Nuclear data relevant to single event upsets in semiconductor memories induced by cosmic-ray neutrons and protons

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The role of nuclear data is examined in the study of single event upset (SEU) phenomena in semiconductor memories caused by cosmic-ray neutrons and protons. Neutron and proton SEU cross sections are calculated with a simplified semi-empirical model using experimental heavy-ion SEU cross-sections and a dedicated database of neutron and proton induced reactions on ^{28}Si. Some impacts of the nuclear reaction data on SEU simulation are analyzed by investigating relative contribution of secondary ions and neutron elastic scattering to SEU and influence of simultaneous multiple ions emission on SEU.

1. Introduction

In recent years, cosmic-rays induced single-event upsets (SEUs) have been recognized as a key reliability concern for microelectronic devices used not only in space but also at the ground level or in airplanes at higher altitude. The SEU is one of the transient radiation effects by which the memory state of a cell can be flipped from a 1 to a 0 or vice versa, resulting in malfunction. As illustrated schematically in Fig.1, the SEU is initiated by the interaction of incident cosmic-ray particles with materials in microelectronics devices. Then, light-charged particles and heavy recoils are generated via the 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 deposited charge is collected at one of the nodes keeping the memory information and the resulting transient current generates an SEU. Knowledge on nuclear physics and radiation physics is indispensable to understand well these elementary processes in the SEU phenomena. Particularly, nuclear reaction data play an essential role in estimating the SEU rate accurately, because the nuclear interaction takes place in the first stage of the SEU process.

So far, we have studied the SEU as one of the applications of high-energy nuclear data [1,2]. A dedicated nuclear reaction database was created using available nuclear data and theoretical model calculations, and was applied to calculations of nucleon-induced SEU cross sections using a semi-empirical model based on SV concept mentioned below. The results were compared with experimental SEU cross sections, and influences of nuclear data on the SEU simulation were investigated.

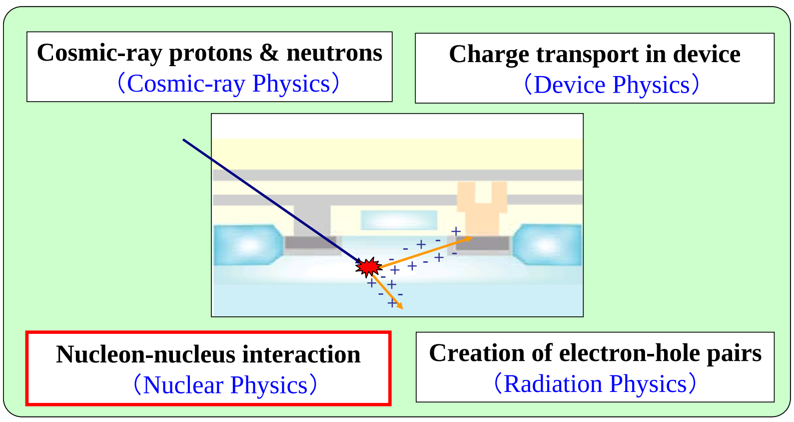

Fig.1 Schematic illustration of SEU phenomena

In this report, our recent work on SEU is summarized. The Monte Carlo simulation method is described in sect. 2. In sect. 3, the calculated SEU cross sections are compared with experimental data. In sect. 4, we discuss the incident energy dependence of secondary-ion dependent SEU fraction and the effect of neutron elastic scattering and simultaneous multiple ions emission on SEU. Finally, a summary and future outlook is given in sect.5.

2. Monte Carlo simulator based on sensitive volume concept

Figure 2 illustrates a general flow chart of SEU simulation. Our calculation model [2] uses a well-known memory cell geometry having a sensitive volume (SV) of rectangular parallelepiped shape as shown schematically in Fig.3. 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. It should be noted that the deposited charge Q_d can be reduced to the deposited energy E_d using the relation, E_d (in MeV) = 0.0225 Q_d (in fC). Therefore, the quantity $f(E_{in}, E_d)$ corresponds to the initial charge deposition distribution.

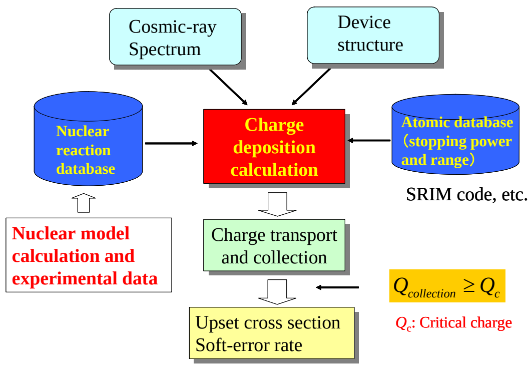

Fig. 2 Flow chart of SEU simulation

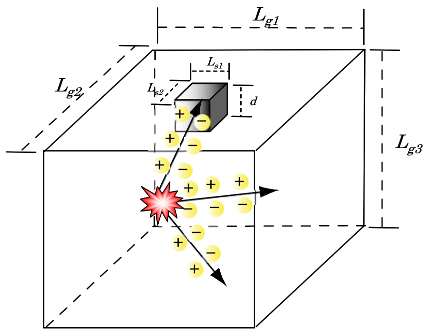

Fig. 3 Schematic illustration of memory cell geometry including the sensitive volume

In the present model, a semi-empirical approach using experimental heavy-ion SEU cross sections [3,4] is applied when one calculates nucleon-induced SEU cross section from the energy deposition distribution, $f(E_{in}, E_d)$, instead of charge transport and collection simulation. The nucleon-induced SEU cross section is expressed by

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

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 of interest, $\sigma_N(E_{in})$ 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 total reaction cross section, $h(E_d)$ the normalized heavy-ion SEU cross section expressed by the following Weibull fitting function:

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

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 deposit 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) is given by

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

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 as illustrated in Fig.2. In the present work, two kinds of neutron and proton databases from 20 MeV to 1 GeV are prepared using the JQMD/GEM code [5,6]. 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 type of secondary ions and their emission energy and angle, so that simultaneous multiple ions emission can be correctly taken into account. Figure 4 shows a comparison of JQMD/GEM calculation with experimental data [7] for the p+Al reaction at 180 MeV, because there is no similar experimental data for Si. For production of heavy ions, the angle-dependent energy spectra are reproduced well by the JQMD/GEM calculation.

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 [8]. 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

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

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.3. 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.

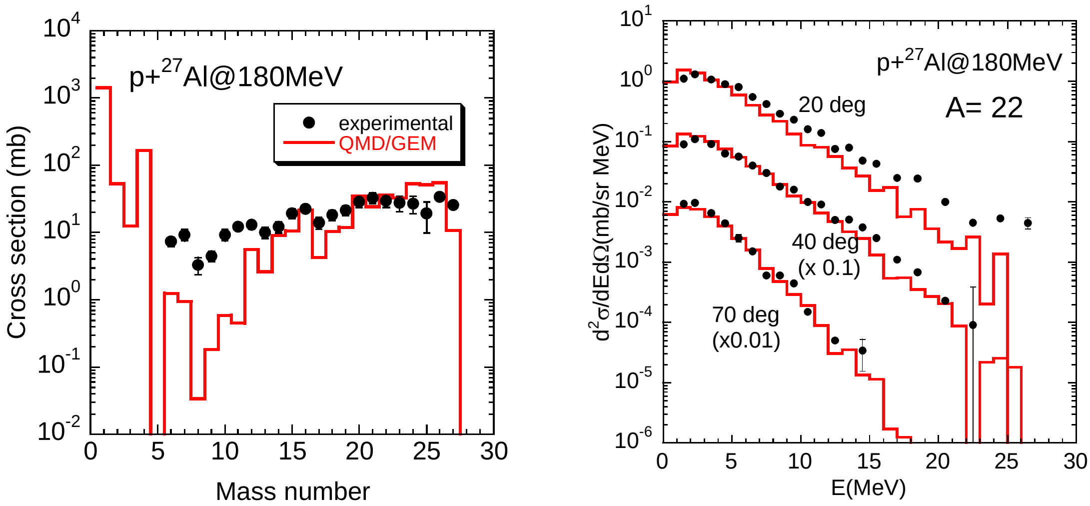

Fig.4 Comparison of JQMD/GEM calculation with experimental data of p+Al reaction at 180 MeV [7]

3. Comparison of calculated proton SEU cross-sections with experimental data

The present semi-empirical model is applied to calculations of proton induced SEU cross-sections for some memory devices at incident energies below 500 MeV. In the calculations, the "event-by-event" nuclear reaction data and the JENDL/HE-2004 data [9] for elastic scattering were used. In Fig.5, two examples of the results are presented with experimental data [10,11] for (a) 256Kb SRAM (HM62256) and (b) 4Mb SRAM (HM628512A), respectively. Other results are also shown in ref.[1]. The Weibull function parameters of heavy-ion SEU cross sections in Eq.(2) were determined by fitting of the experimental data for both devices [10,12]. The dimension of the SV was defined by the saturation cross section, σ_{HI}^{∞}, and the sensitive depth, *d*, which is a free parameter. The interaction volume surrounding the SV was taken to be so large that the calculated proton SEU cross-section was saturated.

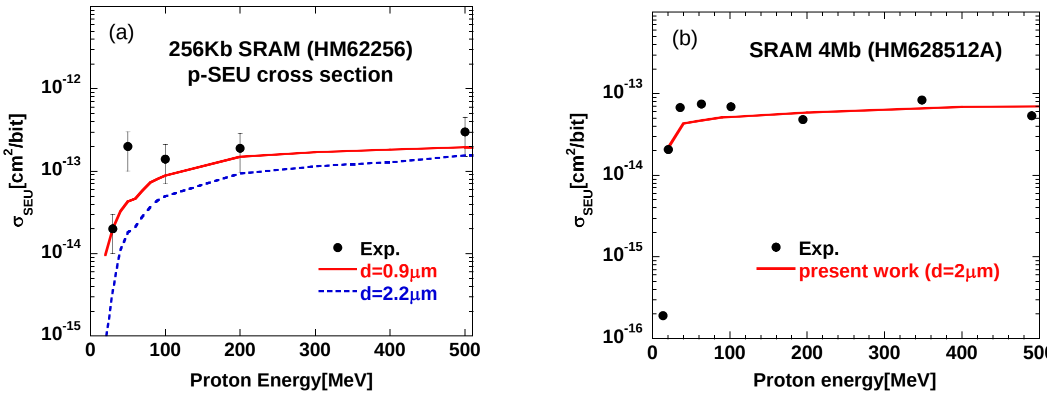

Fig.5 Comparison of calculated proton SEU cross-sections with experimental data [10,11]
(a) 256Kb SRAM and (b) 4Mb SRAM

In Fig.5, our model calculation is generally in good agreement with the measured SEU cross sections in shape and magnitude. The proton SEU cross sections rise steeply at energies below 50 MeV and become nearly constant at energies higher than 100 MeV. The SV size is one of the key parameters in calculations of SEU cross-section using the models based on the SV concept. In Fig.5(a), the dependence of the sensitive depth (d= 0.9 and 2.2 μm [13]) is shown. Our calculation supports the smaller *d* value. However, further investigation will be necessary for reliable determination of the sensitive depth.

4. Discussion

4.1 Relative contribution of secondary-ion on SEU

We have examined relative contribution of secondary ions to SEU cross section for two different Q_c values: (a) Q_c =50fC and (b) 10fC. It is calculated using Eq. (4) as functions of incident energy and critical charge for a device having the sensitive volume V_s = 1 x 1 x 1 μm^3, and the "inclusive" reaction data (without elastic scattering) are used. As can be seen in Fig.6, heavier ions (Na, Mg, and Al) are dominant at lower incident energies, while lighter ions (C,N, and O) contribute as the incident energy increases. As Q_c become smaller, there appears the contribution from lighter ions with atomic mass less than Be, particularly He. Since these light ions have smaller LET than heavy ions, SEU may take place for smaller Q_c. It should be noted that the QMD calculation underestimates the production of secondary ions with A=6 to 12 as shown in Fig.4. Further improvement of the reaction model will be necessary because Q_c is expected to decrease more and more in the future.

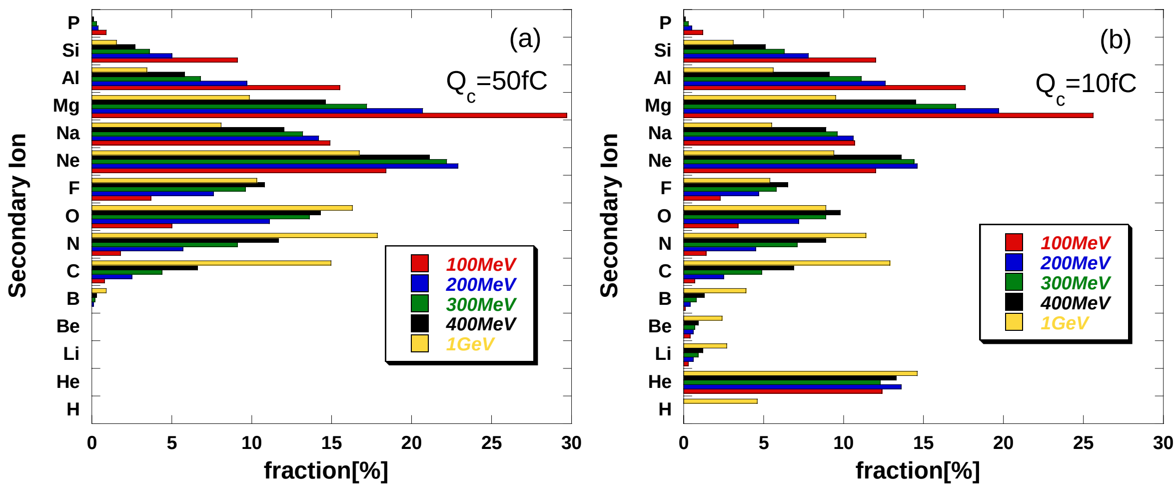

Fig.6 Relative contribution of each secondary ion to SEU cross section: (a) Q_c =50fC and (b) 10fC

4.2 Neutron elastic scattering

The influence of neutron elastic scattering on SEU was examined using JENDL/HE-2004 data [2], because the elastic scattering is not included in the QMD calculation. As shown in Fig.7, the elastic cross section is much larger than the reaction cross section in the incident energy range between 20 and 120 MeV. Therefore, it is of importance to know how the elastic scattering influences on SEU in the incident 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.8. Paying attention to the energy range above 20 MeV, one can find 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. 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 than other heavy recoils as seen in Fig.9. 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 is the most dominant nuclear process as seen in Fig.7 and the other reaction channels are suppressed. Thus, the elastic scattering is expected to play an essential role near the SEU threshold energy for the memory devices with small Q_c.

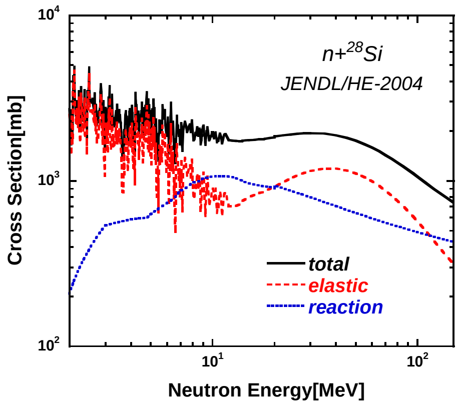

Fig.7 Neutron total, elastic, and reaction cross-section of ^{28}Si taken from JENDL/HE-2004

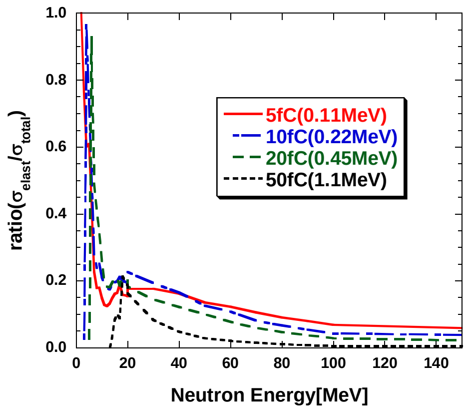

Fig.8 Ratio of the elastic SEU cross section to the total SEU cross section

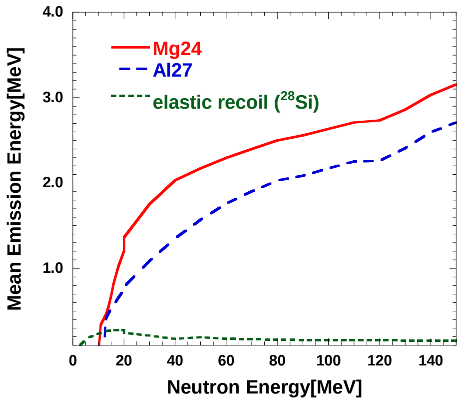

Fig.9 Averaged emission energy for elastic recoil (^{28}Si), ^{27}Al and ^{24}Mg

4.3 Simultaneous multiple ions emission

The effect of simultaneous multiple ions emission on SEU was investigated by comparing the SEU cross sections 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 [2].

In Fig. 10(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 influence on SEU if the size of SV is small. To see the reason, the mean number of emitted ions was examined as functions of the atomic number of generated ions and the incident neutron energy. Secondary light ions, particularly protons and deuterons, are mainly included in the simultaneous multiple ions emission and the total fraction of heavy nuclides is nearly equal to unity. Even if many light ions are generated by a certain nuclear reaction, the energy deposited in the small SV is negligibly small because of their low LET. Also, a geometrical consideration suggests that the probability that more than one ion passes through the SV simultaneously is reduced as the size of SV becomes small. The present analysis indicates 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 case.

Figure 10(b) shows the result for a larger SV size (V_s = 20 x 20 x 2 μm^3) than that used in Fig.10(a). In this case, 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 reaction event is tallied. This leads to enhancement at larger E_c compared to the result of Cal.1.

Through this investigation, we draw a conclusion hat the simultaneous multiple ions emission does not influence seriously on SEUs for the devices having the small SV size. However, such multiple-ions emission is expected to have some sorts of effects on multiple bits upsets (MBUs) [14].

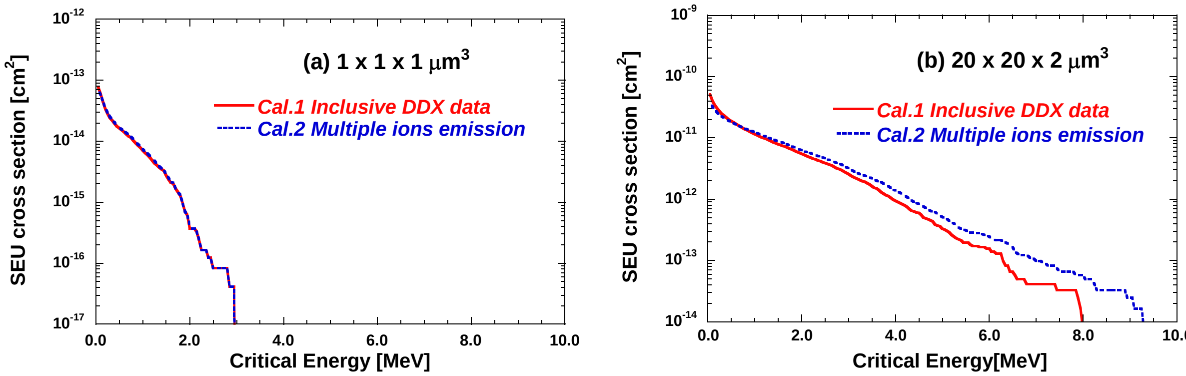

Fig.10 Calculated neutron SEU cross section as a function of critical energy E_c for the following sensitive volume: (a) V_s = 1 x 1 x 1 μm^3 and (b) V_s = 20 x 20 x 2 μm^3

5. Summary and outlook

The results of our recent work on nucleon-induced SEUs were presented from the point of view of the nuclear reaction data relevant to SEUs. The proton SEU cross sections calculated using the semi-empirical model with the "event-by-event" nuclear reaction data and the JENDL/HE-2004 for the elastic scattering reproduced generally well the incident energy dependence of experimental proton SEU cross sections in both shape and magnitude. This indicates that the present semi-empirical model based on the sensitive volume concept has a capability of predicting nucleon-induced SEU cross sections reasonably well if one can obtain available heavy-ion SEU data and reliable information about the sensitive depth.

Some quantitative analyses were performed in order to investigate the crucial impact of nuclear reaction data on SEU simulation. The relative contribution of secondary ions to proton SEU cross section was investigated. As a result, it was found that secondary heavy ions has a larger contribution at low incident energies than light ions, while the latter has a large fraction as the incident energy increases and the critical charge decreases. The analysis indicates that the relative importance of elastic scattering is enhanced when the critical charge is small, because the averaged kinetic energy of the recoil nucleus, ^{28}Si, is smaller than the other heavy recoils. Our calculation for the memory devices with the small SV shows that its fraction becomes at most 20% for Q_c = 5 fC. In addition, the simultaneous 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, it is likely that multiple ions production has some impact on multiple-bit upsets (MBUs) for devices with low Q_c [14].

The critical charge in SRAMs is expected to decrease more and more with progress in high integration in the future [15]. As shown in Fig. 6, our analysis suggests a possibility that light-ion production such as alpha will have a large effect on SEU. The present QMD/GEM model underestimates preequilibrium components for light composite particle emission. This will require further refinement in order to provide more reliable nuclear reaction data for microscopic simulation of SEUs. The present status of the related nuclear data measurements is not satisfactory. Therefore, experimental double-differential cross sections of all secondary ions will be strongly requested to benchmark the nuclear data and/or nuclear model calculations used in SEU simulations.

Acknowledgement

The author is grateful to Akihiro Kodama and Kouta Nishijima for their full cooperation on this work.

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