An SEU Cross Section Model Reproducing LET and Voltage Dependence in Bulk Planar and FinFET SRAMs

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***Abstract*—This paper presents a single event upset (SEU) cross section model reproducing the linear energy transfer (LET) and the voltage dependence in the bulk planar and FinFET static random-access memories (SRAMs). The model predicts both the LET and the applied voltage (V_{DD}) dependence with physically explainable parameters.**

***Index Terms*—single event upsets (SEUs), soft errors, static random-access memories (SRAMs)**

I. Introduction

Soft errors, or single event upsets (SEUs), are one of the most critical reliability issues in modern semiconductor circuits. In fact, static random-access memories (SRAMs) are sensitive to energetic particle impacts. Since radiation is present in both terrestrial and space environments, the circuit designer must consider the soft error rate (SER) and cross sections (XSs) of the SRAMs, regardless of the terrestrial or space application.

Historically, the SER and XSs for the specific environment or the specific particles have been obtained by performing corresponding irradiation experiments. Meanwhile, the irradiation facility often provides the mono-energetic spectrum in the case of the heavy ion irradiation. Therefore, we often interpolate and extrapolate the XS data to estimate the value at an arbitrary point of linear energy transfer (LET). For this purpose, the integral Weibull function (known as the Weibull function) is widely used to fit the XSs data as a function of LET [1]. However, there is no established way to derive the parameters in the Weibull function and to approximate the voltage dependence of the XS [2]. While Kobayashi et al. have proposed a physical model that predicts the XS-LET and XS-V_{DD} curves well for silicon-on-insulator (SOI) SRAMs [2], our previous study had shown its limitations for bulk FinFET SRAMs. This paper presents an extended XS curve model for the bulk planar and FinFET SRAMs [4].

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The paper is organized as follows. Section II presents the proposed model referring to the previous study and the physical background of the model. Section III describes the experimental setup, including the conditions of the samples and irradiation. Section IV discusses the experimental results and the calibration of the model for the bulk FinFET process, followed by an example of its application in the bulk planar process.

II. Proposed model

Based on the previous study that derived eq. (1) [2, eq. (6)], the proposed model is extended to the bulk FinFET SRAMs for considering both drift- and diffusion-based charge collection, which is eq. (2),

$$XS = A_{sat} exp(-\frac{\xi C_{load}}{d_{fnl}} \frac{V_{DD} - V_{DR}}{0.01L}) \tag{1}$$

$$XS = A_{sat} \Bigg[r \cdot exp(-\frac{\xi C_{load}}{d_{fnl}} \frac{V_{DD} - V_{DR}}{0.01L}) + (1-r) \cdot exp(-\frac{\xi C_{load}}{d_{diff}} \frac{V_{DD} - V_{DR}}{0.01L}) \Bigg] \tag{2}$$

where $XS, r, \xi, C_{load}, d_{fnl}, d_{diff}, V_{DD}, V_{DR}$ and L are the SRAM bit cell cross section, ratio of the drift-dominant area, circuit load effect, internal load capacitance, funnel length, equivalent diffusion-based charge collection length, applied voltage to SRAMs, data retention voltage, and LET of incident ions, respectively. A_{sat} is the upper limit of XS for large LET, bounded by the SRAM cell area A_{SRAM}. A_{sat} in eq. (1) was originally introduced as $A_{SRAM}/2$ for SOI SRAM [2]. On the other hand, according to our results [4], the saturated XS for bulk SRAM should be A_{SRAM}. Therefore, the following discussion assumes A_{sat}=A_{SRAM} in eqs. (1) and (2). Note that when r=1, eqs (1) and (2) are identical.

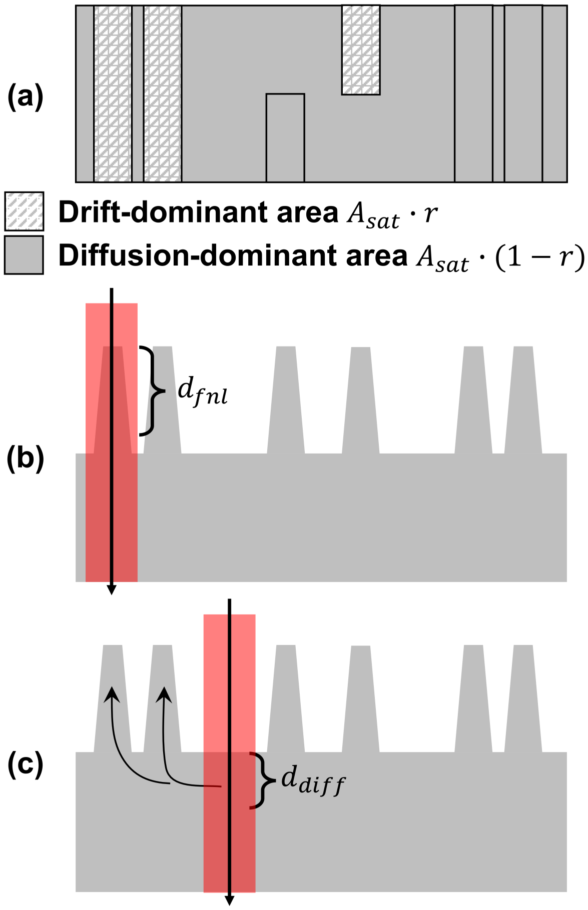

Fig. 1. (a) SRAM top view. The gray and hatched areas represent the diffusion-dominant and drift-dominant areas, respectively. (b), (c) Cross sectional illustrations of SRAM bit cell. d_{fnl} and d_{diff} in eq. (2) represent the equivalent funnel length in the drift-dominant area (b) and the equivalent diffusion-based charge collection length in the diffusion-dominant area (c), respectively.

As shown in Fig. 1(a), $A_{sat} \cdot r$ represents the drift-dominant area, which means the sensitive area in the case of a direct hit of an ion or the high-density plasma column. The other area of $A_{sat} \cdot (1-r)$ corresponds to the diffusion-dominant area. d_{fnl} and d_{diff} represent the equivalent funnel lengths in the drift-dominant area and the equivalent diffusion-based charge collection length in the diffusion-dominant area, respectively, as illustrated in Figs.1(b) and (c). While Fig. 1 exemplifies a FinFET SRAM, a similar discussion can be applied to a bulk planar SRAM. According to [2], the circuit load effect ξ is approximately equal to two, and this value can be applied to a wide range of technology generations.

The proposed model, as expressed in eq. (2), retains the characteristics necessary to converge to the point defined by (mean V_{DR}, A_{SRAM}), regardless of r, which is the ratio of the drift-dominant area to A_{SRAM}. The XS of the model also converges to the A_{SRAM} when L is large enough. The proposed model has been successfully extended with the incorporation of the above two fundamental characteristics, thanks to its inheritance from the original model in eq. (1).

Another feature of the proposed model is that the parameters are physically explainable, which is also inherited from [2]. While some parameters are difficult to accurately estimate from the limited device information available from the foundry, some use cases for obtaining parameters are experimentally validated in the following sections.

III. Experimental setup

In this paper, as an illustrative example, we performed alpha particle irradiation tests using an ^{241}Am source to demonstrate that the XSs under different LET conditions are well predicted with the proposed model, eq. (2). In the test, the V_{DD} dependence of XS was measured to calibrate the model parameters r, d_{fnl} and d_{diff}. Here, C_{load} is treated as a fixed value according to [4], because the parameters (C_{load}/d_{fnl}, C_{load}/d_{diff}, r) need to be estimated intrinsically.

The device under test (DUT) was an SRAM fabricated by a commercial 16-nm bulk FinFET process. The package of the DUT is a quad flat package (QFP), where the top side of the package was decapped before irradiation. A total of 5.5 Mb in the SRAM macros embedded in the DUT were evaluated under irradiation. The details of the evaluation method, including the measurement of V_{DR} and the calculation of event-based XSs, are described in [3], [4]. The SEUs of the DUT were evaluated by irradiation with alpha particles from ^{241}Am under several V_{DD} conditions in the vacuumed chamber. The peak energy of the alpha particles is 5.4 MeV. The LET is calculated by the Stopping and Range of Ions in Matter (SRIM) code [5], and is estimated to be approximately 0.85 MeV·cm^2/mg in the Si block after passing through metal and dielectric layers.

In each irradiation experiment, the V_{DD} was set between 0.35 and 0.9 V, except during write and read operations, in order to assess the V_{DD} dependence. The nominal V_{DD} of the DUT is 0.8 V. Irradiation was controlled by a mechanical shutter placed between the DUT and ^{241}Am, ensuring that unintended irradiation was prevented during the write and read operations.

IV. Results and discussion

Fig. 2 shows the measured SEU XSs as a function of V_{DD} of the 16-nm bulk FinFET SRAM, as well as the calibrated eqs. (1) and (2). Few 2-bit multiple-cell upsets (MCUs) were found during alpha irradiation under the checkerboard (CKB) data pattern, even at 0.35 V condition. As shown in Fig. 2, eq. (2) reproduces the measured data better than eq. (1). The determined parameters of eq. (2) are listed in Table I. While the experimental SEU XSs increase exponentially with decreasing V_{DD}, it is evident that a simple exponential curve does not accurately predict over a wide range of V_{DD}, including the point where (V_{DD},XS) = (mean V_{DR}, A_{SRAM}).

Fig. 3 shows the measured SEU XSs as a function of LET, which are reported in [4], as well as the estimated curve based on the parameters in Table I. LET values of heavy ions were recalculated besed on [4, Table I], taking into account the energy loss in metal and dielectric layers of the DUT. Fig. 3 presents good predictions for the wide range of LETs and the voltage conditions, demonstrating the validity of the proposed model. This suggests that after determining the parameters through alpha irradiation, the proposed model straightforwardly reproduces the measurement results for both LET and V_{DD} dependence. It can make the measurement and evaluation of XS and SER faster, easier, and less expensive, since an alpha irradiation with radioisotopes such as ^{241}Am is relatively simple compared to particle irradiation with accelerator facilities.

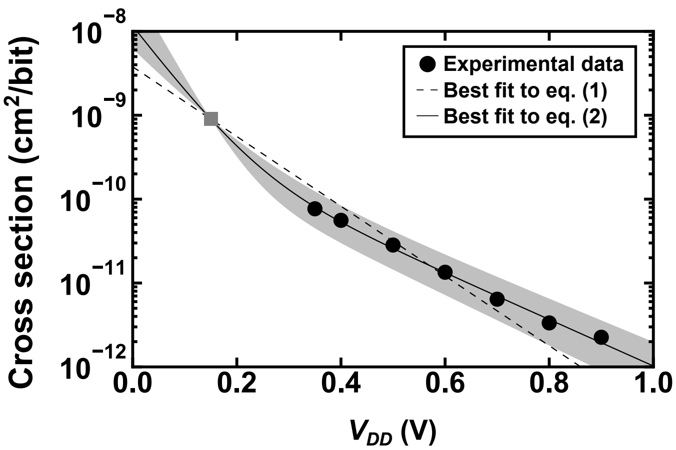

Fig. 2. XS as a function of V_{DD} under alpha irradiation. The black circles represent the experimental results. The error bars, which often represent the standard deviation, were omitted since they are smaller than markers in this case. The solid line represents the best fit result by eq. (2), and the gray shaded area shows the $\pm 1\sigma$ confidence interval band of the estimated parameters d_{fnl},d_{diff},and r. The dashed line represents the best fit result by eq. (1). The gray square plot shows the point where (mean V_{DR}, A_{SRAM}) = (0.15 V, 9×10^{-10} cm^2/bit) [4].

TABLE I
MODEL PARAMETERS FITTED FROM THE RESULTS OF 16-NM SRAMS UNDER ALPHA IRRADIATION

Parameters	Value	Unit	Fitting	Remarks
L	0.85	MeV·cm^2/mg	No (Fixed)	See text.
V_{DD}	-	V	No (Variable)	-
V_{DR}	0.15	V	No (Fixed)	[4]
A_{SRAM}	9×10^{-10}	cm^2/bit	No (Fixed)	[3], [4]
C_{load}	2.96	fF	No (Fixed)	[4]
d_{fnl}	109	nm	Yes	-
d_{diff}	37.3	nm	Yes	-
r	0.258	-	Yes	-

Eq. (2) can also be applied to the bulk planar process. Here, the parameter calibration is performed using the XS data at various LETs yet at a single V_{DD} of 1.2 V. Fig. 4 shows the measured SEU XSs as a function of LET for 65-nm bulk SRAMs [2], [6], as well as the estimated curve using eq. (2) with the parameters in Table II. We can confirm that the model well predicts the voltage dependence below 1.2 V. This suggests the robustness and wide applicability of the proposed model, which can be applied to both bulk FinFET and planar for predicting both LET and V_{DD} dependence.

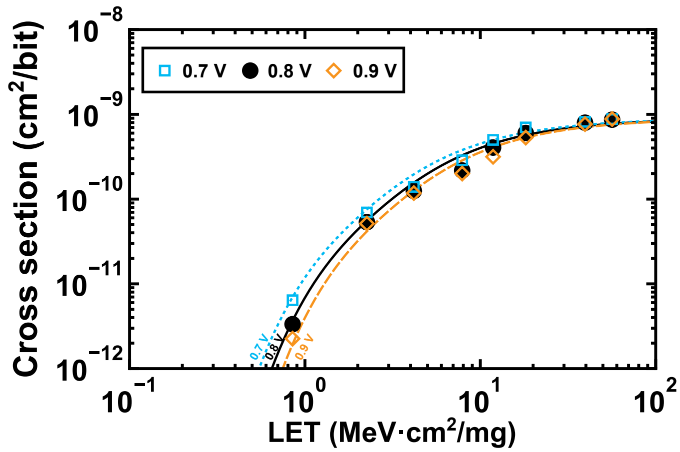

Fig. 3. XS of 16-nm bulk FinFET SRAMs as a function of LET. The square, circle and diamond markers represent the experimental results under 0.7-, 0.8-, and 0.9-V conditions, respectively. The experimental results except for alpha irradiation are taken from [4, Fig. 2]. The error bars, which often represent the standard deviation, were omitted since they are smaller than markers in this case. The data pattern is CKB. The dotted, solid, and dashed lines show the cross section curves predicted by the eq. (2) under 0.7-, 0.8-, and 0.9-V conditions, respectively, with fitted parameters listed in Table I.

TABLE II
MODEL PARAMETERS FITTED FROM THE RESULTS OF 65-NM SRAMS [2], [6]

Parameters	Value	Unit	Fitting	Remarks
L	-	MeV·cm^2/mg	No(Variable)	-
V_{DD}	1.2	V	No(Fixed)	-
V_{DR}	0.02	V	No(Fixed)	[2]
A_{SRAM}	1.78×10^{-8}	cm^2/bit	No(Fixed)	[6]
C_{load}	1.83	fF	No(Fixed)	[2]
d_{fnl}	227	nm	Yes	-
d_{diff}	9.99	nm	Yes	-
r	0.157	-	Yes	-

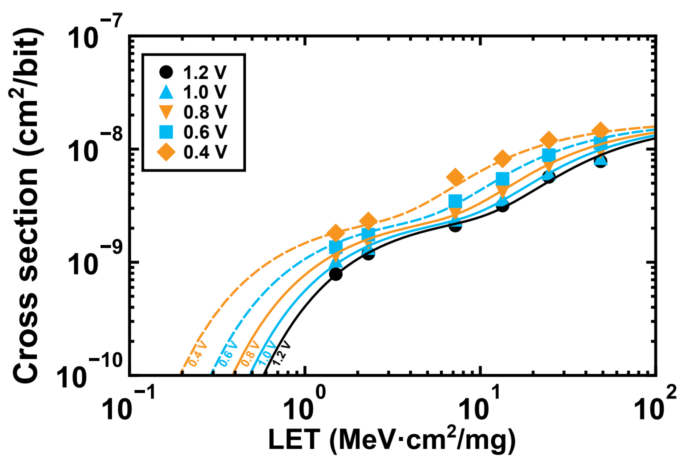

Fig. 4. XS of 65-nm bulk SRAMs as a function of LET. The circle, up-pointing triangle, down-pointing triangle, square, and diamond markers represent the experimental results under 1.2-, 1.0-, 0.8-, 0.6-, and 0.4-V conditions, respectively. The experimental results are taken from [6, Fig. 6]. The solid black, solid blue, solid orange, dotted blue, and dotted orange lines show the cross section curves predicted by the eq. (2) under 1.2-, 1.0-, 0.8-, 0.6-, and 0.4-V conditions, respectively, with the fitted parameters listed in Table II.

V. Conclusions

The XS-LET-V_{DD} curve model for bulk planar and FinFET SRAMs has been proposed in this paper. The proposed model calibrated with only alpha irradiation results reproduced the LET and V_{DD} dependence of 16-nm FinFET SRAMs. The model can also be applied to the 65-nm bulk planar process, and the V_{DD} dependence was well predicted by the calibration using the measured XS-LET data at a specific V_{DD} condition. The proposed model can make the measurement and evaluation of XS and SER faster, easier, and less expensive.

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