Predictive Approach for Neutron-Induced SEU Occurrence in SRAM and EEPROM (Postprint)

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Date: 2023-06-18T00:00:00+00:00

Abstract

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Full Text

Preamble

ChinaXiv Cooperative Journal, NUCLEAR SCIENCE AND TECHNIQUES 26, 050501 (2015)

Predictive Approach to SEU Occurrence Induced by Neutrons in SRAM and EEPROM

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(Received January 13, 2015; accepted in revised form June 11, 2015; published online October 20, 2015)

A simulation approach is developed to obtain the linear energy transfer (LET) spectrum of all secondary ions and predict single event upset (SEU) occurrence induced by neutrons in memory devices. Neutron reaction channels, secondary ion species and energy ranges, and LET calculation methods are introduced respectively. Experimental results of neutron-induced SEU effects on static random access memory (SRAM) and electrically erasable programmable read-only memory (EEPROM) are presented to confirm the validity of the simulation results.

Keywords: Neutron radiation, Memory device, Single event upset (SEU), Linear energy transfer (LET)

DOI: 10.13538/j.1001-8042/nst.26.050501

Introduction

Single event upset (SEU) induced by neutrons in advanced memory devices is currently recognized as one of the major reliability concerns [1–4]. Although neutrons are uncharged particles and cannot directly induce electron-hole pairs in semiconductor devices, they transfer energy and produce recoil and spallation products that are highly ionizing and therefore capable of creating electron-hole pairs in semiconductor materials [5, 6]. Secondary ions, such as recoil and spallation products, can create large numbers of excess carriers and possibly cause SEU in memory devices. Previous literature reports have documented this phenomenon and mechanism [7, 8]. Experiments show that neutron-induced SEU has been identified in memory devices, with cross sections for various memory types measured in different neutron radiation environments [9]. Simulation of neutron-induced SEU effects is mainly based on the Monte Carlo method, which is useful for simulating SEU of a memory chip induced by neutrons and providing a detailed description of the random processes involved. Li et al. provide a Monte Carlo method to simulate the process of energy deposition in sensitive volumes and calculate the SEU cross-section [10].

In addition, as one of the Monte Carlo toolkits, Geant4 is playing an increasingly important role in many nuclear technology applications, especially for neutron transport and nuclear reaction simulation. In Pete Truscott's work, Geant4 was used to simulate neutron SEU effects, with SEU rate predictions showing good agreement with experimental data for devices ranging from large (300 µm) to small (0.5 µm) feature sizes [11]. All the aforementioned research provides a universal understanding of neutron-induced SEU effects and demonstrates that the Monte Carlo method, such as Geant4, is a reasonable and effective approach for neutron SEU simulation.

However, few research papers focus on how to predict the occurrence of SEU for different kinds of memory devices in neutron radiation fields. Practical neutron radiation environments, such as reactor neutrons, terrestrial neutrons, and atmospheric neutrons, provide both thermal and fast neutrons over a wide energy range. In this paper, experiments were performed at the Xi'an Pulsed Reactor (XAPR) at the State Key Laboratory of Intense Pulsed Radiation Simulation and Effect in China, so the incident neutron spectrum in our simulation is the XAPR neutron spectrum. Because of complicated device structures and neutron spectra, it is quite challenging to determine whether memory devices will exhibit SEU effects in neutron radiation environments.

It is well known that linear energy transfer (LET), referring to the energy loss of an incident ion per unit length in material, is an important parameter in detailed analysis of SEU effects. It is commonly presumed that SEU occurs whenever the LET of ions exceeds the SEU threshold of the memory device. Based on this understanding, it is essential to calculate the LET range of all secondary ions induced by neutrons. The objective of this paper is to predict whether SEU occurs in certain memory devices exposed to neutron radiation.

First, to determine the energy spectra of each secondary ion induced by neutrons, the Geant4 Monte Carlo simulation program is adopted to process neutron transport in silicon dioxide and simulate interactions between incident neutrons and target atoms. Second, the LET of secondary ions is calculated using Stopping and Range of Ions in Matter (SRIM). Thus, SEU will occur when the maximum LET exceeds the SEU threshold of a memory device, and vice versa. Finally, reactor neutron radiation experiments on static random access memory (SRAM) and electrically erasable programmable read-only memory (EEPROM) were performed to confirm the simulation predictions.

Simulation Procedure

To predict the occurrence of SEU induced by neutrons in silicon-based memory devices, our simulation calculates the LET spectrum of all secondary ions, considering the incident neutron spectrum, target material, and nuclear reaction channels. The incident neutron spectrum defines the primary neutron energy in the simulation through Monte Carlo random sampling. The target material is defined as silicon dioxide. Top layer materials, such as copper, are not considered in the simulation for two reasons. First, in silicon-based devices, silicon dioxide is the major material for insulation and isolation of adjacent transistors, while other layer materials are minor. Second, the sensitive volume material is silicon, so reactions between the sensitive volume material and neutrons can be included in the reactions between silicon dioxide and neutrons. For reactions between neutrons and silicon dioxide, there are 30 comprehensive nuclear reaction channels, as shown in Table 1 .

The prediction simulation in this paper is primarily based on the Geant4 and SRIM simulation toolkits. The type and energy distribution of secondary ions exported from Geant4 simulation are imported into SRIM to calculate the LET value of each secondary ion. Geant4 uses the NeutronHP model for neutron interactions from thermal energies up to 20 MeV. In this work, the Geant4 Monte Carlo program is first adopted to handle collision, moderation, and nuclear reaction processes, and to simulate the energy distribution of secondary ions produced from nuclear reactions. The initial neutron energy spectrum, physical processes, and reaction channels must be taken into consideration. Figure 1 [Figure 1: see original paper] shows the initial neutron spectrum provided by

XAPR. In the Geant4 primary generator action file, the primary energy of the incident neutron is sampled from this spectrum through random sampling. The neutron energy ranges from 3.6×10^{-3} eV to 20 MeV, with the majority of neutrons in the low energy range and differential flux decreasing with increasing neutron energy after 10 eV.

In Geant4, neutron transport at energies below 20 MeV is based on empirical elastic and inelastic neutron cross-section data drawn from many standard database sources [12]. Ionization due to the recoil nucleus and secondary charged nucleons includes accurate treatment of low-energy electromagnetic processes, using electronic stopping power for protons and α particles, multiple scattering, and δ-ray production from ions [13]. In silicon-based semiconductor devices, when the initial neutron passes through a sensitive region, it interacts with nuclei from the device material, predominantly ^{28}Si and ^{16}O. The reaction is elastic when conserving momentum, or inelastic when the neutron is absorbed followed by ejection of nuclear fragments. The characteristics (ion type and energy) of secondary ions responsible for SEU strongly depend on the type of nuclear reaction [14]. As shown in Table 1, various nuclear reactions can only occur above certain energy thresholds of a few MeV. As neutron energy increases, the number of reaction channels increases. Consequently, low-energy neutrons are not very efficient at creating SEU effects through limited reactions. For neutrons above 17.8 MeV, all reaction channels are open, increasing the probability of generating a secondary ion capable of inducing a bit upset.

The Monte Carlo simulation code SRIM (formerly TRIM) is a collection of software packages developed by Ziegler and Biersack, designed to calculate ion deposition profiles in materials exposed to energetic ion beams [15, 16]. SRIM tables of LET, stopping power, and projected range versus ion energy are especially useful for computation of ion transport in a wide range of simulation applications. In this paper, SRIM is used to calculate the LET values of secondary ions based on ion stopping and range tables. In the LET calculation, the atomic number, mass number, and energy of the incident ion, as well as the type of target material, must be defined. Figure 2 [Figure 2: see original paper] shows the LET of eight types of ions that are secondary products of neutron reactions with Si and O atoms. In silicon, the energy to create an electron-hole pair is 3.6 eV; therefore, 1 $\mathrm{MeV \cdot cm^2/mg}$ LET produces about 10.3 fC/µm of silicon. As shown in the figure, the LET of each ion initially increases with energy and then decreases afterward, and ions with larger atomic numbers can evidently induce larger LET values.

The simulation results for energy range and maximum LET are shown in Table 2 . The energy range of each secondary ion is simulated by Geant4, and the maximum LET is calculated by SRIM. The maximum LET of neutron-induced secondary ions is 9.28 $\mathrm{MeV \cdot cm^2/mg}$, caused by ^{24}Mg at 3.79 MeV. It should be noted that the maximum LET for protons and α particles in silicon is 0.54 and 1.45 $\mathrm{MeV \cdot cm^2/mg}$, respectively. In addition, the SEU cross-section of these particles is smaller than that of most other secondary ions. By dividing the LET range into successive intervals and calculating the proportion of ion numbers in each LET interval, we obtain the LET spectrum of neutron-induced secondary ions, as shown in Figure 3 [Figure 3: see original paper]. The LET is mostly distributed from 0 to 3 MeV · cm^2/mg, with a peak at 0.4 MeV · cm^2/mg mainly caused by secondary low-energy ^{16}O generated from reactions of primary neutrons with oxygen atoms in the material. This LET spectrum is highly useful for predicting SEU occurrence and further investigating ionization effects on the electrical response of memory cells.

In this paper, LET simulation results are used to judge whether SEU will occur by comparing the maximum LET with the threshold of the memory device. Previous literature shows that the SEU threshold is 0.3–0.7 MeV · cm^2/mg for CMOS SRAM with feature sizes of 0.18–0.5 μm, while the maximum LET is calculated to be 9.28 MeV · cm^2/mg in the reactor neutron radiation environment [17, 18]. For this reason, it can be confirmed that SEU will occur in SRAM exposed to reactor neutron radiation.

Previous research shows that the SEU threshold is approximately 37 MeV · cm^2/mg for EEPROM 28LV010, which is much larger than the maximum LET induced by neutrons [19]. Therefore, it can be confirmed that reactor neutrons will induce no SEU in EEPROM devices with similar technological processes.

Experimental Procedure

Neutron SEU experiments were performed at XAPR. The nuclear reactor facility is located at the Northwest Institute of Nuclear Technology (NINT) in China and provides both thermal and fast neutron beams over a range of energies. Neutron fluence was approximately 1.0×10^{14} n/cm^2. The devices under test (DUTs) were SRAM and EEPROM memories. Test data transfer was carried out via USB connection to a personal computer. The test system allowed for rapid detection and storage of SEU events. Before radiation, the pattern 55 HEX (01010101) was written into each storage cell of the DUTs. During radiation, the DUTs were read continuously, and the SEU test could be easily handled by the error detection and record system.

Simulation results predict that SEU will occur for SRAM in a reactor neutron environment, and experimental results are consistent with this prediction. Figure 4 [Figure 4: see original paper] shows single-bit upsets induced by neutron irradiation for Hitachi HM628512C and HM62W8512B. Because a much lower number of SEUs was recorded for Hitachi HM628512A, results for this memory are depicted separately in Figure 5 [Figure 5: see original paper]. SEU occurs once SRAM is exposed to neutron irradiation, and the number of upsets increases linearly with neutron fluence.

The SEU cross-section is estimated from the following formula:

$$\sigma = \frac{N}{N_0 \times \phi}$$

where N_0 is the total bit number of the SRAM block (equal to 2^{19} bits), N is the number of upsets, ϕ is neutron fluence, and N/ϕ equals the slope of zero-crossing linear fitting.

The cross-section is 3.3×10^{-14} cm^2/bit for 0.18 µm SRAM HM628512C, 4.4×10^{-15} cm^2/bit for 0.35 µm SRAM HM62W8512B, and 1.7×10^{-16} cm^2/bit for 0.5 µm SRAM HM628512A. As shown in the figures, SEUs for HM628512C reached 1.7×10^6 at the end of irradiation, reflecting extremely high sensitivity to reactor neutrons. The HM628512C shows greater sensitivity than HM62W8512B and HM628512A because smaller feature size sharply increases the upset cross-section by lowering the critical charge of memory cells.

Simulation results predict that SEU in EEPROM is impossible in reactor neutron environments. SEU tests of EEPROM AT28C256 and AT28C040 were carried out in the neutron radiation environment. As expected, neutron radiation induced no significant SEU effects in EEPROM during read operations, since no error bits were observed in lengthy validation tests.

Conclusion

A simulation approach is presented to predict SEU occurrence induced by neutrons in memory devices. The simulation adeptly processes neutron transport in semiconductor materials, obtains the type and energy distribution of secondary ions, and calculates LET values. The entire simulation procedure provides a method to obtain the energy distribution and LET spectrum of neutron-induced secondary ions, and introduces a practical approach to predict whether SEU will occur by comparing the SEU threshold of a memory device with the maximum LET in a neutron radiation field when the device is exposed to neutron irradiation with a complex spectrum. Experimental results show that three types of SRAM devices exhibit high sensitivity to SEU effects, while two types of EEPROM devices exhibit no SEU effects. Good agreement is obtained between experimental results and simulation predictions. For hardness assurance, SEU effects must be taken into account when the maximum LET in the radiation environment exceeds the SEU threshold of the memory devices.

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Note: Figure translations are in progress. See original paper for figures.