Neutron-induced semiconductor soft error simulation using the PHITS Monte Carlo simulator

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Abstract

We have performed a neutron-induced soft error simulation using the PHITS Monte Carlo simulator. We validated our technique by comparing the MBGR (Modified Burst Generation Rate) values estimated by our simulation and a well known MBGR table by Fujitsu Laboratories, Ltd. We also evaluated a neutron-induced soft error rate of a SRAM cell as a function of the critical charge as well as a representation using a generally used unit, FIT rate [error/10^9 hour/device].

1 Soft error

A charge deposition in a semiconductor memory cell by a cosmic-ray radiation causes a temporary bit information upset. This phenomenon is known as a soft error or also called as a single event upset. Cosmic-ray neutron is one of the most important source of the soft error on the ground. A neutron-nucleus interaction generates ions, protons and other particles. These ions and protons induce electron-hole pairs in a memory cell. Soft error occurs when the charge is greater than a critical charge. Figure 1 shows an image view of a soft error process. By the evolution of semiconductor manufacturing processes, soft error problem is expected to be more serious in future because of the required charge decrease for storing a bit information.

2 Cosmic rays

Protons are the main source of cosmic-rays outside of the earth. Cosmic-ray neutrons are generated by interactions between cosmic-ray protons and atmosphere. The neutron flux on the earth has been measured by IBM [1]. The measured neutron flux in Tokyo is around 12 n/cm^2/hour. Figure 2 shows the theoretical calculation of the energy distribution of cosmic-rays in New York. The best fit of the measured neutron flux distribution by IBM is shown in the equation (1) and (2) [2]. These equations are used for the neutron energy distribution input of our simulation. The flux is normalized to the neutron flux in Tokyo.

$$Flux(E) = 1.5 \times \exp(F(ln(E))) \tag{1}$$

$$F(X) = -5.2752 - 2.6043X + 0.5985X^2 - 0.08915X^3 + 0.003694X^4 \tag{2}$$

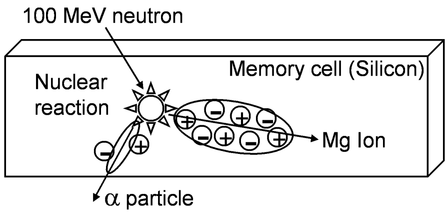

Figure 1: An image view of a neutron-induced soft error process.

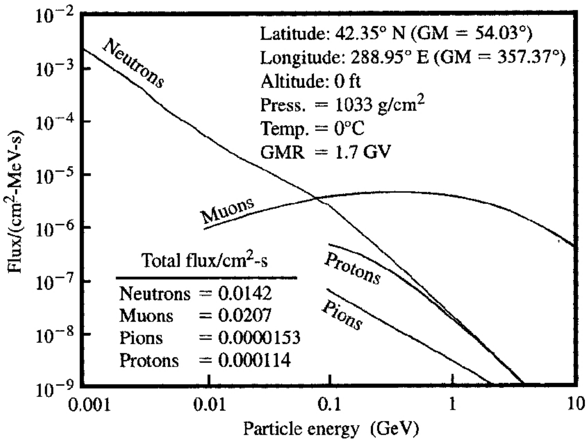

Figure 2: Theoretical energy distribution of cosmic-rays in New York city.

3 Simulation method by the PHITS Monte Carlo simulator

The soft error simulation requires high energy neutron transport up to at least 1000 MeV, neutron-nucleus reaction models, and transportation of generated heavy ions by the spallation. The PHITS Monte Carlo simulator [3] has all those functions. Especially, the implementation of a QMD (Quantum Molecular Dynamics) model is a great advantage.

PHITS is the first general purpose heavy ion transport Monte Carlo code over the incident energies from several MeV/nucleon to several GeV/nucleon. For the heavy ion transport calculation, Shen's formula, the SPAR code, and the JQMD [4] code are included. We show a concept view of the soft error simulation flow chart by the PHITS simulator in Figure 3. Neutron flux, the energy distribution, the direction, and the geometry information are the principal inputs of the PHITS simulator. PHITS outputs deposit energy distribution in the specified sensitive region. Deposit energy distributions caused by a specific particle type are also available. The induced charge is transformed from the deposit energy using the average required energy to produce an electron-hole pair, 3.6 eV/(e-h pair) [5]. For example, if the critical charge is 10 fC, corresponding deposit energy is 0.225 MeV.

4 Validation

As a validation of the PHITS simulation, we compared the MBGR (Modified Burst Generation Rate) values calculated by the PHITS and the well known MBGR table by the NISES simulator (Fujitsu) [6]. The MBGR value is an error rate of the unit volume of a sensitive layer in a memory cell as a function of the sensitive layer depth, d, and the critical charge, Q_C. The Q_C dependence of the soft error rate, SER, of the memory cell with depth d is derived as follows[6],

$$SER(d, Q_C) = MBGR(d, Q_C) \cdot N \cdot V_s \cdot C \tag{3}$$

where $MBGR(d, Q_C)$ is the burst generation rate, N is the neutron flux, V_s is the sensitive volume, and C is the collection efficiency which must usually be determined by experiment. We list the

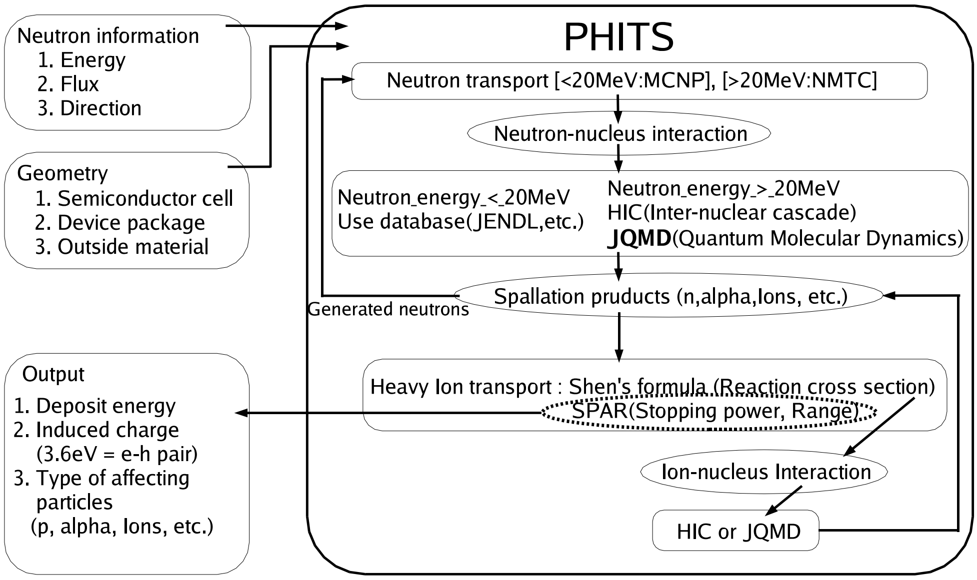

Figure 3: The concept flow chart of the soft error simulation by PHITS.

input geometry below and the schematic view is shown in Figure 4.

Geometry	:	Silicon bulk 1 mm$\times$1 mm$\times$30 μm
Neutron direction	:	Incident vertically in random place.
Neutron energy	:	Random following the IBM model. (10 MeV - 1000 MeV)
Sensitive layer	:	1 mm$\times$ 1 mm$\times$ (0.35 μm, 0.7 μm, 1.4 μm, 2.8 μm, 5.6 μm).
Number of incident neutrons	:	0.5 billions (5.6 μm thick) to 40 billions (0.35 μm thick)

The PHITS outputs deposit energy distribution in the sensitive region. We convert the deposit energy into the induced charge and calculate probability of events where the induced charge is greater than a critical charge. The MBGR value is derived by normalizing the error probability in a unit volume of the sensitive region. Figure 5 shows the critical charge dependence of MBGR values in every depth of the sensitive volume. Results by PHITS simulation and the MBGR table by NISES simulator are shown in the same plot. Two results by different simulators agree well and the difference is as much as only about a factor of two. Currently, publicly available MBGR value by NISES simulation is limited within the critical charge between 10 fC and 150 fC. However, in the state of the art semiconductor processes, the critical charge reaches a few fC mark. We extend the lower limit of the critical charge to 1 fC.

In Figure 5, a crossing point is seen in the MBGR plots by PHITS simulation. Plots of thicker sensitive layer and plots of thinner sensitive layer cross around the critical charge of 20 fC. This is because the major contributing particles are different depending on the deposit energy.

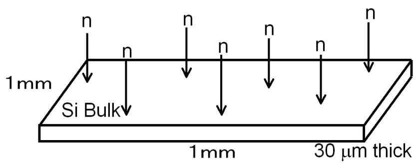

Figure 4: Schematic view of the MBGR calculation.

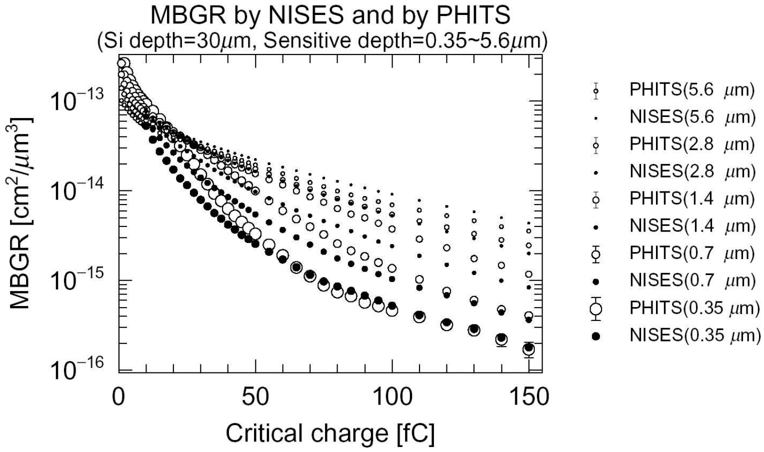

Figure 5: BGR comparison between two methods: by PHITS(CSD) and by NISES(Fujitsu).

If the critical charge is large, only heavy ions with large LET contribute energy deposit and the heavy ions stop close to the place of the nuclear interaction. The MBGR value is bigger if the sensitive layer is thicker, because 1: the probability of a nuclear interaction in the unit volume does not depend on the sensitive layer depth, and 2: the mean trajectory of heavy ions in the sensitive region is longer when the sensitive layer is thicker.

If the critical charge is small, protons are the main source of the energy deposition. The range of a proton is much longer than that of ions. For instance, the range of a 2 MeV proton is about 40 μm in the silicon. This means that the protons traveling from interactions away from the sensitive layer also contribute to the error rate. After normalizing in the unit volume, since the probability that a proton penetrates the sensitive layer does not much depend on the sensitive layer depth, the MBGR values with thinner sensitive layer is bigger when the critical charge is small. The detail of the contributing particles are shown in the next section.

5 SRAM simulation

We performed a more realistic soft error simulation by assuming a simplified SRAM cell. The geometry and the simulation conditions are as follows. The schematic view of this geometry is shown in Figure 6.

Geometry	:	Silicon bulk 40 μm $\times$ 40 μm $\times$40 μm
Neutron direction	:	Incident vertically in random place.
Neutron energy	:	Random following the IBM model.(10 MeV - 1000 MeV)
Neutron flux	:	12 n/cm^2/hour
Sensitive region	:	1.72 μm $\times$ 1.72 μm $\times$ 1.42 μm
Number of incident neutrons	:	40 billions.

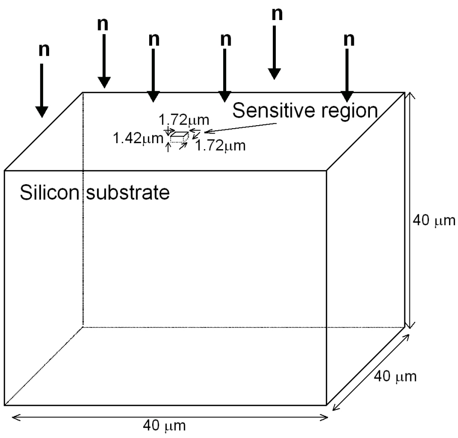

Figure 6: Schematic view of the soft error simulation of a SRAM cell.

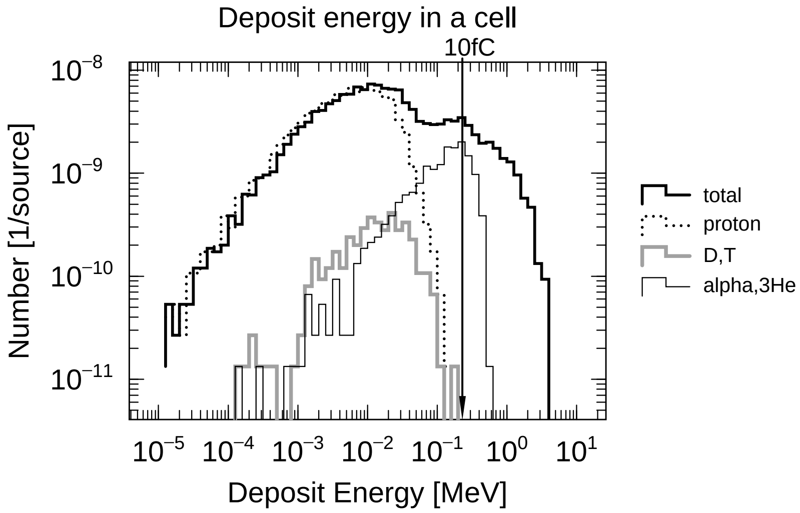

Figure 7: Deposit energy distribution in the sensitive region of a SRAM cell.

As a result of the simulation for a SRAM device, Figure 7 shows deposit energy distributions caused by some typical types of Ions as well as the distribution by all particles including heavy ions. Heavy ions dominate above the deposit energy greater than 0.6 MeV(∼30 fC). Helium ions dominate around the deposit energy of 0.2 MeV(∼10 fC). Below 0.1 MeV(∼5 fC), hydrogen nuclei are more important, especially, protons are the critical source because of the longer range. This effect is also shown in Figure 8, an inflection point is seen at the critical charge is around 10 fC to 20 fC. In future, estimating proton behavior would be much more important for devices with smaller critical charge. Taking into account further materials around the cell will also be important because of the longer proton range.

We evaluated the error rate of a SRAM cell using similar method as MBGR calculation. In this simulation, the probability is not normalized in a unit volume. Figure 8 shows the critical charge dependence of the error rate of a cell. The unit of left axis is the error rate of a cell. The unit of right axis is the FIT rate [error/10^9 h/device] of a device with 1 M cells. For example, in case of a device with 1 M cells, if the critical charge of the device is 10 fC, the device has an error rate of 3300 FIT. If we assume that eight cells are used for storing one byte information, the result shows that a personal computer with 256M bytes memory encounters a soft error every 5 months.

In the same plot, error rate of a cell evaluated simply from MBGR values are also shown. We used equation 3 and MBGR values of the 1.4 μm depth calculated by the PHITS. The collection efficiency is assumed to be one. These two plots agree well around the critical charge is smaller than about 10 fC. Above 10 fC, the difference extends as the critical charge increases. This can be explained as follows. In the MBGR calculation, there is no boundary of the sensitive region in the direction parallel to the silicon surface. If the direction of the trajectory of a generated ion is parallel to the silicon surface, the output of the deposit energy is large. Therefore, the MBGR method tends to overestimate the probability of large deposit energy.

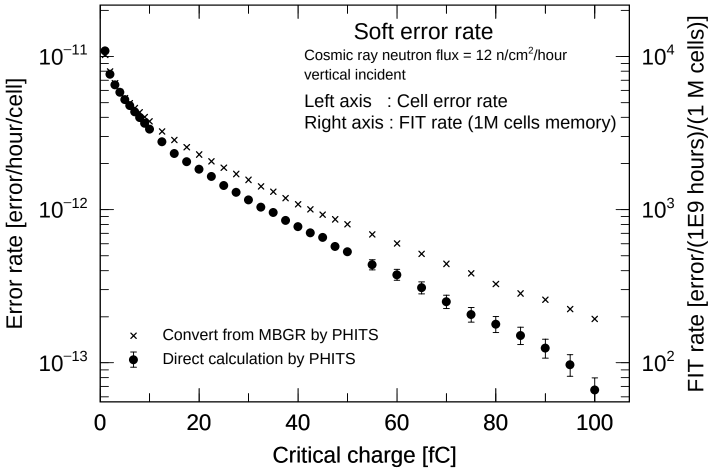

Figure 8: Soft error rate as a function of the critical charge. The unit of left axis is the error rate of a memory cell. The unit of right axis is the FIT rate [error/10^9 h/device] of a device with 1 M cells.

6 Summary

We successfully performed a soft error simulation using the PHITS Monte Carlo simulator. As a result of the validation, our MBGR calculation result agrees with a famous MBGR table by Fujitsu NISES simulator. The soft error rate simulation for a SRAM device shows a critical charge dependence of the error rate. The result shows that the soft error rate increases sharply as the critical charge decreases. We understand that the proton influence increases dramatically below 0.1 MeV deposit energy which corresponds to the critical charge of about 5 fC. Since the soft error critical charges of cutting edge technology devices are already below 5 fC, estimating effects of neutron-induced soft error would be very important for future devices.

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