3.24 Nuclear data relevant to single-event upsets (SEU) in microelectronics and their application to SEU simulation

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A cross-section database for neutron-induced reactions on ^{28}Si was developed 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 was proposed for simulation of the initial process of SEUs. The model was applied to SEU cross-section calculations for semiconductor memory devices. The calculated results were 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.

1. Introduction

In recent years, the radiation effects known as single-event upsets (SEUs) in microelectronics have been recognized as a key reliability concern for many current and future silicon-based integrated circuit technologies [1]. Cosmic-ray neutrons ranging from MeV to GeV are regarded as one of the major sources of the SEUs in devices used on the ground or in airplanes. A microscopic picture of the cosmic-ray induced SEUs is given as follows. Energetic neutrons interact with materials used in the devices, and light charged particles and heavy ions can be generated via a nuclear reaction with a silicon nucleus. They can give rise to local charge burst in a sub micron-size volume, which results in upsets of the memory cell information quantum. Therefore, nuclear reaction data to describe the interaction of neutrons with the nuclides contained in the devices are highly requested as a fundamental physical quantity necessary for SEU simulations. Thus, we have recently developed a cross section database for silicon, using evaluated nuclear data files (JENDL-3.3 and LA150) and QMD calculations for energies ranging from 2 MeV to 3 GeV [1]. So far, it has been applied successfully to several SEU simulations [2][3].

In the present work, we propose a simplified model of calculating SEU cross sections based on the Monte Carlo method as the first stage to apply our developed nuclear reaction database to the SEU simulation, instead of our previous BGR model [2]. Using the present model, we analyze systematic experimental data [4] for SRAM in the energy range up to 160 MeV and a simulation result [3] for DRAM up to 1GeV. In the analyses, the dependence of SEU cross sections on incident neutron energy is investigated, and the secondary ions having the most significant effect on SEUs are specified. In addition, the effect of critical charge and sensitive volume on SEU cross sections is discussed.

2. Cross section database for n+^{28}Si reaction

The JENDL-3.3 library [5] was used to obtain the double-differential cross sections (DDXs) for light charged particles (p and α) and all recoils(^{24,25}Mg, ^{27,28}Al, and ^{27,28}Si) in the n+ ^{28}Si reaction at neutron energies between 2 and 20 MeV. The data for energies between 20 to 150 MeV were taken from the LA150 library [6] in which the DDXs of all recoils are included. We have calculated the cross sections for energies above 150 MeV using the QMD [7] plus statistical decay model (GEM [8]) calculation.

3. A simple Monte Carlo model for charge generation and collection

We consider SEU events in a simplified spherical device as shown in Fig.1. The interaction and sensitive volumes are concentric spheres with radii R_I and R_S, respectively. A nuclear reaction with Si 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 sensitive volume is obtained by using SRIM code [9]. It is assumed that the whole charge (Q) generated by the ions into the sensitive volume is collected into the capacitor, and if Q is greater than the critical charge, Q_c, and then the SEU happens eventually. In this model, the initial processes of the SEU event, namely, nuclear reactions with the Si 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 sensitive volume is introduced as a model parameter, R_S.

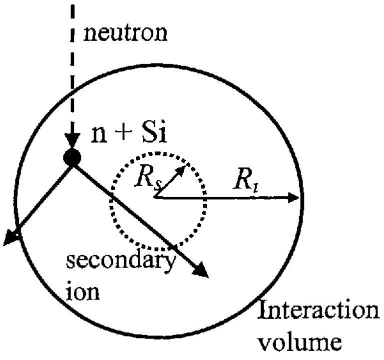

Fig.1 Schematic illustration of simplified spherical device model

Within this simplified model, the SEU cross section for incident neutron energy, E_n, is given by

$$\sigma_{SEU}(E_n) = \sum_j \sigma^j_{SEU}(E_n) = N_{Si} \sum_j \int_{r \le R_I} d\vec{r} \left[\iint_{Q>Q_c} \left(\frac{d^2\sigma_j}{dE_j d\Omega_j} \right) dE_j d\Omega_j \right], \qquad (1)$$

where j denotes the kind of generated secondary ion, N_{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 directions. The three-fold integration over the interaction volume and the energy and angle of secondary ion in Eq.(1) is made using a Monte Carlo method under a condition $Q > Q_c$. The size of the interaction volume, R_I, is determined by a condition where the calculation converges.

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

$$\text{SEU rate} = \int \sigma_{SEU}(E_n)\phi(E_n) dE_n \, , \qquad (2)$$

where the IBM model [10] is used for the cosmic ray flux in the present calculation.

4. Results and discussion

Figure 2 shows a comparison of the calculation with measured data [4] for SRAMs with 256Kb or 1Mb. The measured data are normalized to the data of Cypress. One can notice that the energy dependence of the measured $\sigma_{SEU}(E_n)$ is nearly similar and the magnitude alone depends strongly upon the devices. Accordingly, two parameters, Q_c and R_S, 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 resultant best-fit values are Q_c=53 fC and R_s=1.0 μm. 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 shown in **Fig.3** to see the sensitivities of these parameters to the calculation results. All the calculations are normalized at 40 MeV for comparisons.

In **Fig.4**, the ratio of each secondary ion to the calculated SEU cross-sections is plotted as a function of the incident neutron energy. It is found that heavy ions such as Na, Mg, and Al have a large contribution to SEU and light reaction products such as O and N become significant with increasing energy. One notices that Mg has the most significant contribution at energies below 20 MeV. This can be explained by the energy spectra of secondary ions at an incident energy of 20 MeV shown in **Fig.5**. The critical charge Q_c=53 fC corresponds to the energy deposit, E_{dep}=1.2 MeV. The energy spectra of Mg isotopes are distributed over wider energy range beyond 1.2 MeV compared with the other isotopes, and thus the cross sections of Mg integrated over the energy range become largest. This is the reason why Mg plays the most significant role below 20 MeV in SEUs for the device with Q_c=53 fC. In addition, it is found that the contribution from Si is reduced with decrease in neutron energy. This trend can be explained by the fact that the elastic and inelastic cross sections become small and their angular distributions become more forward-peaked as the neutron energy increases. It should be noted that the present results obtained by these analyses of SRAM are similar to our previous results by the BGR model [2].

Our calculation based on the present simplified model is compared with a more realistic SEU simulation [3] for DRAM with Q_c=30 fC in **Fig.6**. Both results are normalized at 40 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 about 20 % smaller than the latter one above 150 MeV. This may indicate that it is enough possible to investigate the energy dependence of SEU cross sections within the framework of this simplified model, although it is limited to predict the magnitude correctly.

Figure 7 illustrates how lighter reaction products such as C, N and O have the most significant contribution 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 MeV and 1 GeV in **Fig.8**. 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 having the long range affects SEUs predominantly in the high incident energy range.

Finally, the cosmic-ray induced SEU rates were calculated using Eq.(2) as functions of R_s and Q_c. The result is presented in **Fig.9**. The SEU rate is reduced as R_s decreases. In the case of Q_c =0, the SEU rate is proportional to R_s^2, which corresponds to the geometrical cross section of the sensitive volume having the spherical shape. As R_s becomes smaller, the dependence of the SEU rate upon Q_c becomes strong and the SEU rate is reduced remarkably as Q_c becomes large. On the other hand, there is such a correlation that reduction of the sensitive volume size leads to that of Q_c in realistic devices. Therefore, it is expected that the slope of reduction of SEU rate against R_s does not become so steep. More realistic simulation will be necessary to discuss the device scaling effect on SEUs in details.

5. Summary and conclusions

The nuclear reaction database suitable for the neutron-induced SEU simulation was developed 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 following charge deposit by secondary ions, in the SEU phenomena. The SEU cross sections were calculated using the Monte Carlo method, by introducing the assumption that SEU occurs if the initial charge deposited by secondary ions in a sensitive volume exceeds the critical charge. The calculated results reproduced well the energy dependence of the measured SEU cross sections for energies and the other simulation result. From the analyses, it was found that heavy reaction products (Na, Mg, Al, etc.) have crucial contributions at low-incident energies but light reaction products (C, N, O, etc.) become dominant as the incident energy increases. This can be explained by the differences in the range and linear energy transfer of ions.

Nuclear reaction data for the elements except Si included in the devices (e.g., B, N, O, Al, P, Ti, Cu, As, Ta, etc.) will be also required for more detailed SEU simulations. To meet the requirement, one of our future tasks related to SEUs is an extension of the present nuclear reaction database. It is expected that this task will be accomplished in the JENDL high-energy file project [11] that is now in progress.

Acknowledgements

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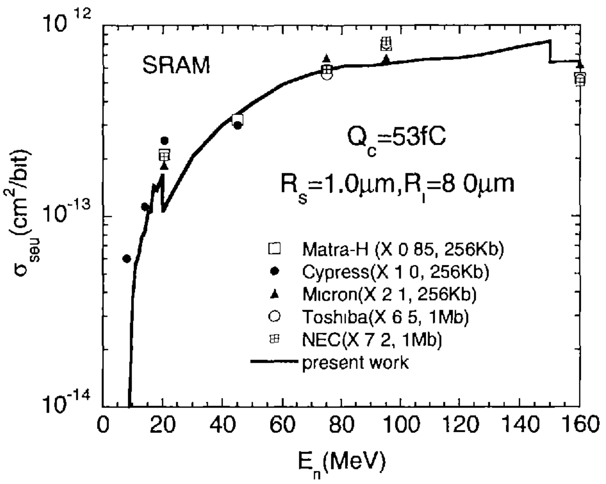


Fig.2 Comparison of calculated SEU cross sections with measured ones [4] for SRAMs. The measured data are normalized to the data of Cypress.

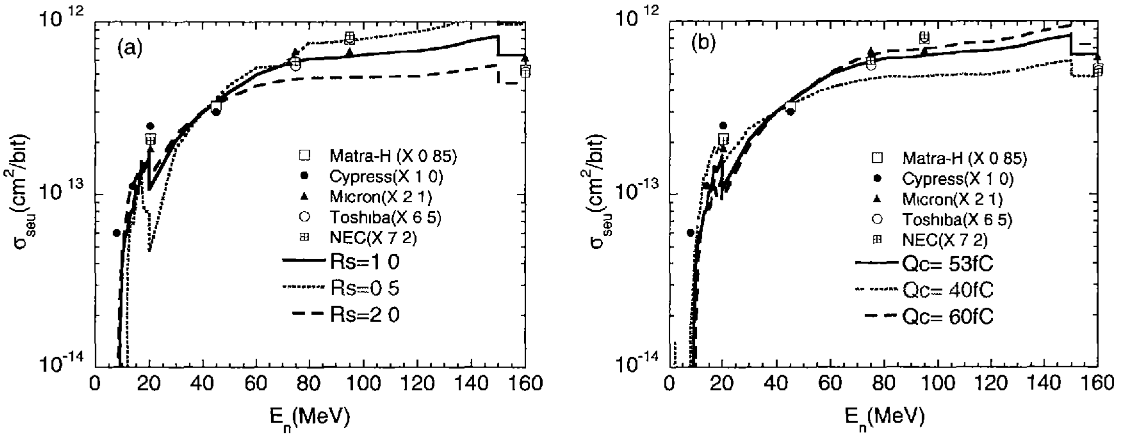
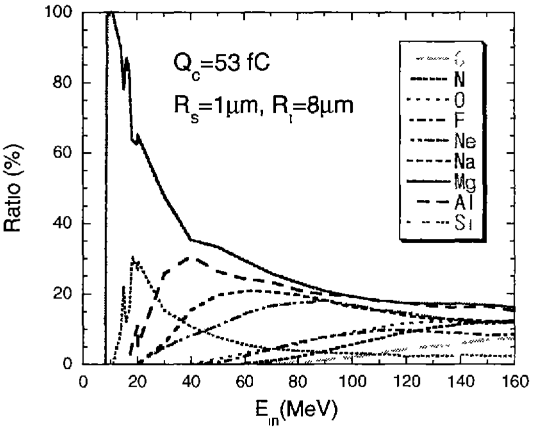


Fig.3 Same as in Fig.2, but the sensitivities of (a) R_s and (b) Q_c to the calculated results are shown.



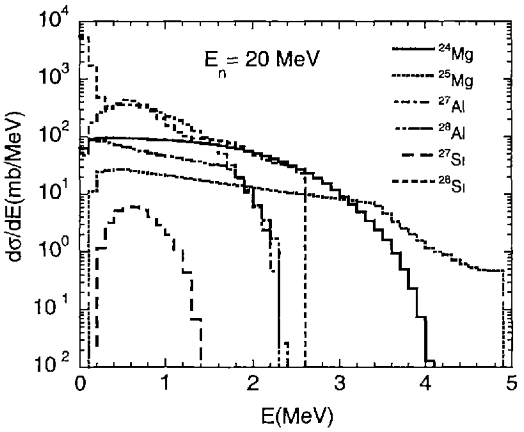


Fig.4 Ratio of each secondary ion to total SEU cross sections as a function of incident neutron energy.

Fig.5 Energy spectra of all secondary ions for an incident energy of 20 MeV.

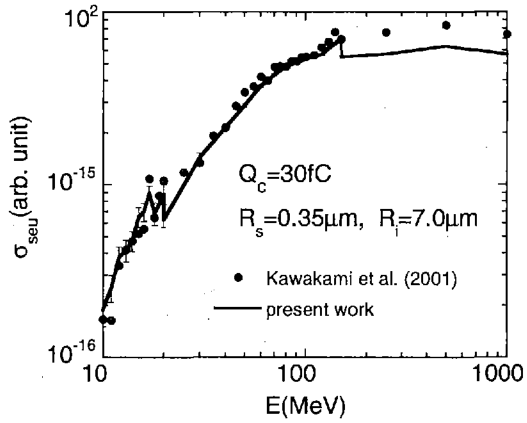


Fig.6 Comparison of calculated SEU cross sections with other simulation result [3] for a DRAM device with Q_c=30 fC. Both results are normalized at 40 MeV.

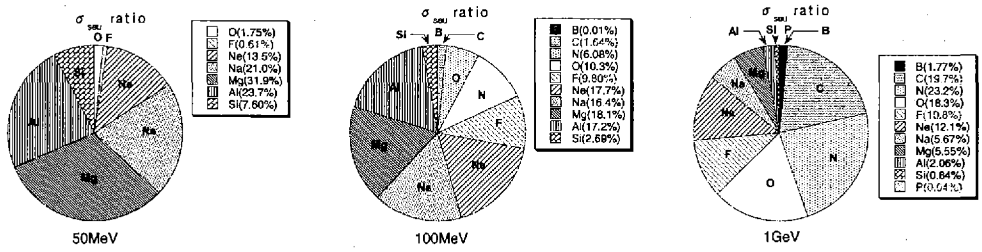


Fig.7 Ratio of each secondary ion to total SEU cross sections at E_n= 50 MeV, 100 MeV and 1 GeV for the device with Q_c=30 fC shown in Fig.6.

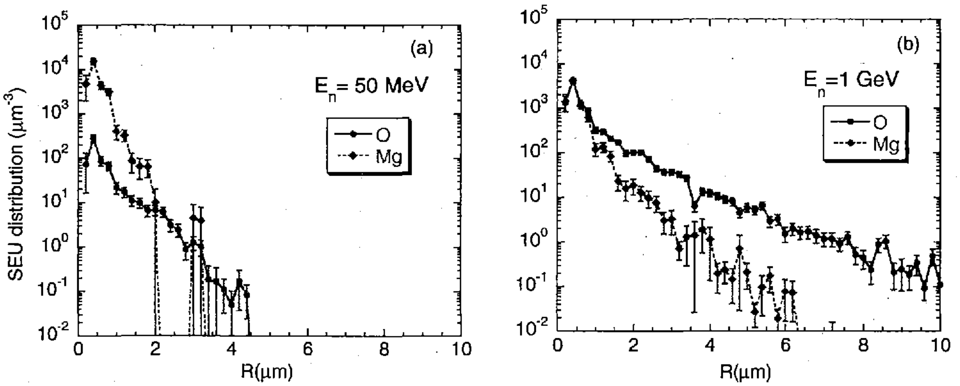


Fig.8 Radial distribution of SEUs at E_n= 50 MeV and 1 GeV for a device with Q_c=30fC and R_s=0.35μm. The error bar indicates the statistical error included in the Monte Carlo calculation.

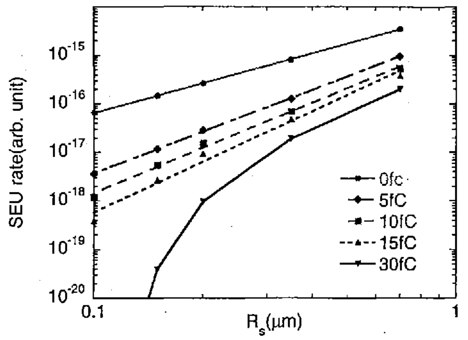


Fig.9 Sensitivities of Q_c and R_s to SEU rate