Development of a Nuclear Reaction Database on Silicon for Simulation of Neutron-Induced Single-Event Upsets in Microelectronics and its Application

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Abstract. We have developed a cross-section database for neutron-induced reactions on $^{28}$Si in the energy range between 2 MeV and 3 GeV in order to analyze single-event upsets (SEUs) phenomena induced by cosmic-ray neutrons in microelectronic devices. A simplified spherical device model is proposed for simulation of the initial processes of SEUs. The model is applied to SEU cross-section calculations for semiconductor memory devices. The calculated results are compared with measured SEU cross sections and the other simulation result. The dependence of SEU cross sections on incident neutron energy and secondary ions having the most important effects on SEUs are discussed.

INTRODUCTION

Radiation effects on microelectronic devices, e.g., single-event upsets (SEUs), have been recognized as one of the key reliability concerns for both current and future integrated-circuit technologies, and the related subjects are being studied extensively [1, 2]. Cosmic-ray neutrons with a wide energy range from MeV to GeV are regarded as one of the major sources of the SEUs in the devices used on the ground or in airplanes. Microscopically, the cosmic-ray-induced SEUs begin with the interaction of energetic neutrons with materials in the devices, and then light-charged particles and heavy ions can be generated via a nuclear reaction with a silicon nucleus. They can give rise to a local charge burst in a sub micron-size volume, which results in upsets of the memory cell information quantum. Therefore, the nuclear-reaction data to describe the probability of neutron interactions are highly requested as a fundamental physical quantity necessary for understanding the SEU phenomena and estimating the SEU rate. To meet this demand, we have constructed a cross section database for silicon, using two evaluated nuclear data files (JENDL-3.3 [9] and LA150 [10]) and the QMD calculation [11], for neutron energies ranging from 2 MeV to 3 GeV. The JENDL-3.3 library [9] was used to obtain the double-differential cross sections (DDXs) for light-charged particles ($p$ and $\alpha$) and all recoils ($^{24}$Mg, $^{25}$Al, and $^{27,28}$Si) in the $n^{+}\rightarrow^{28}$Si reaction for neutron energies between 2 MeV and 20 MeV. The DDXs calculation of the recoils from the JENDL-3.3 library was reported elsewhere [4]. The data for energies above 1646 MeV were taken from the LA150 library [10], in which the DDXs of all recoils are included, but the angular distributions are isotropic in the laboratory system. The cross sections for energies above...
150 MeV were calculated using the QMD [11] plus statistical decay model (GEM [12]).

In Fig. 1, the cross sections of elements produced in the \( n + ^{28}\text{Si} \) reaction are plotted for three incident energies, 10 MeV, 100 MeV, and 1000 MeV. It is seen that secondary ions with a wide mass number range are generated as the incident neutron energy increases.

![Figure 1](image1.jpg)

**FIGURE 1.** Production cross sections of secondary elements.

A SIMPLIFIED MONTE CARLO MODEL FOR CHARGE GENERATION AND COLLECTION

We consider SEU events in a simplified spherical device consisting of silicon, as shown in Fig. 2. This device model is similar to that used in [7]. The interaction and charge-collection volumes are concentric spheres with radii \( R_i \) and \( R_c \), respectively. A nuclear reaction with silicon takes place in the interaction volume, and secondary ions are generated and move in the device while slowing down. The energy deposited by a secondary ion into the charge-collection volume is calculated using the data of the range and energy loss obtained by the SRIM code [13]. It is assumed that the whole charge \( Q \) generated into the charge-collection volume is collected into a portion where the memory information is kept as charge, and if \( Q \) is greater than the critical charge, \( Q_c \), then the SEU happens eventually. In this model, the initial processes of the SEU event, namely, nuclear reactions with the silicon nucleus and the following charge deposition by the secondary ions, are taken into account properly, while the transport calculation of the generated charge by drift and diffusion processes is neglected and the size of the charge-collection volume is introduced as a model parameter, \( R_c \).

![Figure 2](image2.jpg)

**FIGURE 2.** Schematic illustration of the simplified spherical device model.

Using our simplified model, the SEU cross section for incident neutron energy, \( E_n \), is given by

\[
\sigma_{\text{SEU}}(E_n) = \sum_j \sigma_{\text{SEU}}^j(E_n)
\]

\[
\sigma_{\text{SEU}}^j(E_n) = N_{\text{Si}} \int_{r \leq R_i} \int_{Q > Q_c} \left( \frac{d^2 \sigma_j}{dE_j d\Omega_j} \right) dE_j d\Omega_j, \tag{1}
\]

where \( j \) denotes the kind of generated secondary ion, \( N_{\text{Si}} \) is the number density of the Si nucleus, and \( (d^2 \sigma_j/dE_j d\Omega_j) \) is the double-differential production cross section of the secondary ion \( j \). In practical calculations, isotropic angular distribution is assumed for emission of the secondary ion for simplicity; therefore \( (d^2 \sigma_j/dE_j d\Omega_j) \) is replaced by \( (d \sigma_j/dE_j)/4\pi \) in Eq. (1). This assumption represents approximately a situation where neutrons are incident into the device uniformly from any direction. The three-fold integration over the interaction volume and the energy and angle of the secondary ion in Eq. (1) is made using a Monte Carlo method under the condition, \( Q > Q_c \). The size of the interaction volume, \( R_i \), is determined by the condition where the calculation converges.

Using the neutron flux, \( \phi(E_n) \), the cosmic-ray-induced SEU rate is finally obtained by

\[
\text{SEU rate} = \int \sigma_{\text{SEU}}(E_n) \phi(E_n) dE_n. \tag{2}
\]

RESULTS AND DISCUSSION

Figure 3 shows a comparison of the calculation with measured data [8] for SRAMs with 256 Kb or 1 Mb. The measured data are normalized to the data of Cypress. One can notice that the energy dependence of the measured SEU cross sections is nearly similar and the magnitude alone depends strongly upon the devices. Accordingly, two parameters, \( Q_c \) and \( R_c \), were determined.
so that the energy dependence of the measured data is reproduced well, and the magnitude was finally normalized to the data of Cypress. The obtained best-fit values are $Q_c=53 \text{ fC}$ and $R_c=1.0 \mu\text{m}$. The calculation with these values shows satisfactory agreement with the measured data over the whole neutron-energy range. The results with different $Q_c$ and $R_c$ are also presented in Fig. 3 to see the sensitivities of these parameters to the calculation results. All the calculations are normalized at 45 MeV for comparison.

Next, our calculation based on the present simplified model is compared with a more realistic SEU simulation [5] for DRAM with $Q_c=30 \text{ fC}$ in Fig. 4. The error bars on the solid line stand for the statistical errors of our Monte Carlo calculation. Both results are normalized at 100 MeV for comparison. Our nuclear reaction database was also used in the latter simulation. Both calculations show good agreement below 150 MeV, while our calculation is at most 20% smaller than the latter one above 150 MeV. This result may indicate that our simplified model is useful in rough discussion about the neutron energy dependence of SEU cross sections, although it is too simple to predict the magnitude precisely.

Figure 5 illustrates a trend that lighter reaction products such as C, N, and O contribute to SEU largely at the highest incident energy of 1 GeV, while heavier reaction products such as Na, Mg, and Al are dominant at 50 MeV. To see the range effect of these secondary ions, the radial distributions of SEUs are plotted for O and Mg as a function of the distance from the center of the device at $E_n=50 \text{ MeV}$ and 1 GeV in Fig. 6. The contribution from the outer region far from the sensitive region becomes important for light-reaction products such as O. This trend is appreciable as the incident energy increases. Thus, it is found that the generation of light-reaction products in the long range affects SEUs predominantly at high-incident energies.

FIGURE 3. Comparison of calculated SEU cross sections with measured ones [8] for SRAMs. The measured data are normalized to the data of Cypress. The sensitivities of (a) $R_c$ and (b) $Q_c$ to the calculated results are shown.

FIGURE 4. Comparison of calculated SEU cross sections with other simulation results [5] for a DRAM device with $Q_c=30 \text{ fC}$. Both results are normalized at 100 MeV.

FIGURE 5. Ratio of each secondary ion to total SEU cross sections at $E_n=50 \text{ MeV}, 100 \text{ MeV},$ and 1 GeV for the device with $Q_c=30 \text{ fC}$ shown in Fig. 4.
SUMMARY AND CONCLUSIONS

For neutron-induced SEU simulations, the cross-section database of 28Si was constructed for incident energies ranging from 2 MeV to 3 GeV by using the evaluated nuclear data files (JENDL-3.3 and LA150) and the QMD calculation. A simplified spherical device model was proposed to simulate the initial processes, i.e., nuclear reactions and the sequential charge deposit by secondary ions, in the SEU effects. The SEU cross sections were calculated using the Monte Carlo method, by introducing the assumption that the SEUs occur if the initial charge deposited by secondary ions in the charge-collection volume exceeds the critical charge. The calculated results reproduced well the energy dependence of the measured SEU cross sections and the other simulation result. From the analyses, it turned out that heavy-reaction products (Na, Mg, Al, etc.) have important contributions at low-incident energies but light reaction products (C, N, O, etc.) become dominant with increasing incident energy.

This can be explained by the differences in the range and linear-energy transfer of ions.

Nuclear reaction data for the elements except Si (e.g., B, N, O, Al, P, Ti, Cu, As, Ta, etc.) are also required for more detailed SEU simulations. To meet the requirement, an extension of the present nuclear-reaction database is planned, and this task is to be accomplished in the JENDL high-energy file project [14] that is currently in progress.

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REFERENCES