Characterizing Energetic Dependence of Low-Energy Neutron-induced MCUs in 65 nm bulk SRAMs

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***Abstract*—This paper studies the characteristic of MCUs induced by monoenergetic and quasi-monoenergetic low-energy neutrons in 65-nm SRAM. This work is highlighted with the characterized dependence of the MCU cross section on the neutron energy, whereas the evaluated energy dependence of the SEU cross section was consistent with the literature. Both the MCU cross section and its proportion to the total events increase with higher neutron energy. At the onset energy of 6.0 MeV, the MCU proportion is 51 %, while the maximum value of 66 % is at 70 MeV. On the other hand, even at a lower energy of 4.1 MeV, the MCU proportion keeps around 50 %. The high MCU proportion over the wide range of neutron energy suggests the possibility of large-LET secondary ions being generated even by 4.1 MeV neutrons. Also, based on the measured MCU dependence, we calculated the contribution of the low-energy neutron to the total SER of MCU. The calculated result indicates that the low-energy neutrons below 10 MeV are mostly negligible in the terrestrial environment.**

***Index Terms*—low energy neutrons, single event upset, SRAMs, MCUs**

I. INTRODUCTION

Neutrons are considered as the main source of terrestrial cosmic ray-induced single event upsets (SEUs) in semiconductor devices. At present, although the energy of terrestrial neutrons distributes widely from the magnitude of keV to GeV, the JESD89 test standard defines 10 MeV as the minimum energy of neutrons for calculating soft error rate (SER) [1]. On the other hand, the proportion of 1 to 10-MeV neutrons in the total flux of neutrons with energies above 1 MeV is 36 % at New York City [2]. Therefore, clarifying the contribution of low-energy neutron-induced SEUs to the terrestrial SER is demanded.

Several works reported measurement results of 1 to 10-MeV neutron-induced SEU cross sections. J. Baggio et al. reported the SEU cross section induced by 2.5, 4, 6, and 14 MeV neutrons in the SRAMs at technology nodes of 180 nm, 250 nm, and 450 nm [3]. Similarly, A. Hands et al. reported the cross section for 3 and 14 MeV neutrons at 90 nm and older nodes [4] and D. Lambert et al. reported the data for 2.5, 4, 6 and 16.4 MeV neutrons at up to 65 nm nodes [5]. Based on the measurements above, H. Quinn reported that the minimum energy in the current calculation of the terrestrial SER was reasonable, and its error is within less than 15 % [6]. On the other hand, although multiple cells upsets (MCUs) have a larger probability of spoiling the error-correcting code (ECC), low-energy neutrons-induced MCUs are hardly studied. Only [4] compared off-the-shelf SRAMs in terms of MCUs for 14 MeV neutrons. No energy dependence of MCU has been reported as far as the authors know.

In this paper, we characterize the dependence of the MCU cross section on the neutron energy using monoenergetic neutron sources of 6.0, 8.0 and 14.8 MeV. Also, taking advantage of the angular dependence of the peak energy of the all-direction beam, we evaluate the MCU cross section at several energy points from 3 to 8 MeV. Combining the experimental result using quasi-monoenergetic and white neutron sources [7], we clarify whether the low-energy neutrons cause only single bit upsets (SBUs) or MCUs as well as SBUs. Then, based on the measured dependence of the MCU cross section on the energy, the contribution of the low-energy neutrons to the total SER is also analyzed.

II. IRRADIATION TEST USING LOW-ENERGY NEUTRONS

Our static random access memory (SRAM) chips under test were fabricated in a commercial 65-nm process with a deep N-well (DNW) option. DNW enhances parasitic bipolar actions (PBAs) to make MCUs occur more easily among the SRAM cells sharing the same N-well [8]. On each design under test (DUT) board, 16 bulk SRAM chips are mounted. Each chip contains 12 Mbit and thus 192 Mbit for a DUT board. At each spectrum explained below, we repeated static tests of 10-minute duration four to six times. All SRAM cells were initialized to 0, and the operating voltage was set to 1.0 V during the hold time. As shown in Fig. 1, neutron irradiation was incident on the bottom of side of the printed circuit board (PCB), and the neutron traversed the PCB before reaching the DUTs.

For characterization of low-energy neutron-induced SEUs in the SRAM, neutron sources at the national metrology institute of Japan (NMIJ) in Advanced Industrial Science and Technology (AIST) [9] were utilized. At NMIJ, 6.0-MeV neutron beam by the D(d,n)^{3}He reaction and 8.0-MeV neutron beam by ^{9}Be(α,n)^{12}C are provided using a Van de Graaff accelerator, while 14.8-MeV neutron beam by T(d,n)^{4}He are provided using a Cockcroft-Walto accelerator.

The above-mentioned neutron beams at NIJM are all-directional as shown in Fig. 2. Depending on the angle between the exit-to-DUT direction and the vertical line of the beam exit, the neutron spectrum varies. The spectrum corresponding to each beam energy is shown in Fig. 3. It

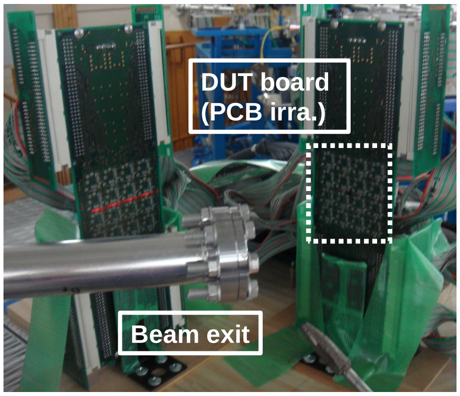

Fig. 1: Experimental setup. The DUT boards were irradiated from the PCB sides.

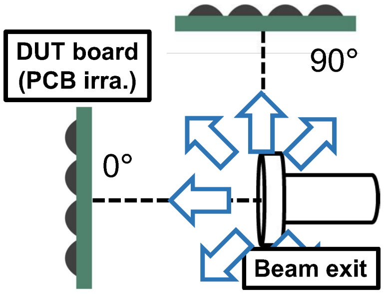

Fig. 2: Direction of irradiation to DUT boards relative to the vertical line of the beam exit. The beam is all-directional.

should be noted that only the spectra in the direction along the vertical line, namely 0°, are measured for the beam of each original energy, while the spectra along the tilt directions are calculated ones. As pointed out by [9], the neutron sources of 14.8 and 6.0 MeV are monoenergetic ones with an uncertainty of energies of 6.2 % at most, which is consistent with their flux accumulating sharply at the peak energies as shown in Fig. 3. Meanwhile, although 8.0-MeV neutron sources are quasi-monoenergetic, we confirmed at least 80 % flux accumulated within 0.1 MeV at its peak energy along 0° direction. Therefore, most neutron sources are regarded as monoenergetic ones except for 90° in the 8.0-MeV beam.

Due to the smaller SEU cross sections for low-energy neutrons, we placed the DUT board at 12 cm from the beam exit while keeping it possible to measure two directions in one irradiation setting, as shown in Fig. 2. Here, the small difference of each chip location on the board varies the peak energy and fluence, but the variations of the peak energy and fluence are at most 4 % and 6 % in 0° direction. Therefore, the chips on the same DUT board are assumed to share the same irradiation environment in case of 0° direction. Meanwhile, the difference of energy reaches at most 16 % (0.6 MeV) in the tilt directions. Although the difference is relatively larger compared to that of 0°, due to small number of errors in each chip, we do not split the results according to the chip locations and consider that all the chips on the same DUT board have the same irradiation environment.

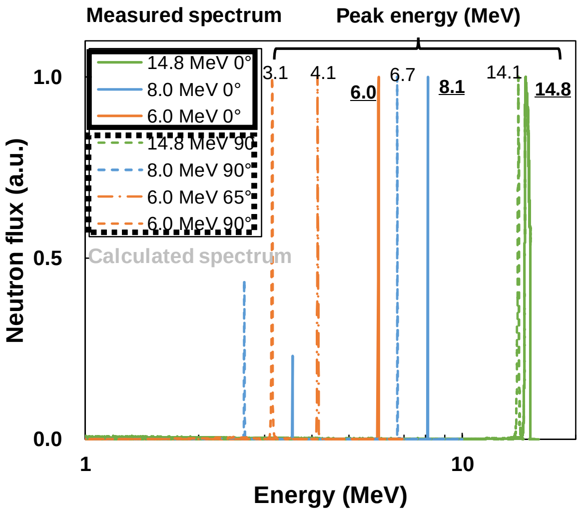

Fig. 3: Spectra of neutrons of the corresponding directions and beam sources.

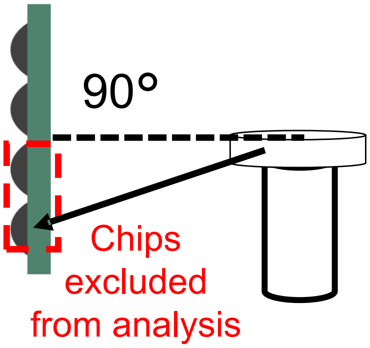

Fig. 4: Chips in the direction of the angle larger than 90° were excluded from the analysis because the calculated spectrum was not reliable due to the metal parts in the way of the neutron beam.

Also, on the DUT board in the direction of 90°, half of the chips were located in the direction of over 90°. As shown in Fig. 4, the metal parts of the beam exit exist in the way of neutrons. Therefore, the calculated spectrum is not reliable and then those chips are excluded from the following analysis.

In this paper, we define the SEU cross section as the one counting the total event number, e.g. both an SBU and 2-bit MCU are counted as one event respectively. For the MCU analysis, we define the MCU cross section as the one counting only MCU events, while the SBU cross section counts only SBU events.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. *Onset energy*

Figure 5 shows the experimental results of the SEU cross section measured with the neutron sources of 6.0, 8.0, and

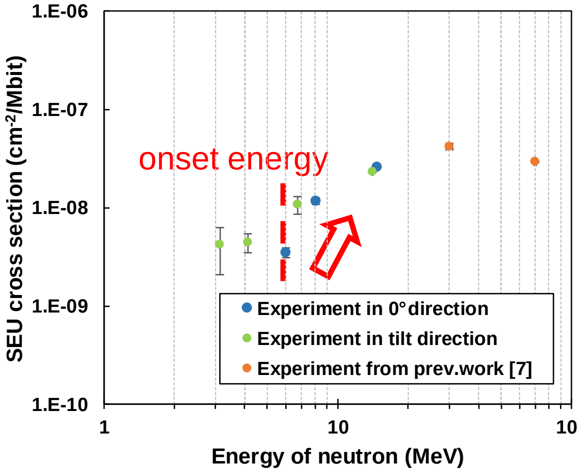

Fig. 5: Measured energetic dependence of SEU cross section at 1.0 V. Error bar corresponds to one standard deviation.

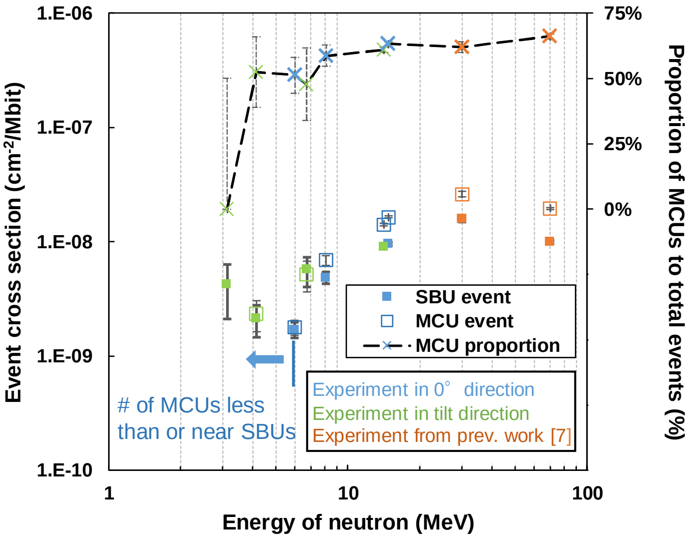

Fig. 6: Energetic dependence of SBU and MCU event cross sections at 1.0 V (left y-axis) and proportion of MCUs at 1.0 V (right y-axis). Error bar is with one standard deviation.

14.8 MeV. Cross sections are plotted at the peak energy of the spectrum. Blue markers are used for measured spectra (at normal incidence), and green markers are used for calculated spectra (experiments in tilt directions). Meanwhile, for comparison, we added the cross sections measured on the same devices using quasi-monoenergetic neutrons of 30 and 70 MeV with the same procedures, which are reported in [7], to the figure. All the results were with the error bars of one standard deviation.

In this figure, the cross section increases by 3.4 X, 2.2 X and 1.6 X from 6.0 MeV to 8.1 MeV, 8.1 MeV to 14.8 MeV, and 14.8 MeV to 30.0 MeV, respectively. The rapid increase to reach saturation is consistent with the energy dependence of SEU cross sections reported in [5]. On the other hand, we observe the minimum and maximum of the SEU cross sections are 3.5×10^{-9} cm^2/Mbit at the energy of 6.0 MeV and 2.6×10^{-8} cm^2/Mbit at 14.8 MeV, respectively. The SEU cross section at 14.8 MeV is similar to another test report for the FPGA in the same technology node [5], which reported 2.0×10^{-8} cm^2/Mbit at 14 MeV. On the contrary, the cross section at 6.0 MeV of 3.5×10^{-9} cm^2/Mbit of our device is slightly larger than the minimum value of 1.3×10^{-9} cm^2/Mbit at 2 MeV in [5]. When we define the onset energy as the energy at which the SEU cross section decreases by one order of magnitude from the saturated value, it is roughly 6.0 MeV in our device.

Figure 5 also shows that the neutron-induced cross section stays almost the same in the region between 3.1 MeV to 6.0 MeV, below the onset energy. Here, it should be noted that only four errors were observed during the 3.1-MeV test. This almost unchanged cross section in this energy region could be attributed to the balance between the increase in neutron-silicon elastic scattering and the decrease in neutron-silicon reaction [10]. Further investigation with simulations is necessary and one of our future work.

B. Dependence of MCU cross section on neutron energy

Next, we discuss the dependence of the MCU cross section on the neutron energy. Figure 6 shows the SBU and MCU event cross sections with the left Y-axis calculated from the same measured data. All the results were with the error bar of one standard deviation. We observed a similar trend of energy dependence in terms of the onset energy and the rapid saturation. In the comparison between the MCU and SBU, we observe that the MCU cross section increases slightly faster than that of SBU above the onset energy of 6.0 MeV. To highlight the relative increase of the MCU, the right Y-axis of Fig. 6 shows the energy dependence of the proportion of MCU to the total events. At 14.8 MeV or above, the proportions are all larger than 60 % and come to saturation.

On the other hand, even when the energy decreases from 6.0 to 4.1 MeV, the proportion still keeps around 50 %. In our device, the high proportion might be attributed to the mechanism of PBAs [11]. However, the large charge needs to be deposited to trigger PBAs [11]. The high proportion of MCU suggests that the reactions between low-energy neutrons and silicon atoms generate secondary ions having large enough linear energy transform (LET) to cause PBA. The PBA effect has a strong dependence on the supply voltage. The experiments at various supply voltages are necessary to investigate the mechanism of MCU for low-energy neutrons.

However, when the energy decreases further to 3.1 MeV, no MCUs were observed and thus, the proportion of MCU was 0% at 3.1 MeV. Combining with Fig. 5, we observe that although the SEU cross sections are similar for 3.1-MeV and 4.1-MeV neutrons, the half of the SEUs are contributed by the MCU at 4.1 MeV while all the SEUs are SBUs at 3.1 MeV. Even if the MCU events would be observed during a longer-time irradiation test for 3.1-MeV neutrons, the proportion of MCUs is supposed to decrease significantly. Our measurement result may indicate that the LET of the secondary ions generated by neutron-silicon elastic scattering and reaction becomes too low to induce MCUs, and there could be a threshold energy value between 3.1 and 4.1 MeV for the MCU occurrence.

C. Contribution of low-energy neutrons to the total SER$_{MCU}$

Based on the experimental result, we fold the SEU cross section with the differential flux of neutrons at Tokyo, Japan. The neutron spectrum above 1 MeV was calculated according to EXPACS [2], which calculates atmosphere cosmic ray spectra, and it is shown in Fig. 7. The formula for SER folding is expressed as follows:

$$SER = \int_{E_{\min}}^{\infty} \sigma(E) \cdot \phi(E) dE, \tag{1}$$

where E is the neutron energy, $\sigma(E)$ is either SEU or MCU cross section induced by the neutrons of the corresponding energy, and $\phi(E)$ is the differential flux of the neutron of the corresponding energy. Here, we assume: 1) the least energy for neutrons to induce SEUs is 1 MeV ($E_{\min}$ = 1MeV), and 2) the neutron-induced cross section is the same in the region between 1 MeV to 3 MeV and it is saturated above 70 MeV. The cross sections at other energy values are calculated using linear interpolation.

The folding results of SER$_{SEU}$ and SER$_{MCU}$ are shown in Fig. 8, where the contributions of neutrons whose energy are 1 to 3 MeV, 3 to 10 MeV and above 10 MeV are separately plotted. From this figure, we observe that the contribution of neutrons below 10 MeV to the total SER is 5.5% for SEU and 2.3% for MCU. This result shows that the contribution of low-energy neutrons to the MCU rate is lower than that to the SEU rate. Meanwhile, regardless of the MCU or SEU rates, the contribution of low-energy neutrons is small compared to the high energy ones in the terrestrial environment. Therefore, although the low-energy neutrons around 4 MeV can still induce MCUs, its contribution to the total MCU rate would be negligible.

IV. CONCLUSION

In this paper, we evaluated the energy dependence of SEUs and MCUs induced by low-energy neutrons with the irradiation experiments. The onset energy, which was defined as the energy at which the cross section becomes one-tenth of the saturated one, was about 6.0 MeV in our 65 nm SRAM devices. The evaluated dependence of SEU cross section on the neutron energy was consistent with the literature. Meanwhile, this work focused on the energy dependence of the MCU cross section. Both the MCU cross section and its proportion to the total SEU events increased with higher energy. However, at the onset energy of 6.0 MeV, the MCU proportion still kept 51 %, while the maximum value of 66 % was at 70 MeV. This high MCU proportion suggests the possibility of large-LET secondary ions being generated even by 4.1 MeV neutrons. On the other hand, no MCUs were observed at 3.1 MeV even while the SEU cross section stayed the same. The contribution of low-energy neutrons below 10 MeV to the total MCU rate was 2.3 % in the terrestrial environment, and low-energy neutrons are responsible for 5.5 % of total SEU rate.

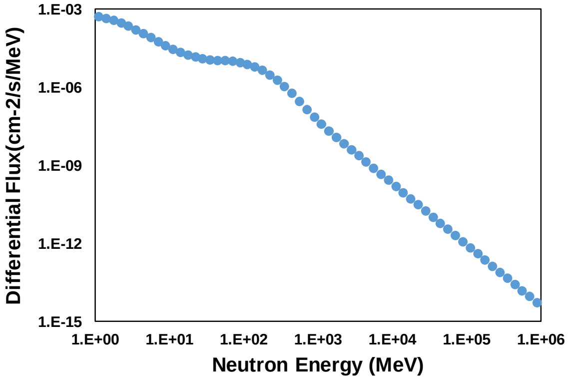

Fig. 7: Neutron spectrum at Tokyo City, Japan calculated with EXPACS [2].

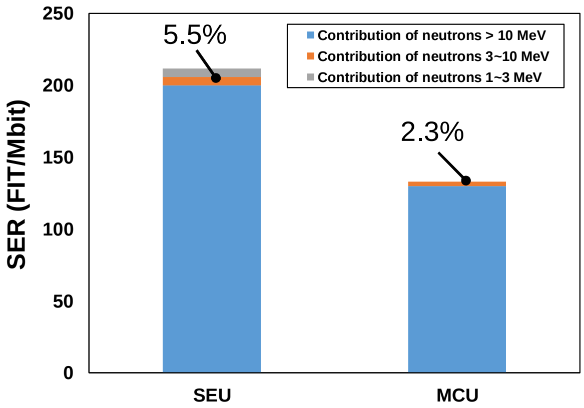

Fig. 8: SERs of SEU and MCU estimated with folding. The contributions of neutrons whose energy is 1 to 3 MeV, 3 to 10 MeV and above 10 MeV are plotted separately. The percentages of the contribution of the neutrons below 10 MeV to the total SER of SEUs and MCUs are also presented in the figure.

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