In this work we focus on Single Event Upsets (SEU), which is a bit flip in a memory device. It is noteworthy that the word "Single" refers to the ability of a single particle impinging on the device to trigger an error. An issue within SEU is the estimation of the sensitivity of a given device for a given environment (space, avionics, ground level applications, etc.). To perform this estimation, either tests under particle beams (which are expensive) and/or simulations of particles interacting with the microelectronic device materials can be conducted. Various codes or methodologies have been previously developed that account for specific effects, components, materials, technologies, and types of particles [3–12]. Many of these may represent the state of the art, but as they are proprietary it is difficult to understand the underlying treatment. Initially, these physical models treated simplistic structures; for example, structures composed only of silicon (abundantly found in microelectronics) were widely used to obtain order of magnitude effects. However, it has been shown that the contribution of other materials is not negligible [13]; thus, later codes have been adapted to account for these materials.

The goal of our work is to elucidate the key ingredients of these codes, accounting for the types of particles (neutron, proton, alpha, heavy ion) and different device materials. Although the GEANT4 toolkit [14] could be used for this task, for historical reasons in our laboratory we instead implemented ourselves the physical processes which significantly impact the effect of radiation on a device. Our first challenge was to account for various existing methodologies within a single code, enabling it to handle the primary sources of radiation (space, the atmosphere, and radioactivity), several major device materials, and the modelling needed for Soft Error Rate (SER) prediction. This work presents the first version of the resulting MC-ORACLE code. In the following sections, we describe the natural particle sources accounted for in MC-ORACLE, the main assumptions underlying the model, the computational method, and some results.

2. Natural particles sources

The application determines the source and types of particles under consideration. For space applications, the relevant particles are essentially heavy ions and protons produced by the sun and other stars [15]. The flux and energy of these particles at a given location can be calculated, for instance, with the OMERE code [16].

For altitude applications such as avionics, the most abundant particles are neutrons [17] produced during the nuclear reaction between space particles and the nuclei of atmospheric atoms. Other particles such as muons, pions, gamma rays, and various ions are also produced [17], but their contributions to SER can be neglected. The neutron flux depends on latitude and altitude, and is described in the Boeing model [18].

For ground level applications neutrons are also a concern, but their flux is typically 300 to 400 times lower than levels found at avionics altitudes [18]. However, the large number of devices used at ground level increases the importance of this effect. A second source of particles that should be accounted for on the ground is

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natural radioactivity. In this case, particles come from the materials of the device itself. Among all radioactive elements, alpha emitters are known to contribute to Soft Errors [19]. Yet, even alpha particles having low stopping powers are known to contribute to SER in modern devices.

3. Main assumptions and input database

In order to simulate how particles interact with the electronic device materials, we made the following assumptions on the physical processes involved.

3.1. Ionization

Ions are transported within the device along a straight line, on which they can only interact by ionization. This assumption is justified since the probability that the energy deposited by direct ionization is sufficient to trigger an error in the device (and thus a nuclear reaction process) indicates only a second-order contribution. The ion energy loss is simulated using the stopping powers pre-calculated with the SRIM code [20]. This allows the calculation of the deposited energy between two points of the track along a straight line (no straggling effect). However, for protons we also account for nuclear reactions which are known to contribute to SER [21].

3.2. Nuclear reactions

Neutrons do not interact by direct ionization; they only interact through nuclear reactions. The simulation of nuclear reactions induced by primary protons or neutrons is performed by inputting pre-calculated nuclear reactions for various incident energies. We chose to use a nuclear database instead of a companion nuclear code in order to decrease the calculation time. Our database has various incident energies and it is easy to include additional ones as required. During nuclear reactions, gamma radiation can be emitted but its deposited energy in the device is very weak. This is because its mean free paths are much longer than the device dimensions. Consequently, the interaction of secondary gamma rays with the device is negligible. The same assumption is applied to nuclear reactions that could be triggered by secondary neutrons and protons, i.e., nucleons that are produced during the initial nuclear reaction. However, the ionization of secondary protons has to be taken into account since it can contribute to the deposited energy.

Our current nuclear database has been pre-calculated using the DHORIN code, described in previous work [22]. This Monte Carlo code handles both elastic and nonelastic processes and provides a detailed history of secondary particles (nature, energy, directions). Its range of validity is from 100 keV up to 200 MeV. This is sufficient for atmospheric purposes since the neutron spectrum rapidly decreases with energy; thus, most neutrons have energy below 200 MeV. It can be used either in a monoenergetic mode or in a spectrum mode. In the latter case, the user provides an energy differential flux and the code selects random energies in the spectrum with respect to the differential flux.

3.3. Upset criterion

Finally, primary and secondary ions are responsible for energy deposition in the device, corresponding to the production of electron–hole pairs. If a sufficiently large number of electron–hole pairs are produced at a given location in the device, we can assume that a soft error occurs. This criterion of energy deposition in a sensitive volume is often used by the radiation community [23]. Each bit of a memory is considered to have its own sensitive volume which is representative of each device. The critical energy (respectively critical charge) is also representative of the device, and represents the minimal energy (resp. charge) required to trigger a single event upset. The energy deposition and the charge production are linked simply by knowing that one electron–hole pair, which corresponds to the elementary charge 1.6×10^{-19} C, requires 3.6 eV in silicon. Both the sensitive volume size and the critical energy can be estimated with a test under beam or TCAD simulations [24]. The shape of the sensitive volume is often considered to be a rectangular parallelepiped (the RPP assumption) [23]. This latter assumption has its physical basis in Silicon on Insulator technology (SOI) since the buried oxide is a frank boundary of the sensitive volume. The RPP assumption is often used to provide trends for bulk technologies even if the sensitive volume has a rather diffuse boundary [25]. For SOI technology, a bipolar gain [26] can be accounted for by MC-ORACLE. For this case, the involved charge is not solely the deposited charge but is the deposited charge enhanced by a factor called the bipolar gain.

4. Computational method

Fig. 1 displays a flowchart of the MC-ORACLE code. The Monte Carlo method is used to simulate hundreds of thousands of primary particles in the structure. As seen in the flowchart, there are three main parts in the code, dealing with A) the structure, B) the particle–structure interaction, and C) the event cross section determination.

4.1. The structure

The device is defined in a universe containing several volumes having three possible shapes: parallelepiped, cylinder, and sphere. Each volume is associated with a material for which we have pre-computed the SRIM table for various ions and the history of nuclear reactions induced by neutrons and protons. Sensitive volumes are defined inside a virtual sensitive layer, which allows for rapid checking of the possibility of an event. Sensitive volumes are regularly spaced parallelepipeds. Fig. 2 shows an example of a bulk structure in which three layers have been defined: the bulk layer composed of silicon (in yellow), the passivation layer composed of SiO_2 (in cyan), and the sensitive layer (Si). This third layer is thin and is located between the bulk layer and the oxide. Sensitive volumes (in orange) are periodically repeated in both directions in the sensitive layer.

4.2. The particle–structure interaction

As described above, the MC-ORACLE code handles incident ions, alpha particle pollution, and nucleons. For incident ions and alpha particles, the ionization is treated using the pre-calculated tables of range and stopping power (SRIM). The neutrons and protons are considered to interact by nuclear reactions. Because the probability of a nuclear reaction is small, we implemented the ability to force the nuclear reaction of each primary particle. The location of this reaction is determined by calculating the mean free path of the particle in each layer; the mean free path is deduced from the nuclear cross section provided by the DHORIN code. After a nuclear reaction, the secondary particles are transported in the structure and interact by ionization.

4.3. The event cross section determination

When an ion crosses one of the sensitive volumes, we calculate the energy deposited inside the volume and store this value in a histogram, showing the number of soft errors as a function of critical energy (or critical charge). If several sensitive volumes are

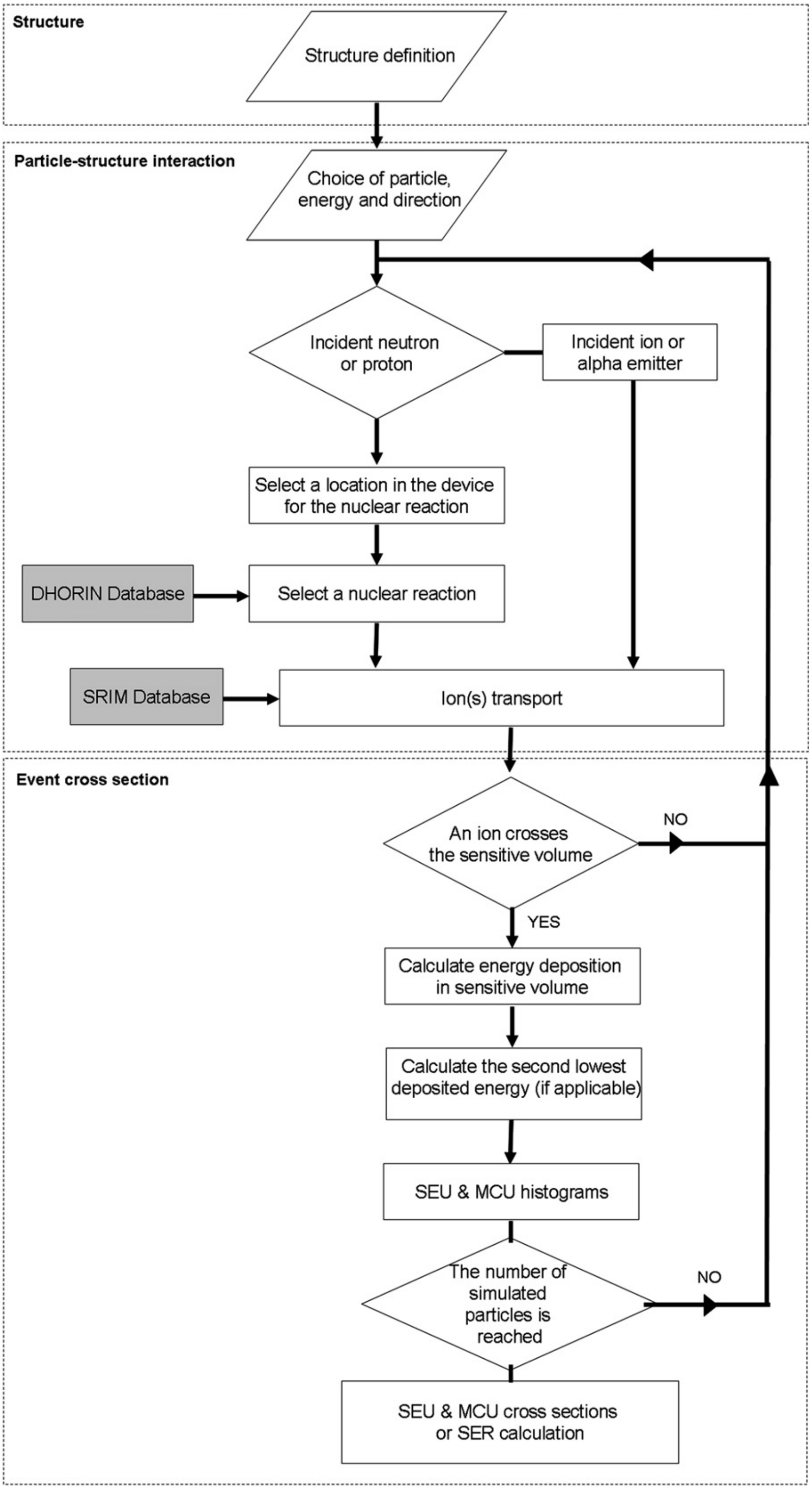

Fig. 1. Simplified flowchart of MC-ORACLE.

crossed by one or several ions, a second histogram is computed using the second lowest energy deposited in a sensitive volume. This histogram is useful for considering the multiple errors within Multiple Cell Upset (MCU). When the forced mode is used, the event is obviously weighted by the probability of interaction of the considered particle in the structure; this is conducted by accounting for the different material layers that can be crossed. This calculation produces two histograms, $n_{SEU}(E_c)$ and $n_{MCU}(E_c)$, which quantify the number of events leading to an energy deposition greater than the critical energy E_c. Except for alpha particles, the fluence Φ is then calculated as the total number of simulated events N_{tot} over the source area A_{source}. The event cross section is finally de-

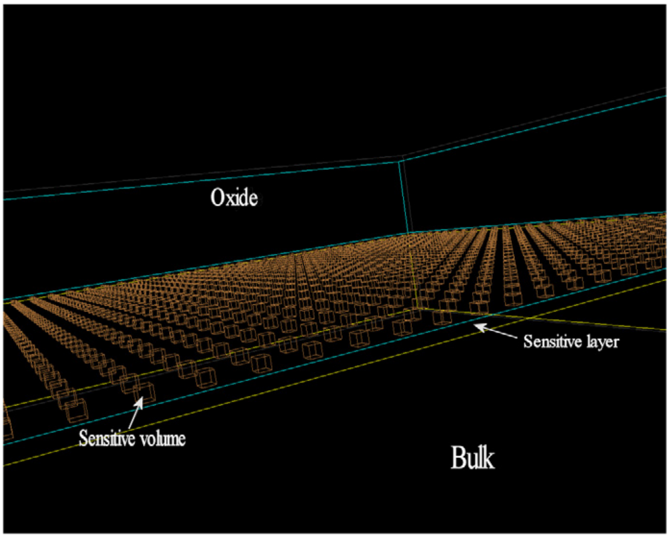

Fig. 2. Example of a bulk structure in RPP MC-ORACLE. The upper layer corresponds to the passivation oxide (SiO_2), and the lower layer is the bulk Si. Cubes are sensitive volumes located in the sensitive layer. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

termined by the ratio of the number of SEU (or MCU) over the fluence:

$$\sigma_{SEU}(E_c) = \frac{n_{SEU}(E_c)}{N_{tot}} A_{source}.$$

A similar expression provides the MCU cross section.

For alpha particles, we directly calculate the SER by determining the number of disintegrations in the device per billion hours. This number is computed from the exponential decay law given by nuclear physics, and involves the half time of the alpha emitter $T_{1/2}$ (in hours) and the initial number of alpha emitters, N_0. The alpha-SER is finally given by:

$$SER_\alpha(E_c) = \frac{n_{SEU}(E_c)}{N_{tot}} N_0 \left(1 - e^{-\ln(2)\frac{10^9}{T_{1/2}}}\right).$$

5. Results examples

5.1. Atmospheric neutrons

As an example, we simulated a SiO_2/Si structure with area 140 µm × 140 µm. Fig. 3 illustrates a nuclear reaction occurring in this simulated structure. The bulk layer (Si) is 25 µm thick, the sensitive layer (Si) is 1 µm thick, and the upper layer (SiO_2) is 24 µm thick. In the sensitive layer we defined 32 × 32 sensitive volumes having dimensions 1 µm × 1 µm × 1 µm. These were repeated with a spatial period of 4 µm in both directions. This kind of structure is similar to that described in [27], in which both the Monte Carlo and reverse Monte Carlo methods were used to simulate a single sensitive volume (1 µm × 1 µm × 1 µm) in a structure composed of only silicon. Because neutrons have an isotropic direction we chose at random a direction for each incident neutron. We then used the "forced mode" to trigger nuclear reactions in the structure. Each nuclear reaction produces secondary ions which deposit energy in the device. In Fig. 3, six ions are produced during the nuclear reaction example. Two of them leave the structure, two are stopped in the oxide, and two cross the sensitive layer (white segments). The simulation terminates when the sensitive layer is crossed 100,000 times. Fig. 4 plots the SEU cross section as a function of critical charge. Also shown in the figure are the results from [27], which used an independent code. Despite the differences between the two codes, the results are in good agreement. The observed discrepancies are attributed to the different nuclear codes used to simulate the nuclear reactions (MC-RED in [27] and DHORIN in this work). Moreover, the structure simulated in [27] is only made of silicon. The Monte Carlo method was applied to a limited volume around the sensitive volume, which led to an underestimation of the cross section. The reverse Monte Carlo method does not account for boundary effects and thus led to an overestimation of the cross section. Consequently, the agreement between MC-ORACLE and the results reported in [27] is correct.

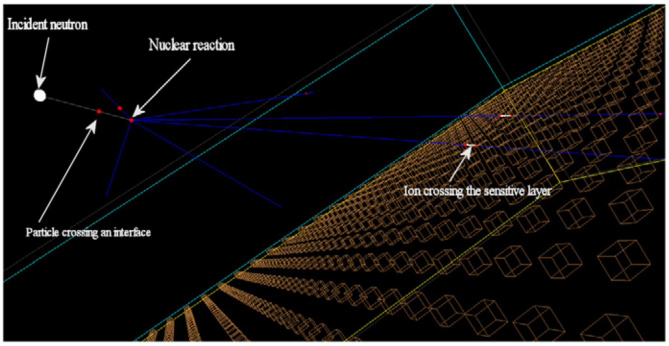

Fig. 3. An example of a neutron-induced nuclear reaction in a device at 100 MeV.

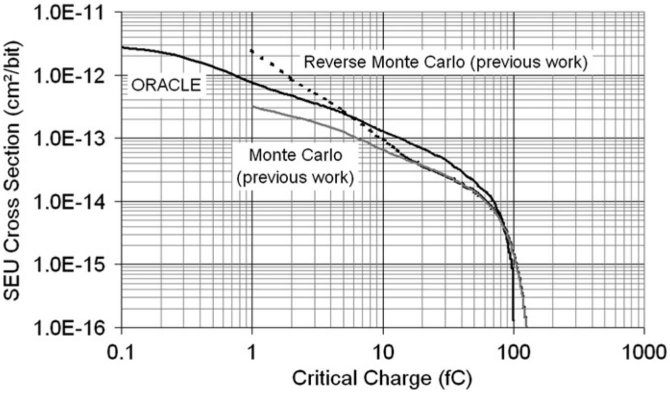

Fig. 4. Comparison between MC-ORACLE and a previous independent work based on another code [27].

5.2. Alpha emitters

In this example we simulated a Si/SiO_2 structure with an alpha source plan located at the top of the SiO_2 layer. Fig. 5 illustrates an alpha particle emitted by a ^{232}Th alpha emitter. The orange points are the simulated alpha emitters. The sensitive volume size is a cube of 0.245 μm^3, which is representative of a 250-nm bulk node [28]. Roche et al. [28] simulated a comparable structure using a property code. No information was provided on the oxide thickness, but a typical value is 7 µm. Fig. 6 compares their results to MC-ORACLE, in which the SER is plotted as a function of critical charge. Results are shown to be in good agreement.

6. Summary and conclusion

We developed the MC-ORACLE code to predict the Soft Error Rate for a given technology. The input parameters are the structure dimensions, the structure materials, the critical energy, and the sensitive volume dimensions (RPP criterion). The code can be applied to not just one type of particle, but to space ions and protons, atmospheric neutrons, and natural alpha emitters. The Monte Carlo approach is used to simulate the interaction of each incident particle in the device. MC-ORACLE provides cross sections and SER

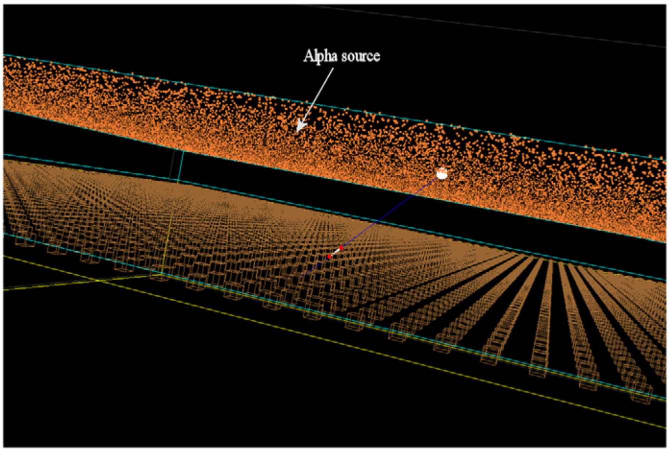

Fig. 5. Example of the MC-ORACLE simulation with a plan alpha source. The orange points are the locations of the simulated alpha emitters, and the white circle is the origin of the current alpha emitter. The blue segment is the alpha path in the oxide, and the white segment is the alpha path in the sensitive layer. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

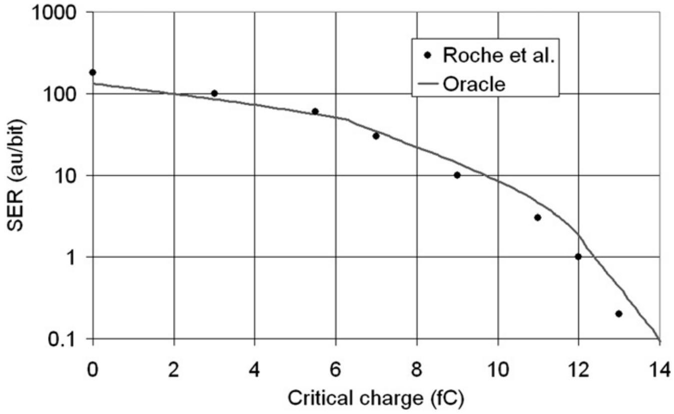

Fig. 6. Comparison between MC-ORACLE and previous work [28].

for both SEU and MCU results. Comparisons with previous work show that the MC-ORACLE results are consistent.

Because the RPP criterion is empirical it has some limitations, particularly for bulk technology in which the sensitive volume could be better represented by a hemispherical shape [25]. It has been proposed to replace the RPP sensitive volume by a more realistic one which can account for the collection charge efficiency. We plan to include these criteria in a future version of MC-ORACLE. Finally, it will be useful to estimate the shape of the current induced by the passage of a particle in the device. The Single Event Transient can be calculated by another approach, the diffusion–collection model [29], which also will be implemented in a future version of MC-ORACLE.

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