Investigation of Nuclear Reaction Data for Analyses of Single-Event Effects in Semiconductor Devices

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We have investigated the effect of simultaneous multiple ions emission in neutron-induced reactions on single-event upsets (SEUs) and the relative importance of elastic scattering in SEUs in order to develop a nuclear reaction database of Si suitable for SEU microscopic simulation. Proton-induced SEU cross sections are calculated using a simplified empirical model that uses experimental heavy-ion induced SEU cross-sections and nuclear data for proton-induced reactions. In addition, an integral test of the proton nuclear data used is carried out though analyses of the energy deposition spectrum measured by bombardment of protons on a fully depleted surface barrier detector.

1. Introduction

In recent years, nucleon-induced single-event upsets (SEUs) have been a serious concern for microelectronic devices used in various radiation environments. For instance, terrestrial cosmic-ray neutrons hitting the earth have the wide energy range from MeV to GeV, and are regarded as one of the major sources of SEUs in the devices used at the ground level or in airplanes. Also, cosmic-ray protons are known to have a serious influence on SEUs in the devices installed in artificial satellites.

The nucleon-induced SEU is initiated by an interaction of incident cosmic-ray particles with materials in microelectronics devices. Light-charged particles and heavy recoils are generated via a nuclear reaction with a constituent atomic nucleus, mainly ^{28}Si, and then deposit the charge in a small sensitive volume (SV) of the device. The charge is collected at one of the nodes keeping the memory information and the resulting current transient generates an SEU. Therefore, reliable nuclear reaction data are required in estimating the SEU rate by numerical simulation methods.

So far we have created a dedicated nuclear reaction database using available nuclear data and theoretical model calculations, and have applied it to the calculation of neutron-induced SEU cross sections using a simplistic model [1]. The cross section data stored in the database consist of “inclusive” energy spectra of each secondary ion, and the angular distribution was assumed to be isotropic. Use of the inclusive data means ignorance of an event that multiple ions are emitted simultaneously, which becomes important with increasing incident energy. In the calculation of upset cross sections, we have used a simplified geometry having a spherical SV and a step-like critical energy required to flip a logical state.

Sophistication of the nuclear reaction database will be necessary for more reliable SEU simulations. In the present work, we pay attention to two nuclear processes, simultaneous multiple ions emission and elastic scattering, and investigate these effects on SEUs quantitatively. Since neutron elastic scattering cross sections of Si are larger than reaction cross sections at intermediate incident energies where cosmic-ray neutrons are expected to provide a large sensitivity to SEU rate, it is of interest to estimate the relative contribution using recent reliable nuclear data [2]. For SEU cross-section calculations, we extend the spherical SV geometry to a rectangular parallelepiped geometry widely used. In addition, intra-cell variation of charge collection is taken into account using experimental heavy ion SEU cross sections under an assumption that their dependence of the deposition energy reflects the variation [3]. Our semi-empirical model is applied to calculations of proton induced SEU cross-sections and comparisons with experimental data and the other model calculation are presented. Finally, an integral test of the nuclear reaction data used in the calculation is also performed by analyses of an energy deposition spectrum obtained by proton bombardment on a fully depleted surface barrier detector (SBD).

2. Monte Carlo simulator based on sensitive volume concept

Our model uses a well-known memory cell geometry having a sensitive volume (SV) of rectangular parallelepiped shape as shown in Fig.1. The SV is defined as the volume containing all the charges deposited by secondary ions generated from the interaction between an incident nucleon and ^{28}Si, which are ultimately collected by a memory node and induce an SEU. One of the important physical quantities relevant to the SEU is the distribution function of the energy E_d deposited in the SV. It is hereinafter denoted by $f(E_{in}, E_d)$, where E_{in} is the incident energy. It is characterized by the nuclear reaction, particularly energy and angular distributions of the generated secondary ions, and ion penetration and linear energy transfer (LET) into the device. Note that the deposited charge Q_d can be reduced to the deposited energy E_d using the expression, E_d (in MeV) = 0.0225 Q_d (in fC).

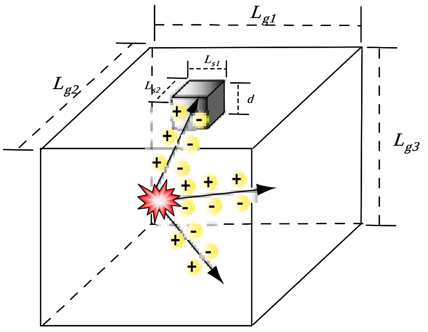

Fig. 1 Schematic illustration of memory cell geometry including the sensitive volume

Using $f(E_{in}, E_d)$, the nucleon-induced SEU cross section is expressed by

$$\sigma_{SEU}(E_{in}) = N_{\mathrm{Si}} V_{\mathrm{int}} \sigma_N(E_{in}) \int_0^\infty f(E_{in}, E_d) h(E_d) dE_d \ , \tag{1}$$

where N_{Si} is the number density of silicon atoms, V_{int} the volume size of the region ("interaction volume") where nuclear reactions occur in the memory cell, $\sigma_N(E_{in})$ the cross section to describe the interaction between an incident nucleon and ^{28}Si, which is given by the sum of elastic scattering cross section and reaction cross section, $h(E_d)$ the normalized heavy-ion SEU cross section expressed by the following Weibull fitting function:

$$h(E_d) = \sigma_{HI}(E_d)/\sigma_{HI}^{\infty} = 1 - \exp\left\{ -\left[\frac{E_d - E_0}{W} \right]^s \right\}, \tag{2}$$

where W and s are shape parameters, σ_{HI}^{∞} is the saturation value of the heavy-ion SEU cross section and E_0 the SEU threshold. Since experimental heavy-ion SEU data are usually given as a function of LET, we need to convert it to the energy using the relation $E_d = d \times LET$, where d represents the sensitive depth. If we assume a step function $h(E_d) = \Theta(E_d - E_c)$, where E_c is called the critical energy required to cause an SEU, then Eq.(1) reduces to

$$\sigma_{SEU}(E_{in}, E_c) = N_{\mathrm{Si}} V_{\mathrm{int}} \sigma_N(E_{in}) F(E_c) \ , \tag{3}$$

where $F(E_c) = \int_{E_c}^{\infty} f(E_{in}, E_d) dE_d$.

The distribution function $f(E_{in}, E_d)$ is calculated by a Monte Carlo method using a nuclear reaction database and a range and energy loss database of secondary ions. In the present work, two kinds of neutron and proton databases from 20 MeV to 1 GeV are prepared using the JQMD/GEM code [4,5]. One consists of so-called "inclusive" double-differential cross sections of all secondary ions including light ions. Another contains the "event-by-event" information, *i.e.*, the kind of secondary ions and their emission energy and angle, so that simultaneous multiple ions emission can be correctly taken into account.

When the former "inclusive" database is used, a secondary ion j is firstly generated in a position chosen randomly in the interaction volume by sampling its energy and emission direction in terms of the double-differential cross sections. Then, the energy deposited by the ion in the SV is calculated numerically using the data of range and energy loss computed by the SRIM code [6]. In this case, $\sigma_N(E_{in}) f(E_{in}, E)$ used in Eqs.(1) and (3) is replaced by $\sum_j \sigma_j(E_{in}) f_j(E_{in}, E)$ where $\sigma_j(E_{in})$ is the production cross section of the ion of type j. Consequently, Eq.(3) can be re-written by

$$\sigma_{SEU}(E_{in}, E_c) = N_{\mathrm{Si}} V_{\mathrm{int}} \sum_j \sigma_j(E_{in}) F_j(E_c) = N_{\mathrm{Si}} V_{\mathrm{int}} \sum_j \int_{E_c}^{\infty} \sigma_j(E_{in}) f_j(E_{in}, E_d) dE_d \ , \tag{4}$$

It should be noted that Eq.(4) was used to calculate SEU cross sections in our earlier work [1].

In case of using the latter "event-by-event" database, a position where a nuclear reaction occurs is chosen randomly in the interaction volume shown in Fig.1. Then the total energy deposited in the SV by all secondary ions generated in a certain reaction event is calculated using the above-mentioned way.

3. Influence of nuclear data on neutron-induced SEU analysis

First, we have investigated the effect of simultaneous multiple ions emission on SEUs by comparing the energy deposit calculated using the above-mentioned two different nuclear reaction databases consisting of the “inclusive” data (denoted hereinafter Cal. 1) and the “event-by-event” data (Cal.2) , respectively. Next, the relative importance of elastic scattering has been examined in the incident energy region below 150 MeV. It should be noted that Eq.(3) was used in both analyses.

3.1 Simultaneous multiple ions emission

In Fig. 2(a), the SEU cross sections calculated by Eq. (3) are plotted as a function of E_c for the case of a small sensitive volume with V_s = 1 x 1 x 1 μm^3. There is no obvious difference between two calculations with different nuclear reaction data sets. This implies that simultaneous multiple ions emission has negligible effect on SEUs if the size of SV is small. To see the reason, we have obtained the mean number of emitted ions as functions of the atomic number of generated ions and the incident neutron energy. As shown in Fig.3, light ions, particularly protons and deuterons, are mainly included in the simultaneous multiple ions emission and the total fraction of heavy ions is nearly equal to unity. Even if many light ions are generated by a nuclear reaction, the energy deposited in the small SV is negligibly small because of their low LET. Also, the probability that more than one ion passes through the SV simultaneously is reduced as the size of SV becomes small. From this analysis, we have found that it is a quite good approximation to use the “inclusive” nuclear data in the calculation of SEU rates for a device having as small SV as this, and therefore it is not necessary to revise the results obtained in our previous work [1] not considering the multiple ions emission.

Figure 2(b) shows the result for a larger SV size (V_s = 20 x 20 x 2 μm^3) than that used in Fig.2 (a), because we will discuss SEU for a device of the similar size in the following section. There is an appreciable difference between two calculations as the critical energy is over 2 MeV corresponding to Q_c=89 fC. Also, a significant difference is seen near E_c=0. Since the sensitive area is much wider than the above case, light ions emitted in the lateral direction can deposit considerable energy along the path in spite of low LET. Thus, the emitted light-ions become involved in SEU as well. If one uses the “inclusive” data, contributions from these light ions are added incoherently, which results in larger value at very small E_c than Cal.2. In the calculation with the “event-by-event” data, the total energy deposited by all the ions generated in a nuclear reaction is tallied. This leads to enhancement at larger E_c compared to the result of Cal.1.

From this investigation, it was found that the simultaneous multiple ions emission that is predominant at high incident energies does not influence seriously on SEUs for the devices having the small SV size. However, it should be noted that the multiple ions emission is expected to have some sort of effects on multiple bits upsets (MBUs).

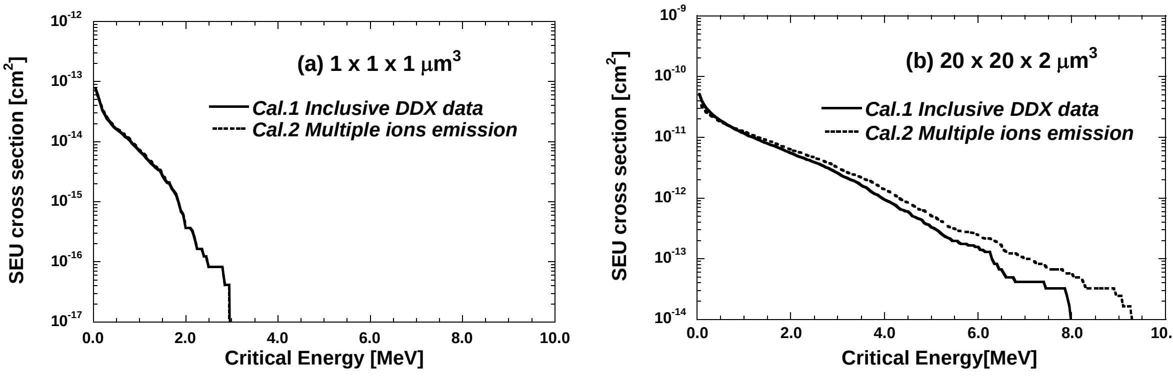

Fig.2 Calculated neutron SEU cross section as a function of critical energy E_c for the following sensitive volume: (a) V_s = 1 x 1 x 1 μm^3 and (b) V_s = 20 x 20 x 2 μm^3

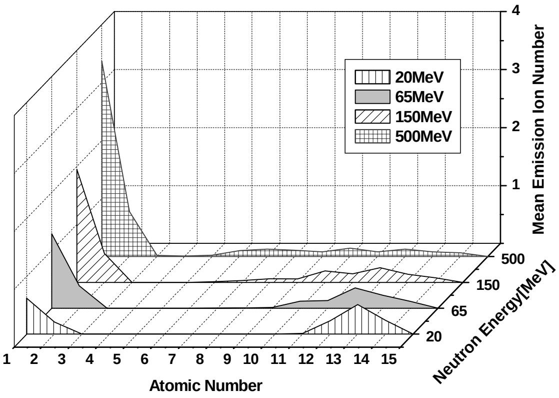

Fig.3 Average number distribution of secondary ions obtained by the QMD calculation

3.2 Elastic scattering

We have examined the effect of elastic scattering on SEU using JENDL/HE-2004 data [2], because the elastic scattering is not included in the QMD calculation. As shown in Fig.4, the elastic cross section is much larger than the reaction cross section in the energy range between 20 and 120 MeV. Therefore, it is of importance to know how the elastic scattering influences on SEU in the energy range of interest.

Relative contribution of the elastic scattering to SEU is calculated as functions of incident energy and critical charge for a device having the sensitive volume V_s = 1 x 1 x 1 μm^3. The ratio of the elastic SEU cross-section to the total SEU cross section is plotted as a function of incident neutron energy in Fig.5. Paying attention to the energy range above 20 MeV, one finds that the contribution of the elastic scattering increases as the critical charge is reduced and the maximum fraction is at most 20 % near 20 MeV. This supports a similar estimation by Barak et al.[7] made in their proton-induced SEU analysis. Less important role of the elastic scattering can be explained by the fact that the average kinetic energy of the recoiled ^{28}Si becomes smaller, because the angular distribution of elastically scattered neutron becomes steeper with increasing incident energy. On the other hand, the ratio increases suddenly up to unity at a certain energy corresponding to the SEU threshold energy below 10 MeV except at Q_c=50 fC. In this energy range, the elastic scattering becomes dominant as seen in Fig.5 and the other reaction channels are suppressed. From the present analysis, therefore, the elastic scattering is expected to play an important role near the SEU threshold energy for memory devices with small Q_c.

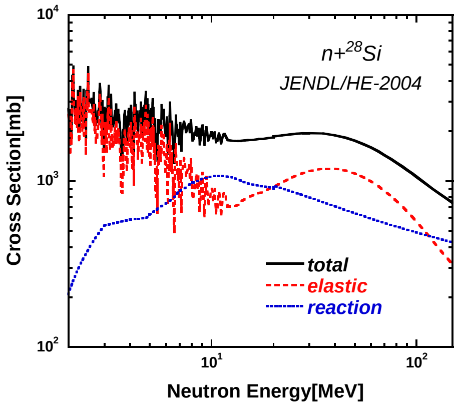

Fig.4 Neutron total, elastic, and reaction cross-section of ^{28}Si taken from JENDL/HE-2004

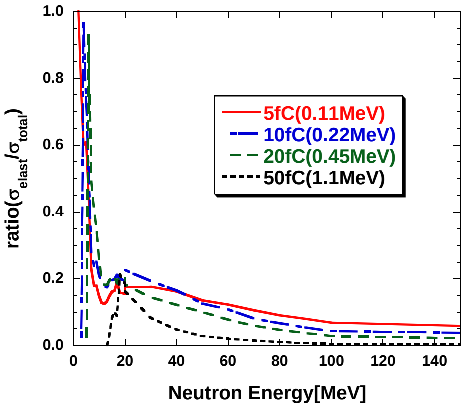

Fig.5 Ratio of the elastic SEU cross section to the total SEU cross section

4. Calculation of proton-induced SEU cross sections

We have applied the present semi-empirical model expressed by Eqs.(1) and (2) to the calculation of proton induced SEU cross-sections for some memory devices at incident energies below 200 MeV. In the calculations, the "event-by-event" nuclear reaction data and the JENDL/HE-2004 data for elastic scattering were used. In addition, the experimental spectrum of the energy deposited by protons in a fully depleted surface barrier detector (SBD) has been analyzed using our Monte Carlo calculation. The results and discussion are given below.

4.1 Results and comparisons

Proton SEU cross sections were calculated using the Weibull function parameters of heavy-ion SEU cross sections for some memory devices whose parameters and experimental data are compiled in Ref.[8]. The dimension of the SV was determined by the sensitive area saturation cross section, σ_{HI}^{∞}, in Eq.(2) and a “standard” value of the sensitive depth, d=2 mm. The interaction volume surrounding the SV (50 x 50 x 50 μm^3.) was taken to be so large that the calculated proton SEU cross-section is saturated

In Fig.6, the result for three devices is shown in comparison with measured data and the other empirical model calculation using an analytic expression proposed by Barak [9,10]. Our model calculation is generally in good agreement with the measured SEU cross sections in shape and magnitude, and particularly shows better agreement than the Barak’s calculation for HM6516. The SV size is a key parameter in SEU cross-section calculations using the models based on the SV concept. Although the sensitive depth used in the present work is the standard value and must have device-dependence, influences of the SV size on the SEU cross section have not been investigated in details because it is beyond the scope of the present work.

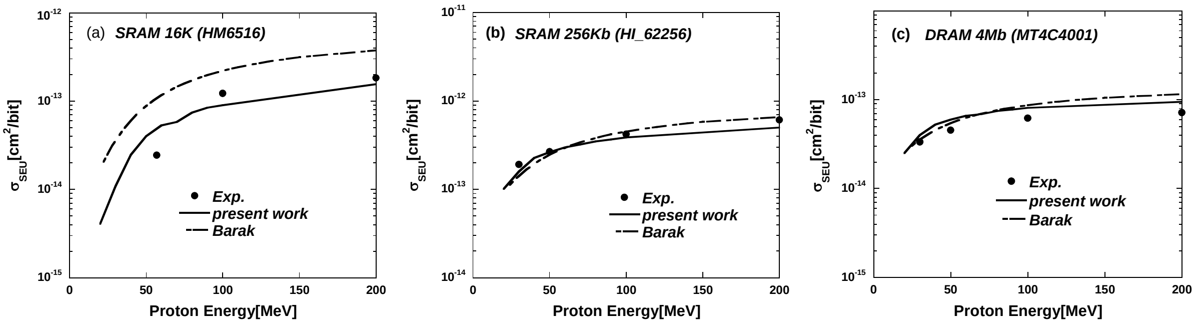

Fig.6 Comparison of calculated proton SEU cross-sections with experimental data and Barak’s work[9,10]

4.2 Analysis of energy deposition spectrum for surface barrier detector

Barak et al.[9,10] have derived an analytic expression of $f(E_{in}, E_d)$ in Eq.(1) based on the experimental spectra of the energy deposited by protons in fully depleted SBDs. Here we compare their experimental data with our Monte Carlo calculation.

Figure 7 show a comparison of experimental and calculated integral spectra for an SBD with thickness of 2 μm and the sensitive area 10 mm^2 at incident proton energy of 300 MeV. The integral spectrum represents the total event numbers obtained by integrating the deposition energy spectrum from a given energy to infinity. Our calculation depicted by the solid line underestimates the measurement at deposition energies above 7 MeV. Since the SBD has the large lateral dimension, the energy deposition by light ions is expected to play an important role from discussion in the above section 3.1. The present version of the QMD code underestimates remarkably the high-energy component of light cluster ions such as deuteron and alpha as described in Ref.[11]. To see whether the underestimation seen in Fig.7 is related to the lack of emission of high-energy light cluster ions, a preliminary calculation was performed using the QMD model improved in Ref.[11]. The result is shown by the dotted line in Fig.7. As expected, better agreement is obtained although underestimation is still seen at energies above 10 MeV. From this consideration, we conclude that the disagreement is probably due to insufficient description of light cluster ions production.

Finally, we discuss whether light cluster ions have a serious effect on the proton SEU cross sections in Fig.6. Since the typical sensitive area for these memory devices in Fig.6 is 20 x 20 μm^2, which is considerably smaller than the sensitive area of the SBD (10 mm^2), the energy deposited by light cluster ions with large kinetic energy is negligibly small compared to the SEU threshold energy E_0. Consequently, it is expected that the high-energy components of light cluster ions play a lesser role in SEU in actual memory devices. A variation of the energy spectra of recoils associated with high-energy light cluster ions emission might effect partially on the total energy deposition. A detailed analysis of the effect is in progress.

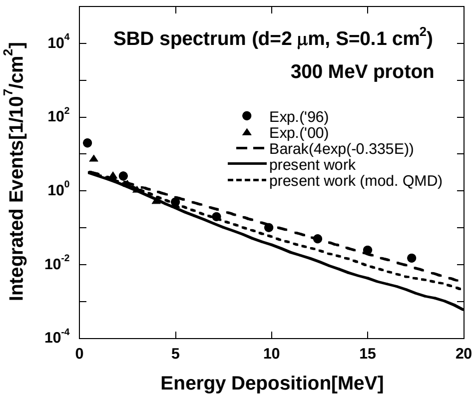

Fig.7 Experimental and calculated integral SBD spectra for E_p=300 MeV

5. Summary and conclusions

We have investigated the effect of multiple ions emission on SEU and the relative importance of elastic scattering in SEU. The multiple ions emission was found to have negligible effects in the case where the sensitive volume (SV) size is sufficiently small because the light ions having low LET are primarily produced in the process. However, multiple ions production probably has some impact on multiple-bit upsets (MBUs) for devices with low Q_c [12]. The qualitative estimation will be necessary in the future. It was found that the relative importance of elastic scattering increases when the amount of critical charge Q_c is small, because the averaged kinetic energy of the recoiled ^{28}Si is smaller than the other heavy recoils. Our qualitative evaluation for the memory devices with the small SV indicated that its contribution has at most 20% for Q_c = 5 fC.

The proton-SEU cross sections were calculated using the semi-empirical model with the "event-by-event" nuclear reaction data and the JENDL/HE-2004 for the elastic scattering. The result reproduced generally well the incident energy dependence of experimental proton-SEU cross sections in both shape and magnitude. The distribution function of the energy deposited in the SV, which is one of the important physical quantities in this model, was compared with the experimental data for the fully depleted SBD with the large lateral dimension. As a result, the underestimation was seen for high-energy deposition, which is probably attributable to the lack of preequilibrium components of light cluster ions such as deuteron and alpha. This will require further refinement of the present QMD model for light cluster ions production in order to provide more reliable nuclear reaction data for microscopic simulation of SEUs.

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