A Terrestrial SER Estimation Methodology Based on Simulation Coupled With One-Time Neutron Irradiation Testing

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***Abstract*— Terrestrial soft error rates (SERs) are generally estimated by performing an experiment using a spallation neutron beam with the energy spectrum being similar to that of the terrestrial neutrons or at least four measurements using various (quasi-)mono-energetic neutron and/or proton sources to determine the parameters of the Weibull function. We here propose a method to estimate the terrestrial SERs based on simulation coupled with one-time neutron irradiation testing which can be applied to various kinds of neutron sources. In this method, the dependences of single-event upset (SEU) cross sections on the neutron energy and the critical charge are calculated by simulation using a particle and heavy ion transport code system (PHITS). The critical charge is used as the only calibration parameter, which is adjusted to reproduce the SER measured by one-time neutron irradiation. The validity of our method is investigated for 65-nm bulk SRAMs with the measured data using various neutron sources in Japan. Our method generally provides reasonable terrestrial SERs compared with those obtained by the Weibull function method. This result indicates the feasibility of evaluating the terrestrial SER using one of the various neutron sources available all over the world, including those not dedicated to SER measurement. We also investigate the necessity of the elaborated geometry of the device under test (DUT) for the accuracy of the simulation. It is shown that detailed material compositions of DUT are not necessary for our method except when the one-time irradiation is performed using the neutron source that contains a high quantity of low-energy neutrons below 8 MeV. Furthermore, we confirm that the configuration of the sensitive volume can be simplified without sacrificing the estimation accuracy. These simplifications in the simulation help to reduce the modeling and calculation costs in SER estimation.**

***Index Terms*— Monte Carlo simulation, neutron radiation effects, neutrons, particle and heavy ion transport code system (PHITS), single-event upsets (SEUs), soft errors.**

I. INTRODUCTION

SINGLE-EVENT upsets (SEUs) caused by neutrons are a reliability problem for microelectronic devices in the terrestrial environment. Evaluations of soft error rates (SERs) are necessary to assure the reliability of devices. Acceleration tests using spallation neutron beams with the energy spectrum being similar to that of the terrestrial neutrons provide realistic SERs more quickly than field tests. However, as described in JESD89B [1], only a few facilities can provide neutron beams with suitable spectra. Therefore, there is a shortage of beam time to live up to the vast demands for SER evaluations. Another evaluation method described in [1] uses the four-parameter Weibull function to fit the SEU cross-section data measured by (quasi-)mono-energetic neutron and/or proton sources. However, the Weibull function method requires at least four experimental data with different energies to determine the fitting parameters. If we can evaluate the terrestrial SER by one-time neutron irradiation and various kinds of neutron sources (i.e., any kind of energy spectrum being not similar to that of the terrestrial neutrons) can be utilized for the evaluation of terrestrial SER evaluation, it will contribute to solving the shortage of beam time and reducing the cost in SER estimation. In [2], an estimation method to obtain the terrestrial SER in a one-time irradiation test has been proposed. However, this method is based on empirical rules, and multiple irradiation tests are required to be conducted if there is a major change in the device structure, such as changing from planar MOSFET to FinFET. In [3], the energy dependence of the SEU cross section has been measured by a one-time neutron irradiation test with the continuum energy spectrum. The time-of-flight technique is used to determine the energy of the neutron that caused the SEU, but it can be applied only for the circuit that can detect an SEU with

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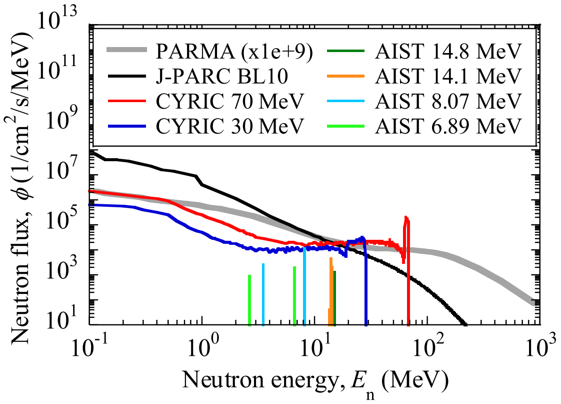

Fig. 1. Energy spectra of neutrons for J-PARC BL10, CYRIC, AIST, and terrestrial environment calculated by PARMA [17].

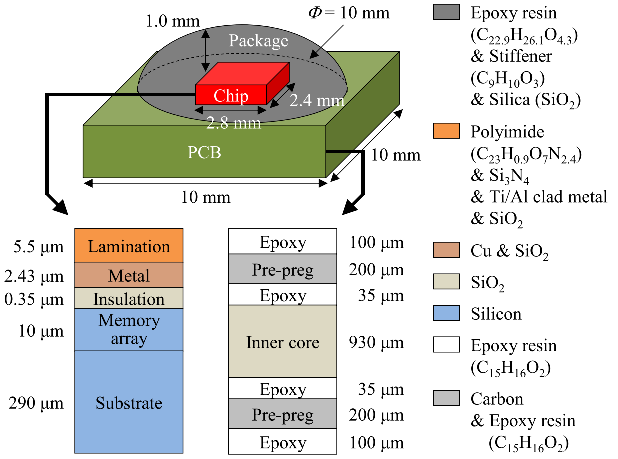

Fig. 2. Configuration of DUT used in PHITS simulation. The stacked structure of the chip and PCB are shown in an enlarged view.

nanosecond time resolution to clarify the SEU cross section at several hundreds of megaeletron volts.

The Monte Carlo simulation is the other method to estimate the terrestrial SER. Several Monte Carlo simulators (e.g., Monte Carlo radiative energy deposition (MRED) software [4], MC-ORACLE [5], and the tool suite for radiation reliability assessment (TIARA) simulation platform [6]) have been developed for the application, and some of them were summarized in an anthology article [7]. This work proposes an estimation method of SER in the terrestrial environment associating any single measured data with a Monte Carlo simulation. Specifically, neutron irradiations on a device under test (DUT) are simulated by a Monte Carlo radiation transport code, and SEU cross sections, $\sigma_{\rm SEU}$ (E_n, $Q_{\rm fit}$), as a function of the incident neutron energy, E_n, and the critical charge, $Q_{\rm fit}$, are calculated with changing E_n. It is difficult to derive the absolute value of critical charge by simulation because the critical charge depends on several conditions (e.g., the fabrication technology, the circuit design, and the device parameters). Therefore, we treat $Q_{\rm fit}$ as the only adjustable parameter and use a single measured data to determine $Q_{\rm fit}$.

We have conducted SEU measurements for 65-nm bulk 6-T SRAMs using various neutron beams with different energy spectra as shown in Fig. 1 for several conditions of irradiation directions and supply voltages ($V_{\rm DD}$) [8], [9], [10]. In this work, we estimate terrestrial SERs by our proposed method using these measured data individually to clarify whether the terrestrial SER estimated by the proposed method depends on the type of neutron source or not. Moreover, to investigate the validity and effectiveness of the proposed estimation method, we compare terrestrial SERs obtained by our method with that obtained by the Weibull function method.

Here, simulation conditions must often be simplified. For example, the system developers must simplify the configuration of the DUT used in simulation when the manufacturer does not disclose the device information. To calculate the collected charge, a simplified model such as a sensitive volume (SV) model [11] must be employed instead of the event-by-event technology computer-aided design (TCAD) simulation because of the unknown device parameters. Some simplifications are also adopted to reduce the simulation cost. On the other hand, there are concerns about the deterioration in the accuracy of the terrestrial SER estimation due to these simplifications. Therefore, the simulations are performed with different levels of simplification for representing the DUT and estimating the collected charge to investigate the influence of simplifications on the SER estimation accuracy in our proposed method.

II. ESTIMATION METHOD

The configuration of the DUT for the simulation shown in Fig. 2 was almost the same as that used in the previous study [12]. Meanwhile, the 40-μm-thick SiO_2 layer placed on the metal layer was newly replaced by the 5.5-μm-thick lamination layer according to the result of the secondary ion mass spectrometry (SIMS) analysis. Irradiations of mono-energetic neutrons from the backside and the frontside of the DUT were simulated by the Particle and Heavy Ion Transport code System (PHITS) [13]. According to the previous study [14], the contribution of neutrons with energies between 0.1 and 10 MeV was not negligible in accelerator environments. Therefore, the lowest neutron energy in our study was set to be 0.1 MeV. The multiple SV (MSV) model [15] was used to calculate the number of collected charges. The configuration and charge collection efficiency reported in our previous study [9] were adopted.

From the PHITS calculation, the number of events, $N(E_n, q)dq$, with the collected charge in $[q, q + dq]$ was derived. The SEU cross sections, $\sigma_{\rm SEU}(E_n, Q_{\rm fit})$, were calculated by the following equation:

$$\sigma_{\rm SEU}(E_n, Q_{\rm fit}) = \frac{A}{N_{\rm in} \times N_{\rm bit}} \int_{Q_{\rm fit}}^{\infty} N(E_n, q)dq \qquad (1)$$

where A is the surface area of the DUT shown in Fig. 2 (i.e., $A = 1.0$ cm^2), $N_{\rm in}$ is the number of incident neutrons in the PHITS calculation, and $N_{\rm bit}$ is the number of SRAM cells placed in the memory chip. Fig. 3 shows the SEU cross sections for various values of $Q_{\rm fit}$ calculated by PHITS + MSV with irradiation directions of the backside and the frontside of the DUT. As described before, $Q_{\rm fit}$ is treated as the only adjustable parameter. The measured data plotted in Fig. 3 was taken from [10] but some of them were corrected because the energy spectra of irradiated neutrons were not strictly

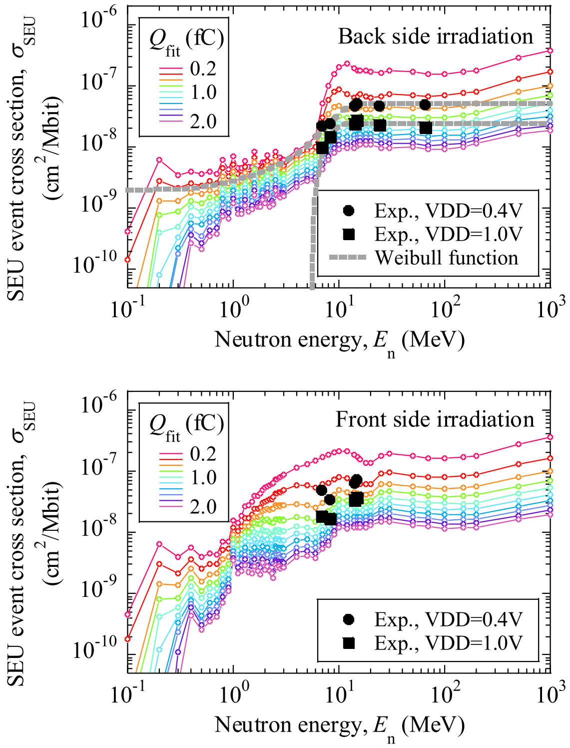

Fig. 3. SEU cross sections for various values of Q_{fit} calculated by PHITS + MSV. Irradiation of mono-energetic neutrons from the backside and frontside of DUT was simulated. Measured data are taken from [10].

mono-energetic and broadened around these nominal energies. To derive the SEU cross sections for mono-energetic neutrons, we have introduced a correction factor, a, which means the contribution ratio of the neutrons around the peak energy on SEUs for each neutron spectrum. The correction factors for each measurement were estimated by PHITS simulation. After that, we derived the SEU cross sections by the following equation:

$$\sigma_{\text{SEU,exp}} = \frac{a N_{\text{SEU,exp}}}{t N_{\text{bit}} \int_{E_{\min}}^{E_{\max}} \phi(E_n) dE_n} \tag{2}$$

where $N_{\text{SEU,exp}}$ is the number of measured SEUs, t is the neutron irradiation time, and $\varphi(E_n)$ is the neutron flux at each neutron facility shown in Fig. 1. $E_{\min}$ and $E_{\max}$ are the lower and upper limits of neutron energy for the peak part of neutron spectrum, respectively.

The value of Q_{fit} was determined so that the number of simulated SEUs, $N_{\text{SEU,calc}}$, equals that of measured SEUs. The number of simulated SEUs was calculated by

$$N_{\text{SEU,calc}}(Q_{\text{fit}}) = t N_{\text{bit}} \int \phi(E_n) \sigma_{\text{SEU}}(E_n, Q_{\text{fit}}) dE_n. \tag{3}$$

It should be noted that the spectra of quasimono-energetic neutrons produced by 70- and 30-MeV protons at CYRIC were derived from PHITS simulation with JENDL-4.0/HE [16].

After Q_{fit} was determined, the terrestrial SER was calculated by

$$\text{SER}_{\text{GND}} = \int \phi_{\text{GND}}(E_n) \sigma_{\text{SEU}}(E_n, Q_{\text{fit}}) dE_n \tag{4}$$

TABLE I
WEIBULL PARAMETERS OF THE SEU CROSS SECTIONS FOR V_{DD} = 1.0 AND 0.4 V

VDD (V)	σ_{Li} (cm^2/Mbit)	E_{0i} (MeV)	W_i (MeV)	S_i
1.0	2.43×10^{-8}	5.14	2.99	1.92
0.4	5.06×10^{-8}	-28.4	37.9	11.4

where $\varphi_{\text{GND}}(E_n)$ is the energy spectrum of terrestrial neutrons at the ground level obtained by the PHITS-based Analytical Radiation Model in the Atmosphere (PARMA) 4.0 [17]. The neutron energy spectrum obtained by PARMA is also plotted in Fig. 1.

In our previous studies [8], [9], [10], the measured data were taken by the neutron irradiation on the backside (i.e., neutrons first reach the PCB) and the frontside (i.e., neutrons first reach the package) of the DUT with the different supply voltages. In this study, the measured data at the nominal supply voltage of 1.0 V and the low supply voltage of 0.4 V were used for the estimation of terrestrial SERs. In addition, the curve fit of the Weibull function is also plotted for 0.4 and 1.0 V in the backside irradiation because there were enough measured data for fitting in these conditions. Weibull parameters for each supply voltage are listed in Table I.

As another simple method to estimate the terrestrial SER using a single measured data, we refer to the step function method. In this method, the terrestrial SER is calculated by the following equation:

$$\text{SER}_{\text{GND}} = \int \phi_{\text{GND}}(E_n) \sigma_{\text{step}}(E_n) dE_n \tag{5}$$

$$\sigma_{\text{step}}(E_n) = \begin{cases} 0, & (E_n < E_{\text{cut}}) \\ \dfrac{N_{\text{SEU,exp}}}{t N_{\text{bit}} \displaystyle\int_{E_{\text{cut}}}^{\infty} \phi(E) dE}, & (E_n \geq E_{\text{cut}}) \end{cases} \tag{6}$$

where E_{cut} is the cutoff energy of SEU cross section. Here, E_{cut} was set to be 6 MeV because the curve of the SEU cross section for the backside irradiation rises rapidly with increasing neutron energy around 6 MeV as reported in [12].

III. Results and Discussion

A. Terrestrial SERs Estimated by Each Method

Fig. 4 shows the terrestrial SERs for the backside irradiation and the frontside irradiation estimated by our proposed method and the step function method with each single measured data at the nominal supply voltage of 1.0 V and the low supply voltage of 0.4 V. The terrestrial SERs for the backside irradiation estimated by the Weibull function method are also shown in Fig. 4 as a reference.

The terrestrial SERs estimated by the step function method with the measured data of 14.1-, 14.8-, 30-, and 70-MeV (quasi-)mono-energetic neutrons are consistent within 50% of that estimated by the Weibull function method. It comes from the fact that the SEU cross sections at these neutron energies are almost saturated. However, the step function method with the measured data of National Institute of Advanced Industrial Science and Technology (AIST) 6.89 and 8.07 MeV provides

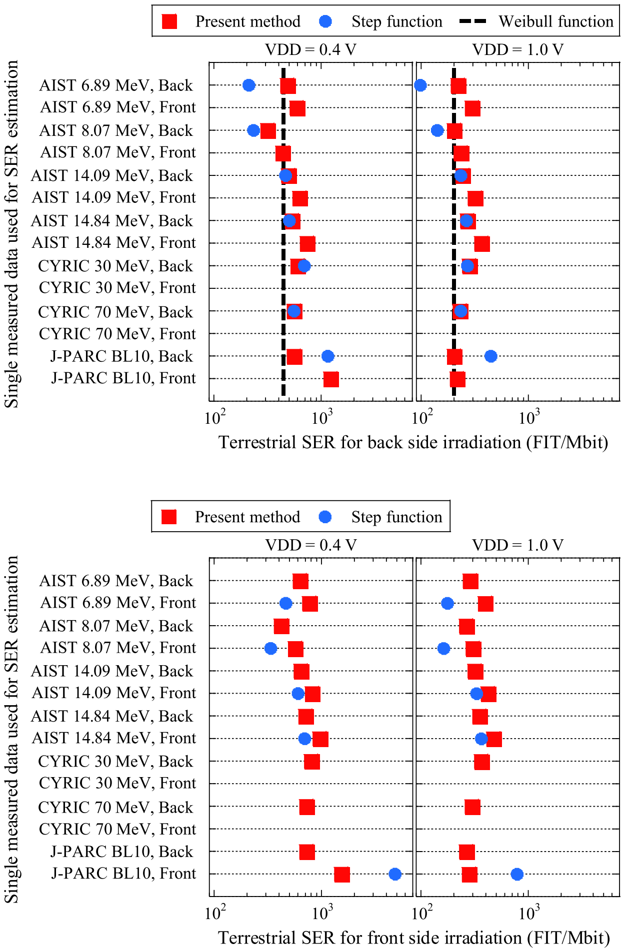

Fig. 4. Terrestrial SERs estimated by our proposed method and the step function method with each single measured data for (top) backside irradiation and (bottom) frontside irradiation at (left) low supply voltage of 0.4 V and (right) nominal supply voltage of 1.0 V. Terrestrial SERs estimated by Weibull function method are also shown for backside irradiation.

much lower terrestrial SERs. This is because the SEU cross sections at these low energies neutrons are significantly lower than the saturated SEU cross section, as reported in [8]. Moreover, the terrestrial SERs estimated by the step function with measured data of J-PARC BL10 are much higher. It is because the neutron beam at J-PARC BL10 contains abundant low-energy neutrons, and SEUs caused by low-energy neutrons are misidentified as those caused by high-energy neutrons in the step function method. The terrestrial SERs estimated by our method are relatively consistent regardless of the measured data used in the terrestrial SER estimation. Specifically, in the case of the nominal supply voltage of 1.0 V, the ratio of minimum and maximum terrestrial SERs is 1.8 in our method, whereas it is 4.8 in the step function method. In the case of the low supply voltage of 0.4 V, the ratio of minimum and maximum terrestrial SERs is 3.9 in our method, whereas it is 14.2 in the step function method.

As stated above, the step function method gives reasonable terrestrial SERs when the measured data taken by (quasi-) mono-energetic neutrons with peak energies above ten-odd MeV [e.g., 14-MeV neutrons from deuterium–tritium (D–T) fusion reaction] are adopted. Moreover, our estimation method provides reasonable terrestrial SERs regardless of a single measured data even if the data is taken by other neutron sources. Examples of such neutron sources include neutrons from deuterium–deuterium (D–D) fusion reactions, neutrons from atomic reactors, and so on. Therefore, more neutron sources can be utilized for terrestrial SER estimation by the proposed method.

It is obvious that neutron sources with too low energy to cause SEUs cannot be applied to estimate terrestrial SERs.

From the calculated SEU cross section in Fig. 3, the energy of neutron sources should be higher than around 0.1 MeV to observe SEUs. According to [14], at such low energy regions, SEUs can occur via elastic scattering of neutrons with target materials because the threshold energies of (n, p) and (n, α) reactions with the major material elements (e.g., silicon, oxygen, and carbon) are several MeV. The maximum energy transferred from a neutron with the energy of E_n by an elastic collision can be expressed by

$$E_{\max} = E_n \frac{4A}{(A+1)^2} \tag{7}$$

where A is the mass number of the target atom. When the secondary ion enters the SV immediately and stops in the SV, all of its energy is deposited in the SV. Therefore, the threshold energy of neutron to occur SEU, $E_{n,\mathrm{th}}$, is as follows:

$$E_{n,\mathrm{th}} \geq \frac{Q_{\mathrm{fit}}}{e} E_{\mathrm{pair}} \frac{(A+1)^2}{4A} \tag{8}$$

where e is the elementary charge, and E_{pair} is the average energy required to generate an electron–hole pair (3.6 eV in silicon). In most cases, the atom nearest to the SV is silicon or oxygen. When $Q_{\mathrm{fit}} = 1.0$ fC, $E_{n,\mathrm{th}} = 0.10$ MeV for oxygen ions, and $E_{n,\mathrm{th}} = 0.17$ MeV for silicon ions, these threshold energies are consistent with our calculation as shown in Fig. 3.

B. Influence of Simplification of DUT

Here, to investigate the influence of the simplification of DUT used in the simulation, we performed simulations for DUTs with three different geometry models: Consider actual compositions of the DUT (so-called DETAILED): The lamination layer, the metal layer, and the insulation layer placed in the chip consist of silicon (so-called MEDIUM): All of the components of DUT consist of silicon (so-called COARSE).

Fig. 5 shows the terrestrial SERs for the backside irradiation and the frontside irradiation estimated by DETAILED, MEDIUM, and COARSE with each single measured data at the nominal supply voltage of 1.0 V and the low supply voltage of 0.4 V. The terrestrial SERs estimated by MEDIUM are almost the same as those estimated by DETAILED regardless of the single measured data, irradiation directions, and the supply voltage. It indicates that terrestrial SERs can be estimated using the simplified configuration of memory chips without losing accuracy, which should be beneficial for most system developers. In the case of using COARSE, the terrestrial SERs estimated with the measured data of J-PARC BL10 and AIST 6.89 MeV for the frontside irradiation are higher especially for the low supply voltage of 0.4 V, while the terrestrial SERs estimated by the other measured data are not significantly different from those estimated by DETAILED.

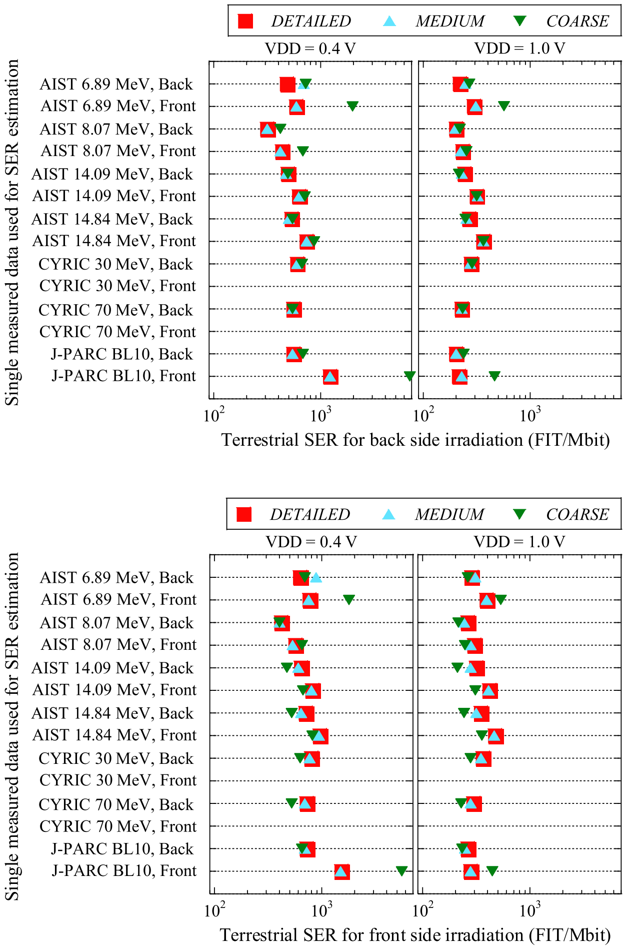

Fig. 5. Terrestrial SERs estimated by DETAILED, MEDIUM, and COARSE geometry models with each single measured data for (top) backside irradiation and (bottom) frontside irradiation at (left) low supply voltage of 0.4 V and (right) nominal supply voltage of 1.0 V.

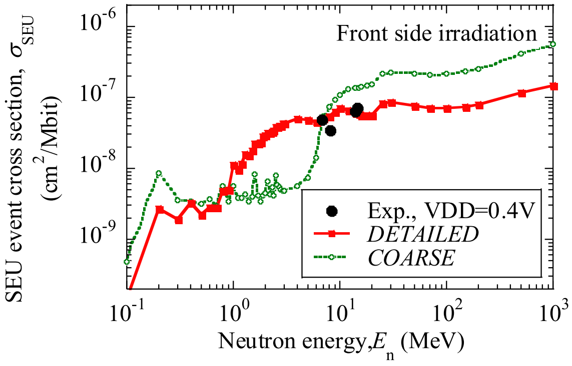

Fig. 6. SEU cross sections for frontside irradiation calculated by DETAILED and COARSE geometry models. Q_{fit} for each calculation was determined individually to match the measured data of AIST 6.89 MeV at a low supply voltage of 0.4 V.

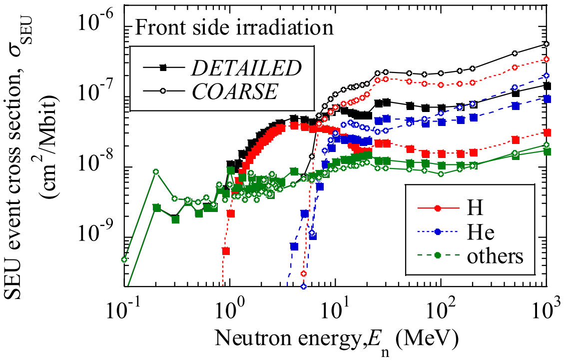

Fig. 7. Contribution of each secondary ion to SEU cross sections for frontside irradiation calculated by DETAILED and COARSE geometry models. The contribution of H ions for low-energy neutrons disappeared due to the replacement of the package from actual composition to silicon.

To investigate the cause of this difference, the SEU cross sections for the frontside irradiation calculated by DETAILED and COARSE geometry models were compared in Fig. 6. Q_{fit} for each calculation was determined individually by the single measured data of AIST 6.89 MeV at the low supply voltage of 0.4 V. Specifically, Q_{fit} is 0.44 and 0.15 fC for DETAILED and COARSE in the case of the frontside irradiation, respectively. When a low Q_{fit} is adopted, the SEU cross sections for high-energy neutrons for COARSE become high and hence the estimated terrestrial SERs become higher than those by DETAILED.

Fig. 7 shows the contribution of each secondary ion to the SEUs. The difference in SEU cross sections for low-energy neutrons comes from the contribution of H ions. As described before, SEUs can occur via elastic scattering at low-energy regions. Elastic scattering generates secondary ions only for the forward direction. In the DETAILED geometry model, hydrogen atoms are abundant in the package, while they are absent in the COARSE geometry model. Therefore, the contribution of secondary H ions generated in the package appears strongly for the frontside irradiation at around a few MeV with DETAILED.

It should be noted that the maximum value of charges deposited by H ions during the passage through the 0.5-μm-thick silicon is about 3.0 fC. Thus, secondary H ions have the potential to cause SEUs. However, sometimes the contribution of H ions on SEU cross section for low-energy neutrons does not appear as reported in [18], for instance. There are several possible reasons for the difference as follows: a small number of hydrogen atoms in the DUT, the existence of shielding material between the source of secondary H ions, and SVs. Therefore, we should pay attention to the geometry model of DUT when we estimate the terrestrial SER for low supply voltages with the measured data taken by low-energy neutrons.

C. Influence of SV Models

We also investigated the influence of calculation models for collecting charges on terrestrial SER estimation. As an alternative to the MSV model, the single SV (SSV) model [11] is sometimes adopted to reduce the modeling and calculation cost. Here, to reveal whether the MSV model is necessary, we estimate terrestrial SERs using PHITS + SSV for comparison. The comparison is performed with each single measured data at the nominal supply voltage of 1.0 V and the low supply voltage of 0.4 V. The size of the SV in the SSV model is defined by the active area of the nMOSFET and the funneling length of 0.5 μm. In addition, PHITS + SSV calculations were performed changing the length of each side of SV with

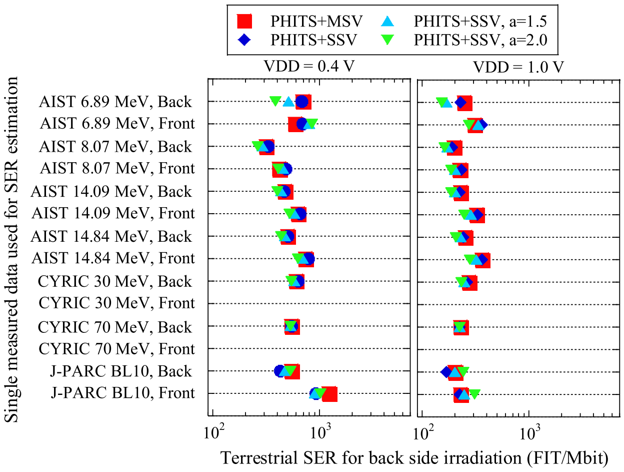

Fig. 8. Terrestrial SERs estimated by PHITS + MSV and PHITS + SSV with each single measured data for (top) backside irradiation and (bottom) frontside irradiation at (left) low supply voltage of 0.4 V and (right) nominal supply voltage of 1.0 V. The MEDIUM geometry model was used for both calculations.

the scale factor, a, of 1.5 and 2.0 to investigate the importance of the SV size accuracy.

Fig. 8 shows the terrestrial SERs for the backside irradiation at the nominal supply voltage of 1.0 V and the low supply voltage of 0.4 V estimated by PHITS + MSV and PHITS + SSV with the MEDIUM geometry model. The terrestrial SERs estimated by PHITS + SSV with a scale factor of 1.0 are consistent within 30% of that estimated by PHITS + MSV when the measured data used for terrestrial SER estimation is the same. This result is almost the same even in the case of the estimation of terrestrial SERs for the frontside irradiation. It was also found that the scale factor of SV size for PHITS + SSV does not significantly affect the estimated SERs.

IV. CONCLUSION

Terrestrial SERs for 65-nm bulk SRAMs were estimated based on PHITS + MSV simulation from one-time neutron irradiation testing. Our proposed method provides reasonable terrestrial SERs regardless of a single measured data used to determine Q_{fit}. This result demonstrates the validity of the proposed estimation method. It is expected that our proposed method can also be applied to the estimation of terrestrial SER of the other technology nodes and other device structures, where its experimental validation is ongoing.

We also evaluated the method that adopted the step function to estimate the terrestrial SER as an alternative. Although it cannot be used with the measured data obtained by low-energy neutrons, the step function method also gave reasonable results when the measured data taken by (quasi-)mono-energetic neutrons with peak energies above ten-odd MeV were adopted.

The influence of simplifications for the DUT and the calculation model of collected charges on the terrestrial SER estimation by our proposed method was also investigated to reveal the necessary level of modeling detail. The actual compositions of the package should be considered to estimate terrestrial SERs with the low supply voltage if the measured data taken by frontside irradiation of neutrons with energies below 8 MeV were used to derive Q_{fit}. For all other cases, detailed material compositions of DUT were not necessary for the terrestrial SER estimation. The terrestrial SERs estimated by PHITS + SSV were almost the same as those estimated by PHITS + MSV, regardless of the scale factor of SV size. Therefore, time-consuming TCAD simulation is not required to estimate terrestrial SERs by means of our method. These simplifications in the simulation help to reduce the cost of SER estimation.

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