Effects of Particle Energy on Proton-Induced Single-Event Latchup

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***Abstract*—The effect of proton energy on single-event latchup (SEL) in present-day SRAMs is investigated over a wide range of proton energies and temperature. SRAMs from five different vendors were irradiated at proton energies from 20 to 500 MeV and at temperatures of 25° and 85 °C. For the SRAMs and radiation conditions examined in this work, proton energy SEL thresholds varied from as low as 20 MeV to as high as 490 MeV. To gain insight into the observed effects, the heavy-ion SEL linear energy transfer (LET) thresholds of the SRAMs were measured and compared to high-energy transport calculations of proton interactions with different materials. For some SRAMs that showed proton-induced SEL, the heavy-ion SEL threshold LET was as high as 25 MeV-cm^2/mg. Proton interactions with Si cannot generate nuclear recoils with LETs this large. Our nuclear scattering calculations suggest that the nuclear recoils are generated by proton interactions with tungsten. Tungsten plugs are commonly used in most high-density ICs fabricated today, including SRAMs. These results demonstrate that for system applications where latchups cannot be tolerated, SEL hardness assurance testing should be performed at a proton energy at least as high as the highest proton energy present in the system environment. Moreover, the best procedure to ensure that ICs will be latchup free in proton environments may be to use a heavy-ion source with LETs $\geq$40 MeV-cm^2/mg.**

I. Introduction

ENERGETIC particles in space can degrade integrated circuit (IC) performance and potentially cause IC failure in space systems through several single-event effect mechanisms. One of the most problematic single-event effects is single-event latchup (SEL) [1]. When a latchup occurs, the latchup state can be cleared only by removing power from the device. SEL can also lead to destructive IC failure. As a result, many space systems cannot tolerate even a single SEL. To ensure part functionality and possibly system survivability, it is critical that hardness assurance tests for SEL be capable of accurately determining IC susceptibility to single-event latchup.

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Both protons and heavy ions can cause SEL in electronics in satellite systems. For some applications, electronics can be exposed to high fluxes of protons and the number of SEL events is dominated by proton strikes. To minimize test costs, devices are often screened for single-event hardness assurance using heavy-ion tests. If the LET threshold for SEL determined by heavy-ion tests is *sufficiently* high, proton testing is often not performed. What LET threshold constitutes sufficiently high is not well defined. In the past, a frequently used guideline is the maximum LET of nuclear recoils that can be produced by energetic proton interactions with silicon ($\sim$13 MeV-cm^2/mg [2]). As long as the LET threshold is above this value, proton testing may be postponed or cancelled. The validity of this assumption has not been fully investigated, especially for today's high-density ICs. To develop accurate hardness assurance SEL test guidelines, the correlation between heavy-ion and proton-induced SEL must be better understood.

It was recently shown that SEL testing at facilities with low maximum proton energies (<100 MeV) can significantly underestimate the probability for latchup and falsely lead to the conclusion that SEL-sensitive devices are latchup-free [3]. This preliminary work examined only a limited number of devices and all testing was performed at room temperature. However, it is well known that susceptibility to SEL can be greater at elevated temperatures [4], [5]. As a result, the effects of proton energy on SEL hardness need to be evaluated at elevated temperatures. Also, in [3] the mechanisms for the variation in SEL hardness between devices were not addressed. To develop reliable hardness assurance tests for space environments, it is essential that we fully understand the mechanisms for the effects of proton energy on SEL hardness.

In this work, we examine issues relevant to proton SEL hardness assurance testing of ICs. SRAMs from several different suppliers are irradiated at room and elevated temperature at proton energies from 20 to 500 MeV over a wide range of fluence levels. To help identify the mechanisms for the degradation in SEL hardness with proton energy, the latchup cross section versus linear energy transfer (LET) was characterized with heavy ions using a broadbeam heavy-ion source for some devices. The effective LETs of energetic nuclear recoils induced by high-energy proton collisions were calculated for a variety of materials common to present-day IC technologies using a modified version of the High-Energy Transport Code (HETC) [6]. These calculations are compared to the experimental results to elucidate the mechanisms for proton-induced SEL

TABLE I
DEVICES USED IN THIS WORK

Vendor	Size (Mbits)	Cell Design	Feature Size (μm)	Bias Voltage (V)
A	4	6T	0.25	3.6
B	4	4T	0.18	5.5
C	1	6T	0.16/0.14	3.3/2.0
D	4	unknown	unknown	5.5
E	4	unknown	unknown	3.6

in present-day ICs. Our data show a much larger variation in SEL cross section and proton energy threshold than previously observed [3]. Nuclear scattering cross section calculations suggest that materials common to present-day SRAMs can make devices more prone to proton-induced SEL. These results have significant implications for proton hardness assurance testing for space environments.

II. Experimental Details

Proton irradiations were performed at the TRIUMF Proton Irradiation Facility [7]. The proton energy was varied from 20 to 500 MeV. Energies from >70 to 105 MeV and <70 MeV were obtained by degrading 116 MeV and 70 MeV primary beams, respectively, using a variable thickness plastic plate. Protons with energies above 105 MeV were obtained by varying the primary beam energy of a second beamline capable of a maximum proton energy of 500 MeV. The proton fluence was measured using a calibrated ion chamber.

For latchup characterizations, SRAMs were irradiated in their preferred power-up logic state, i.e., they were not written with a specific pattern prior to exposure. The power supply current was continuously monitored during irradiation. When the power supply current increased to above a preset limit, a latchup was recorded, the power supply voltage was removed to clear the latchup state, the power supply voltage was reapplied, and the latchup test was continued. The preset limit was set to a current a few milliamps above the static current for the device. The latchup current was limited to 100 mA to minimize potentially destructive latchup effects. To clear latchup, the bias to the device was turned off for 0.5 s after a latchup was detected and then the bias was reapplied. For a given particle flux, this limits the maximum latchup rate that can be accurately measured. Because some SRAMs were exposed to high fluence levels and were repeatedly put into a latched state, the SEL cross sections of SRAMs were measured before and after repeated SEL characterizations. Within experimental uncertainty, the same SEL cross sections were measured before and after repeated characterization, suggesting that proton-induced displacement damage and total ionizing dose effects were negligible, and that there were no latent effects caused by repeated latchup testing [8].

Table I lists the devices used in this work. Given in the table are the memory size of the SRAM, cell design if known (four or six transistors), technology feature size, and the tested bias voltage. All SEL characterizations were performed under worst-case biasing conditions, i.e., maximum bias voltage. Note that vendor C SRAMs operate using dual external supply voltages, e.g., 3.3 V and 2.0 V.

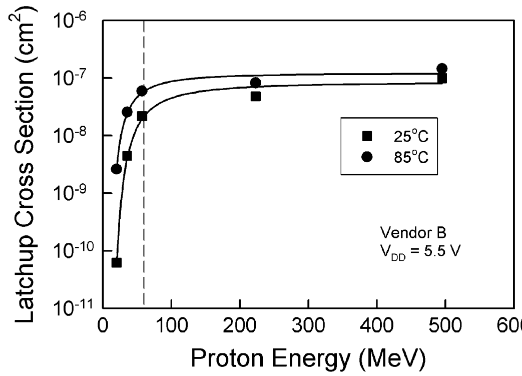

Fig. 1. Latchup cross section versus proton energy for SRAMs from vendor B measured at room temperature and at 85 °C.

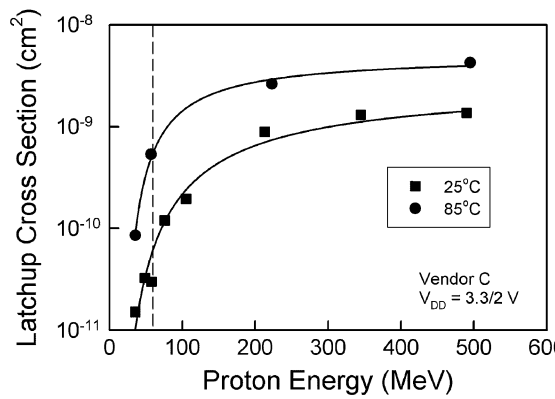

Fig. 2. Latchup cross section versus proton energy for SRAMs from vendor C measured at room temperature and at 85 °C.

III. Proton-Induced Latchup

A. Energy and Temperature Dependence

Based on room temperature measurements of the SEL cross section versus proton energy, it has been shown that low-energy proton (<100 MeV) measurements can significantly underestimate the SEL cross section and may lead to the false conclusion that SEL-sensitive SRAMs are latchup-free [3]. We first explore the effects of temperature on present-day ICs from two different technologies with soft to moderate proton-induced SEL hardness. Figs. 1 and 2 are plots of the latchup cross section for SRAMs from vendors B and C, respectively, measured at 25 °C (room temperature) and at 85 °C. Vendor B SRAMs have a very high SEL saturation cross section with a low proton energy latchup threshold (soft), while vendor C SRAMs have a much lower SEL saturation cross section (moderately hard). For both SRAMs, temperature does not appear to have a large effect on the proton latchup threshold energy (the lowest energy where latchup was detected). The measured thresholds are approximately 20 and 35 MeV for vendor B and C SRAMs, respectively, at both 25 °C and 85 °C. Within experimental uncertainty, the saturation (highest energy) cross section measured at 25 °C and 85 °C are equal for vendor B SRAMs. At lower energies, the cross section varied more with measurement temperature. For measurements taken at 85 °C, the SEL cross section is roughly the same for all energies above ~60 MeV (noted by the dashed line in the figure). Hence, as long as the proton energy is

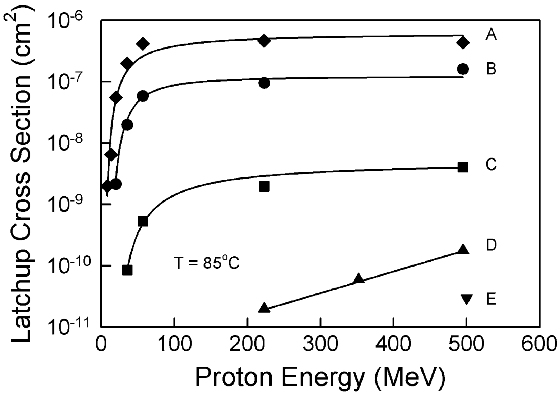

Fig. 3. Latchup cross section versus proton energy for four different technologies. SEL measurements were taken at a temperature of 85 °C.

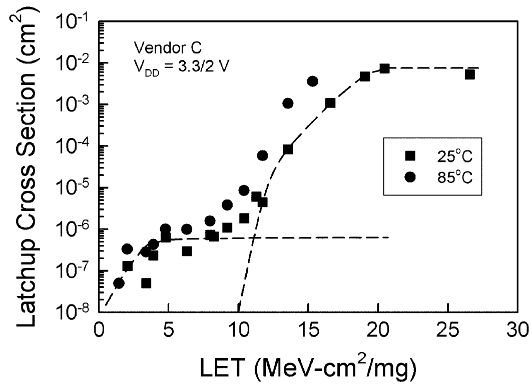

Fig. 4. Heavy-ion latchup cross section versus LET for SRAMs from vendor C measured at room temperature and 85 °C.

above ~60 MeV, proton energy and temperature have little effect on the measured probability for latchup for these SRAMs. For vendor C SRAMs, the SEL cross section is much higher at 85 °C than at 25 °C. However, at 25 °C the cross section at an energy of 500 MeV is 40 times more than it is at 60 MeV, while at 85 °C the cross section at an energy of 500 MeV is only about seven times more than it is at 60 MeV. Thus, for vendor C SRAMs, proton energy still has some effect on SEL cross section when measured at elevated temperature, but this effect is much less than at room temperature.

The above results show examples of soft and moderately SEL-hard technologies where the requirement for testing at very high proton energies is lessened when measured at elevated temperature. However, this is not always the case. Fig. 3 is a plot of the SEL cross section for vendor A, D, and E SRAMs measured at 85 °C. For comparison, the SEL cross sections for vendor B and C SRAMs are also plotted. Similar to vendor B SRAMs, vendor A SRAMs have a high SEL cross section and low threshold energy and there is almost no difference in the measured cross section for proton energies greater than ~60 MeV. Vendor D and E SRAMs are much harder than vendor A, B, or C SRAMs. In fact, no latchups were detected at 25 °C for vendor D and E SRAMs for any proton energy. At 85 °C, the lowest energy at which latchups were detected for vendor D SRAMs was 223 MeV, while for vendor E SRAMs, latchups were only detected at 490 MeV, the highest energy examined. In addition to a significantly higher proton energy threshold for latchup for vendor D and E SRAMs, the latchup cross sections were very low. Unlike the results of Figs. 1 and 2 for vendor B and C SRAMs, proton energy has a substantial effect on the probability for detecting latchup at elevated temperature. These results clearly show the importance of testing using a high-energy proton source. *Even testing at a facility with a maximum energy of 200 MeV would probably have falsely concluded that vendor D and E SRAMs were latchup-free.* The above results show that the worst-case temperature for SEL testing of present-day SRAMs is still maximum temperature [4], [5]. They also show that for systems where latchups cannot be tolerated, latchup testing should be performed using protons with energies at least equal to the maximum proton energy of the system environment. Because of practical issues regarding the availability of high-energy proton sources, it is imperative to investigate alternative hardness assurance test methodologies, as discussed below.

The maximum trapped proton energy in the Earth's radiation belts is around 400 MeV [9]. Because of the very high proton-energy threshold measured for vendor E SRAMs, we would not expect trapped protons to cause latchup in these SRAMs. However, it is possible that the energy dependence for latchup in vendor E SRAMs is similar to the energy dependence of vendor D SRAMs, but with a lower cross section. If vendor E SRAMs were irradiated to higher fluence levels than in Fig. 3, it is conceivable that latchups could be detected at lower proton energies (e.g., those present in the Earth's radiation belts). Although the proton fluence levels required to observe latchup would be much higher than obtainable in most systems, if many of these SRAMs were used in a system, in aggregate, the total cross section would be much higher and could result in realistic latchup probabilities for some space environments [10]. Conclusively excluding the possibility of latchup in such systems would require irradiating SRAMs to still higher fluence levels, probably necessitating the characterization of many SRAMs to avoid total dose damage of individual SRAMs. However, if we could gain a better understanding of the mechanisms causing the differences in cross section with energy for the different SRAMs, it might be possible to develop more reliable (and more practical) hardness assurance test guidelines for SEL.

B. Comparison to Heavy-Ion SEL

To obtain insight into the mechanisms for the differences in proton-induced SEL thresholds and cross sections for the different SRAMs shown in Fig. 3, we measured the heavy-ion-induced SEL cross sections for some of these SRAMs and performed nuclear scattering cross section calculations for proton interactions with materials common in present-day IC technologies. We first explore the effect of temperature on the heavy-ion SEL results for vendor C SRAMs. Fig. 4 is a plot of the SEL cross sections versus LET (charge deposited per unit depth) for vendor C SRAMs measured at 25 °C and 85 °C. The data suggest two different mechanisms may be contributing to latchup in these SRAMs. Fig. 4 shows a bimodal increase in SEL cross section with LET. For low LETs ($<$10 MeV-cm^2/mg), the SEL cross section is around 6×10^{-7} cm^2. For higher LETs ($>$10 MeV-cm^2/mg), the SEL cross section increases by more than

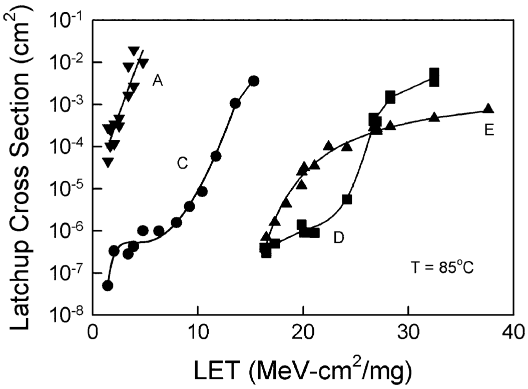

Fig. 5. Heavy-ion latchup cross section versus LET for SRAMs from vendors A, C, D, and E measured at 85 °C.

four orders of magnitude to nearly 10^{-2} cm^2. The threshold LET for the large increase in SEL cross section is between 10–15 MeV-cm^2/mg at 25 °C. The threshold LET for the large increase in cross section decreases slightly as the temperature is increased to 85 °C. This small decrease in threshold LET at high temperature for the large increase in cross section appears to be responsible for the major effect of temperature on the proton SEL cross section for vendor C SRAMs (Fig. 2). The small shift observed with temperature results in a ten times increase in cross section for the heavy-ion data and appears to correlate with the increase in proton response of this device with temperature.

The heavy-ion SEL cross sections for vendor A, C, D, and E SRAMs measured at 85 °C are shown in Fig. 5. Note that the ion-beam flux could not be sufficiently lowered to accurately measure the saturated SEL cross sections for vendor A, C, and D SRAMs at 85 °C. The SEL threshold LETs for the different SRAMs vary considerably. Defining the SEL threshold LET as the LET where latchups are first detected, the SEL threshold LET for vendor A and C SRAMs is $\sim$1.5 MeV-cm^2/mg and the threshold LET for vendor D and E SRAMs is $\sim$16.3 MeV-cm^2/mg. If one instead defines the SEL threshold LET as the LET where the SEL cross section is one percent of the maximum saturated SEL cross section, the SEL threshold LETs for vendor A, C, D, and E SRAMs are approximately 1.6, 11, 25, and 20 MeV-cm^2/mg, respectively. These results show that the SEL threshold LET is strongly technology dependent. The specific technology parameters leading to the variation in SEL threshold LETs were not studied in this work. Past work has shown that technology parameters such as substrate type and design layout rules play important roles in latchup sensitivity [1]. What is pertinent here is that these results show that to observe proton-induced latchup in vendor D and E SRAMs, the nuclear recoils generated by proton interactions must have very high LETs.

The LET of protons (ranging from 0.035 to 0.002 MeV-cm^2/mg for 10 to 500 MeV protons in Si) is too low to deposit sufficient charge within the sensitive volume to directly cause single-event effects in most present-day IC technologies. Instead, protons (and neutrons) induce single-event effects by generating secondary particles with much higher LETs (e.g., alpha particles and heavy ions) through nonelastic and elastic collisions with the device materials. Based on the analysis of Hiemstra and Blackmore [2], as low-energy protons (e.g., 50 MeV) collide with low Z materials like Si, the nuclear recoils generated will have LETs less than $\sim$11 MeV-cm^2/mg (the maximum LET is determined primarily by the LET of Si nuclear recoils). For protons with energies above 50 MeV, the maximum LET of the nuclear recoils increases only slightly. For example, for 500 MeV protons, the nuclear recoils can have LETs up to $\sim$13 MeV-cm^2/mg. The maximum LET of nuclear recoils generated by proton interactions with Si is considerably higher than the LET threshold for vendor A SRAMs. Hence, the heavy-ion SEL data of Fig. 5 for vendor A suggest that proton-induced SEL in these SRAMs can be accounted for by proton interactions with Si. (Proton interactions with other materials, including high-Z materials as discussed below, could also be contributing to SEL in vendor A SRAMs.) It is interesting to note that the SEL cross section for vendor A and B SRAMs saturates at a proton energy of roughly 50 MeV, which coincides with the proton energy where the increase in LET of the nuclear recoils saturates. At least some of the observed proton-induced SEL for vendor C SRAMs can also be accounted for by proton interactions with Si (the low saturation cross section region). However, the LET where the SEL cross section saturates in the high cross section region is well above that for nuclear recoils produced by proton interactions with Si. For vendor D and E SRAMs, the SEL threshold LETs ($>$16 MeV-cm^2/mg) are considerably above the maximum LET of nuclear recoils generated by proton interactions with Si. Therefore, for vendor D and E SRAMs, and probably also for vendor C SRAMs, the nuclear recoils must be generated by a mechanism other than proton interactions with Si.

C. Nuclear Scattering Calculations

To determine possible mechanisms for the proton-induced latchup results of vendor D and E SRAMs, nuclear scattering cross section calculations were performed for three high-Z materials (Cu, Ti, and W) common in many present-day SRAMs. Almost all present-day high-density ICs, including SRAMs, use W plugs and some advanced ICs use Cu metallization to improve circuit speed. Calculations were also performed for O and Si for completeness. Simulations of proton interactions with the different materials were performed using a modified version of the High Energy Transport Code (HETC). The modified code is referred to as the Bruyères-le-Châtel Intranuclear Cascade (BRIC). BRIC is an improved version of the HETC code and can calculate cascade, fragmentation, evaporation, and fission reactions using Monte Carlo techniques [6]. For the first steps of the reaction, the intranuclear cascade model is used to calculate the interaction of the incident proton with the target nucleus. The final steps of the reaction are described by an evaporation process by calculating the de-excitation of the nucleus, from one nuclear level to a lower one. We calculated the reaction process only at the atomic level, assuming very thin targets to avoid transport issues. 500 000 cascades were followed for each proton energy producing secondary ions from $Z = 1$ to $Z = 76$ for the heaviest target simulated (i.e., W). The LET spectra of secondary ions with $Z \geq 2$ are calculated using the TRIM tables of Ziegler [11].

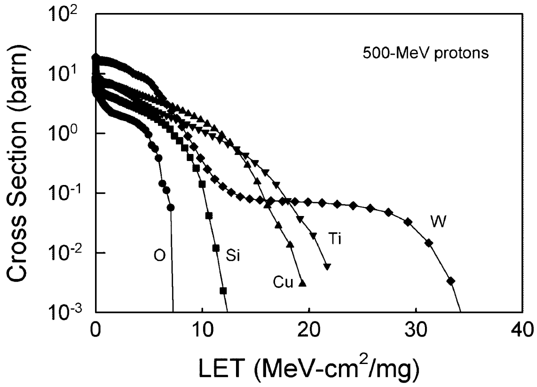

Fig. 6. Calculated cumulative production cross section versus LET for O, Si, Cu, Ti, and W for 500 MeV protons.

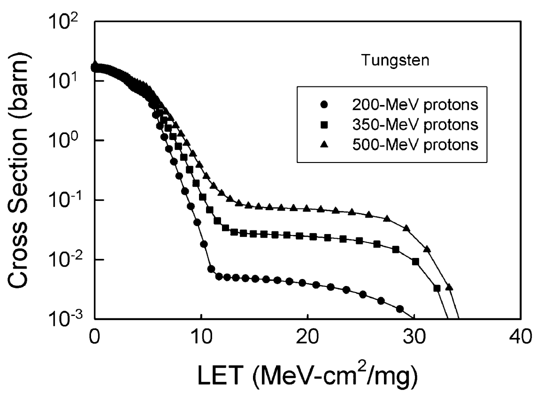

Fig. 7. Calculated cumulative production cross section versus LET for W for 200 to 500 MeV protons.

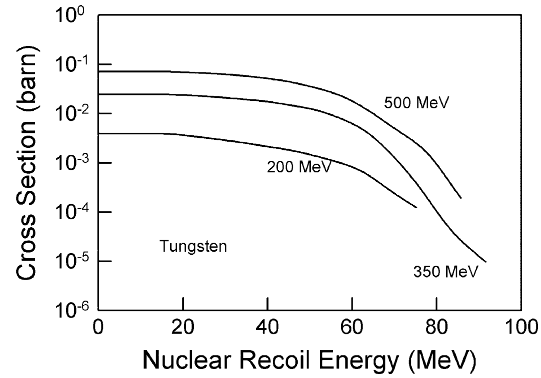

Fig. 8. Calculated cumulative production cross section for proton interactions with W versus nuclear recoil energy for nuclear recoils with LETs $>$ 25 MeV-cm^2/mg.

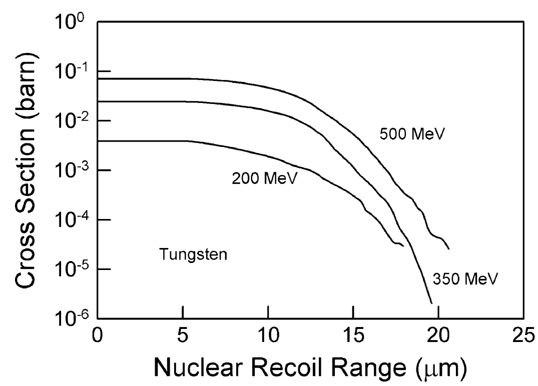

Fig. 9. Calculated cumulative production cross section for proton interactions with W versus the range of nuclear recoils for nuclear recoils with LETs $>$ 25 MeV-cm^2/mg.

Fig. 6 is a plot of the calculated cumulative production cross section versus LET for 500 MeV proton collisions with O, Si, Cu, Ti, and W. The total number of heavy ions/cm^3 can be determined by multiplying the cross-section (in units of barn; 1 barn $= 1 \times 10^{-24}$ cm^2) by the proton fluence and by the number of atoms/cm^3. The calculated production cross section is consistent with the calculations of Hiemstra and Blackmore [2]. Examining the cross sections for the different materials, it is immediately evident that proton interactions with high-Z materials can lead to nuclear recoils with much higher LETs than proton interactions with O or Si.

The dependence of the calculated cumulative production cross section on proton energy is given in Fig. 7 for proton interactions with W. The cumulative production cross sections are shown for proton energies of 200, 350, and 500 MeV. In Fig. 7, we see that the LET of the nuclear recoils for proton collisions with W can be very high. The maximum LET for proton collisions with W is $\sim$30 MeV-cm^2/mg for 200 MeV protons and $\sim$34 MeV-cm^2/mg for 500 MeV protons. The hump in the cross section data for W leading to the high LET values is not due to W recoils. Instead, high energy proton collisions with W initiate fission reactions producing two very energetic heavy ions. Not only does the maximum LET produced by the nuclear recoils increase with proton energy, in addition, the cross section increases with proton energy (i.e., the probability of initiating the fission of a W nucleus increases with proton energy).

Proton interactions with W can generate numerous types of nuclear recoils. Particles generated that have LETs $>$ 25 MeV-cm^2/mg range from K to Xe (Z $=$19 to 54) for 200 MeV protons, from K to Ba (Z $=$19 to 56) for 350-MeV protons, and from K to Pr (Z $=$19 to 59) for 500 MeV protons. Most of the particles produced by fission reactions have a Z roughly equal to Z(W)$/2$, or $\sim$37 (e.g., Rb). The nuclear recoils can have relatively high energies. Fig. 8 is a plot of the calculated cumulative production cross section versus nuclear recoil energy for 200, 350, and 500 MeV proton interactions with W. For 350 and 500 MeV protons, nuclear recoils can have energies as high as 85 MeV. As the proton energy increases, the cumulative cross section increases (for a given nuclear recoil energy) consistent with the calculations of Fig. 7. These energetic nuclear recoils can have ranges in Si on the order of several to many microns, sufficient to trigger latchup in present-day ICs. Fig. 9 is a plot of the cumulative production cross section versus the range of the nuclear recoils for 200, 350, and 500 MeV protons. The cumulative production cross section for nuclear recoils with a range of 10 μm is only about 51%, 38%, and 34% lower than the cumulative cross section for nuclear recoils with a range of 1 μm for 200, 350, and 500 MeV proton interactions with W, respectively. Destructive physical analysis (DPA) was performed on some of the SRAMs examined in this work. Cross sections of devices show that the drain junction depths are of the order of 0.25 μm and the well depths are of the order of 1 μm. These depths are typical of high-density ICs fabricated today. Hence, the range of nuclear recoils produced by energetic protons with W can be significantly greater than the junction depths in high-density ICs and is sufficient to trigger latchup in high-density ICs.

Considering the widespread use of W in present-day high-density ICs and the high LET values of the secondary ions generated by proton collisions with W, nuclear recoils produced by proton interactions with W could be a major source of latchups in vendor D and E SRAMs. Unfortunately, DPAs performed on these SRAMs did not include material analysis. However, DPA cross sections did show that intermediate dielectric layers were smoothed by chemical mechanical polishing (CMP) and that metal plugs were present. The use of W is the industry standard for high-density ICs for metal plugs used in conjunction with CMP [12]. Hence, it is very likely that these SRAMs were fabricated using W plugs. Because of the small volume of W in ICs compared to Si, the nuclear scattering cross section, and hence the SEL cross section, is expected to be much lower (e.g., vendor D and E SRAMs) than for protons colliding with Si (e.g., vendor A and B SRAMs). Further, these nuclear scattering calculations indicate that high-energy proton interactions with the high-Z materials used in present-day high-density ICs can generate nuclear recoils with much higher LETs than for older technologies without such high-Z materials.

The SEL cross section versus proton energy was calculated for proton interactions with W from the calculated cumulative production cross section to further confirm whether proton interactions with W could lead to the proton energy dependence for SEL observed in vendor D SRAMs. The volume of W material close to the sensitive regions was taken from reverse engineering evaluations of other similar SRAMs (these evaluations are not available for vendor D SRAMs). For the evaluated SRAMs, the dimensions of the W pads connecting source/drain regions to metal layers was approximately $0.1 \times 0.1 \times 1$ μm^3. Therefore, for a 4 Mbit (6T) SRAM, the W volume is close to 5×10^{-7} cm^3. Based on the data of Fig. 5, a practical heavy-ion SEL threshold LET for vendor D SRAMs is 25 MeV-cm^2/mg (the LET value where the SEL cross section is one percent of the saturated cross section). Using these assumptions and our nuclear scattering calculation results, the calculated cross section is given in Fig. 10. Plotted are the calculated and measured SEL cross sections for vendor D SRAMs for proton energies from 200 to 500 MeV. The calculated SEL cross section can be adjusted to better match the measured SEL cross section, if we assume that only one out of ten *generated* nuclear recoils can cause a latchup. This assumption is reasonable considering the fact that secondary ions are generated in all directions from the W pads and only a small fraction of the secondary ions will be in a direction that can cause latchup. The adjusted calculation is also shown in Fig. 10. The adjusted calculation agrees remarkably well with the measured cross section. While further study is required to remove the assumptions built into these calculations, the key results of this comparison are that the calculated cross sections (both the adjusted and nonadjusted cross sections) have approximately the same proton energy dependence as the measured cross section, and are of the right order of magnitude to explain the observed proton SEL cross sections. Therefore, these results are consistent with the assertion that high-energy proton-induced latchups for vendor D SRAMs are due to proton interactions with W.

High LET nuclear recoils can be generated by proton interactions with other high-Z materials, as shown in Figs. 11 and 12. The maximum LET for proton collisions with Cu is $\sim$19 MeV-cm^2/mg for 200 MeV protons and $\sim$21.6 MeV-cm^2/mg for 500 MeV protons. The maximum LET for proton collisions with Ti is $\sim$17 MeV-cm^2/mg for 200 MeV

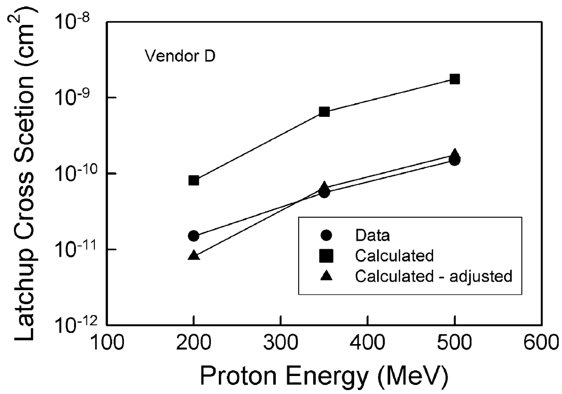

Fig. 10. Comparison of the measured SEL cross section for vendor D SRAMs to the calculated SEL cross section using the simulations results of proton interactions with W. Two calculated curves are shown. The calculated curve assumes that every generated nuclear recoil leads to a latchup. The calculated-adjusted curve assumes that only one out of ten generated nuclear recoils leads to a latchup.

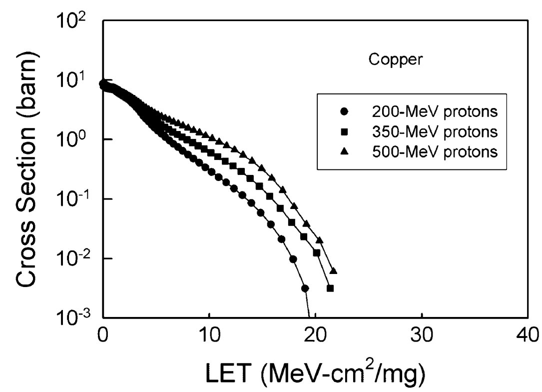

Fig. 11. Calculated cumulative production cross section versus LET for Cu for 200 to 500 MeV protons.

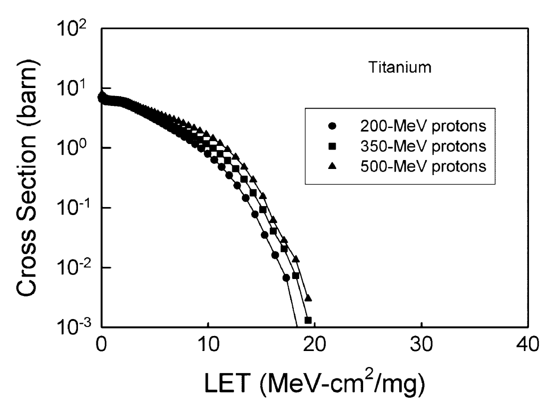

Fig. 12. Calculated cumulative production cross section versus LET for Ti for 200 to 500 MeV protons.

protons and $\sim$19.4 MeV-cm^2/mg for 500 MeV protons. The maximum LETs for Cu and Ti correspond to low-energy Cu and Ti recoils, respectively. Because the maximum LETs of the nuclear recoils generated by proton interactions with Cu and Ti are not significantly more than the LET thresholds of vendor D and E SRAMs, the number of nuclear recoils with sufficient LET to cause latchup in these SRAMs is small (as determined from the cumulative production cross section). The maximum LET of nuclear recoils generated by proton interactions with W is much larger than the LET thresholds of vendor D and E SRAMs and hence, proton interactions with W will generate significantly more nuclear recoils sufficient to cause latchup than for proton interactions with Cu or Ti. As a result, nuclear recoils generated by proton interactions with W are more likely the primary contributors to single-event latchups in these SRAMs. However, many manufacturers of advanced ICs have replaced Al metallization with Cu metallization for improved speed, and the use of Cu metallization is becoming more prevalent in future technologies. Because of the large volume of metallization in circuits, the use of Cu metallization (and other high-Z materials) may tend to make future SRAM and other high-density ICs more sensitive to proton-induced SEL than older technologies. Many other high-Z materials are currently used or being considered for use in advanced technologies. These include cobalt (frequently used in place of titanium in silicides), hafnium (considered a front-runner in the search for alternative dielectrics), and heavy metals such as tantalum that are being considered for advanced dual metal-gate CMOS technologies [13]. As more of these materials become commonplace in tomorrow's technologies, single-event effects due to high-LET secondary particles may be of increasing importance.

D. Hardness Assurance Implications

System requirements often necessitate the characterization of both heavy-ion and proton SEL hardness. To save money, devices are frequently screened for single-event latchup first using heavy ions prior to proton testing. If devices are sufficiently insensitive to heavy ions, proton testing may not have to be performed. One question that is often asked is what minimum heavy-ion SEL threshold LET is required to ensure devices will not latchup in proton environments? A general rule-of-thumb that has often been used is that if the SEL threshold LET is above $\sim$15 MeV-cm^2/mg, then devices will not latchup in proton environments. This is based on the fact that the maximum LET for nuclear recoils generated by proton interactions with Si is $\sim$13 MeV-cm^2/mg. If the measured heavy-ion SEL threshold is above this value, proton SEL testing could be delayed or cancelled. The results of this work suggest that this rule-of-thumb may not be appropriate for high-density ICs (e.g., SRAMs). The maximum LET for nuclear recoils generated by proton interactions with W is closer to 34 MeV-cm^2/mg. In light of the fact that almost all high-density ICs incorporate W, a better rule-of-thumb for high-density ICs might be that if the SEL heavy-ion LET threshold is $\geq$40 MeV-cm^2/mg the devices will not latchup in proton environments. For simpler devices which may not use high-Z materials, the old rule-of-thumb may still be valid.

Of course, our results also indicate that proton-induced latchups due to high-LET secondary particles are rare events (i.e., have low cross sections), and therefore proton SEL hardness assurance test decisions should be made bearing overall system reliability requirements in mind. Hardness assurance decisions should take into account issues such as the flux of high-energy protons in the system environment and the probability of SEL that can be tolerated. For instance, if SEL events are only detected at proton energies above that of the maximum proton energy of the environment, a maximum SEL rate can be determined at the maximum energy of the environment (assuming one latchup). If this SEL rate is below the acceptable latchup rate no further testing would be warranted and the device can be considered to have passed SEL test requirements. In some cases, the maximum proton energy of the environment is above the maximum proton energy of readily available proton radiation sources. For example, the maximum proton energy of a proton radiation source could be 200 MeV, while the maximum proton energy of the environment could be 400 MeV. Even in this case, testing at 200 MeV could result in satisfactory estimates of SEL hardness in the environment. If no SEL events are detected at a proton energy of 200 MeV, one can determine a maximum SEL rate for proton energies up to 200 MeV by assuming one latchup at the maximum test fluence. For proton energies from 200 to 400 MeV, one could assume one latchup for every 10^4 protons/cm^2 and calculate a maximum SEL rate. (Based on a reasonable upper reaction rate for protons with standard IC materials.) If the number of protons in the environment with energies above 200 MeV is very small, this can still result in a very low SEL rate. If the combined SEL rate at 200 MeV and at energies between 200 and 400 MeV is below the acceptable latchup rate no further testing would be warranted and the device can be considered to have passed SEL test requirements.

Our results strongly suggest that proton SEL hardness assurance testing should be performed at the maximum proton energy of the system environment and maximum use temperature. For trapped protons in the Earth's radiation belts, the maximum proton energy is around 400 MeV. For other environments and other applications, the maximum proton energy could be even higher. For example, protons with much higher energies can be generated in high-energy colliders. This poses a serious hardness assurance problem because there are few proton facilities worldwide that can produce very high proton energies (i.e., 500 MeV). A second problem in hardness assurance testing is that the cross section of high-Z materials is small compared to that for Si. Because of the small cross section for even high-energy protons to create secondary particles with high LET it is possible that a part may not latchup at proton energies of 500 MeV during testing. Whether the upper bound on proton SEL rate that can be established is low enough for a given application will of course be system-dependent. Therefore, the best procedure to ensure devices are truly SEL-free may be to test them using broadbeam heavy-ion sources, where high-LET ions can be produced directly. For devices that show heavy-ion SEL threshold LETs between 10 and 40 MeV-cm^2/mg, further comprehensive testing in a high-energy proton environment may be necessary to determine the true proton-induced SEL sensitivity.

IV. Summary

We have found that the proton-energy threshold for SEL and the maximum SEL cross section can vary significantly between device technologies. In general, increasing the SEL characterization temperature increased the proton-induced SEL cross section. However, for some SRAMs, characterizing SEL hardness at elevated temperature decreased the difference in SEL cross section when measured at low and high proton energies. For other SRAMs, latchup was only detected at elevated temperature and at very high proton energies ($>$200 MeV). For one SRAM, latchups were only detected at a proton energy of 490 MeV. These results show that ideally proton-induced SEL hardness assurance testing should be performed at the maximum temperature and the maximum proton energy of the system environment. Combining measurements of the heavy-ion SEL threshold LET with proton nuclear scattering calculations, we determined that the cause of high proton energy SEL thresholds for some SRAMs was likely the generation of nuclear recoils with LETs up to 34 MeV-cm^2/mg by high-energy proton interactions with W. Tungsten is common to many present-day high-density ICs. These results suggest that the high-Z materials used in present-day high-density ICs may make them more sensitive to proton-induced latchup than older technologies. Because of the potentially low cross section of W and other high-Z materials in high-density ICs (compared to Si), the SEL cross section for high-density ICs can be very low, making hardness assurance for proton-induced latchup in such devices difficult. Thus, the optimum procedure to ensure devices are truly SEL-free in proton environments may be to test them using heavy ions with LETs $\geq$ 40 MeV-cm^2/mg.

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