Characterizing Energetic Dependence of Low-Energy Neutron-Induced SEU and MCU and Its Influence on Estimation of Terrestrial SER in 65-nm Bulk SRAM

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***Abstract*— Characterizing low-energy neutrons (<10 MeV)-induced single-event upsets (SEUs) and multiple cells upsets (MCUs) is essential to validate the current standard for terrestrial soft error rate (SER) and investigate its enhancement. Following our preliminary analysis on the contribution of the low-energy neutrons to the total terrestrial SER at the nominal operating voltage of 1.0 V by Liao *et al.* (2020), this article newly presents and analyzes the data measured at the low operating voltage of 0.4 V. The dependence of SEU cross section on the neutron energy is similar between the operating voltages of 0.4 and 1.0 V, including onset energy of around 6 MeV. The existence of MCUs at 4.1-MeV neutrons was also confirmed at both the operating voltages. Based on the measurement, we approximate the dependence of SEU and MCU cross sections as Weibull functions of the neutron energy. The terrestrial SER of SEUs and MCUs was calculated by folding the Weibull function and the flux spectrum. The calculated result indicates that the SER originating from the low-energy neutrons is less than 6% in the terrestrial environment at New York and Tokyo City. We confirm that disregarding the flux of neutrons below 10 MeV in the acceleration factor calculation at accelerated neutron tests, which follows the current standard defined in JESD89, could give a reasonable SER estimation accuracy for both SEUs and MCUs. On the other hand, for covering the beams having an extremely high proportion of low-energy neutrons, considering the flux of neutrons above 6 MeV would be an option for better SER estimation.**

***Index Terms*— Low-energy neutrons, multiple cells upsets (MCUs), single-event upset (SEV), static random access memories (SRAMs).**

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I. Introduction

SOFT errors induced by the terrestrial neutrons in the secondary cosmic ray jeopardize the reliability of the semiconductor devices. According to the test standard of JESD89 [2], the flux of neutrons with energies more than 10 MeV is taken into account for the calculation of the soft error rate (SER). However, the energy of the terrestrial neutron has a wide range from keV to GeV. The proportion of neutrons within the energy range from 1 to 10 MeV, after this referred to as low-energy neutrons, to the total terrestrial neutrons above 1 MeV is 36% at New York City (NYC) [3]. Therefore, characterizing low-energy neutrons inducing SER is vital to validate the current standard for terrestrial SER.

Several works characterized single-event upset (SEU) cross sections induced by low-energy neutrons [4]–[6] and reported their influence on terrestrial SER calculation [7]. In addition to the terrestrial environment, Cecchetto *et al.* reported the impact of low-energy neutrons on SER at high-energy accelerator environments [8]. On the other hand, the dependence of multiple cells upset (MCU) cross section on neutron energy is less characterized except our previous work [1] as the author investigated.

For investigating low-energy neutron-induced SEUs and MCUs, we conducted irradiation experiments using low-energy neutron beams of 6.0, 8.0, and 14.8 MeV, combining the previously measured cross sections using 30- and 70-MeV neutron sources [9]. A preliminary analysis on the contribution of the low-energy neutrons to the total terrestrial SER of SEUs and MCUs has been presented in [1]. This article further discusses the impact of low-energy neutrons disregarded in the acceleration factor calculation using spallation neutron sources. We quantify the errors of the terrestrial SEU and MCU rates estimated with accelerated irradiation testing for this discussion. We also examine the appropriateness of 10-MeV threshold for both SEU and MCU rates with the experimental data at BL10 of Material and Life Science Facility (MLF), Japan Proton Accelerator Research Complex (J-PARC) [10]–[12], which has a large portion of low-energy neutrons.

Also, for analyzing the impact of the operating voltage on the energetic dependence of MCUs, especially the onset energy, this article reports a new set of measurement data at an operating voltage of 0.4 V in the irradiation campaign using monoenergetic low-energy neutron sources. All the discussions in this article will cover the nominal voltage of 1.0 V and the low operating voltage of 0.4 V.

This article is organized as follows. Section II introduces the set-up of the experiment using monoenergetic low-energy neutron sources. In Section III, combining the additional experimental data using 30- and 70-MeV neutron sources, we discuss the energetic dependence of SEU and MCU cross sections at the operating voltages of 1.0 and 0.4 V. Based on the measurement, we approximate the dependence of SEU and MCU cross sections as Weibull functions of the neutron energy. The terrestrial SER of SEUs and MCUs were calculated by folding the Weibull function and the flux spectrum in Section IV. The impact of minimum energy of neutrons on the calculated terrestrial SER is also discussed in Section IV. Finally, Section V gives concluding remarks.

II. Irradiation Test Using Low-Energy Neutrons

The details on the design under test (DUT) boards and set-up were described in our conference article [1]. Here, we only introduce the necessary information with some additional explanation that is not included in [1]. We fabricated the static random access memory (SRAM) for irradiation tests at a commercial 65-nm technology node. Due to a fabrication option of deep N-well (DNW), the parasitic bipolar actions (PBAs) are enhanced, leading to a higher probability of the occurrence of MCUs among the memory cells of SRAM that were fabricated in the same N-well [13], [14]. We performed static tests, and the operating voltage was set to 1.0 or 0.4 V during the hold time. The neutrons were injected into the DUTs from the backside, which is the side of the printed circuit board (PCB). Besides, Abe *et al.* [15] reported that the packaging material would influence the irradiation result for a low-energy neutron source. However, the compositions of some materials used for packaging are not disclosed. On the other hand, the PCB material is less uncertain. Therefore, we irradiated the chips from the PCB side.

We utilized the all-direction neutron source at the National Metrology Institute of Japan (NMIJ) in Advanced Industrial Science and Technology (AIST) [16]. The energy spectrum corresponding to each beam configuration (neutron source and DUT direction) is shown in Fig. 1 (© [2021] IEEE. Reprinted, with permission, from [1]). The method to obtain the spectra is different at the directions between 0° and the others. At 0° (ON-axis) direction, the flux is measured by a thick radiator (TR) detector [17]. The TR detector consists of a 0.5-mm-thick polyethylene radiator disk of 89 mm^2 area mounted in front of a totally depleted silicon surface barrier detector of 150 mm^2 area and 300 μm depth. On the other hand, at 65° and 90° (OFF-axis) directions, the simulation of Monte Carlo N-Particle Transport Code for Accelerator Neutron Target (MCNP-ANT) [18] is utilized. We regarded most neutron sources as monoenergetic ones, while the only

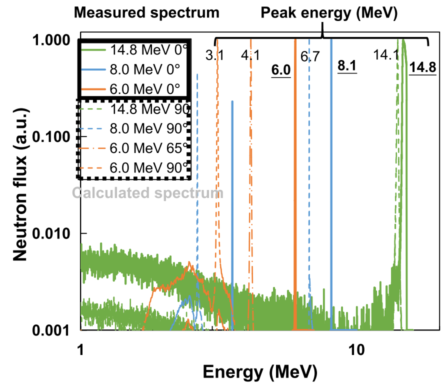


Fig. 1. Spectra of neutrons of the corresponding directions and beam sources. © [2021] IEEE. Reprinted, with permission, from [1].

exception is 90° in the 8.0-MeV beam because only 60% neutrons accumulate within 0.1 MeV from its peak energy.

As discussed in [1], due to the short distance from the beam exit to the DUT boards, the slight location difference of each chip on the board varies the peak energy and fluence. However, it was not considered in [1]. On the other hand, in this article, we calculated the fluence considering the chip location inside the board. In the following results, the horizontal error bars indicate the energy range of neutrons at the chips on the DUT board.

In this article, we use the same definition of the SEUs and MCUs as our previous work [1]. We count the number of SEU events as the total event number. In this definition, a single bit upset (SBU) is counted as one SEU event, and an $n(\geq 2)$-bit MCU is also counted as one event. We further separate the MCU and SBU events from the SEU events to investigate the dependence of the MCU cross section on the neutron energy. In our static test, MCU events were detected according to the physical locations of bit upsets regardless of their logic word addresses. Note that, in each round of the static test, the proportion of upset bits to the total memory bits was small enough to ensure the low probability of pseudo-MCUs consisting of multiple SBUs.

III. Energetic Dependence of Low-Energy Neutron-Induced SEUs and MCUs

A. Onset Energy

In this work, the onset energy is defined the same as our previous work [1], at which energy the neutron-induced SEU cross section decreases to 0.1 X for the initial time from the saturated value in the high-energy region. Figs. 2 and 3 show the measured dependence of the SEU cross section on energy at operating voltages of 1.0 and 0.4 V, respectively. The x-axis coordinate of each data point represents the peak energy of the spectra of each neutron beam. Blue markers are used for the results with the measured spectra at ON-axis directions, and green markers are used for the result with the calculated spectra in the OFF-axis directions. All the results were with the vertical error bars standing for one standard deviation in cross section, and the horizontal error bars standing for the energy range of neutrons at the chips on the DUT board. It should be noted that the result of 1.0 V in Fig. 2 is similar to [1,

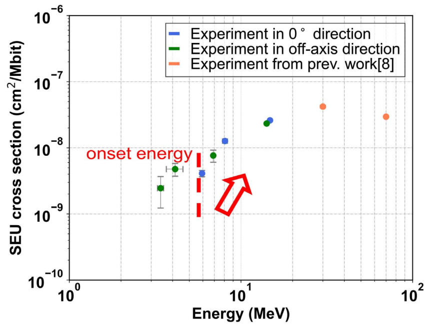


Fig. 2. Measured energetic dependence of SEU cross section at 1.0 V. Vertical error bars stand for one standard deviation in cross section and the horizontal error bars stand for the energy range of neutrons at the chips on the DUT board. The onset energy is roughly 6 MeV for our devices at operating voltage of 1.0 V. It should be noted that this figure is similar to [1, Fig. 5], but the cross sections in OFF-axis direction are recalculated by considering the difference of the flux at each chip location.

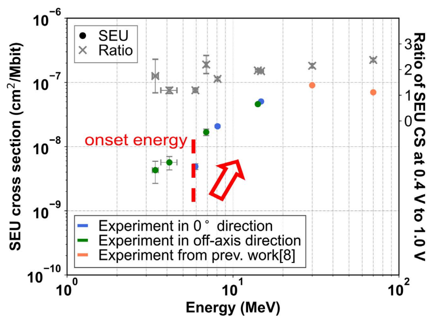


Fig. 3. Measured energetic dependence of SEU cross section at 0.4 V with left y-axis. The ratio of SEU cross section at 0.4–1.0 V is also plotted with the right y-axis. Vertical error bars stand for one standard deviation in cross section and the horizontal error bars stand for the energy range of neutrons at the chips on the DUT board. The onset energy is roughly 6 MeV for our devices at operating voltage of 0.4 V.

Fig. 5], but the cross sections in the OFF-axis direction are recalculated by considering the difference of the flux at each chip location.

At both the nominal voltage of 1.0 V and the low operating one of 0.4 V shown in Figs. 2 and 3, we observe a similar trend of the dependence of SEU cross section on the neutron energy, where a rapid increase starts from around 6 MeV and the cross section reaches saturation at about 30 MeV. This observation indicates that a lower operating voltage may not influence the onset energy of energetic dependence of neutron-induced SEU cross sections. According to our definition of the onset energy, the figures show that it is roughly 6.0 MeV in our devices.

Despite the unchanged onset energy at operating voltages of 0.4 and 1.0 V, a lower operating voltage leads to a lower critical charge and, consequently, a higher SEU cross section. Moreover, we observe the SEU cross section ratio at 0.4–1.0 V is not constant with energy variation, as shown in Fig. 3 with the right y-axis. The ratio increases as the neutron energy increases from 6.0 to 30 MeV, where the ratios at 3.1 and 6.7 MeV with large error bars are excluded. The increasing ratio indicates, on the contrary, the SEU cross section of SRAMs operating at low voltage decreases more significantly compared to the nominal operating voltage as the energy of

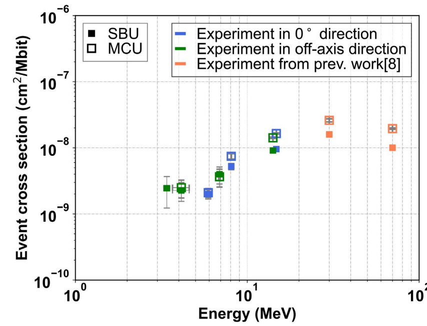


Fig. 4. Energetic dependence of SBU and MCU event cross sections at 1.0 V. Vertical error bars stand for one standard deviation in cross section and the horizontal error bars stand for the energy range of neutrons at the chips on the DUT board. It should be noted that this figure is similar to [1, Fig. 6], but the cross sections in OFF-axis direction are recalculated by considering the difference of the flux at each chip location.

neutron becomes lower. As we will discuss in the following section, this characteristic influences the contribution of low-energy neutrons to the total SER of SRAMs operating at different voltages.

At the range of the energy from 3.1 MeV to the onset energy of 6.0 MeV, both Figs. 2 and 3 show that the SEU cross section induced by the neutrons with the energy at this region stay almost the same at both voltages. The reason why the cross section in this low-energy region is not decreasing to zero could be attributed to the neutron–silicon elastic scattering below the onset energy. Watanabe *et al.* [19] report that the elastic scattering releases heavy secondary ions with a short stopping range and induces SEUs.

B. Energetic Dependence of MCU Cross Section

Figs. 4 and 5 show the cross sections of SBU and MCU events at operating voltages of 1.0 and 0.4 V, respectively, where the SBU and MCU events are categorized from the SEU events. All the results were with the vertical error bars standing for one standard deviation in cross section, and the horizontal error bars standing for the energy range of neutrons at the chips on the DUT board. It should be noted that the result of 1.0 V in Fig. 4 is similar to [1, Fig. 6], but the cross sections in the OFF-axis direction are recalculated by considering the difference of the flux at each chip location. We observed a similar energetic dependence trend in terms of the onset energy and the rapid saturation at both operating voltages.

The comparison between the MCU and SBU at 1.0 V in Fig. 4 was presented in detail in our previous article [1]. As the key observation from that article, we found the proportion of MCU to the total events stays high even at 4.1 MeV. This is because in our device, MCUs are often caused by PBA at the operating voltage of 1.0 V, which is reported in [20]. PBA stands for parasitic bipolar action. A secondary ion generated by nuclear reaction perturbates the well potential, and the parasitic bipolar transistor (source–well–drain) becomes “on” [13], [14]. When PBA happens, the memory cells of SRAM that were fabricated in the same well are likely to upset together, and the MCU occurs. Because

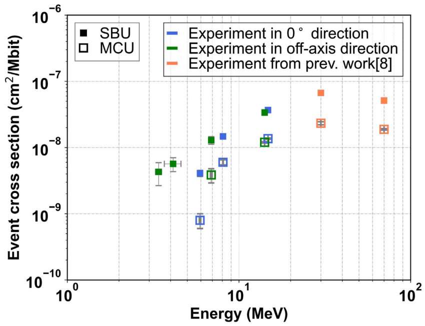


Fig. 5. Energetic dependence of SBU and MCU event cross sections at 0.4 V. Vertical error bars stand for one standard deviation in cross section, and the horizontal error bars stand for the energy range of neutrons at the chips on the DUT board.

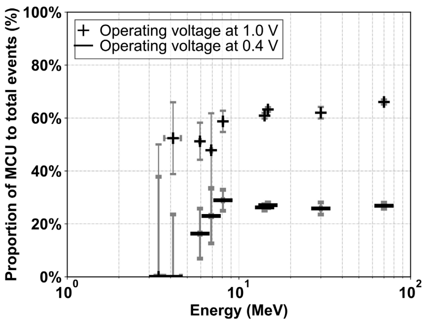


Fig. 6. Energetic dependence of the proportion of MCU events to the total SEU events at 1.0 and 0.4 V. Error bar is with one standard deviation.

triggering PBAs needs a large charge, we concluded in [1] that the reactions between silicon atoms and low-energy neutrons release secondary ions with large linear energy transform (LET).

At an operating voltage of 0.4 V, Figs. 5 and 6 show a similar trend of energetic dependence of MCU and its proportion to the total events. At both operating voltages, our measurement results show that MCUs occur even below 6 MeV. On the other hand, as the difference between 0.4 and 1.0 V, Fig. 6 shows the proportion of MCU at 0.4 V is less. The PBA effect contributing to the high proportion of MCUs becomes much weaker at a lower operating voltage.

IV. Evaluation on Terrestrial $\mathrm{SER}_{\mathrm{SEU}}$ and $\mathrm{SER}_{\mathrm{MCU}}$ Based on Measured Energetic Dependence of Cross Sections

A. Contribution of Low-Energy Neutrons to the Terrestrial $\mathrm{SER}_{\mathrm{SEU}}$ and $\mathrm{SER}_{\mathrm{MCU}}$

Based on the experimental result, we fold the SEU (including SBU and MCU) and MCU cross sections with the differential flux of neutrons above 1 MeV calculated with EXPACS [3] at Tokyo, Japan, and NYC, USA. For SER folding, we used the widely used and the same formula as [1]

$$\mathrm{SER} = \int_{E_0}^{\infty} \sigma(E) \cdot \phi(E) dE \tag{1}$$

where E stands for the energy of the neutron, $\sigma(E)$ stands for either neutron-induced SEU or MCU cross section as a

TABLE I

Fitted Parameters in Weibull Functions of (2) for Energetic Dependence of SEU and MCU Cross Sections at 0.4 and 1.0 V

	voltage (V)	A	A_0	w	S
SEU	1.0	3.96×10^{-8}	2.45×10^{-9}	9.97	0.77
MCU	1.0	2.60×10^{-8}	0	8.68	0.77
SEU	0.4	8.59×10^{-8}	4.29×10^{-9}	11.71	0.90
MCU	0.4	2.33×10^{-8}	0	10.43	0.76

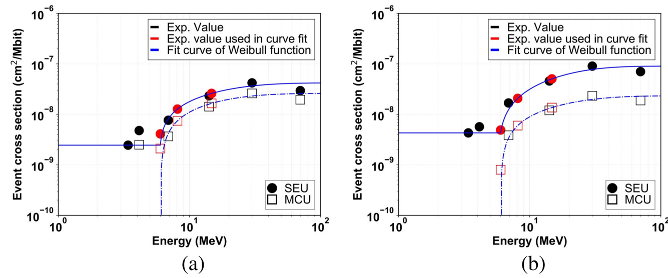


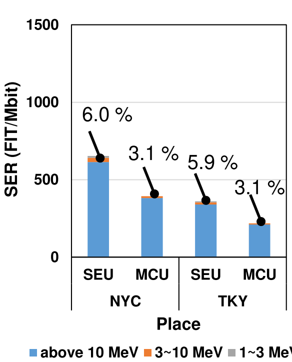
Fig. 7. Curves fitted to Weibull function of (2) for the dependence of SEU (including SBU and MCU) and MCU cross sections on energy at (a) 1.0 V and (b) 0.4 V. The lines stand for the fitted curve, while the red markers stand for the experimental values used in curve fitting and the black markers stand for other experimental values. (a) SEU and MCU fitting at 1.0 V. (b) SEU and MCU fitting at 0.4 V.

function of the neutron energy E, and $\phi(E)$ stands for the differential flux as a function of the neutron of energy E. As will be stated below, although the function for approximating the energetic dependence is different, the assumptions for the dependence are the same as [1]: 1) the cut-off energy for neutrons to induce upset events is 1 MeV ($E_0 = 1$ MeV); 2) the cross section keeps the same value at the energy range from 1 to 3 MeV; and 3) the cross section comes to the saturated value above 70 MeV. Note that Autran *et al.* [21] reports the SER of thermal neutrons, which are defined as neutrons with energy below 1 eV, is estimated to be 5 FIT/Mbit at 65-nm node in simulation, and its contribution is less than 1% to the total SER at 45 nm in the experiment. With these assumptions, we utilize Weibull function to approximate the energetic dependence of SEU and MCU cross sections as follows:

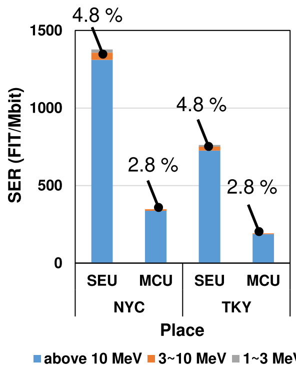
$$\sigma(E) = A\left(1 - e^{\left(\frac{E - E_{\mathrm{onset}}}{w}\right)^{S}}\right) + A_0 \tag{2}$$

where E_{onset} is equal to the onset energy of 6.0 MeV, A is the saturating value of the cross section and equal to $\sigma_{\max} = \sigma_{30\,\mathrm{MeV}}$ from our experimental data, and A_0 is the constant cross section in 1–3 MeV region and equal to $\sigma_{3.1\,\mathrm{MeV}}$ for SEUs and 0 for MCUs. Other parameters in the Weibull function are fitted by Scipy of Python using least nonlinear squares with the data of cross sections at 6.0, 8.1, and 14.8 MeV, at which the beam spectra are the measured ones and more reliable. Fig. 7(a) and (b) show the curves fitted with the experimental data of SEU and MCU cross section at 1.0 and 0.4 V. The detailed parameters are listed in Table I.

The folding results of $\mathrm{SER}_{\mathrm{SEU}}$ and $\mathrm{SER}_{\mathrm{MCU}}$ are shown in Fig. 8(a) and (b) for operating voltages of 1.0 and 0.4 V, respectively. The contributions of neutrons whose energy are 1–3 MeV, 3–10 MeV, and above 10 MeV are plotted in



(a)



(b)

Fig. 8. SERs of SEU and MCU at NYC and Tokyo estimated with folding at (a) 1.0 V and (b) 0.4 V. The contributions of neutrons whose energy is 1–3, 3–10, and above 10 MeV are plotted separately. The contribution of the neutrons below 10 MeV to the total SER is also presented numerically in the figure. It should be noted that (a) is similar to [1, Fig. 8], but the type of the function of energetic dependence of cross sections is Weibull function, instead of linear interpolation in [1]. (a) SERs at 1.0 V. (b) SERs at 0.4 V.

different colors. It should be noted that Fig. 8(a) is similar to [1, Fig. 8], but the type of the function of the energetic dependence of cross sections is Weibull function, instead of linear interpolation in [1]. From these two figures, we observe that the low-energy neutrons below onset energy contribute to the total SEU and MCU rate negligibly at each operating voltage.

On the other hand, at a lower operating voltage of 0.4 V, we notice that the total SERs are higher due to a smaller critical charge compared to the nominal operating voltage, while the relative contribution of low-energy neutrons decreases. Let us look back at the ratio of cross section at 0.4–1.0 V in Fig. 8(b) with right y-axis. We could find the lower proportion is consistent with the relatively large decrease in SEU cross section at low-voltage operation with the decrease in neutron energy.

B. Impact of Disregarding the Flux of Neutrons Below 10 *MeV in the Acceleration Factor Calculation*

Terrestrial SER is often estimated by accelerated irradiation tests using spallation neutron sources. Due to the small cross section and consequent limited contribution of low-energy neutrons, JESD89 [2] suggests that the low-energy neutrons should not be counted in calculating the acceleration rate of the high-flux test environment to the low-flux terrestrial environment. However, the spectrum difference between the terrestrial environment and the test environment brings some error into the estimated SER. This section quantifies the estimation error supposing several neutron sources at widely used beam facilities and BL10 of MLF, J-PARC.

To avoid confusion in the discussion below, we define terrestrial SER as the SER obtained by folding the NYC spectrum with an energy-dependent cross section. We also define the estimated SER as the SER calculated by folding or measured at accelerated neutron test, either of which is divided by the acceleration rate. According to the definition above, the estimated SER is calculated in an irradiation campaign as follows:

TABLE II

PROPORTION OF LOW-ENERGY NEUTRONS IN THE TOTAL FLUX AND THE ACCELERATING RATE ACC CORRESPONDING TO THE MINIMUM ENERGY $E_{\min}$

Facility	% of 1-10 MeV	Acc corresponding to $E_{\min}$ $(\times 10^9)$		
		1 MeV	6 MeV	10 MeV
ChipIr	78 %	4.08	1.89	1.67
BL10 at J-PARC	92 %	0.96	0.21	0.14
LANSCE	55 %	0.86	0.72	0.66
TRIUMF	30 %	0.66	0.72	0.74
RCNP	57 %	0.29	0.21	0.20
NYC (Ref.)	36 %	-	-	-

$$\mathrm{SER_{estimated}} = \frac{\mathrm{SER_{facility}}}{\mathrm{Acc_{facility}}} = \frac{\mathrm{SER_{facility}}}{\int_{E_{\min}}^{\infty}\phi_{\mathrm{facility}}(E)dE / \int_{E_{\min}}^{\infty}\phi_{\mathrm{NYC}}(E)dE} \quad (3)$$

where $\phi_{\mathrm{facility}}(E)$ and $\phi_{\mathrm{NYC}}(E)$ are the differential neutron fluxes at a beam facility and NYC. $\mathrm{SER_{facility}}$ is the SER calculated by cross section folding with (1), and $\mathrm{Acc_{facility}}$ is the acceleration rate of beam facility, which is defined as the ratio of integration flux of the neutron source to integration flux at NYC. As shown in this equation, $\mathrm{Acc_{facility}}$ depends on minimum energy $E_{\min}$, which is the lower limit of the integration, namely, defines the energy threshold of negligible low-energy neutrons. We evaluate the difference between the estimated SER and the terrestrial SER as the estimation error supposing the terrestrial SER is correct.

To analyze the estimation error dependent on different minimum energies, we select 1 MeV, 10 MeV, and a medium value of 6 MeV, close to the onset energy of neutron-induced SEUs and MCUs in our device. Meanwhile, as various spectra $\phi_{\mathrm{facility}}(E)$ of spallation neutron sources, we select popular facilities of Los Alamos Neutron Science Center (LANSCE) [7], [22], TRIUMF [23], ChipIr [24], the Research Center for Nuclear Physics (RCNP) [25], and J-PARC [11], [12]. The proportion of low-energy neutrons in each facility and NYC are shown in Table II. From the table, we could understand BL10 at J-PARC contains an extremely high proportion of low-energy neutrons. The table also includes accelerating rate Acc corresponding to each minimum energy $E_{\min}$.

Using (1), we calculate $\mathrm{SER_{facility}}$ by folding the cross section with the differential flux of each neutron source. The estimated SER at each beam facility is shown in Figs. 9 and 10 for operating voltages of 1.0 and 0.4 V, respectively. From these two figures, we observe that for both SEUs and MCUs, setting the minimum energy to 6 and 10 MeV produces a smaller estimation error compared to 1 MeV. The most accurate estimation for SEUs is achieved when $E_{\min}$ is 6 MeV at ChipIr, BL10, and TRIUMP, while 10 MeV is better at LANCSE and RCNP. This tendency is similar at nominal and low operating voltages. At all the facilities and operating voltages, the best MCU estimation is achieved with $E_{\min} = 10$ MeV.

On the other hand, the estimation error is vastly different among facilities. The estimation at TRIUMF is relatively

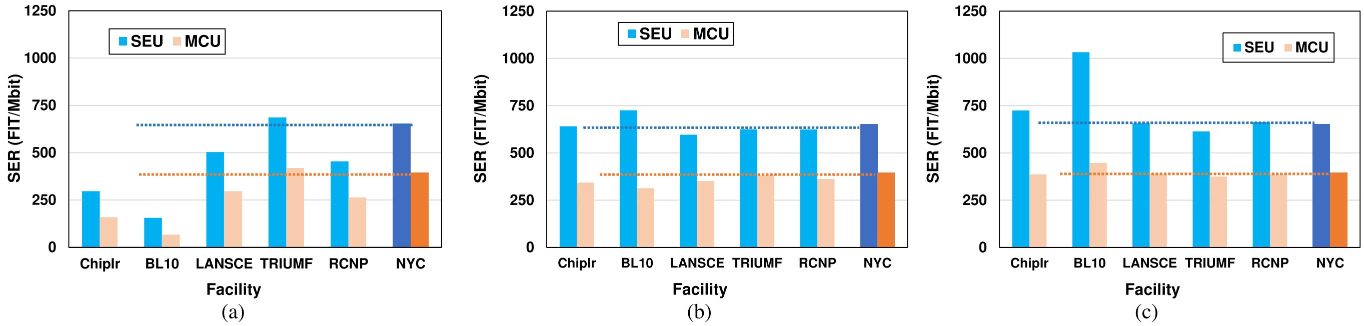


Fig. 9. SER estimation in unit of failure in time (FIT) rate with different minimum energy $E_{\min}$. (a) $E_{\min}$ = 1 MeV, (b) $E_{\min}$ = 6 MeV, and (c) $E_{\min}$ = 10 MeV. In each figure, terrestrial SER at NYC is added to the right side for comparison.

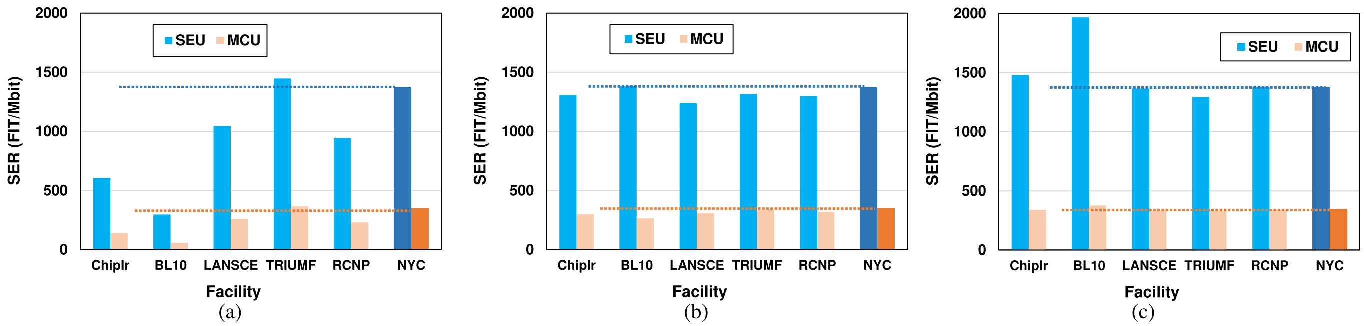


Fig. 10. SER estimation in unit of FIT rate with different minimum energy $E_{\min}$. (a) $E_{\min}$ = 1 MeV, (b) $E_{\min}$ = 6 MeV, and (c) $E_{\min}$ = 10 MeV. In each figure, terrestrial SER at NYC are is to the right side for comparison.

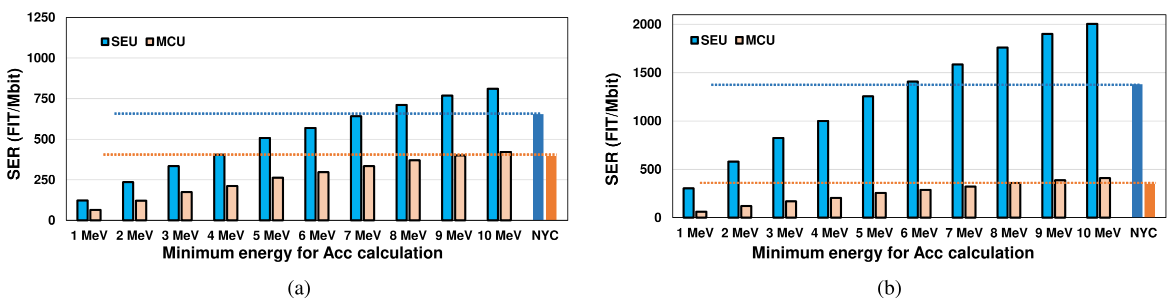


Fig. 11. Estimated SER from the experimental data at (a) 1.0 V and (b) 0.4 V in the irradiation campaign at BL10. In each figure, terrestrial SER at NYC is added to the right side for comparison. (a) Estimated SER from the real experimental data at BL10, 1.0 V. (b) Estimated SER from the real experimental data at BL10, 0.4 V.

stable regardless of the value of minimum energy, thanks to its proportion of low-energy neutrons compatible with the terrestrial environment. Even if the minimum energy was set to 1 MeV, the maximum estimation error at TRIUMF is relatively precise for both SEUs and MCUs, taking into account two operating voltages. In contrast, the estimation at RCNP and LANSCE has more significant errors. When the minimum energy was set to 6 or 10 MeV, on the other hand, the SER estimation error becomes acceptable, even though the beams at RCNP and LANSCE have more low-energy neutrons. The most suitable minimum energy for estimating MCU rates at LANSCE, TRIUMF, and RCNP is 10 MeV, while the least error of SEU rate estimation is with $E_{\min} = 6$ MeV at TRIUMF, and with $E_{\min} = 10$ MeV at RCNP and LANSCE, respectively.

Meanwhile, due to a significantly large proportion of low-energy neutrons, the accuracy of estimated SER at ChipIr and BL10 is sensitive to $E_{\min}$. In the case of $E_{\min} = 1$ MeV, the SEU rate is underestimated significantly at ChipIr and BL10 at two voltages of 1.0 and 0.4 V. But, conversely, if with $E_{\min} = 10$ MeV, the SEU rate is overestimated at ChipIr and BL10. The medium value of 6 MeV achieves the most accurate estimation of the SEU rate for both the facilities with a large proportion of low-energy neutrons in their beams.

Moreover, the data in the real irradiation campaign at BL10 with the same device and testing procedure reported in [10] also supports the above observation. Fig. 11 shows the actual influence of the minimum energy on the estimated SERs. It should be mentioned that the difference from the results in Figs. 9 and 10 is that the $\mathrm{SER}_{\mathrm{facility}}$s are calculated from the number of SEU and MCU events measured in the irradiation experiments instead of folding the cross sections with the spectrum. Fig. 11 indicates that the SEU rate estimation becomes the most accurate at 6–7 MeV. As for the MCU rate, the accuracy is the highest at 9 MeV, which is consistent with other facilities in Figs. 9 and 10.

On the other hand, you might find a difference between the SERs estimated from BL10 experiments in Fig. 11 and the

SERs estimated by folding the cross sections in Figs. 9 and 10. For example, at 1.0-V operating voltage, the SER estimated from the experiment is with 810 FIT/Mbit in Fig. 11(a), while that from the folding is 1032 FIT/Mbit when the same $E_{\min} = 10$ MeV is applied. Such a difference could be attributed to the source of BL10 containing a significant amount of low-energy neutrons, as shown in Table II. A more accurate estimation using the response function needs more measurement data to accurately characterize the low-energy region curve.

V. Conclusion

Between the nominal and low voltages of 1.0 and 0.4 V, the dependence of SEU cross section on the neutron energy is similar, including the onset energy. The existence of MCU at 6.0-MeV neutrons was also confirmed at both the operating voltages. As for the 0.4-V operation, the overall proportion of MCU is lower than that of 1.0 V due to the weaker PBA effect at lower operating voltage.

The low-energy neutrons contribute to the total SER of MCUs was around 3% at 1.0 and 0.4 V in the terrestrial environment. In contrast, low-energy neutrons contribute around 6% and 5% to the total SER of SEUs at 1.0 and 0.4 V, respectively. When estimating terrestrial SER, the current standard of disregarding the flux of neutrons below 10 MeV in the acceleration factor calculation is reasonable for the spallation beams whose low-energy neutron portion is 30% to 60%. However, for the beams with more low-energy neutrons, the 10-MeV threshold may significantly overestimate the SEU rate. In this case, the threshold of 6 MeV, which corresponds to the onset energy, is more appropriate for SEU rate estimation. Also, the 6-MeV threshold works for other facilities in SEU rate estimation, while 10 MeV is good for MCU rate estimation at all facilities.

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References

[1] W. Liao, K. Ito, Y. Mitsuyama, and M. Hashimoto, "Characterizing energetic dependence of low-energy neutron-induced MCUs in 65 nm bulk SRAMs," in *Proc. IEEE Int. Rel. Phys. Symp. (IRPS)*, Apr. 2020, p. P49.

[2] JEDEC, *Measurement and Reporting of Alpha Particle and Terrestrial Cosmic Ray Induced Soft Error in Semiconductor Devices*, JEDEC Standard JESD89A, Oct. 2006, pp. 1–85.

[3] T. Sato, "Analytical model for estimating terrestrial cosmic ray fluxes nearly anytime and anywhere in the world: Extension of PARMA/EXPACS," *PLoS ONE*, vol. 10, no. 12, Dec. 2015, Art. no. e0144679.

[4] J. Baggio, D. Lambert, V. Ferlet-Cavrois, P. Paillet, C. Marcandella, and O. Duhamel, "Single event upsets induced by 1–10 MeV neutrons in static-RAMs using mono-energetic neutron sources," *IEEE Trans. Nucl. Sci.*, vol. 54, no. 6, pp. 2149–2155, Dec. 2007.

[5] A. Hands, P. Morris, C. Dyer, K. Ryden, and P. Truscott, "Single event effects in power MOSFETs and SRAMs due to 3 MeV, 14 MeV and fission neutrons," *IEEE Trans. Nucl. Sci.*, vol. 58, no. 3, pp. 952–959, Jun. 2011.

[6] D. Lambert *et al.*, "Single event upsets induced by a few MeV neutrons in SRAMs and FPGAs," in *Proc. IEEE Radiat. Effects Data Workshop (REDW)*, Jul. 2017, pp. 114–118.

[7] H. Quinn, A. Watkins, L. Dominik, and C. Slayman, "The effect of 1–10-MeV neutrons on the JESD89 test standard," *IEEE Trans. Nucl. Sci.*, vol. 66, no. 1, pp. 140–147, Jan. 2019.

[8] M. Cecchetto, R. Garcia Alia, S. Gerardin, M. Brugger, A. Infantino, and S. Danzeca, "Impact of thermal and intermediate energy neutrons on SRAM SEE rates in the LHC accelerator," *IEEE Trans. Nucl. Sci.*, vol. 65, no. 8, pp. 1800–1806, Aug. 2018.

[9] W. Liao, M. Hashimoto, S. Manabe, S.-I. Abe, and Y. Watanabe, "Similarity analysis on neutron- and negative muon-induced MCUs in 65-nm bulk SRAM," *IEEE Trans. Nucl. Sci.*, vol. 66, no. 7, pp. 1390–1397, Jul. 2019.

[10] J. Kuroda *et al.*, "Measurement of single-event upsets in 65-nm SRAMs under irradiation of spallation neutrons at J-PARC MLF," *IEEE Trans. Nucl. Sci.*, vol. 67, no. 7, pp. 1599–1605, Jul. 2020.

[11] F. Maekawa *et al.*, "NOBORU: J-PARC BL10 for facility diagnostics and its possible extension to innovative instruments," *Nucl. Instrum. Methods Phys. Res. A, Accel. Spectrom. Detect. Assoc. Equip.*, vol. 600, no. 1, pp. 335–337, Feb. 2009.

[12] M. Harada, F. Maekawa, K. Oikawa, S.-I. Meigo, H. Takada, and M. Futakawa, "Application and validation of particle transport code PHITS in design of J-PARC 1 MW spallation neutron source," *Prog. Nucl. Sci. Technol.*, vol. 2, pp. 872–878, Oct. 2011.

[13] G. Gasiot, D. Giot, and P. Roche, "Multiple cell upsets as the key contribution to the total SER of 65 nm CMOS SRAMs and its dependence on well engineering," *IEEE Trans. Nucl. Sci.*, vol. 54, no. 6, pp. 2468–2473, Dec. 2007.

[14] T. Uemura, T. Kato, and H. Matsuyama, "Impact of parasitic bipolar action and soft-error trend in bulk CMOS at terrestrial environment," in *Proc. IEEE Int. Rel. Phys. Symp. (IRPS)*, Apr. 2013, p. 6C.

[15] S.-I. Abe *et al.*, "Impact of hydrided and non-hydrided materials near transistors on neutron-induced single event upsets," in *Proc. IEEE Int. Rel. Phys. Symp. (IRPS)*, Apr. 2020, p. 8C.

[16] H. Harano, T. Matsumoto, J. Nishiyama, A. Uritani, and K. Kudo, "Accelerator-based Neutron Fluence Standard of the National Metrology Institute of Japan," in *Proc. AIP Conf.*, Mar. 2009, vol. 1099, no. 1, pp. 915–918.

[17] H. Harano *et al.*, "Characterization of the 2.5 MEV neutron field for monoenergetic fast neutron fluence standard at the national metrology institute of Japan," in *Proc. Int. Workshop Fast Neutron Detectors Appl. PoS(FNDA)*, Jan. 2007, p. 017.

[18] M. Yoshizawa, T. Sugita, J. Saegusa, Y. Tanimura, and M. Yoshida, "A Monte Carlo program for estimating characteristics of neutron calibration fields using a pelletron accelerator," *J. Nucl. Sci. Technol.*, vol. 39, no. 2, pp. 1240–1243, Aug. 2002.

[19] Y. Watanabe *et al.*, "Nuclear data evaluations for JENDL high-energy file," in *Proc. AIP Conf.*, May 2005, vol. 769, no. 1, pp. 326–331.

[20] W. Liao *et al.*, "Measurement and mechanism investigation of negative and positive muon-induced upsets in 65-nm bulk SRAMs," *IEEE Trans. Nucl. Sci.*, vol. 65, no. 8, pp. 1734–1741, Aug. 2018.

[21] J. L. Autran, S. Serre, S. Semikh, D. Munteanu, G. Gasiot, and P. Roche, "Soft-error rate induced by thermal and low energy neutrons in 40 nm SRAMs," *IEEE Trans. Nucl. Sci.*, vol. 59, no. 6, pp. 2658–2665, Dec. 2012.

[22] P. W. Lisowski and K. F. Schoenberg, "The Los Alamos neutron science center," *Nucl. Instrum. Methods Phys. Res. A, Accel. Spectrom. Detect. Assoc. Equip.*, vol. 562, no. 2, pp. 910–914, Jun. 2006.

[23] E. W. Blackmore, P. E. Dodd, and M. R. Shaneyfelt, "Improved capabilities for proton and neutron irradiations at TRIUMF," in *Proc. IEEE Radiat. Effects Data Workshop*, Jul. 2003, pp. 149–155.

[24] C. Cazzaniga and C. D. Frost, "Progress of the scientific commissioning of a fast neutron beamline for chip irradiation," in *Proc. J. Phys., Conf.*, vol. 1021, May 2018, Art. no. 012037.

[25] Y. Iwamoto *et al.*, "Evaluation of the white neutron beam spectrum for single-event effects testing at the RCNP cyclotron facility," *Nucl. Technol.*, vol. 173, no. 2, pp. 210–217, Feb. 2011.