Neutron-Induced Soft Error Simulator and Its Accurate Predictions

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Abstract—**We developed the Neutron Induced Soft Error Simulator (NISES) to clarify the role of cosmic ray neutrons in soft errors (SEs). A recently proposed nuclear reaction theory forms the foundation of the nuclear reaction database of the NISES. NISES accurately reproduces the measured neutron-induced charge collection data in SOI diode test structures and the neutron-induced SER data in sub-half micron CMOS circuits. The need for neutron-induced SE simulator like NISES should increase with the recognition of the importance of cosmic ray neutron-induced SEs.**

I. Introduction

Several researchers have recently reported evidence supporting the significant effects of cosmic ray neutrons on VLSI circuits at ground level [1]-[7]. In space, cosmic rays consist mostly of protons, but also of helium, oxygen, and other ions. If a proton or other ion enters the atmosphere and collides with a nucleus in the air, it produces various secondary particles (Fig. 1). Neutrons are the most important factor causing soft errors (SEs) at ground level. If a neutron incidents on a silicon chip and collides with the Si (or other) nucleus, some ions are generated (Fig. 2), and a large number of charges are generated by the reaction products. If these charges are collected and pass a critical threshold, an SE occurs. It was shown that soft error rates (SERs) induced by α-particles from radioactive impurities in electronic materials are negligible and SERs are dominated by cosmic ray neutrons, especially for DRAMs [2]-[5]. We simulated neutron-induced SERs in sub-half micron CMOS circuits and predicted that SERs in logic circuits are also dominated by neutrons [6], [7].

The numerical approach is important for neutron-induced SEs, because we cannot easily carry out neutron-accelerated testing or cosmic ray neutron field testing. Neutron-accelerated testing needs a high-energy neutron or proton beam [3]-[5] and cosmic ray neutron field testing is time consuming [1], [2]. In this work, we report our Neutron-Induced Soft Error Simulator (NISES) developed to clarify the role of cosmic ray neutronis in SEs. The NISES is similar to the SEMM developed by G. R. Srinivasan et al. [8] except for the nuclear reaction data. Our nuclear reaction data is based on the Antisymmetrized Molecular Dynamics (AMD) [9]-[12], a recently proposed and highly accurate nuclear reaction theory. This report also covers the NISES applications to show the predictability of NISES.

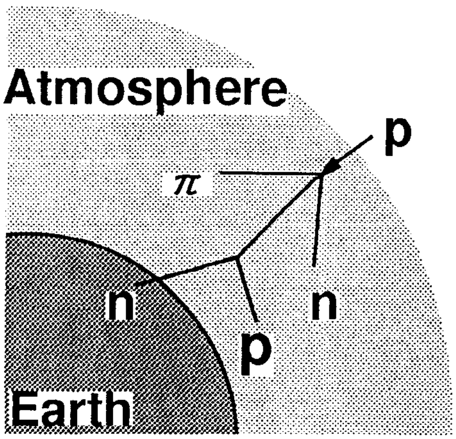

Fig. 1. Secondary cosmic ray neutrons.

II. Neutron-Induced Soft Error Simulator

The most important process in neutron-induced SE phenomena is the neutron-nucleus reaction in the Si substrate. However, obtaining accurate information about n+^{28}Si reaction is difficult due to the complexity of the phenomena and the lack of measured n+^{28}Si reaction data. We could avoid this difficulty using AMD [9]-[11], which describes nucleus-nucleus reactions in a quantum mechanical approach and is applicable to a wide range of nuclear reaction phenomena. The AMD wave function for the nuclear system is described by a single Slater determinant in which single particle wave functions are expressed as Gaussian wave packets. The time evolution of the centroid of the wave packets is determined by an equation of motion derived from the time-dependent variational principle. In AMD simulations for nucleus-nucleus reactions, the Cooling method sets the ground state of the nucleus. The dynamical process of the reaction is then simulated by following the equation of motion, in which two-nucleon collision processes due to residual interaction are also incorporated. In the final stage, the statistical evaporation process is described by an additional statistical evaporation model.

Our n+^{28}Si reaction database includes 300,000 reaction events for neutron incident energies of 10, 20, 30, 40, 60, 80, 100, 125, 150, 200, 300, and 500 MeV. These were obtained by repeating the above AMD simulation procedure. Figure 3 is a cross section example in the reaction

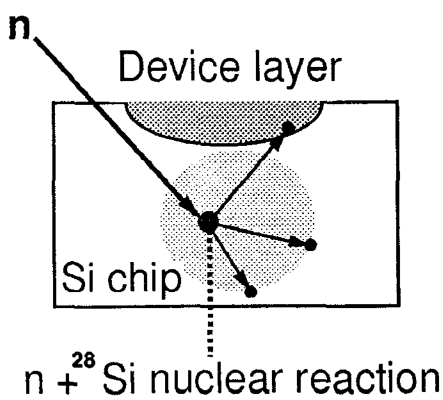

Fig. 2. Neutron-induced reaction in the Si substrate.

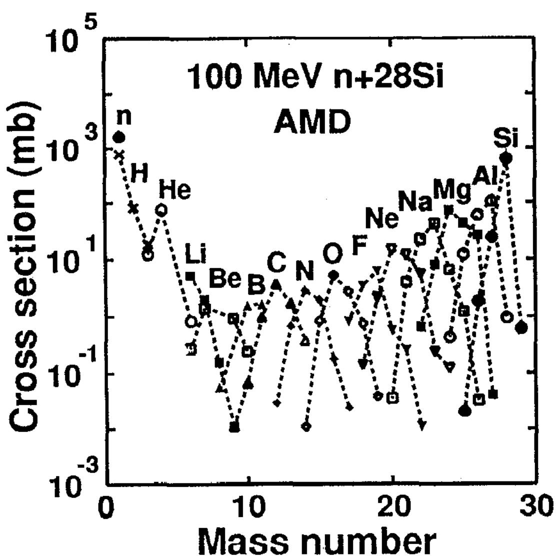

Fig. 3. Example in the nuclear reaction database.

database. The Figure shows cross sections for various reaction products in a n+^{28}Si reaction with a neutron incident energy of 100 MeV. It is shown that the many kinds of ions are produced by the reactions. The database includes information on the energy and angle distribution of reaction products.

Figure 4 outlines the NISES. The neutron spectrum and device structure are input data. The electron-hole pair generation data is based on the well-known Ziegler's code [13]. Neutron-silicon reactions are randomly generated in the silicon substrate using a Monte Carlo procedure. We defined a sensitive volume around a sensitive junction. If the reaction product passes through the sensitive volume, the charges induced in the sensitive volume are calculated. We assumed that when these charges pass a critical threshold (or a "critical charge"), an SE occurs. The NISES is applicable for neutron-induced SER predictions in arbitrary circuits and is also applicable for neutron-induced charge collection phenomena.

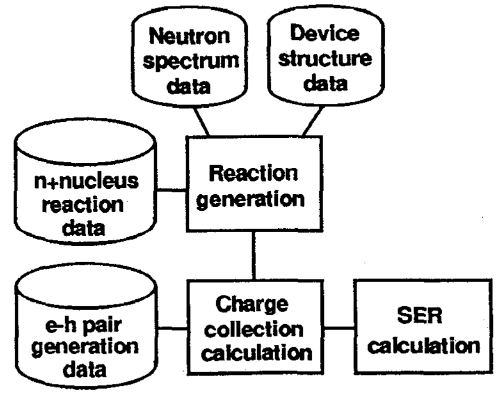

Fig. 4. Outline of NISES.

III. Verification of Simulator

Figure 5 shows measured and simulated charge collection results in SOI diode test structures. It illustrates charge collection counts from all nuclear reaction products as a function of the collected charge for an array of 100 μm $\times$ 100 μm diodes fabricated on SOI substrates with 2-, 5-, and 10-μm active silicon thickness. The experiment was performed at the Los Alamos National Laboratory WNR facility using a pulsed neutron beam. The beam has an energy spectrum similar to the sea-level atmospheric neutron energy spectrum for neutron energies of less than 800 MeV [12]. Because charges induced only in the SOI region were detected, we assumed the diode region multiplied by the SOI thickness to be a sensitive volume in the simulation. Although the simulations do not include any fitting parameters, the simulation results agree well with the measured results. This indicates the accuracy of the database in the NISES.

To apply the NISES to bulk silicon devices, we approximated the sensitive volume as a rectangular parallelepiped, with dimensions determined by the junction area and depletion area in the lateral direction and the funneling length [14] in the vertical direction. Figures 6 and 7 show the measured and simulated SERs as a function of critical charge for CMOS SRAM and Latch circuits. The circuits used for the SER measurements were 128 kbit CMOS SRAMs and 16 kbit Latch circuits fabricated with 0.35 μm gate length CMOS technology. We used the WNR neutron beam in the experiment. The simulated SERs agreed with the measured SERs within a factor of 2 to 3.

We simulated neutron-induced SERs in sub-half micron CMOS SRAM and Latch circuits assuming the sea-level atmospheric neutron spectrum and compared them to simulated α-induced SERs [7]. Then, we predicted that SERs in Latch circuits are dominated by neutrons and that neutron-induced SERs in CMOS SRAMs are in the same order as α-induced SERs, if the bump bonding technology is used. Results in Fig. 6 and 7. jus-

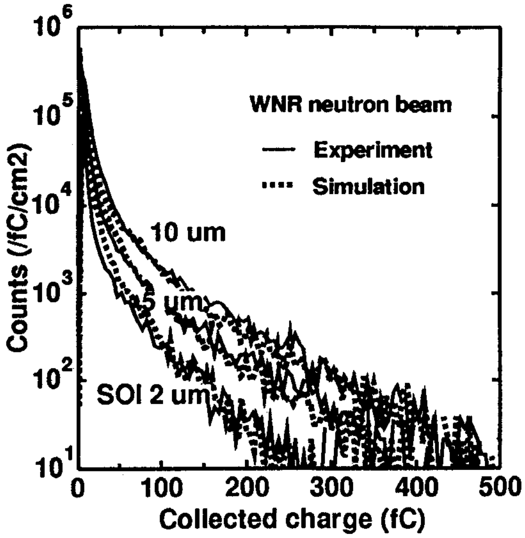

Fig. 5. Reaction-induced charge in SOI 2, 5, 10 μm chips for simulated and experimental results.

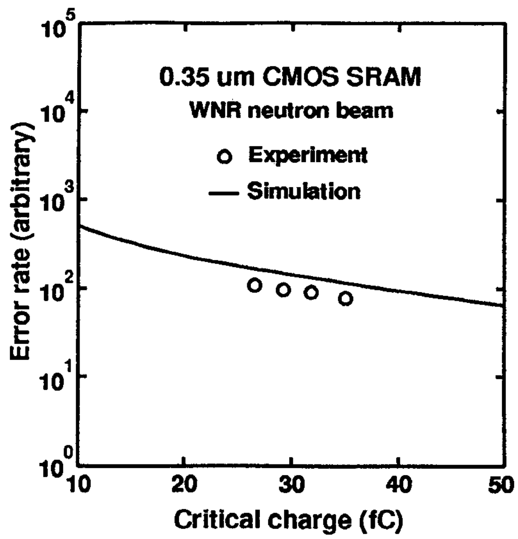

Fig. 6. Measured and simulated neutron-induced SERs for CMOS SRAM.

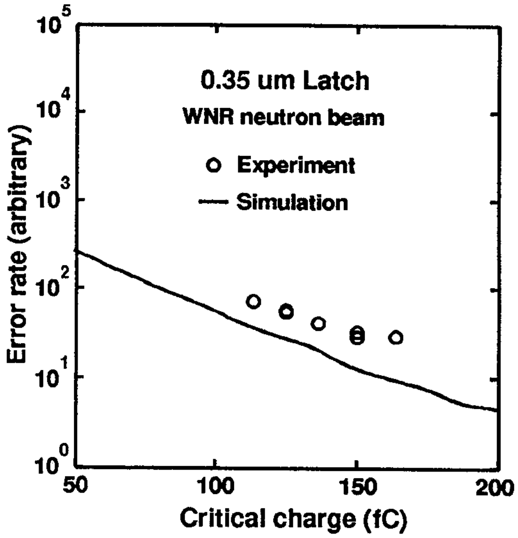

Fig. 7. Measured and simulated neutron-induced SERs for Latch circuit.

tify these previous predictions. It has also been shown that neutrons were dominant in SERs in DRAMs [2]-[5]. Therefore, although α-accelerated testing have often been done in circuit development, we should not rely on α-testings for estimation of SERs. However, field testing is time consuming and neutron-accelerated testing requires heavy task. Thus, NISES must be helpful for such circuit development.

IV. Conclusion

We have developed Neutron-Induced Soft Error Simulator (NISES), which has a nuclear reaction database based on Antisymmetrized Molecular Dynamics (AMD) simulation results. It accurately reproduced the measured neutron-induced charge collection data in SOI diode test structures and predicted the neutron-induced SERs in sub-half micron CMOS SRAM and Latch circuits within a factor of 2 to 3. These reflect the high ability of NISES to analyze neutron-induced SE phenomena and make NISES helpful in circuit development. The need for neutron-induced SE simulator like NISES should increase with the recognition of the importance of cosmic ray neutron-induced SEs.

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