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Impact of Heavy Ion Energy and Nuclear Interactions on Single-Event Upset and Latchup in Integrated Circuits

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35-Word Abstract

The impact of heavy ion energy on the SEU and SEL response of commercial and radiation-hardened CMOS ICs is explored. The role of nuclear interactions and implications for hardness assurance and rate prediction are discussed.

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***Abstract*— The impact of heavy ion energy on the SEU and SEL response of commercial and radiation-hardened CMOS ICs is explored. The role of nuclear interactions and implications for hardness assurance and rate prediction are discussed.**

I. Introduction

RECENTLY, the role of nuclear interactions between high-energy ions and the materials in integrated circuits has received growing attention [1]–[3]. Typically, single-event upsets (SEUs) due to heavy ions are assumed to result from direct ionization caused by the release of electron-hole pairs along the path of an energetic charged particle incident on a device or IC. This is in contrast to proton and neutron SEU, where upsets are attributed to ionization by reaction products (e.g., spallation products and Si recoils) produced indirectly by nuclear interactions between an incident energetic particle and the materials in the IC. Koga suggested [1] that ions with very low LET ($<$ 1 MeV-cm^2/mg) might cause SEUs due to nuclear interactions that would be observable if the threshold LET for direct ionization-induced upsets was high (for example, as would be the case for SEU-hardened ICs). More recently, Warren, *et al.'s* experiments [2] on hardened 4-Mbit SRAMs seem to support this mechanism, with high-energy heavy ion SEU observed for LETs less than 2 MeV-cm^2/mg in an SRAM that appears to have a direct ionization upset threshold LET of greater than 20 MeV-cm^2/mg. Unfortunately, no equivalent low-energy data was presented to more conclusively prove that high-energy nuclear interactions were the mechanism for the observed results. In [4], we showed data taken at high- and low-energy heavy ion accelerators indicating that in some cases significant differences exist between SEU cross sections as a function of ion energy. While it was conjectured that these differences were due to the effects of nuclear interactions as described in [2], [3], the limited data that were available did not overwhelmingly support this hypothesis. In addition, it was shown that it is critical to perform SEE measurements below the direct ionization threshold at sufficiently high ion fluence to ensure that any differences due to ion energy effects can be resolved.

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In this summary, we describe new high and low-energy measurements of SEE in a variety of ICs from multiple manufacturers. ICs tested include commercial and radiation-hardened devices fabricated in bulk silicon and silicon-on-insulator technologies. The ICs studied here are primarily CMOS SRAMs but also include an analog-to-digital converter (ADC). While previous studies have focused on the impact of ion energy and the role of nuclear interactions on SEU response, in this summary we also explore the importance of ion energy on single-event latchup (SEL) response. Finally, implications for hardness assurance and rate prediction are discussed.

II. Experimental Details

Low-energy heavy ion irradiations were performed using the tandem Van de Graaff at Brookhaven National Laboratory (BNL), while high-energy heavy ion irradiations were performed at the Texas A&M University (TAMU) heavy ion cyclotron. Beams at BNL ranged in energy from 2-8 MeV/amu, while the high-energy beams at TAMU ranged from 13-40 MeV/amu. A complete table of the heavy ion beams used will be included in the final paper. Static SEU cross sections in SRAMs were measured using either a Hewlett Packard HP82000 digital ASIC tester or a TEMIC dedicated portable memory tester. A checkerboard pattern was loaded into the memory, the SRAM was exposed to heavy ions, and following the irradiation the memory was read and the number of errors counted. In all cases the same test setup was used for the same parts for both low- and high-energy ions to eliminate any variation in cross section due to test setup. Single-event latchup cross sections were measured using a computer-controlled power supply. The IC was allowed to power up into its preferred state (i.e., no specific pattern was written), the IC was exposed to heavy ions, and during the irradiation the power supply current was monitored. If the current exceeded a predetermined value (set just above the static current), a latchup was counted and the IC power supply was cycled. Experiments were performed using ions at both normal and angled incidence; data from angled irradiations are plotted using effective LET as defined by the standard inverse cosine law. The implications of this will be discussed below. Throughout this summary the term "low-energy" will be used to refer to BNL ions with energy less than 10 MeV/amu, while TAMU ions with energy greater than 10 MeV/amu will be referred to as "high-energy".

Six different device types were studied in this work, two for SEU and four for SEL. For SEU, 256-Kbit fully depleted 0.2-μm SOI SRAMs from Mitsubishi Heavy Industries (MHI) with body ties were tested [5], as well as a 256-Kbit 0.5-μm bulk SRAM fabricated at Sandia National Laboratories [6]. For SEL, three commercial SRAMs and a commercial ADC were tested. Table 1 lists more detailed information on the device types and bias conditions used. For SEU, all tests were performed at the minimum rated bias voltage, while SEL tests were performed at the maximum rated bias voltage and a temperature of 85°C. All parts were delidded for experiments at both heavy ion test facilities.

TABLE I
DEVICES USED IN THIS WORK.

Study	Vendor	Part No.	Size (bits)	Bias Voltage (V)
SEU	MHI	N/A	256K	1.8
SEU	Sandia	EC256K	256K	4.5
SEL	ST Microelectronics	M68AW511	4M	3.6
SEL	Samsung	K6X4008C1F	4M	5.5
SEL	Vendor A	N/A	1M	1.6
SEL	Analog Devices	AD7827BR	N/A	5.5

III. Single-Event Upset Experimental Results

The 256-Kbit radiation-hardened Sandia SRAM was designed as a special test IC to have regions of differing SEU sensitivity. The SRAM is split into 16 blocks (16K each) with different-sized feedback resistors used for SEU hardening. Blocks 8-15 of the SRAM comprise 128K of the SRAM and have the nominal (largest) size feedback resistors used in the technology, while the other eight 16K blocks have resistors ranging down to no feedback resistance in Block 0. Figure 1 shows the measured low-energy (BNL) upset cross section curves for the 256K Sandia SRAM, indicating that the SEU threshold LET varies between the blocks from less than 10 to about 30 MeV-cm^2/mg (the nominal design target). This range of direct ionization threshold LET allows us to examine the effects of ion energy on SRAM blocks that have differing upset thresholds but that are otherwise identical in layout.

Figure 2 shows the high and low-energy SEU cross sections for Block 6 of the Sandia 256K SRAM. Downward pointing arrows indicate that the data point is an upper bound and that no upsets (or latchups in the case of SEL data) occurred at this point. Data for Blocks 8-15 were previously analyzed and included in [4], but the characteristics of Block 6 are similar. First, note that the high and low-energy data converge at high LET. In this range direct ionization dominates and is expected to be energy independent [7]. Note also that a low-energy data point taken at TAMU by degrading the high-energy beam (green upside-down triangle) lies exactly on the BNL data. However, between LET's from 12 to 20 MeV-cm^2/mg, the TAMU data lie significantly above the BNL data.

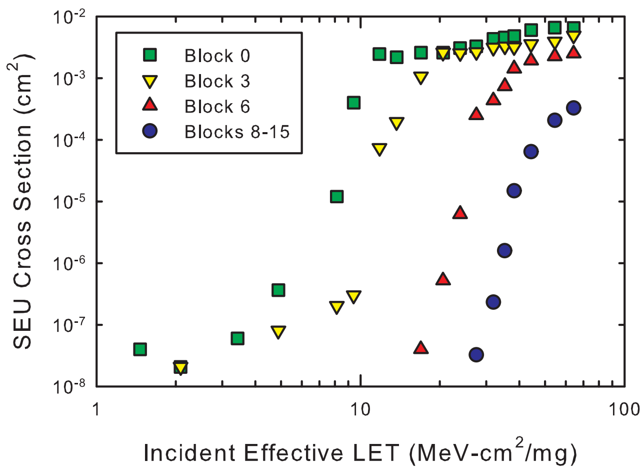

Fig. 1. Measured SEU cross section for Sandia 256-Kbit SRAMs taken with low-energy (BNL) heavy ions. Different blocks of the SRAM have different feedback resistors for SEU hardening. Data for blocks 8-15 have been normalized to a single 16K block size.

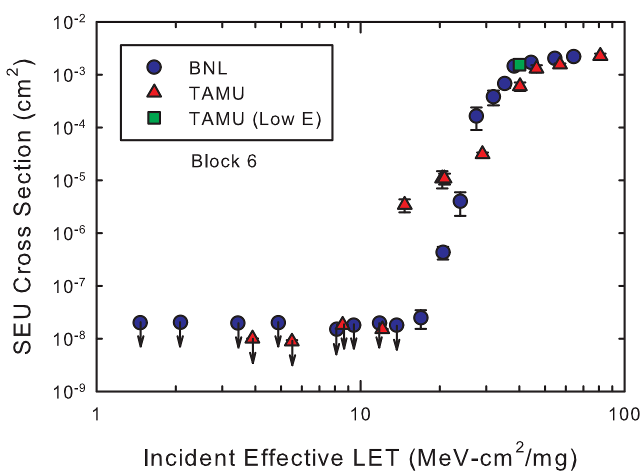

Fig. 2. Measured SEU cross section for Block 6 of the Sandia 256K SRAM taken with low-energy (BNL) and high-energy (TAMU) heavy ions.

At an LET of 15 MeV-cm^2/mg, the TAMU cross section is nearly 3 orders of magnitude greater than the cross section measured at BNL. For both facilities, no incident particle with LET less than 10 MeV-cm^2/mg ever causes an upset, even after irradiation to fluences in excess of 10^8 ions/cm^2. If we assume for the moment that the BNL data give a true indication that the threshold LET for direct ionization-induced SEU is $\sim$20 MeV-cm^2/mg, this indicates that incident particles with LET below 10 MeV-cm^2/mg at these energies (whether at BNL or TAMU) are unable to produce secondary particles (via nuclear interactions) with LET greater than 20 MeV-cm^2/mg.

The high and low-energy SEU cross sections for Block 3 of the Sandia 256K SRAM are shown in Figure 3. Once again, at high LET all of the cross section data converge to a single curve. However, at lower LETs ($<$10 MeV-cm^2/mg) something interesting happens. Even at BNL, there is a "tail" in the cross section curve, with upsets occurring down to LETs of 1.5 MeV-cm^2/mg (albeit with very low cross section). At TAMU, this tail in the cross section curve is more than an order of magnitude higher. If we again assume that the "main" part of the BNL curve indicates a true threshold LET for

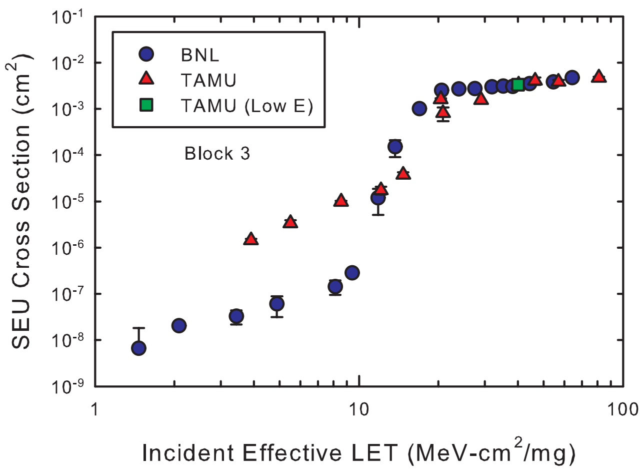

Fig. 3. Measured SEU cross section for Block 3 of the Sandia 256K SRAM taken with low-energy (BNL) and high-energy (TAMU) heavy ions.

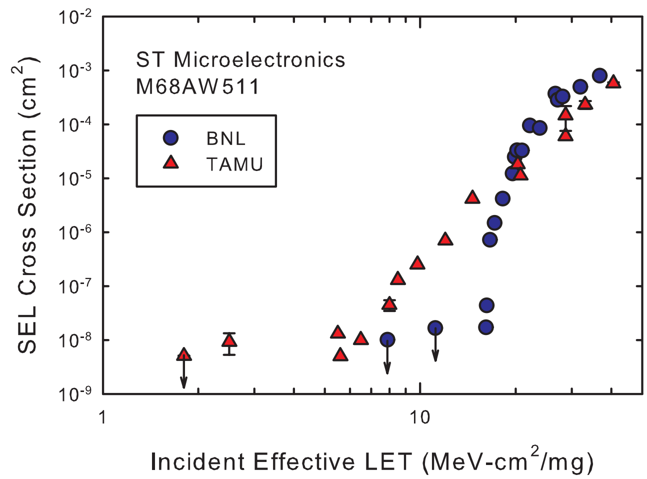

Fig. 4. Measured SEL cross section for 4-Mbit ST Microelectronics SRAMs taken with low-energy (BNL) and high-energy (TAMU) heavy ions.

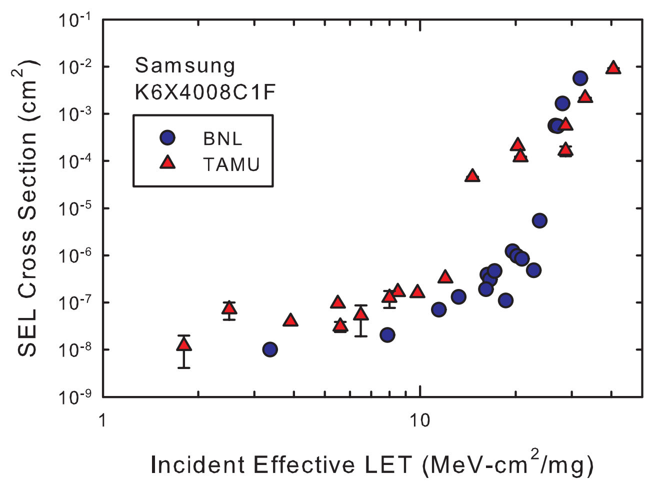

Fig. 5. Measured SEL cross section for 4-Mbit Samsung SRAMs taken with low-energy (BNL) and high-energy (TAMU) heavy ions.

direct ionization-induced upsets of ~10 MeV-cm^2/mg, these data suggest that both high and low-energy ions are capable of producing secondary particles above this threshold. For example, silicon recoil atoms have a maximum LET of about 15 MeV-cm^2/mg and would be able to cause upsets in this block of the SRAM.

Data for Block 0 (no feedback resistors) are similar to Block 3, with the exception that the tails in the cross section curve for both BNL and TAMU are nearly an order of magnitude higher in cross section, suggesting that even more secondary particles produced by nuclear interactions are able to exceed the direct ionization threshold LET (~8 MeV-cm^2/mg) for this block. In the full paper, we will present the data for this block of the Sandia SRAM, as well as high and low-energy data for the Mitsubishi 256K SOI SRAM.

IV. Single-Event Latchup Experimental Results

If heavy ions can cause nuclear reaction-induced SEU, it is reasonable to expect that the same mechanism could lead to SEL, especially in high-energy heavy ion environments. Such reactions have recently been proposed to cause SEL in high-energy proton environments [8]. Accordingly, we have performed high and low-energy heavy ion SEL testing on several commercial ICs known to exhibit latchup.

High and low-energy SEL cross sections for an ST Microelectronics 4-Mbit SRAM (M68AW511) are shown in Figure 4. The characteristics are remarkably similar to the SEU cross sections discussed up to this point. The high-energy SEL cross section curve shows latchup occurring at much lower LET values than the low-energy data. For example, the only LET at which latchup did not occur at TAMU was 1.8 MeV-cm^2/mg, while at BNL the same part was latchup-free at an LET of 11 MeV-cm^2/mg. At an LET of 15 MeV-cm^2/mg, the high-energy SEL cross section is nearly 3 orders of magnitude higher than at low energy. At high LET, the high-energy SEL curve falls somewhat below the low-energy curve; the reason for this discrepancy is currently unknown.

Figure 5 shows high and low-energy SEL cross sections for a Samsung K6X4008C1F 4-Mbit SRAM. While it is difficult to decipher much from this dataset, a couple of observations can be made. First, similar to the soft blocks of the Sandia 256K SRAM, there is a substantial tail in the SEL cross section data at both low and high energy. In fact, no LET at which any test was performed at either facility ever produced zero latchups. In the low-LET tail region, the high-energy data exhibit a higher SEL cross section than the low-energy data, but the difference is smaller than observed in Figure 3 for SEU in the Sandia SRAM. At intermediate LETs near 15 MeV-cm^2/mg, the largest difference in SEL cross section is observed, similar to the ST Microelectronics SRAM. Finally, it appears that at the highest LETs, the high-energy curve may once again fall below the low-energy curve, also similar to the ST Microelectronics SRAM. In the full paper, results will be shown for the Vendor A SRAMs and Analog Devices AD7827 ADC.

V. Discussion and Hardness Assurance Implications

The data of Figures 2 through 5 clearly show that significant differences can exist between SEU and SEL cross sections measured using low and high-energy heavy ions. These differences are observed near or below what appears to be the direct ionization threshold for upsets or latchup. At LETs beyond the direct ionization threshold LET, high and low-energy SEE data appear to be in better agreement, with the low-energy data being in some cases conservative, as previously observed [7]. Of course, for cases where low-energy ions have insufficient range to reach the entire sensitive volume(s), high-energy ions will show different results throughout the LET range.

Our results here are consistent with the mechanism of SEU or SEL caused by secondary particles that result from nuclear interactions within the IC [3]. While we cannot definitively rule out the possibility that ion track structure or unexpected design sensitivities could play a role in these results, it does not seem likely. The fact that Block 6 of the Sandia SRAM exhibits a hard cutoff to upsets below an incident LET of $\sim$15 MeV-cm^2/mg, while Block 3 exhibits continued upsets below an incident LET of 2 MeV-cm^2/mg is very suggestive of a nuclear interaction mechanism. Because the only difference between these two blocks of the SRAM is the feedback resistor size, we would expect both to have similar sensitive volumes and any unexpected design sensitivity to be highly unlikely. If this is true then the low-LET tail in the SEU response cannot be coming from some new upset region and is thus very likely to be due to secondary particles produced with LET greater than 10 MeV-cm^2/mg. Since high-energy ions will produce more nuclear interactions, the fact that the high-energy curve shows an even larger tail is also suggestive of an interaction-driven mechanism.

For very SEU-soft devices it has been shown that even if such effects exist, they will be difficult to detect because the direct ionization threshold LET is so low [4]. It might therefore be argued that this effect is important only for SEU-hardened ICs that have a relatively high direct ionization threshold LET. However, it is not unusual for commercial ICs that may be soft to SEU to have relatively high latchup threshold LETs [8]. For such ICs, this mechanism may be important for SEL even if it does not greatly affect SEU response. Even in hardened devices, SEE testing must be performed with very high fluences (we recommend $\geq 5\times10^7$ ions/cm^2) of heavy ions to observe this mechanism.

If the observed differences in high and low-energy SEE response are indeed due to secondary particles, our existing framework for understanding, analyzing, and predicting SEE phenomena must be significantly altered. Because upsets may be caused by secondary particles with higher LET than the primary incident ion, standard techniques for plotting event cross sections against the incident ion LET must be revisited. In addition, the concept of effective LET breaks down, since secondary particles don't necessarily follow an inverse cosine law based on the angle of incidence of the primary particle. This will require new methods of analyzing and plotting heavy ion data, for example as a function of energy, incident angle, and normally-incident LET rather than lumping all of these into a single parameter of effective LET. Finally, standard heavy ion error rate prediction tools typically depend on the validity of the effective LET concept and LET distribution functions based on direct ionization. Accurate error rate predictions for ICs with significant heavy ion nuclear interaction effects will require extensive experimental characterization at multiple energies as well as detailed nuclear physics calculations to determine secondary particle distributions [3]. Such calculations will also be needed to extrapolate results to the actual space environment, where particle energies can reach hundreds of GeV/amu (far above the "high-energy" range studied here). These calculations will require accurate descriptions of the materials present in ICs and their locations relative to SEU-sensitive volumes. These themes will be explored further in the full paper.

VI. Summary

We have studied the impact of heavy ion energy and the possible role of nuclear interactions on SEU and SEL in CMOS ICs. Above the threshold LET for direct ionization-induced SEE, little difference is observed in single-event upset and latchup cross sections measured using low *vs.* high energy heavy ions. However, below the threshold LET for direct ionization-induced upsets, we find significant differences between low- and high-energy heavy ion test results. The data suggest that secondary particles produced by nuclear interactions play a role in determining the SEU and SEL hardness of integrated circuits, especially at low LET. Although the cross sections for nuclear reaction-induced SEE from heavy ions are small, in such cases high-energy heavy ion testing may be required, depending on the overall error rate requirements of a given system. The presence of significant heavy ion nuclear interaction effects will challenge current methods for analyzing and predicting SEE phenomena.

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