

Sensitive Volume Allocation Aligned With a Physics-Based Analytical Cross Section Model for Monte Carlo-Based Proton-Induced SEU Simulation

Kozo Takeuchi^{ID} and Masanori Hashimoto^{ID}, *Senior Member, IEEE*

Abstract—This article proposes a method for constructing physically reasonable multiple sensitive volumes (SVs) and predicting upset cross sections (XSs) in particle transport Monte Carlo simulations. The validity of the method is discussed with the proton-induced single event upsets (SEUs) on several static random access memories (SRAMs). All simulated XSs for proton energies from 0.7 to 230 MeV, except for a few data points, agreed with the experimental data within a factor of 0.3–3.

Index Terms—Monte-Carlo (MC) simulation, multiple sensitive volumes (MSVs), protons, single event upsets (SEUs), static random access memories (SRAMs).

I. INTRODUCTION

PROTONS are among the most abundant particles in the space environment, particularly in low-Earth orbit, where many entities are working to build constellations of satellites. Commercial off-the-shelf (COTS) parts are gaining attention for risk-tolerant space applications due to their high performance, wide availability, and lower cost compared to traditional space components. However, these COTS parts, often manufactured using highly scaled fabrication processes, are expected to encounter challenges related to single-event effects in orbit.

Static random access memories (SRAMs) are known to be among the smallest and most radiation-sensitive circuits in semiconductor chips. Protons may trigger single event upsets (SEUs) through both indirect and direct ionization. These proton-induced energy depositions in the semiconductor material may occur simultaneously, depending on factors such as proton energy, material properties, and other conditions [1].

Since Rodbell et al. [2] demonstrated that proton direct ionization (PDI) causes upsets in 65-nm silicon-on-insulator SRAMs and latches, subsequent studies have evaluated memory elements on 65-nm silicon-on-insulator [3],

65-nm bulk [4], and 45–32-nm bulk [5]. Dodds et al. [6], [7], [8] employed heavily degraded high-energy protons to simulate shielded space environments and examined both the upset rate in orbit and the underlying mechanisms of PDI-induced upsets.

Recent studies have investigated SEU cross sections (XSs) for SRAMs ranging from 65 to 16 nm under both quasi-monoenergetic low-energy proton and heavily degraded high-energy proton irradiations [9], [10], [11]. Monte Carlo (MC) simulations, incorporating empirical multiple sensitive volumes (MSVs) and calibrated charge collection weights with heavy ion (HI) XS data, were used to calculate and analyze upset rates under specific orbital and environmental conditions. However, the empirically constructed MSVs and charge collection weights do not match or reflect the physical dimensions and charge collection phenomena in many cases [4], [12]. The calibration of weights and sensitive volumes (SVs) using HI-induced SEU XS data involves numerous iterations of MC simulations. It is worth mentioning that there are many other methods for calculating or modeling SEUs under specific radiation conditions (e.g., Autran and Munteanu [13] summarized the major existing methods).

Our previous work [14], on the other hand, proposed an analytical relationship between the charge deposited by HIs and the SEU XS of SRAMs. Since its parameters have physical meanings and units, they may facilitate a systematic understanding of SVs and their charge collection weights.

Meanwhile, another of our previous works [15] proposed an analytical model for the neutron soft-error rate (nSER), utilizing an empirical relationship between linear energy transfer (LET) and flux for secondary particles induced by neutron-Si interactions through the burst generation rate [16]. In contrast, no equivalent relationship model currently exists for secondary particles induced by proton-Si interactions. Therefore, particle-transport MC simulations are commonly employed to predict proton-induced SEU XSs.

This work proposes an SV allocation method in MC simulation based on physics-based analytical XS, rather than empirically setting SVs and their charge collection weights. In the proposed method, the depths of SVs are defined as the charge collection lengths (or depths) determined by funneling and diffusion mechanisms. The SEU XSs against protons

Received 2 December 2025; revised 7 January 2026; accepted 12 January 2026. Date of publication 15 January 2026; date of current version 18 August 2026. This work was supported by Japan Aerospace Exploration Agency. (Corresponding author: Kozo Takeuchi.)

Kozo Takeuchi is with Japan Aerospace Exploration Agency, Tsukuba 305-8505, Japan (e-mail: takeuchi.kozo@jaxa.jp).

Masanori Hashimoto is with the Department of Informatics, Kyoto University, Kyoto 606-8501, Japan (e-mail: hashimoto@i.kyoto-u.ac.jp).

Color versions of one or more figures in this article are available at <https://doi.org/10.1109/TNS.2026.3654595>.

Digital Object Identifier 10.1109/TNS.2026.3654595

0018-9499 © 2026 IEEE. All rights reserved, including rights for text and data mining, and training of artificial intelligence and similar technologies. Personal use is permitted, but republication/redistribution requires IEEE permission.

See <https://www.ieee.org/publications/rights/index.html> for more information.

Authorized licensed use limited to: Kyoto University. Downloaded on October 06, 2026 at 09:45:04 UTC from IEEE Xplore. Restrictions apply.

TABLE I
LIST OF SYMBOLS IN (1)

Symbols	Remarks	Unit
XS	SEU XS per SRAM bit cell	cm ² /bit
A _{SRAM}	Area of SRAM bit cell	cm ²
<i>r</i>	Ratio of the funneling-based charge collection dominant area to A _{SRAM}	-
ζ	Circuit loading factor (= 2)	-
C _L	Internal load capacitance	fF
d _{fnl}	Funneling-based charge collection length	nm
d _{diff}	Diffusion-based charge collection length	nm
V _{DD}	Power supply voltage	V
V _{DR}	Data retention voltage	V
<i>L</i>	LET of incident ions	MeV·cm ² /mg

were then calculated by the analytical relationship proposed in [14] instead of setting the charge collection weights. (Details are provided in Section II.) The proposed method and simulation may help reduce the burden of experimentally acquiring proton-induced SEU XSs since the proposed SV allocation has the potential to predict proton-induced SEU XSs straightforwardly from HI-induced SEU XSs.

The rest of this article is organized as follows. The details of the proposed method for predicting proton-induced SEU XSs as a function of proton energy are explained in Section II. Section III describes the setup for the simulation, followed by the results and discussion of the method in Section IV.

II. PROPOSED METHOD

Our previous work [14] demonstrated that the SEU XS is well expressed as the function of LET and V_{DD}, as shown in the following:

$$XS = A_{SRAM} \left[r \cdot \exp \left(-\frac{5\zeta C_L}{d_{fnl}} \frac{V_{DD} - V_{DR}}{0.01L} \right) + (1 - r) \cdot \exp \left(-\frac{5\zeta C_L}{d_{diff}} \frac{V_{DD} - V_{DR}}{0.01L} \right) \right] \quad (1)$$

where symbols in (1) are listed in Table I. Equation (1) has been extended from the original single-exponential model [17] to a double-exponential model to account for both funneling- and diffusion-based charge collection processes of the transistor. The parameters of *d*_{fnl} and *d*_{diff} represent the effective lengths corresponding to the two charge collection mechanisms. The value of 0.01 is a unit conversion factor for MeV·cm²/mg to fC/nm in (1).

This work proposes simulating the *L* distribution in SVs induced by protons and secondary particles through MC simulation so that (1) may predict the SEU XS as a function of proton energy. Our idea is that we interpret the parameters of *d*_{fnl} and *d*_{diff} as the depth values of two rectangular parallelepiped (RPP) SVs, SV_{fnl} and SV_{diff}, in the MC particle transport simulation since they represent physical charge collection lengths. Fig. 1 shows the two stacked RPP SVs introduced to calculate the deposited charge in each SV. *L*_{SRAM} and *W*_{SRAM}, which are the length and width of the SRAM bit cell, respectively, are assumed. Here, we do not need to consider the sizes of sensitive transistors since such an area factor is already included as parameter *r* in (1).

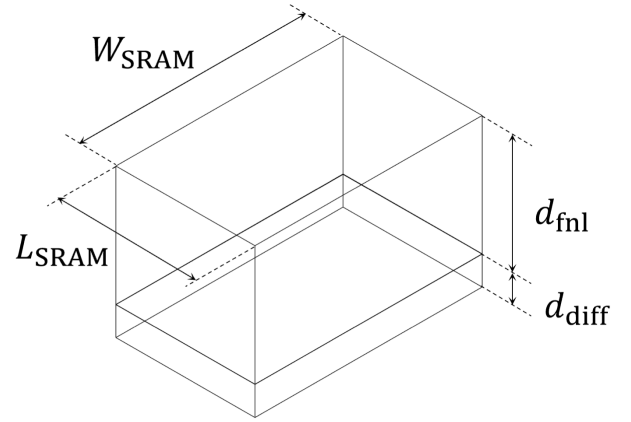


Fig. 1. Proposed two stacked SVs.

The deposited energy is logged in each run of the MC simulations. *E*_{fnl}(*i*, *j*) and *E*_{diff}(*i*, *j*), which represent the energies deposited by the *i*th proton injection in the *j*th SV_{fnl} and the *j*th SV_{diff}, respectively, are then used as inputs for the following equation to calculate XS(*i*, *j*) for the *i*th proton injection and *j*th SVs:

$$XS(i, j) = XS_{fnl}(i, j) + XS_{diff}(i, j) \\ = A_{SRAM} \cdot r \cdot \exp \left(-\frac{5\zeta C_L}{E_{fnl}(i, j)} \frac{V_{DD} - V_{DR}}{e/W} \right) \\ + A_{SRAM} \cdot (1 - r) \cdot \exp \left(-\frac{5\zeta C_L}{E_{diff}(i, j)} \frac{V_{DD} - V_{DR}}{e/W} \right) \quad (2)$$

where *e* and *W* are the elementary charge (1.602 × 10⁻¹⁹ C) and the energy required to produce a single electron-hole pair (known as *W*-value) in Si (3.6 eV/pair), respectively. XS_{fnl}(*i*, *j*) and XS_{diff}(*i*, *j*) correspond to the XS of funnel- and diffusion-based charge collections for the *i*th proton injection in the *j*th SV_{fnl} and SV_{diff}, respectively. Unless otherwise specified, the term “proton injection” refers to the generation of primary particles in the simulation.

It is obvious that *E*_{fnl}(*i*, *j*) > 0 and *E*_{diff}(*i*, *j*) > 0 hold for each *i*th proton and *j*th SVs. Specifically, in the case where *E*_{fnl}(*i*, *j*) = 0 (or *E*_{diff}(*i*, *j*) = 0), we assume that XS_{fnl}(*i*, *j*) = 0 (or XS_{diff}(*i*, *j*) = 0) as the limiting value as *E*_{fnl}(*i*, *j*) (or *E*_{diff}(*i*, *j*)) approaches + 0. The predicted XS (*X̂S*) is then calculated as the average of the total expected XS value across the injected protons that deposited any charge as follows:

$$\hat{XS} = \frac{1}{n} \sum_{i=1}^n \left(\sum_{j=1}^m XS(i, j) \right) \quad (3)$$

where *n* and *m* are the total numbers of injected protons that deposit any charge in one or more SVs and the total number of each type of SV, respectively. In this work, *m* = 10000 is used, as described later. The term enclosed in parentheses in (3) represents the total expected XS value from the *i*th proton injection. Fig. 2 illustrates the concept of the term. The total expected XS value represents the sum of the black squares for each proton injection.

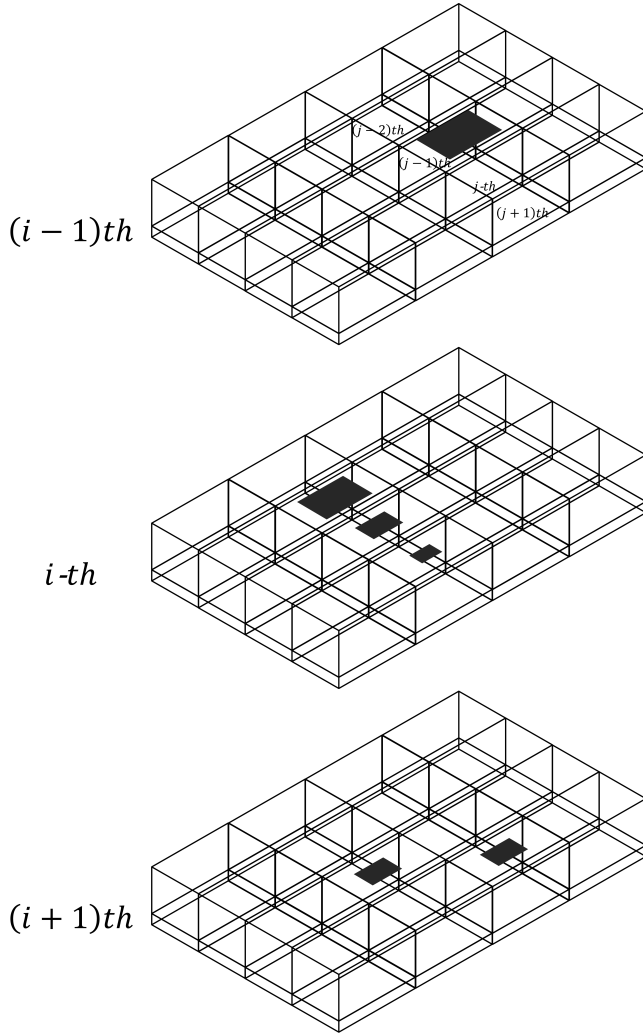


Fig. 2. Illustration of the XS calculation principle based on (3). Examples of the $(i-1)$ th, i th, and $(i+1)$ th proton injections are shown. Based on the charge deposited in each SV, the XSs are calculated using (2), as represented by the black squares. The total area of the black squares for each proton injection represents the expected XS value. For example, the top illustration shows the case for the $(i-1)$ th particle irradiation where a proton strikes the j th SVs, and the XS is calculated as indicated by the black square.

The proposed model assumes two main use cases: 1) identifying generational trends and voltage dependence and 2) evaluating specific devices in detail. In both use cases, the parameters A_{SRAM} , V_{DD} , L_{SRAM} , and W_{SRAM} are typically available in the literature or in device datasheets since they are fundamental to SRAM bit-cell design. Two other parameters (V_{DR} and C_L) are not commonly reported, so reasonable values must be assumed.

The remaining parameters in Table I are determined differently depending on the use case. In use case 1), because the parameters in our model have physical meaning and physical units—unlike those of the cumulative Weibull function—reasonable values can be assigned directly for a given technology node. In use case 2), by extracting the parameters from HI data for a particular SRAM through fitting, the model can predict proton-induced cross sections for that same SRAM.

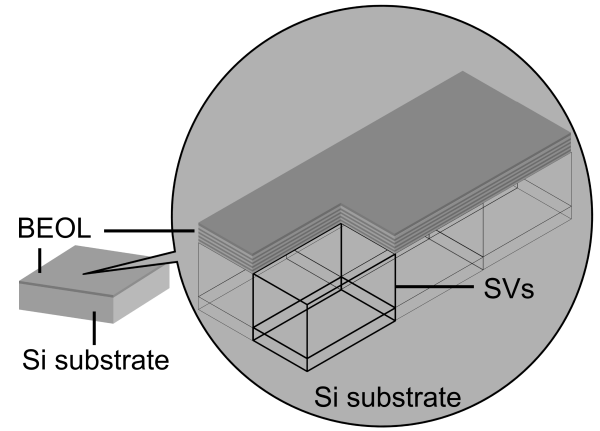


Fig. 3. Illustration of the MC simulation setup. The model was placed under vacuum conditions.

III. SIMULATION SETUP

A. Parameters' Extraction

To execute simulations, the parameters related to configuring SVs need to be determined. In this article, SEU XSs under HI irradiation from the literature are used to extract the parameters. The data were obtained from the literature using the plot digitization program [18]. The SEU XS experimental data under HI irradiation for 16-nm [11], [19], 40-nm [10], [11], and 65-nm [4], [20] SRAMs were used for the parameter extraction. All the fittings are performed using the non-linear least-squares minimization and curve-fitting method in Python (lmfit) [21].

B. MC Simulations

The proton-induced SEU XSs for the given devices were simulated using Geant4 [22], [23], which is a toolkit for simulating the interaction of particles through matter. The setup of the MC simulations is depicted in Fig. 3. The 100×100 stacked SVs were arranged in an array-like structure on a $1 \times 1 \text{ mm}^2$ Si substrate with a thickness of $300 \mu\text{m}$. The back-end-of-line (BEOL) structures were located above the substrate, as secondary particles travel across the cells.

Approximately 6, 4, and $6.5 \mu\text{m}$ thicknesses of the BEOL are assumed for the 16-, 40-, and 65-nm SRAMs, respectively. The BEOL layer information, along with the material properties of copper (Cu) and porous carbon-incorporated silicon oxide (SiOC) layers [24], is used to construct the BEOL layers in the simulation.

Protons with energies from 0.7 to 230 MeV were irradiated and transported from the top side (the BEOL side) to cover the entire array of SVs in the simulation. At least 5×10^7 protons were transported in the simulation for the entire array for all cases (which is equivalent to 10^{13} – 10^{14} protons/cm²), ensuring full coverage of the SV array. The “QGSP_BIC_HP” and “G4EmLivermorePhysics” physics lists from the toolkit were used for the simulation. Note that the “G4EmStandardPhysicsP_option4” physics list in “QGSP_BICP_HP” can handle the Coulomb elastic

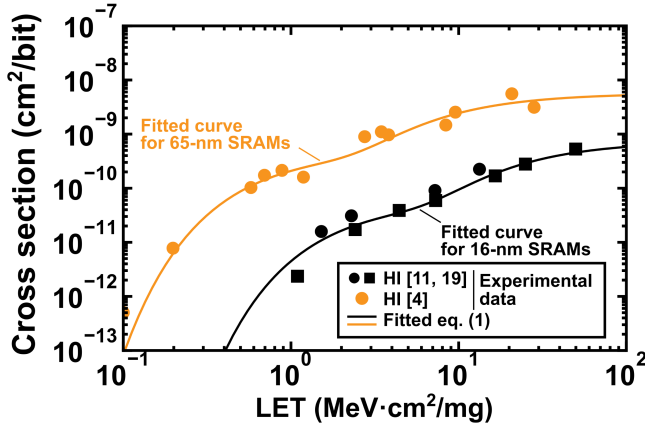


Fig. 4. Experimental SEU XSs and fit curves as a function of LET for 16- and 65-nm SRAMs. The symbols represent the experimental SEU XSs for 16-nm [11], [19] and 65-nm [4] SRAMs. The lines indicate the fit curves using (1).

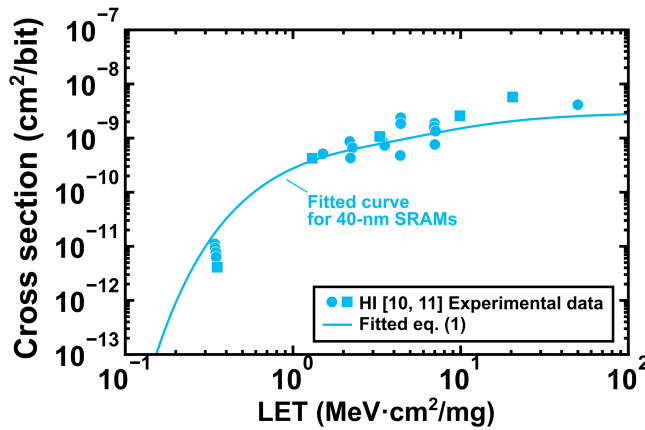


Fig. 5. Experimental SEU XSs and fit curve as a function of LET for 40-nm SRAMs. The symbols represent the experimental SEU XSs for 40-nm [10], [11] SRAMs. The line indicates the fit curve using (1).

process, which plays an important role in the 2–12 MeV energy range for proton-induced SEU simulations, according to previous studies [25].

IV. RESULT AND DISCUSSION

A. Extracted Parameters

Figs. 4 and 5 show the fitting results for the 16- and 65-nm SRAMs and 40-nm SRAMs, respectively. The fittings were successfully performed for all samples, enabling the extraction of parameters. Table II shows a summary of the parameters assumed and extracted from the literature.

Since the values of V_{DR} for 40- and 60-nm SRAMs could not be obtained from the literature, the values of $25\%V_{DD}$ are assumed. While this may result in a loss of accuracy for the V_{DD} dependence, it is not expected to affect the predictions at nominal V_{DD} . According to [26, Fig. 7], the mean V_{DR} ranges from 0.1 to 0.3 V for 16- to 45-nm SRAMs; therefore, our assumption seems reasonable. The values of C_L are assumed to be realistic based on Q_c , the minimum charge required to flip bits, as reported in the literature [27].

TABLE II

SUMMARY OF MODEL PARAMETERS ASSUMED AND EXTRACTED BY THE RESULTS OF 16-, 40-, AND 65-NM SRAM

Parameters	16-nm	40-nm	65-nm	Unit
Q_c [27] ($\approx 2C_L V_{DD}$)	0.71-0.83	0.71	0.32-1.3	fC
C_L from Q_c^*	0.52	0.32	0.34	fF
V_{DD}	0.8	1.1	1.2 [28]	V
V_{DR}	0.15	0.275	0.3	V
A_{SRAM}	7.4×10^{-10} [29]	3.0×10^{-9} [30]	5.7×10^{-9} [28]	cm ² /bit
$d_{fl}^\dagger$	130	187	352	nm
$d_{diff}^\dagger$	12.6	22.7	31.8	nm
$r^\dagger$	0.0822	0.381	0.0873	-
L_{SRAM}	180 [31]	350 [32]	458 [28]	nm
W_{SRAM}	411	857	1235	nm

* The value of C_L is estimated from Q_c , which is derived from simulation results reported in the literature.

† The parameters marked with † are extracted from experimental data.

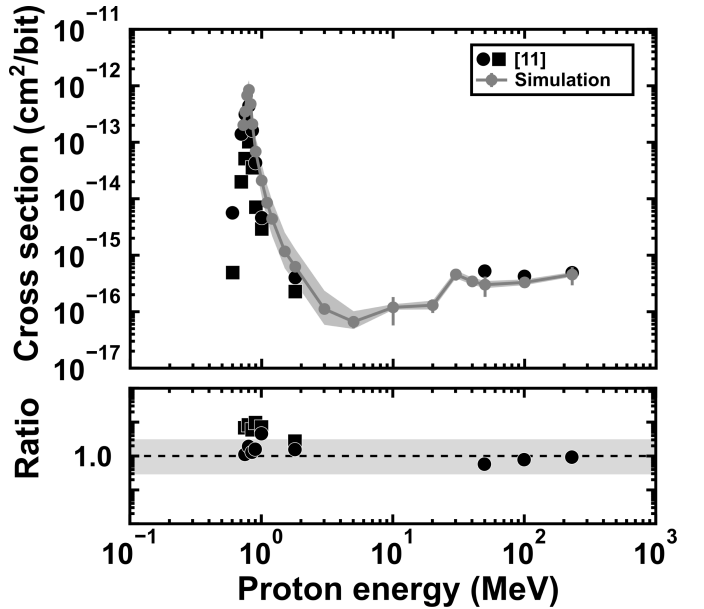


Fig. 6. Predicted XS curve as a function of proton energy. The gray circles and line predict the simulated proton-induced SEU XS of the 16-nm SRAMs. The black circles show the experimental data of proton-induced SEU XSs [11]. The error bars represent the standard error of the mean. However, they are invisible (smaller than markers) in some cases. The gray band in the top figure indicates the approximate XS variation resulting from a $\pm 10\%$ change in C_L according to the Q_c values in Table II. The bottom subfigure shows the ratio of the predicted XS to the experimental XS as a function of proton energy. The gray hatched band indicates the range from 0.3 to 3. Note that the ratio was calculated using the nearest experimental XS data point.

Likely due to the effect of multiple-cell upsets (MCUs), the data above $10 \text{ MeV} \cdot \text{cm}^2/\text{mg}$ exceed the A_{SRAM} of the 40-nm SRAMs. In general, our fitting method works well for the event-based XS. Meanwhile, in this particular case, the extracted parameters were almost identical regardless of whether XS values above $10 \text{ MeV} \cdot \text{cm}^2/\text{mg}$ were included or not in Fig. 5.

B. MC Simulations

Figs. 6–8 show the predicted XS and the experimental results of proton-induced SEU XS for the 16-, 40-, and 65-nm SRAMs, respectively. A fairly good agreement is observed,

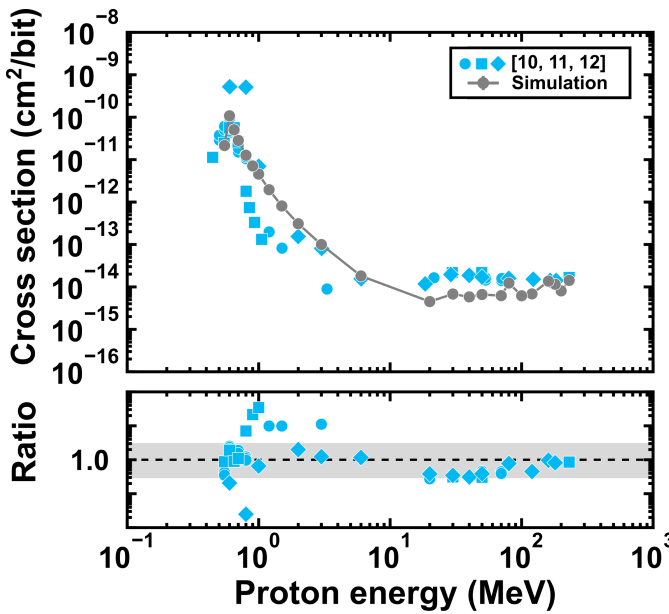


Fig. 7. Predicted XS curve as a function of proton energy. The gray circles and line predict the simulated proton-induced SEU XS of the 40-nm SRAMs. The error bars represent the standard error of the mean. However, they are invisible (smaller than markers) in some cases. The light blue circles, squares, and diamonds show the experimental data of proton-induced SEU XSs [10], [11], [12]. The bottom subfigure shows the ratio of the predicted XS to the experimental XS as a function of proton energy. The gray hatched band indicates the range from 0.3 to 3. Note that the ratio was calculated using the nearest experimental XS data point.

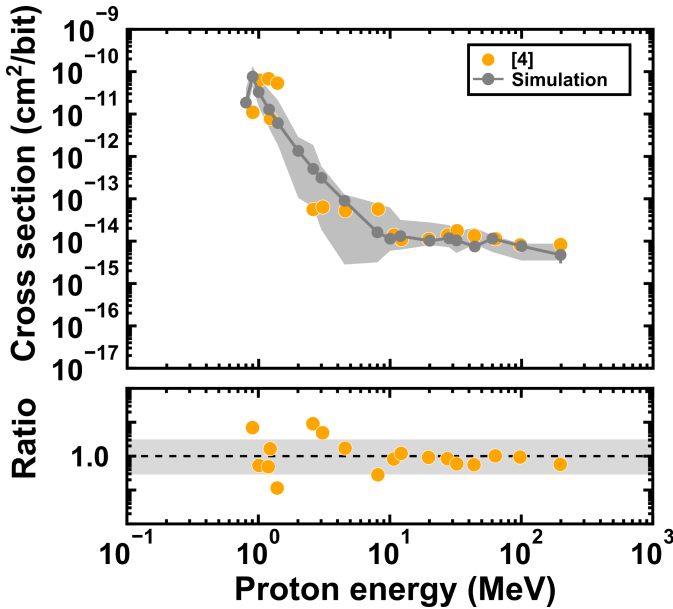


Fig. 8. Predicted XS curve as a function of proton energy. The gray circles and line predict the simulated proton-induced SEU XS of the 65-nm SRAMs. The error bars represent the standard error of the mean. However, they are invisible (smaller than markers) in some cases. The gray band in the top figure indicates the approximate XS variation resulting from a $\pm 30\%$ change in C_L according to the Q_c values in Table II. The orange circles and squares show the experimental data of proton-induced SEU XSs [4]. The bottom subfigure shows the ratio of the predicted XS to the experimental XS as a function of proton energy. The gray hatched band indicates the range from 0.3 to 3. Note that the ratio was calculated using the nearest experimental XS data point.

achieved by directly fitting to the HI results without any additional parameter calibration, such as charge collection

weights or extra RPP SVs. All simulated XSs, except for a few data points, agreed with the experimental data within a factor of 0.3–3. Points located below the dashed line in the bottom subfigure in Figs. 6–8 indicate that the model underestimates the XSs, whereas points above the line indicate overestimation.

As shown in Fig. 6, the simulation results quantitatively support the peak position and overall dependence on proton energy. All simulated XS values for 16-nm SRAMs, except for the point at 1 MeV, agreed with the nearest experimental data within a factor of 0.3–3 as shown in the bottom subfigure of Fig. 6.

Fig. 7 shows the predicted XS curve for 40-nm SRAMs as a function of proton energy. By comparison with the experimental data, the peak position and overall dependence on proton energy were properly reproduced. All simulated XS values agreed with the nearest experimental data within a factor of 0.3–3.

In Fig. 8, the predicted XS curve is plotted together with the experimental data for 65-nm SRAMs. While Fig. 8 shows good consistency in overall characteristics, some discrepancies appear at intermediate proton energies, particularly in the few-MeV region. The proton-induced XS data below 20 MeV down to 2.6 MeV may involve uncertainties due to degraded proton beam irradiation in the dataset [4]. All simulated XS values, except at proton energies in the few-MeV region, agreed with the nearest experimental data within a factor of 0.3–3.

C. Advantages and Limitations of the Proposed Method

Advantages of our prediction method include the ability to straightforwardly configure SVs based on the SRAM bit cell size and two depth parameters calibrated from HI data. Using the deposited energy in these SVs, the XSs at a given proton energy can be calculated instantly via (2). Thus, we can exclude any empirical assumptions of SVs of the SRAM bit cell.

On the other hand, to configure the BEOL modeled in the simulations of this study, the peak positions and cutoff energies of protons for each experimental dataset were referenced from the literature. This gives a limitation of the proposed method, as it requires a comprehensive XS dataset starting from low energy. In addition, the accuracy of XS measurements for low energy protons is sensitive to the experimental setup, especially when a degrader is used to generate the low energy protons. For predicting proton-induced SEUs without such data, detailed information on the BEOL of the given sample, such as layer thicknesses and material compositions, must be obtained in another way since it is essential for accurate estimation. In this work, layer thicknesses from similar fabrication processes were also used as references.

Table III summarizes related works. While semi-empirical RPPs are necessary to configure SVs in previous studies that are not based on the SRAM charge collection manners, our approach utilizes parameters from the SEU physics model, which accounts for both funneling- and diffusion-based charge collection mechanisms. Our method does not require calibration of charge collection weights, whereas such calibration was necessary in previous studies. Among them, our method is the

TABLE III
COMPARISON OF RELATED WORKS

	[4]	[12]	This work
SVs	Semi-empirical RPPs	Empirical RPPs	Physics model based RPPs extracted by HI XS
Charge collection weights	Calibrated by HI and high energy proton XS	Calibrated by proton XS	No calibration needed
Critical charge	SPICE-based estimation	Calibrated by proton XS	Literature-based estimation
BEOL	Assumed	Assumed	Assumed
Prediction capability	Yes	No	Yes

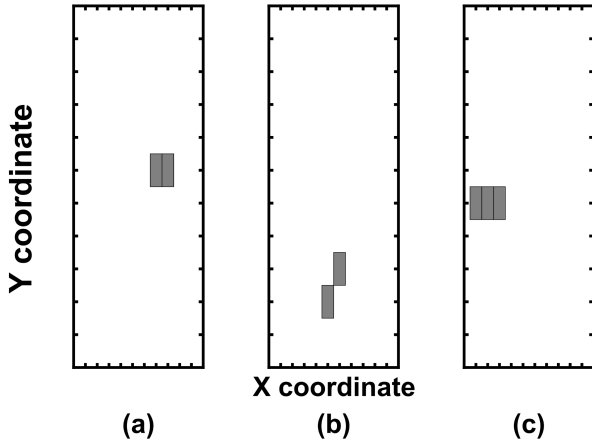


Fig. 9. Examples of fail bit maps under 60 MeV proton irradiation in the MC simulation with 16-nm SRAMs. (a) and (b) 2-bit MCUs. (c) 3-bit MCUs. The gray square indicates the location where energy deposition occurred during a particle event in which the XS exceeded 10^{-20} cm²/bit.

only approach that can predict proton-induced SEU XS across the entire proton energy range based on HI SEU XS data.

D. Outlook for MCUs Prediction

Since the SVs in the simulation are arranged in an array-like structure, we can evaluate MCU behavior for each particle event. Fig. 9 shows examples of fail-bit maps in which the XS is greater than 10^{-20} cm²/bit, to eliminate extremely low energy depositions such as those from gamma rays and electrons, for example, under 60 MeV proton irradiation in the simulated 16-nm SRAMs. Up to 3-bit MCUs were observed in the fail-bit map. This is consistent with our previous findings [33], which also reported up to 3-bit MCUs under experimental 60 MeV proton irradiation. Note that the experimental results [33, Fig. 11] were obtained using similar 16-nm SRAMs under low-voltage conditions. While further investigation is required, this finding suggests the possibility of predicting MCU behavior under proton irradiation through MC simulations, enabled by physics-based and SRAM cell area-informed SVs.

V. CONCLUSION

This article proposes an SV allocation method based on a physics-based analytical XS model, constructed using HI test

results, to predict proton-induced SEU XSs. The predicted XSs demonstrate good agreement with the experimental SEU XSs for 65-, 40-, and 16-nm SRAMs. All simulated XSs, except for a few data points, agreed with the experimental data within a factor of 0.3–3. Unlike the conventional approach, this method relies on the XS analytical equation and its parameters, and does not require empirical setting of the SVs and charge collection weights. The proposed method and simulation may help reduce the burden of experimentally acquiring proton-induced SEU XSs. Beyond predicting XSs, this approach may provide insight into MCU behavior through physics-based and SRAM cell area-informed SVs.

REFERENCES

- [1] R. Reed, "Fundamental mechanisms for single particle-induced soft errors," in *Proc. IEEE NSREC Short Course*, Jul. 2008, pp. 14–18.
- [2] K. P. Rodbell, D. F. Heidel, H. H. K. Tang, M. S. Gordon, P. Oldiges, and C. E. Murray, "Low-energy proton-induced single-event-upsets in 65 nm node, silicon-on-insulator, latches and memory cells," *IEEE Trans. Nucl. Sci.*, vol. 54, no. 6, pp. 2474–2479, Dec. 2007.
- [3] D. F. Heidel et al., "Low energy proton single-event-upset test results on 65 nm SOI SRAM," *IEEE Trans. Nucl. Sci.*, vol. 55, no. 6, pp. 3394–3400, Dec. 2008.
- [4] B. D. Sierawski et al., "Impact of low-energy proton induced upsets on test methods and rate predictions," *IEEE Trans. Nucl. Sci.*, vol. 56, no. 6, pp. 3085–3092, Dec. 2009.
- [5] N. Seifert, B. Gill, J. A. Pellish, P. W. Marshall, and K. A. LaBel, "The susceptibility of 45 and 32 nm bulk CMOS latches to low-energy protons," *IEEE Trans. Nucl. Sci.*, vol. 58, no. 6, pp. 2711–2718, Dec. 2011.
- [6] N. A. Dodds et al., "Hardness assurance for proton direct ionization-induced SEEs using a high-energy proton beam," *IEEE Trans. Nucl. Sci.*, vol. 61, no. 6, pp. 2904–2914, Dec. 2014.
- [7] N. A. Dodds et al., "The contribution of low-energy protons to the total on-orbit SEU rate," *IEEE Trans. Nucl. Sci.*, vol. 62, no. 6, pp. 2440–2451, Dec. 2015.
- [8] N. A. Dodds et al., "New insights gained on mechanisms of low-energy proton-induced SEUs by minimizing energy straggle," *IEEE Trans. Nucl. Sci.*, vol. 62, no. 6, pp. 2822–2829, Dec. 2015.
- [9] A. Coronetti et al., "Assessment of proton direct ionization for the radiation hardness assurance of deep submicron SRAMs used in space applications," *IEEE Trans. Nucl. Sci.*, vol. 68, no. 5, pp. 937–948, May 2021.
- [10] S. Lüdeke et al., "Proton direct ionization in sub-micron technologies: Test methodologies and modeling," *IEEE Trans. Nucl. Sci.*, vol. 70, no. 4, pp. 667–677, Apr. 2023.
- [11] M. Glorieux et al., "Methods for proton direct ionization SEU characterization and orbital error-rate estimation," *IEEE Trans. Nucl. Sci.*, vol. 71, no. 8, pp. 1707–1714, Aug. 2024.
- [12] A.-G. Şerban, A. Coronetti, R. G. Alía, and F. Salvat-Pujol, "RPP model trends across technology nodes for the MC simulation of SEUs in commercial bulk planar CMOS SRAMs under proton irradiation," *IEEE Trans. Nucl. Sci.*, vol. 72, no. 2, pp. 133–146, Feb. 2025.
- [13] J. L. Autran and D. Munteanu, "Multiscale, multiphysics modeling and simulation of single-event effects in digital electronics: From particles to systems," *IEEE Trans. Nucl. Sci.*, vol. 71, no. 1, pp. 31–66, Jan. 2024.
- [14] K. Takeuchi, T. Kato, and M. Hashimoto, "An SEU cross section model reproducing LET and voltage dependence in bulk planar and FinFET SRAMs," in *Proc. IEEE Int. Rel. Phys. Symp. (IRPS)*, Apr. 2024, pp. 1–4.
- [15] K. Takeuchi, T. Kato, R. Nakamura, and D. Kobayashi, "Predicting neutron SERs from alpha-ray test results through SEU physics parameter extraction," in *Proc. IEEE Int. Rel. Phys. Symp. (IRPS)*, Monterey, CA, USA, Mar. 2025, pp. 1–6.
- [16] Y. Tosaka et al., "Measurements and analysis of neutron-reaction-induced charges in a silicon surface region," *IEEE Trans. Nucl. Sci.*, vol. 44, no. 2, pp. 173–178, Apr. 1997.
- [17] D. Kobayashi et al., "An SRAM SEU cross section curve physics model," *IEEE Trans. Nucl. Sci.*, vol. 69, no. 3, pp. 232–240, Mar. 2022.

- [18] A. Rohatgi. (2023). *WebPlotDigitizer: HTML5 Based Online Tool To Extract Numerical Data From Plot Images*. [Online]. Available: <https://github.com/automeris-io/WebPlotDigitizer>
- [19] N. Tam et al., "Multi-cell soft errors at the 16-nm FinFET technology node," in *Proc. IEEE Int. Rel. Phys. Symp.*, Apr. 2015, pp. 4B.3.1–4B.3.5.
- [20] J. Wang, J. Prinzie, A. Coronetti, S. Thys, R. G. Alia, and P. Leroux, "Study of SEU sensitivity of SRAM-based radiation monitors in 65-nm CMOS," *IEEE Trans. Nucl. Sci.*, vol. 68, no. 5, pp. 913–920, May 2021.
- [21] M. Newville et al., "LMFIT/LMFIT-PY: 1.3.2," Zenodo, Geneva, Switzerland, Jul. 2024, doi: [10.5281/zenodo.12785036](https://doi.org/10.5281/zenodo.12785036).
- [22] S. Agostinelli et al., "GEANT4—A simulation toolkit," *Nucl. Instrum. Methods Phys. Res. A, Accel. Spectrom. Detect. Assoc. Equip.*, vol. 506, no. 3, pp. 250–303, Jul. 2003. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0168900203013688>
- [23] Geant4 Collaboration. (2024). *Geant4-11.2.1*. Accessed: 2025. [Online]. Available: <https://geant4.web.cern.ch/download/11.2.1.html>
- [24] H. Lee et al., "Structural characterization of porous low-k SiOC thin films using X-ray porosimetry," in *Proc. IEEE Int. Interconnect Technol. Conf.*, Jun. 2003, pp. 54–56.
- [25] P. Caron, C. Inguibert, L. Artola, R. Ecoffet, and F. Bezerra, "Physical mechanisms of proton-induced single-event upset in integrated memory devices," *IEEE Trans. Nucl. Sci.*, vol. 66, no. 7, pp. 1404–1409, Jul. 2019.
- [26] E. I. Vatajelu and J. Figueras, "Statistical analysis of 6T SRAM data retention voltage under process variation," in *Proc. 14th IEEE Int. Symp. Design Diag. Electron. Circuits Syst.*, Apr. 2011, pp. 365–370.
- [27] D. Kobayashi, "Scaling trends of digital single-event effects: A survey of SEU and SET parameters and comparison with transistor performance," *IEEE Trans. Nucl. Sci.*, vol. 68, no. 2, pp. 124–148, Feb. 2021.
- [28] P. Bai et al., "A 65nm logic technology featuring 35nm gate lengths, enhanced channel strain, 8 cu interconnect layers, low-k ILD and 0.57 μm^2 SRAM cell," in *IEDM Tech. Dig.*, Dec. 2004, pp. 657–660.
- [29] S.-Y. Wu et al., "A 16nm FinFET CMOS technology for mobile SoC and computing applications," *IEEE Int. Electron Devices Meeting*, pp. 9.1.1–9.1.4, Dec. 2013.
- [30] NEC Corporation.(2009). *40nm Node CMOS Platform 'UX8'*. [Online]. Available: <https://www.nec.com/en/global/techrep/journal/g09/n01/pdf/090113.pdf>
- [31] K. Takeuchi et al., "Characteristic charge collection mechanism observed in FinFET SRAM cells," *IEEE Trans. Nucl. Sci.*, vol. 69, no. 8, pp. 1833–1839, Aug. 2022.
- [32] C. Qi et al., "Role of elastic scattering in low-energy neutron-induced SEUs in a 40-nm bulk SRAM," *IEEE Trans. Nucl. Sci.*, vol. 69, no. 5, pp. 1057–1065, May 2022.
- [33] K. Sakamoto et al., "Multiple-cell upset analysis on 16/12-nm bulk FinFET SRAM caused by proton irradiation," *IEEE Trans. Nucl. Sci.*, vol. 72, no. 4, pp. 1470–1478, Apr. 2025.