Calculation of neutron-induced single-event upset cross sections for semiconductor memory devices

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Neutron-induced single-event upset (SEU) cross sections for semiconductor memory devices are calculated by the Burst Generation Rate (BGR) method using LA150 data and QMD calculation in the neutron energy range between 20 MeV and 10 GeV. The calculated results are compared with the measured SEU cross sections for energies up to 160 MeV, and the validity of the calculation method and the nuclear data used is verified. The kind of reaction products and the neutron energy range that have the most effect on SEU are discussed.

1. Introduction

In recent years, much attention has been paid to cosmic-ray induced soft errors in semiconductor memory devices used at sea level and in aircrafts as well as in artificial satellites in space[1]. Cosmic rays at sea level consist of mainly neutrons, protons, pions, and muons over a wide energy range from MeV to GeV. These energetic cosmic-ray particles interact with materials used in semiconductor memory devices, and fast heavy ions can be generated via a nuclear reaction with a silicon nucleus. These ions can give rise to local charge burst in a micron volume, which results in upset of the memory cell information quantum that is called "single-event upset (SEU)". This is known as a microscopic picture of the cosmic-ray induced soft errors. Therefore, quantitative estimation of the soft errors requires more reliable nuclear reaction data for silicon in the high-energy range and modeling of charge transport in microelectronics devices.

In the present work, we focus on the soft errors induced by neutrons having about 95% of the cosmic rays at sea level. Neutron-induced SEU cross sections are calculated by the Burst Generation Rate (BGR) method[2] using LA150 data[3] and QMD calculation[4] in the neutron energy range between 20 MeV and 10 GeV. The calculated results are compared with measured SEU cross sections up to 160 MeV[5], and the kind of reaction products and the neutron energy range that are crucial to the SEU are also investigated.

2. A Method of calculating SEU cross sections

2.1 Burst Generation Rate (BGR) model

The SEU rate is defined by

$$\text{SEU rate} = \int \sigma_{SEU}(E_n)\phi(E_n)dE_n \ , \tag{1}$$

where $\sigma_{SEU}(E_n)$ is the SEU cross section for a neutron energy, E_n, and $\phi(E_n)$ is the neutron flux. Using the Burst Generation Rate (BGR) method[2], $\sigma_{SEU}(E_n)$ is given by

$$\sigma_{SEU}(E_n) = C \cdot V \cdot BGR(E_n, Q_c), \tag{2}$$

where C is the charge collection efficiency and V is the sensitive volume per bit. The BGR is defined as the probability that the charged particles and ions with energy more than a critical energy E_r are emitted in the nuclear reaction, and is given as a function of incident neutron energy, E_n and critical charge, Q_c which can be converted into E_r using the relation E_r(MeV) = 22.5 Q_c (pC).

$$BGR(E_n, Q_c) = \sum_i BGR(E_n, Q_c, A_i, Z_i)$$
$$= N_{Si} \sum_i \iint_{E_r}^{E_{\max}^{(i)}} \left(\frac{d^2\sigma}{dEd\Omega} \right)^{(i)} d\Omega dE, \tag{3}$$

where N_{Si} is the number density of silicon atoms, and the index i stands for the kind of reaction product with mass number A_i and atomic number Z_i. $(d^2\sigma/dEd\Omega)^{(i)}$ is the double-differential production cross section of the reaction product i.

In the previous papers related to the BGR model[2], $E_{\max}^{(i)}$ was assumed to be the maximum emission energy of the reaction product i. However, this treatment might overestimate the BGR when one considers the energy deposit of ions with high energy in a finite volume. Since the energy deposit in a small volume depends on the linear energy transfer (LET), we newly introduce an "effective depth d " as a parameter for BGR calculations. By taking into account the LET, $E_{\max}^{(i)}$ is estimated as the maximum energy of the reaction product i that deposits energy above E_r within the depth d. Note that isotropic angular distribution is assumed for emission of the reaction products for simplicity.

This naïve method does not account for transport of local burst charge in a medium, and therefore corresponds to the zero-order approximation to charge transport. In the present work, the product of C and V is treated as a normalization parameter that can be determined so as to fit experimental $\sigma_{SEU}(E_n)$ data as mentioned below.

2.2 Input data

LA150 nuclear data[3] are used for energies from 20 to 150 MeV. For energies above 150 MeV, the JQMD code[4] based on the QMD plus statistical decay model (SDM) is employed to calculate the energy spectra of reaction products. The default parameters are used in the JQMD calculations. The total reaction cross section calculated by QMD is normalized to a systematics given by Niita[6]. Note that light charged-particles (p, d, t, ^{3}He, and α) and those heavy ions with their atomic numbers less than 5 are not considered in the SEU calculations because the energy deposit by these particles and ions is very small and their effect on SEU is negligible.

The SRIM code[7] is used to calculate the LET necessary to estimate the maximum energy $E_{\max}^{(i)}$ in Eq.(3).

3. Results and discussions

Figure 1 shows a comparison of calculations with measured data [5] for SRAMs with 256Kb or 1Mb. The measured data are normalized to the data of Cypress. As can be seen in Fig.1, the measured SEU cross sections shows a weak dependence on chips and have a similar energy dependence. The normalization constant CV in Eq.(2) was determined so as to provide the BGR function calculated with Q_c=0.1pC and d=1μm a best fit to the data of Cypress. The solid curve with Q_c =0.1pC and d=1μm shows satisfactory agreement with the measured data. Use of a finite effective depth d=1μm leads to a decrease in the calculated SEU cross section with increasing neutron energy, as can be seen from a comparison between the solid curve and the dotted one.

Calculations of the SEU cross section are extended to incident energies above 150 MeV. The QMD plus SDM calculation was used to obtain the relevant nuclear reaction data, *i.e.*, energy spectra of all emitted heavy nuclei. Before the nuclear data are inputted to calculations of SEU cross-sections, one should see to what extent the QMD plus SDM calculation can reproduce experimental differential data. Since there is no experimental data for neutron-induced reactions on ^{28}Si, we have applied the QMD plus SDM calculation to the proton-induced reaction on ^{27}Al at 180 MeV[8] and examined the applicability. Comparisons of the calculation with experimental data are shown in Figs.2 to 4. The calculated results are in good agreement with the experimental data to a similar extent to the AMD calculation[9], except for production of heavy ions with $A < 11$.

Calculated BGR functions with LA150 and QMD nuclear data are plotted for energies up to 10 GeV together with the calculated reaction cross section, σ_R, in Fig.5. A discontinuity of the calculated BGR functions appears at an incident energy of 150 MeV, because the nuclear data used is altered at this energy. For neutron energies above 100 MeV, the BGR function calculated with infinite depth $d=\infty$ shows the energy dependence similar to the reaction cross section that is almost independent of the energy. On the other hand, the BGR function with a finite effective depth d=1μm decreases with an increase in neutron energy. This may be due to an increase in the average kinetic energy of the reaction products, which leads to reduction of the energy deposited in the medium because the LET becomes small. In the energy range less than 100 MeV, the BGR function decreases as the incident energy decreases, while the reaction cross section increases. This opposite behavior can be explained from two main causes. One of them is that major components among the reaction products for lower incident energies are light ions, such as protons and alpha particles, which provide negligible contribution to SEU. Furthermore, the energy spectra of residual heavy nuclei are shifted to the low energy side and the contribution to BGR functions becomes small in a case with rather large Q_c corresponding to high threshold energy E_r. This can be seen from Fig.6 that shows a dependence of Q_c on BGR functions in the case of d=1μm. It is found that the dependence is strong and Q_c affects the shape of the BGR functions at low incident energies.

Using the BGR functions given in Fig.6, the incident energy range having the most effect on the SEU rate has been examined by assuming a neutron flux distribution at sea level given by IBM group[1]. The resultant integrated SEU rate is plotted as a function of the incident neutron energy in Fig.7. A major contribution (up to about 90 %) to the SEU rate comes from neutrons up to 400 MeV for semiconductor memory devices with these Q_c values. Therefore, this means that the relevant nuclear data of silicon with high accuracy are necessary for reliable estimation of the SER rate, particularly, at energies ranging from 20 to 400 MeV.

Finally, we have investigated the kind of reaction products that influence largely the SEU. The result is presented for two incident energies, 150 MeV and 1 GeV, in Fig.8. Both the cases show that production of heavy ions such as Ne, Na, and Mg plays a major role in the SEU because such ions have large LET.

4. Conclusion

The BGR functions were calculated in the neutron energy range between 20 MeV and 10 GeV using the neutron nuclear data of LA150 and the QMD calculation by considering the LET of reaction products. The SEU cross sections obtained using the calculated BGR functions reproduced well the energy dependence of the experimental ones up to 160 MeV for SRAMs with 256Kb or 1Mb by introducing the finite effective depth *d* as a parameter. The incident energy range having the most effect on the SEU rate at sea level was found to be 20 to 400 MeV, particularly, for devices with small effective charge Q_c. In addition, it was found that the reaction products that influence the SEU strongly are the heavy ions such as Ne, Na, and Mg having large LET.

This work is the first step towards establishment of a reliable method of evaluating soft errors in semiconductor memory devices. From the point of view of the nuclear reaction data, a new evaluation [10] in JENDL High energy file should be applied to calculations of the neutron-induced SEU cross sections in order to see a dependence of the nuclear data used. In addition, calculations of proton and pion induced SEU cross sections will be interesting to see similarities and differences in effects of neutrons, protons, and pions on the SEU in order to enhance understandings of the mechanisms of soft errors.

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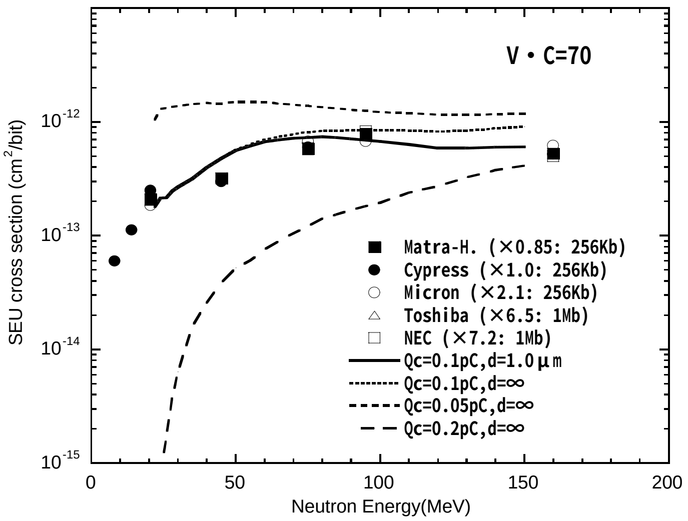

Fig.1 Comparison of the calculated SEU cross sections with the measured ones taken from Ref.[5]. Each measured data is normalized to the data of Cypress.

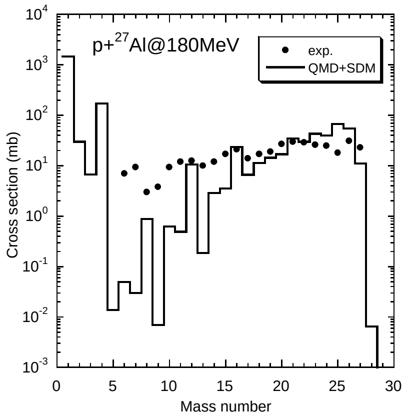

Fig.2 Mass distribution calculated with QMD plus SDM in the proton-induced reaction on ^{27}Al at 180MeV. The experimental data are taken from Ref.[8].

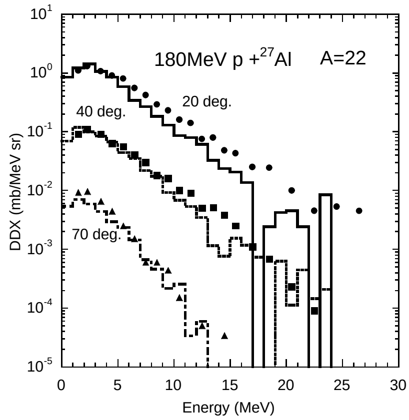

Fig.3 Measured and calculated double-differential production cross sections for fragments with A=22 in the proton-induced reaction on ^{27}Al at 180 MeV. The measured data are taken from Ref.[8]

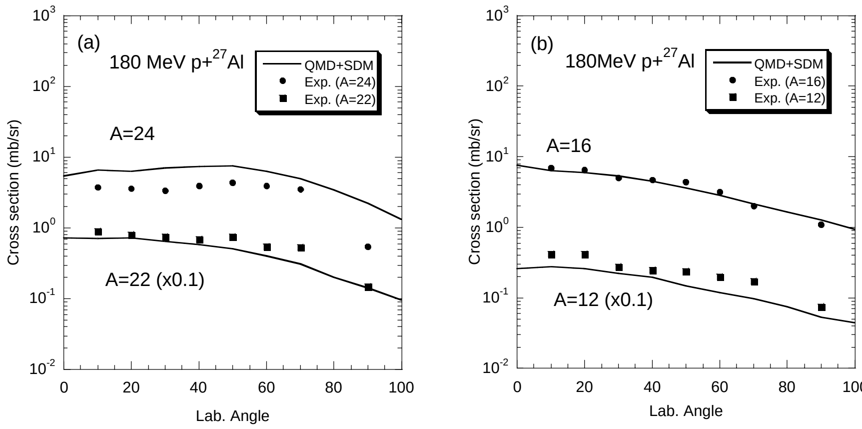

Fig.4 Measured and calculated angular distributions of fragments with (a) A=24 and 22 and with (b) A=16 and 12 in the proton-induced reaction on ^{27}Al at 180 MeV. The measured data are taken from Ref.[8].

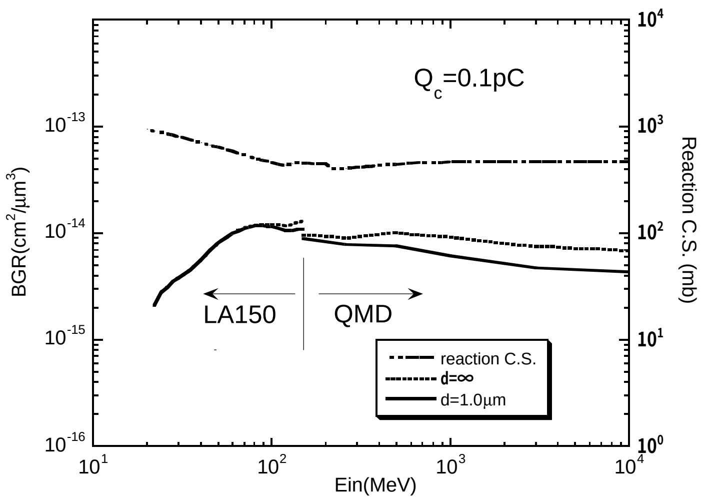

Fig.5 BGR functions calculated with critical charge Q_c=0.1pC and total reaction cross sections.

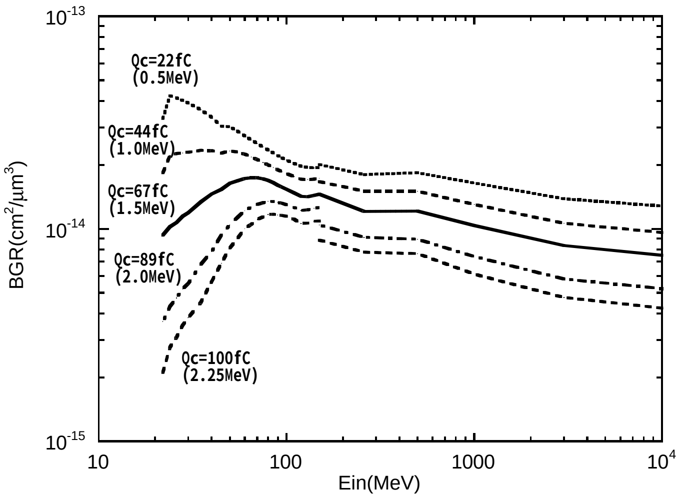

Fig.6 Dependence of BGR functions on critical charge Q_c. The effective depth d is fixed to be 1 μm.

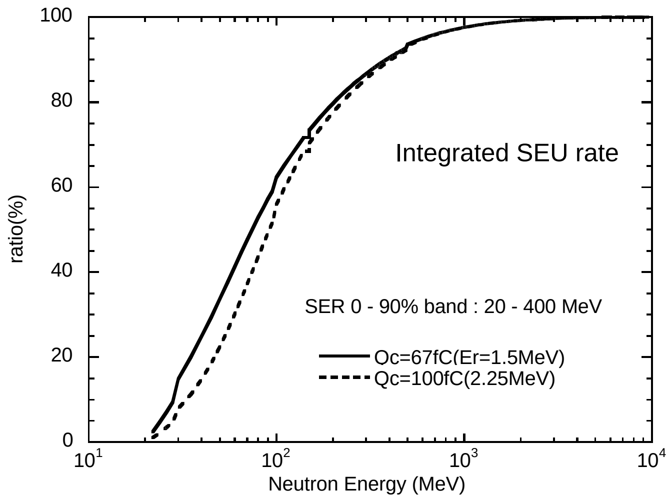

Fig.7 Integrated SEU rate as a function of neutron energy.

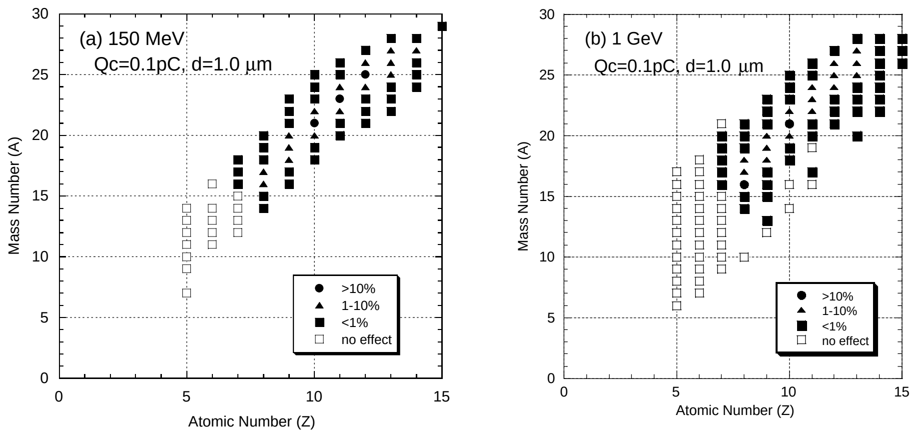

Fig.8 Distribution of the reaction products having effects on SEU for two incident neutron energies of (a) 150 MeV and (b) 1 GeV.