3.26 Soft Errors of Semiconductors Caused by Secondary Cosmic-ray Neutrons

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Cosmic-ray spallations in the atmosphere produce high energy neutrons, and these neutrons wake up an upset of bits on memory devices. This phenomenon is called 'soft error' or 'single-event upset'. The neutron originated soft errors are mainly caused by nuclear reactions between a silicon nucleus and a high energy neutrons, which produce α-particles and Mg, Al and other fragments. A preliminary analysis have been made on the neutron induced soft errors by simulating behaviors on neutrons and α-particles of their nuclear reaction product in Si with MCNP-X[1](LANL) and LAHET150(LANL) datasets.

Key words: Semiconductor, Neutron, Cosmic-ray, Single-event-upset, Soft error

1. Introduction

Semiconductor soft errors on memory bits caused by secondary cosmic-ray neutrons were reported in 1979 by Zieglar[2][3]. In those days, attention was only paid to the soft error caused by α-particles[4] from decay of a very small amount of radioactive impurities in semiconductors. The soft error by secondary cosmic-ray neutrons had not been remarked until 1990's. In 1994, however, O'Gorman,et al. reported that the contribution of neutrons to the soft error was almost equal to that of α-particles from the radioactive impurities for 288Kbit DRAM[5] chips. In 1996, IBM, Boeing, Fujitsu, etc[6-11]. pointed out that the soft error rate increases with an increase of integration density of semiconductor devices. The neutron induced soft errors would be dominant for DRAM integrated with higher density than 4Mbits, comparing with α-particle induced ones[11-13]. To estimate the neutron induced soft error rate, we have made a preliminary transport calculation on neutrons and α-particles of their nuclear reaction product in Si with MCNP-X(LANL) and LAHET150(LANL) datasets.

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2. Process

In this section, we will describe semiconductor soft error processes due to cosmic-ray neutrons. A. Neutrons produced in cosmic-ray spallations reach on the ground of the earth. Fig.1 shows the particle flight path. The rates of secondary cosmic-rays are summarized in Table 1. Muons consist about 60% of secondary cosmic-rays and neutrons consist about 40% of them. Electric charge in a semiconductor cell by a deposit energy from a cosmic-ray muon induced is negligible. However, heavy nuclei fragments produced by a nuclear reaction between a neutron and a silicon nucleus deposit huge amount of energy that brings about a single event upset. Thus, about 99% of soft-errors by secondary cosmic-rays are caused by cosmic-ray neutrons[14, 15].

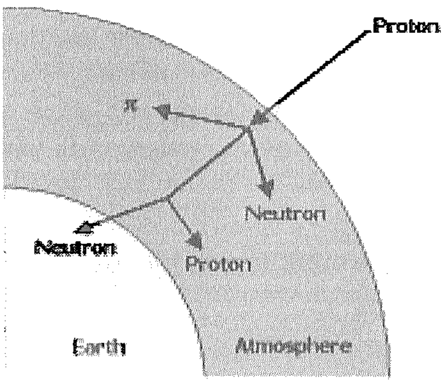


Fig.1 Secondary Cosmic-ray Neutrons

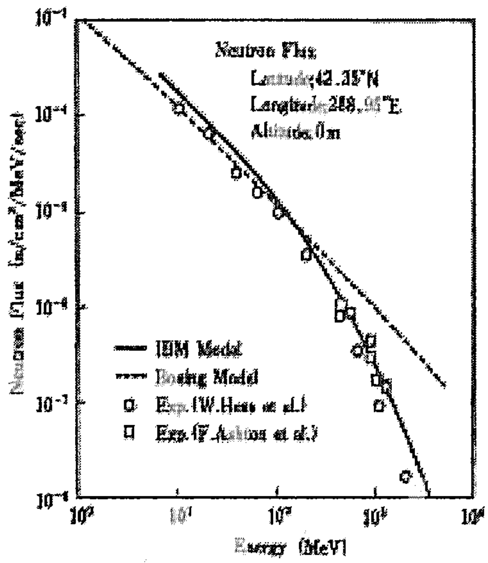


Fig.2 Neutron Energy Spectrum

Table1. A main component of Secondary Cosmic-ray [sea level]

Secondary Cosmic-ray	Rate [sea level]	Reaction on the Semiconductor	Electric Charge
Muon	59.1%	Electromagnetic Interaction	~0.5fc/μm
Neutron	40.5%	Nuclear Reaction	150fc/μm
Proton	0.325%	Electromagnetic Interaction (20%) Nuclear Reaction (80%)	1~3fc/μm 150fc/μm
Pion	0.044%	Electromagnetic Interaction + Nuclear Reaction	Low Charge

According to the IBM model, the cosmic-ray neutron spectrum[14, 15] on the ground is represented by the following Formula(1) and Fig.2. Table2 shows the neutron flux[14, 15].

$$FLUX=1.5\exp\{F(\ln(E))\} \quad \ldots \text{Formula (1)}$$

$$F(x)=-5.2752-2.6043x+0.5985x^2-0.08915x^3+0.003694x^4 \quad (10MeV<E<10GeV)$$

Table2. Neutron Flux (E>10MeV)

New York;	20	n/cm²/hour
Tokyo;	12	n/cm²/hour
Denver;	97.6	n/cm²/hour
London;	22.8	n/cm²/hour

B. Formula (2) shows dominant processes producing α-particles and other heavy ions in a silicon by an insident neutron. Fig.3 shows an example of images of the interactions.

Nuclear Reaction (Example) ... Formula (2)

$n + {}^{28}Si \rightarrow p + {}^{28}Al$

$n + {}^{28}Si \rightarrow n + p + {}^{27}Al$

$n + {}^{28}Si \rightarrow 2n + 2p + {}^{25}Mg$

$n + {}^{28}Si \rightarrow n + \alpha + {}^{24}Mg$

$n + {}^{28}Si \rightarrow etc$

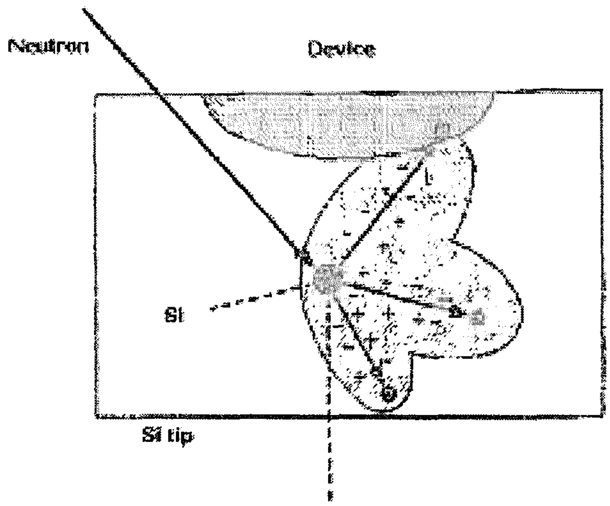


Fig.3 Nuclear Reaction

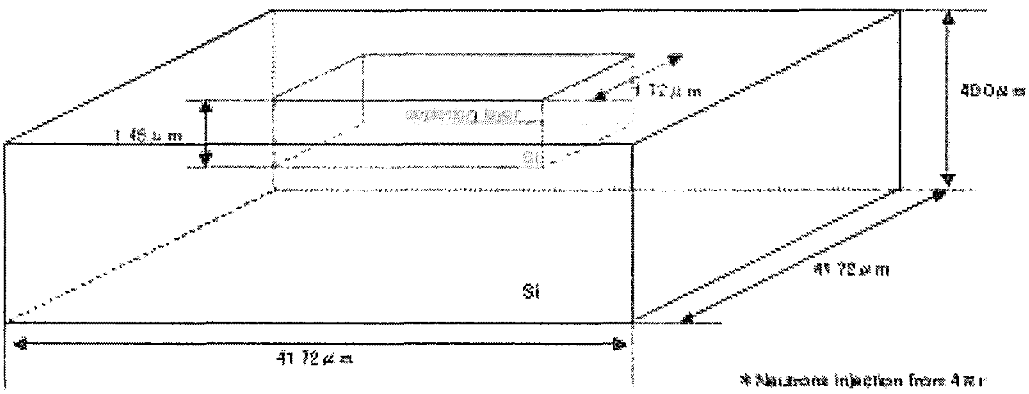
C. The α-particle or the other heavy ion deposit some energy on a memory bit. If the generated charge by the deposit energy is greater than the threshold of a single-event upset, a soft error occurs. Unfortunately, the complete cross section list of the interactions is not publicly opened. Therefore, in this report, we have analyzed only the phenomena related to α-particles.

D. An upset of a bit on memory devices has an energy threshold. For example, an upset of a bit on common SRAM devices occurs when a bit is given an electric charge around 10fC to 30fC. The energy of 3.6 eV is required to create an electron-hole pair in Silicon. Therefore, the 10fC and the 30 fC correspond to the deposit energy of 0.23 MeV and 0.68 MeV. Less than about 3000 Fit is preferable as for the soft error rate of a semiconductor (Fit = failure in time ; failure=upset of bit, time=1.0E+9hour).

3. Analysis

We calculated an expected soft error rate on a 1Mbit SRAM device caused by neutrons generated from cosmic rays. The soft error rate is calculated from the number of event that the energy deposition in the depletion layer is greater than the soft error threshold. Note that on this analysis, we only take into account the energy deposition by an α-particle produced from a nuclear reaction between an incident neutron and a silicon nucleus. We used a neutron transport Monte Carlo code, MCNP-X on this simulation. Fig.4 shows the geometry of a SRAM cell used for the input of the simulation. In the simulation, neutrons are generated on the surfaces of the silicon substrate shown in Fig.4. The place of the neutron origin is randomly selected on the surfaces event-by-event and the direction of the neutron is also randomly selected but only directed to the inside of the substrate. The neutron spectrum is based on the IBM model shown in Fig.2 . We assumed that the injected neutron flux is 12 n/cm²/hour, which is the experimentally measured neutron flux in Tokyo shown in Table 2.

Fig.4. Analyzed Model



4. Results and discussion

We generated 1.04×10^9 neutrons in the Monte Carlo simulation. It corresponds to the real time of 8.67E+11 hours by using the generated area of 1.0E-4cm² and the flux of 12 n/cm²/hour. The CPU time is about 20 hours on the 1.9GHz Pentium4 Linux PC. Assuming that the soft error threshold is 30fC (0.68MeV), 7 events are observed as an energy deposition greater than the threshold in the depletion layer by an a-particle. From this result, the soft error rate is derived as 8.4E-12 errors/hour/cell. Therefore, the soft error rate of the 1Mbit SRAM device is expected to be 8.4E-6 errors/hour and it corresponds to 8400 Fit.

Fig.5 shows the deposit energy by an α-particle in the depletion layer of the cell as a function of number of neutrons generated. This figure shows about 1/6 portion of the total generated neutrons with the histogram bin size of around 3000 event. In this plot, three events can be seen as an energy deposition greater than 30 fC (0.68 MeV). Note that this 1/6 portion is selected as an example of a statistical soft error rich region in this simulation.

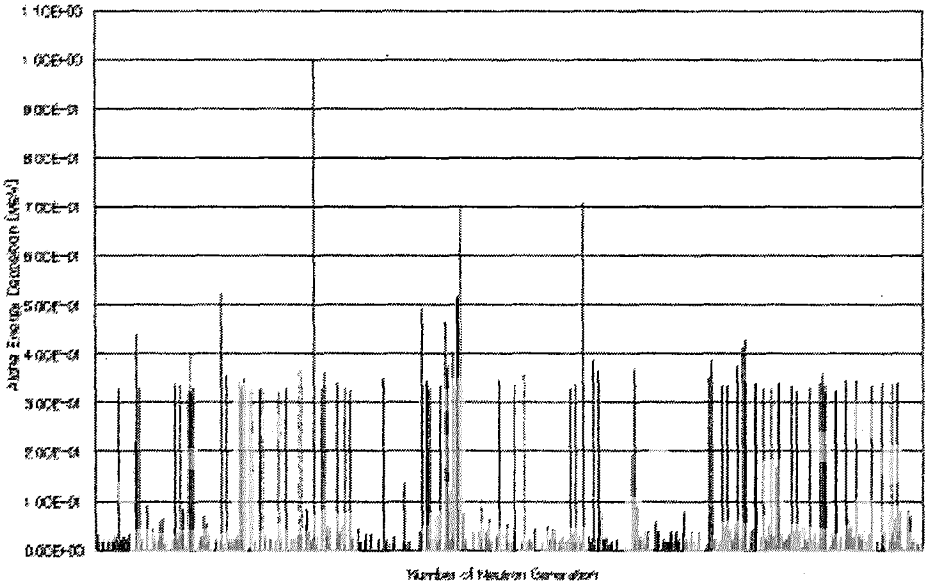


Fig.5 Alpha Particle Energy Deposition about 1 device

The result of 8400±3200Fit (68% confidence level) is larger than a preferable upper limit of 3000 Fit. However, since this simulation result has a large statistical uncertainty, we need more statistics to improve the statistical precision. In addition to the statistics, we have to think of the following subjects.

* Heavy ion fragments effect other than α-particles.
* Simulate more accurate geometry of the cell.
* Chemical properties other than silicon, like impurities doped to semiconductors, coating materials, and other layers like metal and SiO_2.
* Broader energy spectrum of neutrons outside of 10 MeV to 150 MeV.

5. Conclusion

In this study, we calculated the soft error rate of a 1Mbit SRAM cell caused by an α-particle generated from cosmic-ray neutrons using a neutron transport and the interaction Monte Carlo code MCNP-X . The result shows the soft error rate of 8400±3200 Fit (68% confidence level, statistical error only). We will improve the analysis accuracy by simulating more detailed geometry and the chemical composition, and by improving the nuclear cross section file used for the simulation code.

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