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The Effect of Neutron Energy on Single Event Upsets and Multiple Bit Upsets

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ABSTRACT: Neutron-induced charge collection and time-of-flight measurements are presented. Simulations show that 14 MeV neutrons can approximate both SEU and MBU responses of low-critical-charge devices to a terrestrial neutron environment.

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INTRODUCTION

Neutron-induced single event effects (SEEs) have become a major concern for the reliability of modern and developing semiconductor technologies [1],[2]. As device dimensions continue to shrink, the susceptibility to neutron-induced single event upsets (SEUs) [3],[4] and multiple bit upsets (MBUs) [5],[6] in static random access memories (SRAMs) is increasing. Recent studies have shown that MBUs must be taken into account for 130 nm and smaller technology nodes [6]. Although error correcting codes and bit interleaving can effectively reduce the MBU rate, they increase the memory complexity and access time, and may not be suitable for all memories [7].

It is ideal to qualify parts in a radiation environment that is as similar to the natural one as possible. There are a few facilities that provide accelerated neutron testing with an energy spectrum similar to that of the natural one at a terrestrial level [8]. However, due to cost and accessibility, alternative tests for neutron vulnerability have been investigated [9],[10]. In [10], a comparison was made of the SEU cross section as measured by the neutron energy spectrum at the Weapons Nuclear Research facility (WNR) at Los Alamos National Lab and a monoenergetic 14 MeV neutron source. It was observed that, for multiple SRAMs from different technology nodes, the SEU cross section measured with the 14 MeV neutrons was within a factor of two of that measured with the WNR neutrons. However no comparison of MBU cross sections was done.

With the increasing diversity of materials found in today's semiconducting devices, it is important to understand the mechanisms of neutron-induced SEEs for materials beyond silicon and SiO_2, and their dependence on neutron energy. It has been shown that high-energy protons (>100 MeV) can cause proton-induced fission events in tungsten, and that the resulting fission fragments can have a higher linear energy transfer (LET) and a longer range than silicon or oxygen recoils [11]. It is known that for high neutron energies, neutron-induced fission in tungsten can occur [12], but it has not been assessed how significant these events can be for devices in a terrestrial-level neutron radiation environment, nor has the impact of these events on MBUs been analyzed.

In this work, we present experimental charge collection data that demonstrate the effect that high-Z materials near sensitive volumes can have on SEEs for devices in a terrestrial neutron environment. In addition, we present time-of-flight (TOF) measurements of each charge collection event, thereby showing the effect that neutron energy has on charge deposition. Finally, through Monte Carlo simulations, we investigate the effect that neutron energy has on SEUs and MBUs in a representative SRAM structure.

EXPERIMENT AND SIMULATION METHODS

Neutron irradiations were performed at the WNR facility at Los Alamos National Lab, using the Target 4 Flight Path 15L (T4FP15L) that provides a neutron energy spectrum similar to the terrestrial neutron energy spectrum, but with a flux approximately six orders of magnitude greater. The neutron energies in this flight path extend up to nearly 800 MeV. Because of the small cross section for neutron-induced nuclear reactions, the devices were irradiated to a high fluence of 3×10^{12} cm^{-2} at both normal incidence (perpendicular to the surface) and at a grazing incidence.

The pulse height analysis (PHA) system described in [13] was used to perform the charge collection measurements. In PHA, the charge collected from a reverse-biased diode forms a current pulse that is passed to a charge-sensitive preamplifier. The preamplifier integrates the current over time and outputs a pulse whose height is proportional to the collected charge. The pulse is then processed, digitized and histogrammed. Only pulses whose heights exceed a predetermined threshold are digitized. The system was calibrated on-site using an alpha source and a surface barrier detector as the charge collection device.

A TOF system was integrated into the PHA system to measure the energy of the incident neutron that caused each charge collection event. The TOF measurements were made using an Ortec 566 time-to-amplitude converter. The start pulse was provided by the facility at the time of the neutron generation. The stop pulse was retrieved from the NIM output of a Mesytec MPRS-16 preamplifier/shaping amplifier used for the charge collection measurement. The neutron flight distance used for T4FP15L was 18 m.

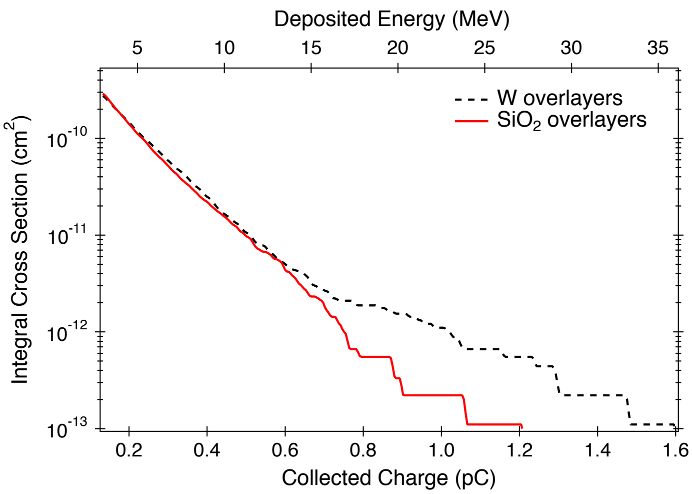

Fig. 1 Experimental cross section curves of the neutron-induced charge collected for both diode overlayer configurations.

The custom-made bulk silicon diodes used in this study are described in [11]. Briefly, the diodes have charge collection regions that are 2.1 µm thick with a cross sectional area of 0.18 mm^2. Two types of overlayer configurations were used: one configuration has an overlayer of tungsten (W) plugs (with 43% W coverage) directly above the charge collection region, while the other has only SiO_2 overlayers. The total thickness of material covering the diodes is the same in both cases. The diodes' relatively large cross section allows for more frequent detection of the neutron-induced charge deposition events, and thus provides better statistics over shorter exposure times. Also, the inclusion of larger-than-typical amounts of W in the diode overlayers was intentional in order to make their role in charge deposition more observable.

For the Monte Carlo computer simulations performed in this study, the MRED simulation tool developed at Vanderbilt University was used [14]. A description of MRED will be included in the full paper.

CHARGE COLLECTION MEASUREMENTS

The charge collection data from the normally incident neutron irradiation done at WNR is shown in integral cross section form in Fig. 1. A given point on integral cross section curve is proportional to the probability that the collected charge exceeds the value given on the x-axis. Displaying the data in this form is useful because it allows the charge collection cross section to be read directly from the curve for a given amount of minimum charge collected, Q_{min}. That is, it is the cross section for collecting at least that given amount of charge. Fig. 1 shows that for Q_{min} less than 0.6 pC, the effect of the W layer on the charge collection cross section is minor. However, for high Q_{min}, the presence of W can increase the charge collection cross section (a statistical analysis of these high charge collection events will be included in the full paper). These high charge collection events are caused by highly ionizing secondary particles from neutron-W collisions. Similar charge collection curves are observed from neutrons incident at a grazing angle (plot to be included in the full paper), which indicate that these highly ionizing secondary particles are emitted isotropically from the neutron-W collision, which suggests neutron-induced fission as the mechanism.

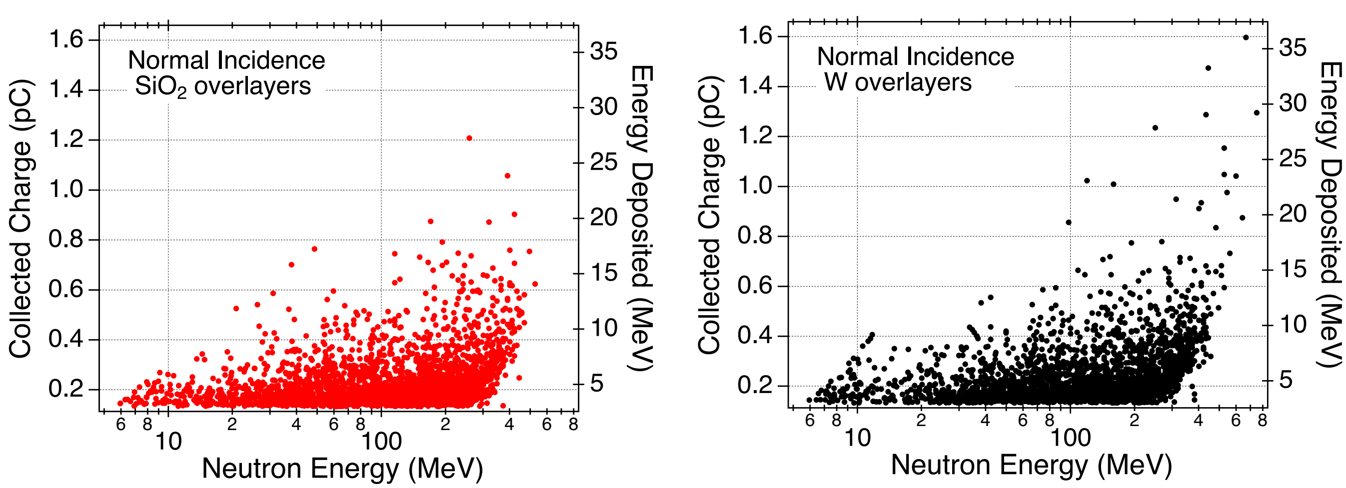

Fig. 2 Scatter plots of the experimental TOF neutron energies for each corresponding charge collection event for normally incident neutrons.

For each charge collection event, TOF measurements were made on the incident neutron. Fig. 2 shows a scatter plot of the neutron energy and corresponding charge collected for both diode overlayer configurations. These data show a trend indicating that the higher energy neutrons cause the largest charge collection events, as one would expect. From these data, we can conclude that for devices with a high critical charge, Q_{crit} (the minimum amount of charge required to cause an SEE), low energy neutron beams would greatly under predict the SEU cross section and could even incorrectly predict a device to be SEL immune to terrestrial level neutrons (see [11],[15]).

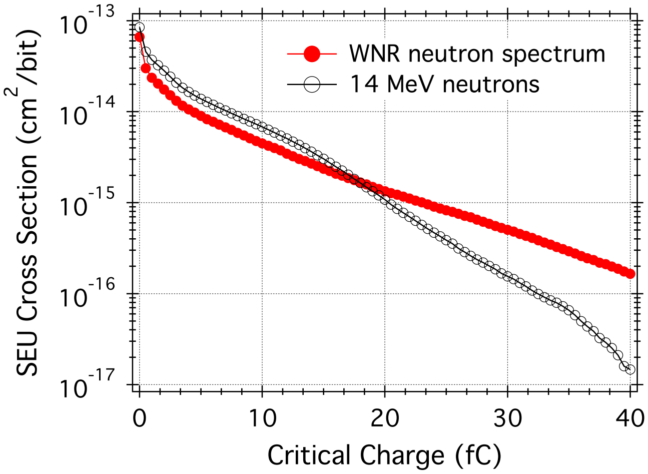

Fig. 3 Simulated SEU cross section as a function of critical charge for two different neutron energies at normal incidence.

SEU AND MBU SIMULATIONS

Using MRED, Monte Carlo simulations were used to investigate the SEU and MBU response to the WNR neutron spectrum compared with a monoenergetic 14 MeV neutron beam. The device simulated was a 35 µm × 35 µm × 21 µm silicon block with a 10 × 10 array of sensitive volumes, each having dimensions of 0.4 µm × 0.4 µm × 1 µm, spaced evenly by 1.3 µm. These sensitive volume dimensions and spacing are similar to those in 130 nm and 90 nm technology SRAMs as reported in [16] and [5]. The sensitive volume array is centered in the silicon block, with 10 µm spacing between the end of the array and the edge of the silicon to prevent edge effects. For both runs, 10^9 neutrons were simulated and were randomized at normal incidence over the surface of the silicon block. The amount of charge deposited in each sensitive volume from each incident neutron was recorded for post processing. Here an SEU is considered to occur if the deposited charge exceeds Q_{crit} in only one sensitive volume, and an MBU is considered to occur if the deposited charge exceeds Q_{crit} in two or more sensitive volumes for a single neutron strike.

Fig. 3 shows SEU cross section curves as a function of Q_{crit} for the simulated neutron spectra from WNR and the 14 MeV neutron beam. The simulations show that for $Q_{crit} < 20$ fC, the 14 MeV and WNR SEU cross sections are within a factor of two, in agreement with the data from [10]. However, for $Q_{crit} > 20$ fC, the 14 MeV neutron SEU cross section is significantly lower than the WNR spectra, and for $Q_{crit} > 40$ fC, the discrepancy is over an order of magnitude. These results suggest that a 14 MeV neutron beam can approximate SEU testing at a facility with a neutron spectrum for SRAMs with an adequately low Q_{crit}.

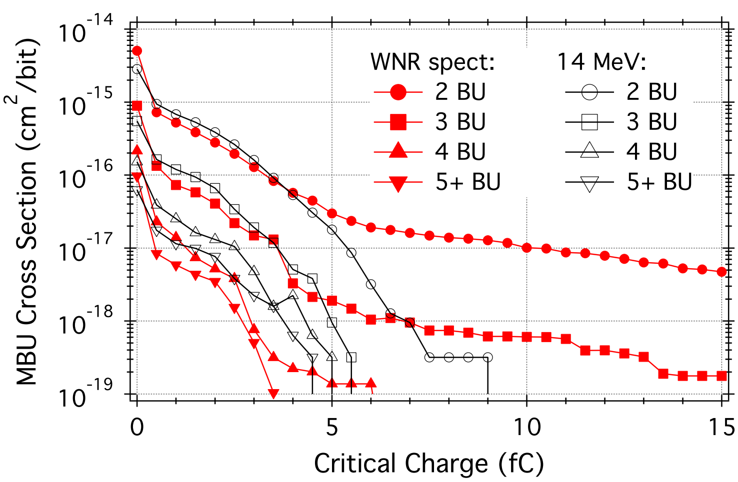

Fig. 4 Simulated MBU cross sections as a function of critical charge for two different neutron energies at normal incidence.

For the MBU analysis of this structure, the cross sections were generated for 2, 3, 4, and 5+ bits upset (BU) as shown in Fig. 4. Overall, the predicted MBU cross section of the 14 MeV neutrons is within a factor of two of the WNR MBU cross section for $Q_{crit} < 3$ fC. However, for $Q_{crit} > 5$ fC, the MBU cross section of the 14 MeV neutrons is significantly lower than the WNR MBU cross section. This is because the secondary products from the 14 MeV neutrons are unable to deposit large amounts of charge over multiple bits. A quick analysis of the mechanism of the 14 MeV neutron MBU events reveals that they are largely caused by secondary alpha particles, from neutron-silicon inelastic collisions, which have a sufficient range to deposit femtocoulombs of charge in multiple bits. Since the maximum range of the silicon recoils from collisions with 14 MeV neutrons is less than 2 μm, they are unable to cause more than the occasional 2 BU event. Meanwhile, the high-energy neutrons from the WNR spectrum are able to produce silicon recoils with a range of several microns, and these recoils can cause high-Q_{crit} MBU events.

CONCLUSIONS

Experimental data presented here show that the presence of high-Z materials, like tungsten, can increase the SEU cross section for high Q_{crit} devices exposed to the terrestrial neutron environment because of the presence of high energy (>100 MeV) neutrons. Simulations show that for devices with a low Q_{crit}, a monoenergetic 14 MeV neutron beam can be used to estimate the SEU and MBU response to the terrestrial neutron environment, in agreement with [10]. However, the time-of-flight data and simulations presented here demonstrate that 14 MeV neutrons do not produce highly ionizing secondary particles, and thus cannot estimate the SEE response that a device with a high Q_{crit} will have in a terrestrial neutron environment, especially if tungsten is present near the sensitive volumes.

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