

Article

Derivation of Neutron SEE Cross-Section Energy Dependence from White Neutron Irradiation Experiments at CSNS-ANIS

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Abstract

White neutron Single Event Effect (SEE) cross-sections were measured for two Static Random Access Memories (SRAMs) on the Atmospheric Neutron Irradiation Spectrometer at the China Spallation Neutron Source, and we applied the unfolding technique using a particle swarm optimization algorithm to extract the neutron energy dependence of SEE cross-sections from the experimental data. The calculated results agree well with the experimental data, validating this method. This method demonstrates how white neutron SEE experimental data can be effectively used with unfolding techniques to obtain the neutron energy dependence of SEE cross-sections for microelectronic devices.

Keywords: SRAM; white neutron source; single event upset; unfolding technique

1. Introduction

When primary cosmic rays enter the atmosphere, they interact with atmospheric nuclei (mainly nitrogen and oxygen), producing secondary particles such as neutrons, protons, gamma rays, pions, muons, etc., which form the atmospheric radiation environment [1]. Neutrons are the dominant component of the atmospheric radiation environment and can induce Single Event Effects (SEEs) in microelectronic devices, threatening their safe and reliable operation. Neutrons induce SEEs via recoils produced by nuclear reactions between neutrons and device materials, a process called the indirect ionization mechanism [2–5]. Neutron SEE cross-sections depend on the properties of recoils (energy, yield, linear energy transfer (LET), etc.), which in turn depend on neutron energy; consequently, neutron SEE cross-sections are dependent on neutron energy. The neutron energy dependence of SEE cross-sections is an important aspect in the study of neutron SEEs. If the neutron energy dependence of SEE cross-sections is known, it can be combined with the neutron energy spectrum of the application environment to predict neutron SEE error rates.

JEDEC standards JESD89A [6] and IEC-62396 [7] recommend using monoenergetic neutrons, quasi-monoenergetic neutrons and monoenergetic protons to obtain the neutron energy dependence of SEE cross-sections. Monoenergetic neutrons with energies below 20 MeV are mainly obtained through various nuclear reactions induced by different light particles, such as $T(p,n)$, ${}^7\text{Li}(p,n)$, $D(d,n)$, etc. Above 20 MeV, higher incident energies trigger a multi-body breakup reaction, so only quasi-monoenergetic beams are available—these contain a “peak” component from two-body reactions and a “tail” from multi-body breakup processes. However, when using quasi-monoenergetic neutrons, and because tail neutrons can also induce SEEs, the influence of tail neutrons needs to be considered in order to extract the peak-only cross-section. To address this issue, the unfolding technique has been widely employed [8–10].



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With the increasing availability of white neutron sources, researchers explored using white neutron SEE experimental data to obtain the neutron energy dependence of the SEE cross-sections. Yahagi et al. used the white neutron source at LANSCE, obtained modified neutron energy spectra by changing the thicknesses of polyethylene shields, and employed the unfolding technique to calculate the four parameters of the Weibull function [11]. In recent years, the time-of-flight (TOF) method has also been used for this purpose [12,13]. However, TOF is not universally applicable to all devices because for neutrons above 1 MeV, flight times are only a few nanoseconds, requiring the device tester to record an SEE within this short window—this is often achievable for some devices and introduces large errors.

In this paper, we employ a comprehensible unfolding technique to obtain the neutron energy dependence of SEE cross-sections by using white neutron experimental data and apply it to the white neutron SEE experimental data obtained from white neutron SEE experiments conducted on the Atmospheric Neutron Irradiation Spectrometer (ANIS) at the China Spallation Neutron Source (CSNS). This method will make the unfolding technique better able to obtain the neutron energy dependence of SEE cross-sections of microelectronic devices by using white neutron SEE experimental data.

2. The Principle of Calculation

When neutrons strike a device, they can cause SEEs via nuclear reactions with device materials and subsequent indirect ionization. The number of SEEs induced by neutrons with a specific energy spectrum during irradiation can be described using the following formula:

$$N_{SEE} = C \int \frac{d\Phi}{dE} \sigma(E) dE \quad (1)$$

where N_{SEE} is the number of SEEs induced by neutrons, C is the capacity of the device (bits), $\frac{d\Phi}{dE}$ is the neutron energy spectrum ($\text{n} \cdot \text{cm}^{-2} \cdot \text{MeV}^{-1}$), and $\sigma(E)$ is the energy-dependent function of neutron SEE cross-sections (cm^2/bit), which can often be expressed as the Weibull function, Bendel's function or a linear function. Formula (1) represents a general expression. In the case when neutrons are monoenergetic, we can get the commonly adopted definition of the SEE cross-section $N_{SEE} = C\sigma(E)\Phi$. According to Formula (1), if we get the neutron spectrum $\frac{d\Phi}{dE}$ and the number of SEEs during experiment N_{SEE} , we can establish the equation for solving $\sigma(E)$; each set of experimental data corresponds to one equation. If the spectra are different, the established equations will also be linearly independent. Therefore, multiple equations can be obtained by irradiating the device with neutrons of different energy spectra; then, the energy-dependent function of neutron SEE cross-sections $\sigma(E)$ can be obtained by solving these equations. More equations provide more constraints and thus improve accuracy. In this paper, the energy-dependent function of neutron SEE cross-sections is chosen as the Weibull function:

$$\sigma(E) = \begin{cases} 0, & E < E_{th} \\ \sigma_{sat} \left\{ 1 - e^{[-(\frac{E-E_{th}}{W})^s]} \right\}, & E \geq E_{th} \end{cases} \quad (2)$$

where σ_{sat} is the saturation cross-section, E_{th} is the threshold energy, W is the width parameter, and s is the shape parameter.

The principle of solving the equation set is an iterative process, described as follows: first, a set of initial Weibull function parameters is chosen to define $\sigma(E)$ and then integrated with neutron energy spectra during the irradiation experiments according to Formula (1). Then, the calculated values of the number of neutron SEE N_{SEE}^{cal} are obtained. Next, the

mean square error (MSE) between the calculated values and experimental ones of N_{SEE} is calculated:

$$MSE = \frac{1}{N} \sum \left(\frac{N_{SEE}^{cal} - N_{SEE}^{exp}}{N_{SEE}^{exp}} \right)^2 \quad (3)$$

where N is the number of neutron energy spectra. The smaller the MSE is, the closer the calculated values (N_{SEE}^{cal}) are to the experimental (N_{SEE}^{exp}) ones, and the neutron energy dependence of the SEE cross-sections is closer to the correct solution. The minimum of MSE can be achieved by iterative algorithms. When the maximum number of iterations is reached or the MSE value falls below a certain limit (e.g., 0.001 in this work), the iteration process are stopped. Otherwise, the parameters of the Weibull function are modified, and the MSE is recalculated following the above process. The Weibull function parameters are obtained after stopping the iteration process, which represent the solution to the equation set; following this, the energy-dependent function of neutron SEE cross-sections $\sigma(E)$ can be obtained. The aforementioned process transforms the problem of solving equations into an optimization problem, which can be addressed using optimization algorithms.

3. Experiments

3.1. Devices

Table 1 lists the devices used for the neutron irradiation experiments. ESA SEU Monitor is a 250 nm CMOS-based SRAM fabricated by the European Space Agency (ESA). It is a radiation-hardened device that can prevent multi-bit upset (MBU) and also has a high LET threshold for single event latch-up (SEL); its SEL threshold is 80 MeV·cm²/mg. CY7C1318KV18 is a 65 nm CMOS-based DDR-II SRAM manufactured by Cypress Semiconductor Corporation, whose operating voltage is 1.8 V, and it is written and read through a motherboard tester. The motherboard tester is powered at nominal voltage of 12 V.

Table 1. SRAMs' information for neutron irradiation experiments.

ID	Reference	Technology Node	Capacity
A	ESA SEU Monitor	250 nm	16 Mbit
B	CY7C1318KV18	65 nm	18 Mbit

The effect to be measured in both devices is single event upset (SEU). The two SRAMs are programmed with the checkerboard pattern. Both devices were irradiated at normal beam incidence.

3.2. Experiment Facility

The white neutron irradiation experiment was conducted on the ANIS which is located at the CSNS. The CSNS consists of an accelerator that can deliver protons with energy to achieve a kinetic energy of 1.6 GeV. These protons then reach the W-Ta spallation target and react with the target material to produce white neutrons through spallation reaction. The ANIS is in the forward direction at an orientation of 41° to the proton beam [14].

The energy range of the ANIS covers thermal neutrons up to 1.6 GeV. The ANIS has thermal neutron filters in order to decrease the fluence of thermal neutrons [14]. In this experiment, 4 cm of polyethylene and 2 cm of B₄C were used as the thermal neutron filter. Additionally, the ANIS has neutron flux controllers with W blocks of different thicknesses in order to reduce the neutron flux intensity [14]. In this experiment, 5 cm of W blocks was used as the neutron flux controller. When there is no filter and no neutron flux controller, the differential energy spectrum matches the JEDEC standard well [15]. In this experiment, we also used a combination of a thermal neutron filter and neutron flux controller, so four

different kinds of neutron spectra were used to irradiate two devices. The neutron energy spectra for the above situations, with the accelerator operating at a power of 140 kW, are shown in Figure 1. During the irradiation experiment, the real-time accelerator power $P(t)$ was recorded at a fixed interval of 5 s, together with the start time t_s and end time t_e . Assuming a linear proportionality between the neutron yield and the beam power, the instantaneous neutron flux $\varphi(t)$ for each 5 s interval was obtained by scaling the reference value, $\varphi(t) = \varphi_{140} \times [P(t)/140]$, where φ_{140} is neutron flux when the accelerator operates at a power of 140 kW. Consequently, the total neutron fluence Φ was obtained by summing the contributions of all intervals between the t_s and t_e : $\Phi = \sum_i \Delta t \varphi_i = \sum_i \Delta t \times \varphi_{140} \times [P_i/140]$. The number of SEUs and the neutron fluence for all energy ranges during irradiation of the two SRAMs are listed in Table 2.

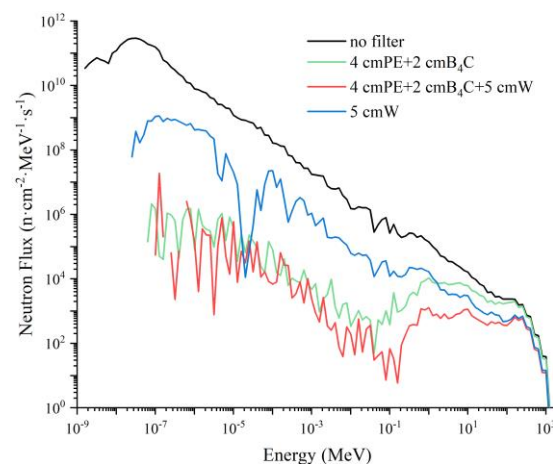


Figure 1. Neutron energy spectra for different situations when the accelerator is operating at a power of 140 kW.

Table 2. The number of SEEs and neutron fluence during irradiation.

ID	Neutron Spectrum	Neutron Fluence (n/cm ²)	Number of SEUs
A	No filter	1.88×10^9	558
	4 cm PE + 2 cm B ₄ C	1.15×10^9	558
	4 cm PE + 2 cm B ₄ C + 5 cm W	6.88×10^8	398
	5 cm W	1.14×10^9	570
B	No filter	1.86×10^9	584
	4 cm PE + 2 cm B ₄ C	4.79×10^8	257
	4 cm PE + 2 cm B ₄ C + 5 cm W	1.30×10^8	91
	5 cm W	2.55×10^8	106

4. Results

4.1. Minimize MSE by Using Particle Swarm Optimization

The principle of calculation to obtain the energy-dependent function of neutron SEE cross-sections through white neutron SEE experimental data was introduced in Section 2. After SEE experiments, the number of SEEs caused by neutrons N_{SEE} and neutron energy spectra $\frac{d\Phi}{dE}$ are known and therefore the neutron energy dependence of SEE cross-sections can be calculated with the Formula (1). With four different neutron spectra used in the experiments, we established four equations for each SRAM to determine the energy-dependent function of neutron SEE cross-sections.

We employed the particle swarm optimization (PSO) algorithm to solve these equations. The fundamental idea behind this algorithm is to find the optimal solution through the collaboration and information sharing of individuals in a group [16]. The PSO algorithm

has numerous applications in optimization functions and neural network training. Each particle corresponds to a candidate solution in a four-dimensional space (the four Weibull parameters). All individuals form a group, representing a set of possible solutions. Since the Weibull function has four parameters, there are four variables to be determined, and the position of each individual is represented by coordinates in a four-dimensional space.

In the initialization stage, we established 10 independent groups, with each group comprising 100 individuals. The minimum MSE value was selected from the results of these 10 groups. We set the maximum number of iterations to 200 and stop the iterative process when the MSE drops below 0.001. Once the calculation is completed, the minimum value of MSE and the corresponding parameters of the Weibull function are output.

In the initialization stage, the range of the four parameters of the Weibull function must also be set. For the saturation cross-section σ_{sat} , after experiments, the average SEE cross-sections of different energy spectra can be calculated based on the following formula of the SEE cross-section

$$\sigma_{avg} = \frac{N_{SEE}}{C\Phi} \quad (4)$$

where Φ is the total fluence of neutrons. According to the definition of the Weibull function, the saturation cross-section is the maximum value of the cross-section, so the average cross-section σ_{avg} must be smaller than σ_{sat} ; therefore, the range of σ_{sat} was taken to be between 1 time and 10 times the largest average cross-section. The ranges of the remaining three parameters are determined by empirical values: the range of E_{th} was taken to be between 1 MeV and 14 MeV, the range of W was taken to be between 1 MeV and 30 MeV, and the range of s was taken to be between 0.5 and 5.

Although not required by the calculation method, we had previously measured 14 MeV monoenergetic neutron SEU cross-sections for both devices on the Cockcroft–Walton accelerator at the China Institute of Atomic Energy (CIAE). We therefore incorporated these data as an optional constraint in the PSO to guide the solution toward physically reasonable values, particularly in the low-energy region. Specifically, we required that the calculated cross-section at 14 MeV agree with the experimental value within a relative error of 30%. This constraint is not essential to the calculation method but helps reduce ambiguity in the parameter space. We chose 14 MeV because it lies in the sensitive region of the Weibull curve (near the knee) and reliable monoenergetic data were readily available; other energies could be used similarly if available.

4.2. The Results of the Calculation

After calculation using the PSO algorithm, the four parameters of the Weibull function are obtained, which can be used to calculate the energy-dependent function of neutron SEE cross-sections. The parameters of the Weibull function calculated by the method of the two SRAMs are listed in Table 3, and the calculated and the experimental results of the SEU cross-sections of the two SRAMs are shown in Figures 2 and 3. Since the cross-sections at high energy approach the saturated cross-section for the Weibull function, and cross-sections of these two SRAMs approach the saturation cross-section before 100 MeV, the upper limit of the x -axis of Figures 2 and 3 is 100 MeV. Based on the equivalence of proton and neutron SEE, it is generally assumed that the SEE cross-sections of proton and neutron above 50 MeV are equal [6]. Due to the lack of neutron SEU cross-sections larger than 20 MeV for the two devices, the proton SEU cross-sections of the two devices are shown here in order to demonstrate the effectiveness of the calculation method [5,17]. As can be seen from Figures 2 and 3, for SRAM A, the calculated neutron SEU cross-sections are in agreement with the experimental neutron and proton SEE cross-sections well; for SRAM B, the calculated neutron SEU cross-sections are in agreement with the experimental ones

well, but larger than proton SEE cross-sections. Overall, the calculation method presented in this paper is effective.

Table 3. The parameters of the Weibull function for two SRAMs.

ID	σ_{sat} (cm ² /bit)	E_{th} (MeV)	W (MeV)	s
A	3.60×10^{-14}	3.48	13.66	2.38
B	3.58×10^{-14}	2.81	11.44	3.38

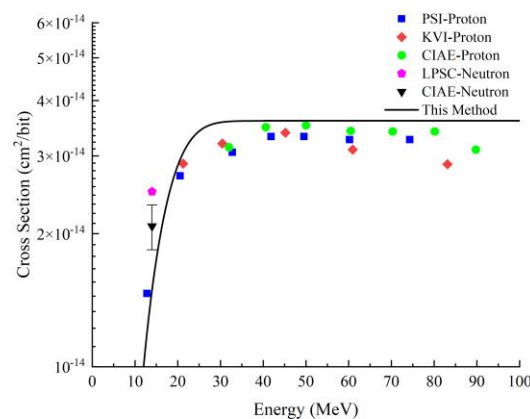


Figure 2. The calculated and experimental SEU cross-sections of SRAM A.

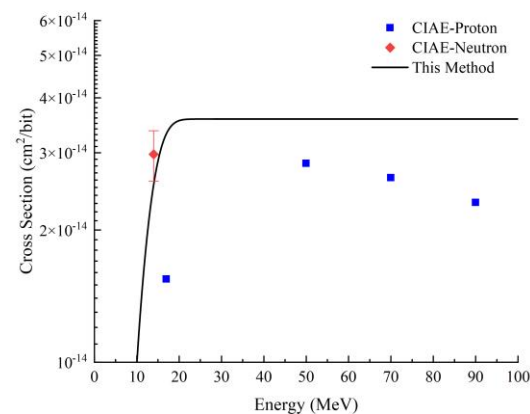


Figure 3. The calculated and experimental SEU cross-sections of SRAM B.

5. Discussion

The neutron energy-dependent function of SEE cross-sections of two SRAMs is calculated in Section 4. The accuracy of the calculation results can be verified by using other data from white neutron experiments. We measured the Soft Error Rates (SERs) of these two SRAMs at the CIAE 100 MeV cyclotron-based white neutron source. The neutron spectrum at 1 μ A proton current, simulated with Geant4, is shown in Figure 4. Here, SER can be calculated by the following formula:

$$SER = C \int \frac{d\phi}{dE} \sigma(E) dE \quad (5)$$

where C is the capacity of the device (bits), $\sigma(E)$ is the neutron energy-dependent function of SEE cross-sections (cm²/bit), and $\frac{d\phi}{dE}$ is the time-related neutron spectrum (n·cm⁻²·MeV⁻¹·s⁻¹). The calculated SER and experimental ones of two SRAMs are listed in Table 4. For SRAM A, the experimental SER and the calculated ones are in good agreement, with a relative error of 7.64%. For SRAM B, the calculated SER deviates from the

experimental value by 37%. Although this deviation is larger than that of SRAM A, it remains acceptable for SER estimation purposes. In practice, uncertainties in neutron spectral measurements, beam fluence monitoring, and the intrinsic variability of the atmospheric neutron field often lead to prediction uncertainties of a factor of two or more. Therefore, a 37% discrepancy is still within the generally accepted tolerance for engineering reliability assessments. In summary, the calculation results are accurate, which also proves the validity of the calculation method introduced in Section 2.

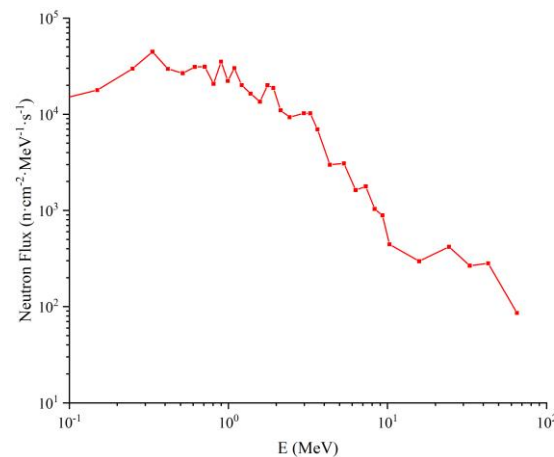


Figure 4. Neutron energy spectrum of white neutron source at the CIAE.

Table 4. SER of two SRAMs.

ID	Experimental SER (Upsets/Hour)	Calculated SER (Upsets/Hour)
A	31.01 ± 3.07	28.64
B	54.19 ± 4.43	34.14

6. Conclusions

We conducted the white neutron SEE experiments on two SRAMs at the ANIS of the CSNS, and employed the unfolding technique with PSO algorithm to calculate the neutron energy dependence of SEE cross-sections based on experimental data. The calculation results are in good agreement with the experimental ones, validating the effectiveness of the calculation method. This calculation method effectively broadens the accessibility of neutron energy dependence of SEE cross-sections, particularly for devices for which TOF methods are difficult to implement. In addition, it enhances the scientific value of spallation neutron sources equipped with white-neutron facilities, enabling them to serve not only as radiation test platforms but also as versatile tools for cross-section characterization. The method is general and can be readily extended to other microelectronic devices, thereby supporting more accurate soft error rate predictions in realistic atmospheric neutron environments.

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Data Availability Statement: The data presented in this study are available upon reasonable request from the corresponding authors.

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Abbreviations

The following abbreviations are used in this manuscript:

SRAM	Static random access memory
LET	Linear Energy Transfer
SEE	Single Event Effect
SEU	Single Event Upset
MBU	Mult-bit Upset
SER	Soft Error Rate
CSNS	China Spallation Neutron Source
ANIS	Atmospheric Neutron Irradiation Spectrometer
CIAE	China Institute of Atomic Energy
PSO	Particle Swarm Optimization

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