

Nuclear Reaction Models Responsible for Simulation of Neutron-induced Soft Errors in Microelectronics

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Terrestrial neutron-induced soft errors in MOSFETs from a 65 nm down to a 25 nm design rule are analyzed by means of multi-scale Monte Carlo simulation using the PHITS-HyENEXSS code system. Nuclear reaction models implemented in PHITS code are validated by comparisons with experimental data. From the analysis of calculated soft error rates, it is clarified that secondary He and H ions provide a major impact on soft errors with decreasing critical charge. It is also found that the high energy component from 10 MeV up to several hundreds of MeV in secondary cosmic-ray neutrons has the most significant source of soft errors regardless of design rule.

I. INTRODUCTION

In recent years, radiation effects have been recognized as one of serious reliability issues for modern microelectronic devices operating under various cosmic-ray environments. In terrestrial environment, it is known that secondary cosmic-ray neutrons cause soft errors due to single-event effects. Physics-based simulation of the soft error phenomena is an effective and powerful tool in understanding the phenomena as well as designing radiation-tolerant devices. To simulate the soft error phenomenon accurately, it is necessary to employ highly reliable models describing various physical processes involved in the soft errors as shown in Fig. 1, *i.e.*, nuclear reactions, charge deposition, and charge collection. In particular, the modeling of nuclear reactions is of great importance in simulations of terrestrial neutron induced soft errors initiated by nuclear interaction with constituent materials. It is expected that prediction of generated secondary ions has an impact on simulation of the subsequent charge deposition and collection processes.

Recently, we have developed a multi-scale Monte Carlo simulation framework for terrestrial neutron induced soft errors by linking a particle transport code PHITS [1] and a 3-D TCAD simulator HyENEXSS [2], and have performed Monte Carlo calculations of soft error rates (SERs) for MOSFETs from a 65 nm down to a 25 nm design rule [3, 4]. In the present work, SER calculations are carried out using the PHITS-HyENEXSS code system with different nuclear reaction models, and the influence of nuclear reactions on soft error simulation is investi-

gated. Through analyses of calculated SERs, we discuss the major secondary ion species causing neutron-induced soft errors and the incident energy range having a large impact on them.

II. CALCULATION METHOD

Details of the PHITS-HyENEXSS code system are described elsewhere [3, 4]. We have applied the code system to Monte Carlo calculations of SERs for 65 nm, 45 nm, 32 nm, and 25 nm design rule NMOSFETs whose parameters are given in Refs. [3, 4].

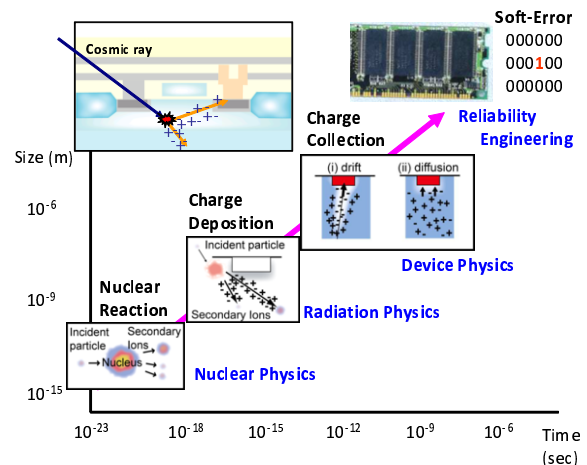


FIG. 1. Spatial and temporal evolution of physical processes involved in soft error phenomena.

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Fig. 2 shows the test device structure used in PHITS calculation for a 25 nm technology NMOSFET. An analysis volume with the size of $20\ \mu\text{m} \times 10\ \mu\text{m} \times 10.25\ \mu\text{m}$ is placed on a $1.0\ \text{mm} \times 1.0\ \text{mm} \times 0.5\ \text{mm}$ silicon substrate as two-dimensional grid. The detection volume defined by the active area $0.175\ \mu\text{m} \times 0.098\ \mu\text{m}$ times the sensitive depth $0.5\ \mu\text{m}$ is located in each analysis volume. Terrestrial neutrons with the energy distribution ranging from 1 MeV to 1 GeV given by the JEDEC standard [5] are incident vertically on the device in the PHITS simulation. Information on all the secondary ions entering or being generated in the analysis volume is recorded in the dump file event by event. Among them, the events expected to be responsible primarily for the soft errors are selected using a filtering condition [3, 4]. Then, full 3-D device simulations are made for these selected events with default physical models implemented in HyENEXSS.

The number of events, $N(q)dq$, with the collected charge in $[q, q + dq]$ interval is obtained by the device simulation for all the events in the filtered dump file. Finally, the SER per bit is calculated as a function of the critical charge Q_c as follows

$$SER(Q_c) = \frac{F \times A}{N_{in} \times N_{bit}} \int_{Q_c}^{\infty} N(q)dq, \quad (1)$$

where F is the total neutron flux in units of $\text{cm}^{-2}\text{s}^{-1}$, A is the surface area of the test device shown in Fig. 2, N_{in} is the number of incident neutrons in PHITS calculation, and N_{bit} is the number of bit cells placed in the device.

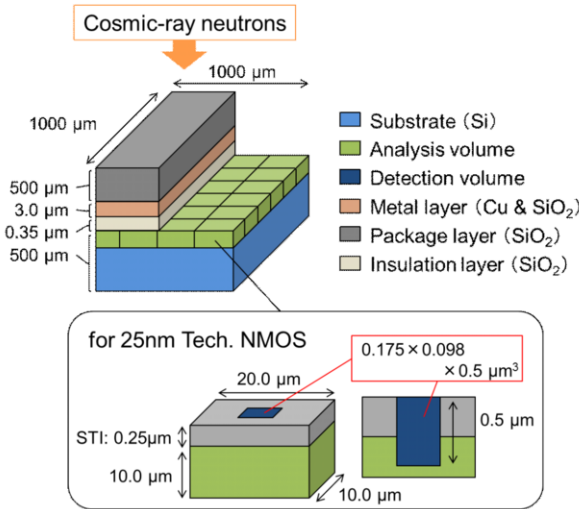


FIG. 2. Configuration of the test device structure for the 25 nm NMOSFET.

III. RESULTS AND DISCUSSION

A. Validation of Nuclear Reaction Models

Through our past validation of the nuclear reaction models used in PHITS code [6, 7], we recommended that the combined use of the event generator mode (e-mode) with JENDL-3.3 [8] below 20 MeV and the modified Quantum Molecular Dynamics (MQMD) model [9] plus Generalized Evaporation Model (GEM) [10] above 20 MeV is the most suitable in the soft error simulation. It should be noted that MQMD has not yet been implemented in the present version of PHITS. Also it was confirmed that the use of the latest JENDL-4.0 [11] obtains the almost same result as that of JENDL-3.3.

In Fig. 3, calculated cross sections for $^{28}\text{Si}(n, \alpha)$ reaction are compared with experimental data [12–15] below 100 MeV. The QMD and MQMD calculations are in better agreement with the experimental data above 20 MeV than the INC calculation, whereas the e-mode calculation with JENDL-3.3 provides better agreement with the experimental data below 20 MeV than the QMD and MQMD model calculations. Figs. 4 and 5 show the double-differential cross sections of the $^{28}\text{Si}(n, \alpha)$ reaction at two incident energies of 96 MeV [15] and 175 MeV [16], respectively. It is found that the MQMD model improves agreement with the measurement [15, 16] at high emission energies remarkably, compared with the INC and QMD models.

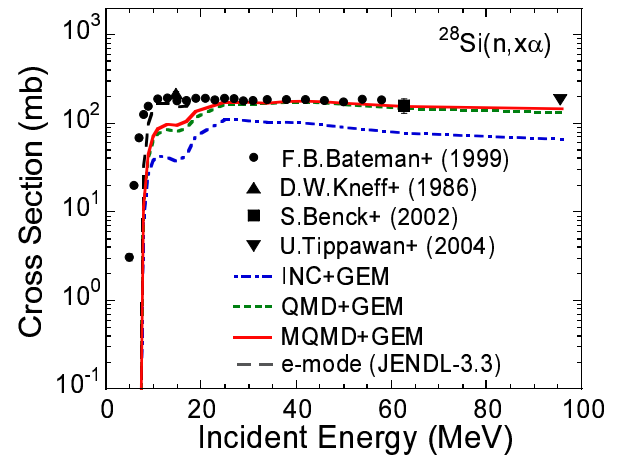


FIG. 3. Calculated and experimental cross sections for $^{28}\text{Si}(n, \alpha)$ reaction. The experimental data are taken from [12–15].

B. SER Analysis

Neutron-induced SERs for a 25 nm NMOSFET were calculated using two different reaction models, namely,

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