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Hardness Assurance Testing for Proton Direct Ionization Effects

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***Abstract*—The potential for using the degraded beam of high-energy proton radiation sources for proton hardness assurance testing for ICs that are sensitive to proton direct ionization effects are explored.**

***Index Terms* - Hardness assurance testing, proton direct ionization effects, single-event upset**

I. Introduction

Historically, the linear energy transfer (LET) of protons has been too small to cause single-event effects (SEE) by direct ionization. Instead, protons induce SEEs by creating secondary particles through proton/material nuclear interactions. These secondary particles can have much higher LETs than the incident protons. As a result, high-energy proton radiation sources (>180 MeV) are often used for proton hardness assurance testing. The high proton energies of these sources are preferred for single-event latchup (SEL) testing for devices that contain overlayers with high-Z materials [1]. The proton energy can also be degraded to determine the single-event upset (SEU) cross section vs proton energy. If one assumes proton direct ionization effects are not important, almost all proton testing can be performed using a single high-energy proton facility.

However, it has been recently shown that proton direct ionization effects can lead to orders of magnitude increases in single-event upset cross section at very low proton energies (<2 MeV) in highly-scaled ICs [2]–[8]. For example, Figure 1 shows the SEU cross section vs proton energy for 45 and 65-nm IBM silicon-on-insulator (SOI) SRAMs. For both SRAMs, as the proton energy is decreased, there is a very large increase in SEU cross section due to proton direct ionization effects [4].

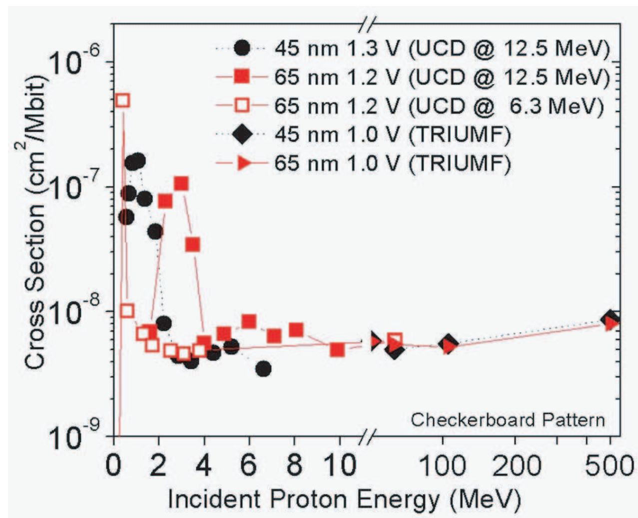

Fig. 1. SEU cross section vs proton energy for IBM 45-nm and 65-nm SRAMs [4].

Proton tests using low-energy proton radiation sources to study proton direct ionization effects can be challenging. The proton energy should be relatively monoenergetic to resolve the effects of large increases in SEU cross section by small changes in proton energy. Many advanced ICs (e.g., ball-bonded ICs) cannot be exposed from the topside and must be exposed through the back substrate. Whether the device is exposed from the top or backside, the top overlayers or the back substrate will result in energy straggle of the low-energy protons and the proton energies at the device sensitive volumes must be estimated using simulations of the physical scattering mechanisms. These properties make characterization testing for direct ionization effects using low-energy proton radiation sources difficult for all but the most knowledgable users. As an alternative approach, one may start by using higher energy protons and degrade the proton energy using appropriate materials. This can result in a wide energy spectrum of protons, some of which may have sufficiently low energy to cause SEU by direct ionization. Indeed, in principle, this is very similar

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to the physical processes by which low-energy protons are generated at the device level in satellite systems. This approach does not have the energy resolution to determine the precise effect of direct ionization on SEU cross section. However, it can potentially be used to identify devices that are sensitive to proton direct ionization effects.

In this work, we explore the potential for using high-energy proton radiation sources to identify ICs that are sensitive to proton direct ionization effects. IBM 45 and 65-nm SOI SRAMs were irradiated at TRIUMF's proton cyclotron facility over a range of proton energies by degrading a monoenergetic 70-MeV proton beam. The use of this procedure for hardness assurance testing of devices that may be sensitive to proton direct ionization effects is discussed. An overall approach for performing proton hardness assurance testing is also outlined.

II. Experimental Details

Proton irradiations were performed on 36-Mbit 45-nm and 1-Mbit 65-nm SOI SRAMs fabricated at IBM in their partially-depleted SOI technology. The device details of these SRAMs have been described previously [2]–[4]. The dependence of SEU cross section on proton energy for these SRAMs has been determined using low-energy proton radiation sources [2]–[4] (see Figure 1). The 45-nm and 65-nm SRAMs were irradiated with a power supply biases of 0.9 and 1.0 V, respectively. All IC measurements were performed using a Certimax digital tester. Devices were irradiated in a static condition with a checkerboard pattern written into the memory.

All irradiations were performed at the TRIUMF Proton Irradiation Facility [9], [10]. The proton energy was varied by degrading a 70-MeV primary beam using a variable thickness plastic (lucite) plate (range shifter). As will be discussed below, the proton energy can be degraded by increasing the thickness of the plastic plate. However, this also increases the amount of energy straggle. If the range shifter thickness is sufficiently large, a large fraction of the total number of protons can have low enough energies to cause SEU by direct ionization. All devices were irradiated from the backside through the silicon substrate. The silicon substrate will further degrade the beam energy and increase the amount of energy straggle. Devices were also irradiated by placing a metal lid (0.43 mm thick) and/or an aluminum plate (1.6 mm thick) over the back of the device to simulate the additional effects of a package lid and a thin satellite wall on the measured SEU cross section.

III. Results

Figure 2 is a plot of the SEU cross section vs proton energy for the IBM 45-nm SRAMs. Data are shown for devices with no metal layers (only the back substrate and buried oxide), with a metal lid, and with a metal lid and an aluminum plate. For all irradiations, the protons must go through the back substrate and buried oxide to reach the device sensitive layers. The back substrate was not intentionally thinned. For the irradiations with no metal layers (red circles), the SEU cross section saturates at proton energies above ~20 MeV. As the proton energy is decreased below 20 MeV, the SEU cross section starts to decrease and reaches a minimum around 13.5 MeV. As the proton energy is decreased further, the SEU cross section begins to increase and reaches a peak value at a proton energy around 6.5 MeV. This peak is attributed to proton direct ionization effects. At this proton energy, the energy straggle is significant and some protons that reach the sensitive layers will have low enough energies to cause SEU by direct ionization. For a single metal lid and for a metal lid plus an aluminum plate covering the back of the device, the same general trend in SEU cross section vs proton energy is observed. The major difference is that as the thickness of the materials covering the back increases, the proton energy corresponding to the peak in the SEU cross section due to direct ionization effects increases, i.e., the peak in cross section due to direct ionization does not disappear as the overlayer thickness increases. The proton energy peak due to direct ionization occurs at energies of 13.7 and 22.5 MeV for the lid and lid + Al, respectively. These results are consistent with Monte Carlo physics-based simulations of proton direct ionization effects [5].

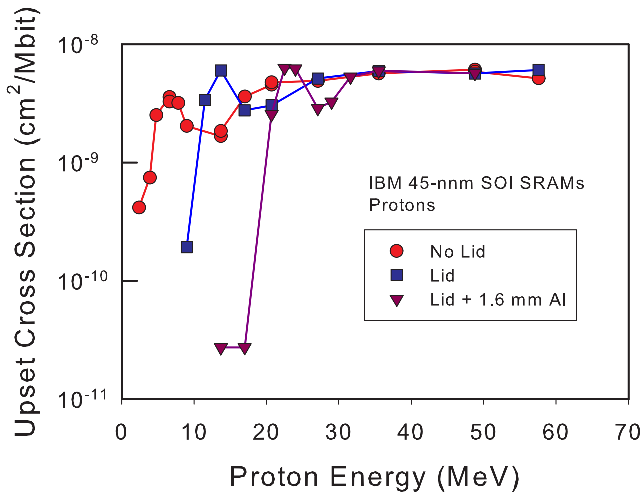

Fig. 2. SEU cross section vs proton energy for IBM 45-nm SRAMs.

Based on the results of Figure 2, the high-energy TRIUMF irradiations were able to determine that 45-nm SRAMs are sensitive to proton direct ionization effects. However, the magnitude of the peaks corresponding to the low-energy irradiations (Figure 1) and the high-energy irradiations are considerably different. Considering the energy straggle of the degraded proton beam at TRIUMF, this is not surprising [3], [4]. This difference is discussed in more detail below.

Figure 3 is a plot of the SEU cross section vs proton energy for the IBM 65-nm SRAMs. Data are shown for devices with and without a metal lid covering the back of the device. Data are shown for devices with metal lids taken on two different test dates. For the proton irradiations without a metal lid, there is a ledge in the upset cross section at low proton energies. This ledge is likely due to proton direct ionization effects. For the irradiations with a metal lid, the ledge has disappeared. Thus, for the 65-nm SRAMs, the peak in the cross section due to direct ionization is not nearly as well defined as the peak in the cross section for the 45-nm SRAMs.

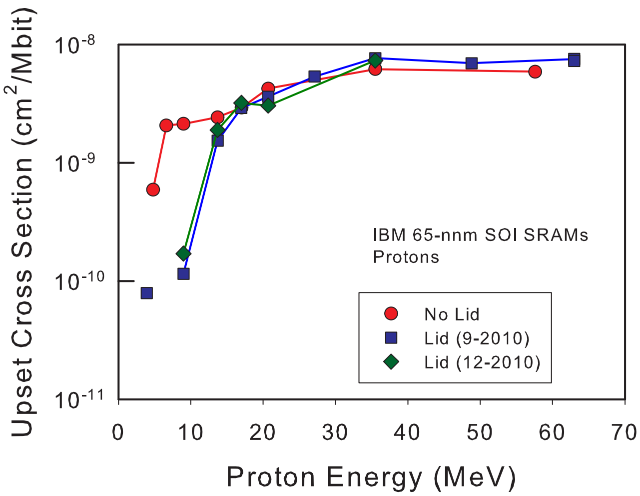

Fig. 3. SEU cross section vs proton energy for IBM 65-nm SRAMs.

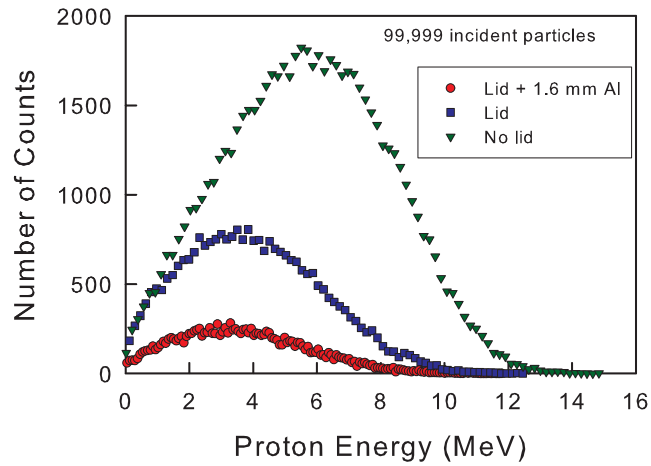

Fig. 4. Simulated number of protons (counts) versus proton energy for three metal overlayer conditions. The simulations count 99,999 protons at 70 MeV passing through material with varying thicknesses.

IV. SRIM Simulations

To better understand the results of Figures 2 and 3, we performed SRIM simulations of the proton energy spectrum at the silicon - buried oxide interface of the back-side of irradiated DUTs. The simulated proton beam counts 99999 protons at 70 MeV passing through materials with varying thicknesses. As discussed above, the proton energy was degraded using a variable thickness plastic plate. In addition to the plastic plate, the proton beam passes through several other apparatus for beam spreading, collimation, and dosimetry [9]. These materials are included in the simulations. By themselves, these materials cause some energy straggle and energy loss. For a plastic thickness of zero, SRIM simulations show that these materials by themselves cause a 6 MeV reduction in proton energy and an energy straggle of 0.76 MeV (defined at one sigma).

Figure 4 is a plot of the number of protons (counts) versus proton energy determined by SRIM simulations in the top silicon layer for radiations with no lid and no Al plate, with a lid and no Al plate, and with a lid and an Al plate. A total of 99,999 incident protons were used in the simulations. The thickness values for the plastic range shifter correspond to the direct ionization peaks in Figure 2. Namely, referring to Figure 2, for curves with no lid, with a lid, and with a lid and an Al plate, the range shifter values resulted in average energies of 6.63, 13.7, and 22.5 MeV, respectively. In Figure 4, the peak energies are 5.51, 3.84, and 3.29 MeV and the total number of protons in the distributions are 68362, 26456, and 16158, for the curves with no lid, with a lid, and with a lid and an Al plate, respectively. Hence, the number of protons that stop in the device increases rapidly as the peak in energy distribution approaches zero. For all three curves, there was not a significant difference in the amount of energy straggle. The amount of straggle (defined at one sigma) varied from 4.02 to 5.12 MeV. This is consistent with the results of Figure 2, which show qualitatively the same shape of cross section curve due to direct ionization for the three different radiation conditions.

V. Discussion - Hardness Assurance Issues

Upsets can occur due to proton direct ionization effects if the proton energy spectrum at the sensitive volume includes protons with LETs above the threshold for direct ionization. Thus, if the LET threshold occurs at a proton energy of 1 MeV, then protons below this energy may be able to induce upset by direct ionization. For example, for the curve for proton irradiations with a metal lid and an Al plate in Figure 4, there are 1264 protons with an energy at or below 1 MeV. Thus, approximately 10% of the total number of protons in the proton spectrum of Figure 4 may be able to induce upset by direct ionization. Considering the fact that 99,999 incident protons were used in the simulations, only about 1.3% of the total number of incident protons still remain in the proton spectrum. Thus, to obtain these low energy protons, a considerably larger number of protons have lost all of their energy and have been stopped in the device.

Clearly, to best observe proton direct ionization effects, one wants to maximize the number of protons in the energy spectrum below the proton energy threshold. However, there is a tradeoff between increasing the fraction of protons in the energy spectrum with low energies by decreasing the peak energy and the reduction in the total number of protons as protons are stopped in the device as the proton energy is decreased. This is evident by comparing the three curves in Figure 4. Each of these curves corresponds to one of the direct ionization peaks observed in Figure 2. For the no lid and no Al plate curve, the energy peak is at relatively high energy, however, because the total number of protons is high, there are still a relatively large number of protons that can cause upsets by direct ionization. As the range shifter thickness is increased further (data not shown), the energy peak of the spectrum decreases, but the total number of protons also decreases, and there are actually fewer protons available that can cause upset by direct ionization. For the other two curves, the optimum energy spectrums occur at lower peak energy values. Even though the energy peak values are different, the number of protons at low energies is within a factor of two (likely within experimental and simulation uncertainty). For example, the total number of protons with energies at or below 1 MeV are 1944, 2143, and 1264 for the radiations with no lid, with a lid, and with a lid and an Al plate, respectively.

As mentioned above, peaks due to direct ionization of protons were successfully detected for the 45-nm SRAMs, but they were not successfully detected for the 65-nm SRAMs. The cause for this is uncertain. One possible explanation could be the sensitivity of the SRAMs due to direct ionization. It is plausible to assume that the 45-nm SRAMs are more sensitive to proton direct ionization effects than the 65-nm SRAMs. As the SRAMs become more sensitive to proton direct ionization effects, they may upset at lower LETs (higher proton energies). If this is the case, for a given proton energy spectrum (e.g., the energy spectrums of Figure 4) a larger fraction of the protons will be able to contribute to upset by direct ionization, making it easier to observe the contribution of direct ionization in the measured upset cross section curves. However, based on the results of [4], there does not appear to be major differences in the upset sensitivities of the 45 and 65-nm SRAMs.

To obtain a larger fraction of low energy protons, which can result in upset by direct ionization, one method is to decrease the primary energy of the proton beam. This, of course, will depend on facility capabilities. If the primary beam energy is decreased, the straggle of low proton energies is reduced and fewer protons will be stopped in the device. As has been done in the past, one could use special techniques to obtain very low energy protons with minimum amounts of energy straggle [3], [4]. This is necessary to determine the true extent of proton direct ionization effects. However, from a practical hardness assurance testing standpoint, this may not be necessary. For example, in a system, the vast majority of the electronics are embedded in the system, and are shielded by the satellite wall and other materials. As a result, there is a minimum proton energy required for protons to penetrate these materials. The materials in the paths of the protons will cause proton energy straggle and energy loss, similar to what is shown above for the TRIUMF irradiations. Thus, for hardness assurance testing, it may not be necessary to use very low energy proton beams, and degraded primary beams with energies greater than 20 MeV may be more practical.

One final point is what is the real impact of proton direct ionization on the soft-error rate for electronics embedded in a space system? As noted above, as the proton energy is degraded by materials in the paths of the protons, some protons may have sufficiently low energy to cause upset by direct ionization. However, the number of these protons may be a small fraction of the total number of protons incident on the system (and ultimately the device). Even though direct ionization may greatly increase the upset cross section when measured using monoenergetic protons, its impact on the upset cross section (and soft error rate) in a system may be considerably less. This will be discussed in more detail in the final paper.

VI. Summary

The potential for using the degraded beam of high-energy proton radiation sources for proton hardness assurance testing for ICs that are sensitive to proton direct ionization effects are explored. SRAMs sensitive to direct ionization effects were irradiated with protons whose energies were degraded using a variable thickness plastic plate. Data show peaks in the measured upset cross section curves due to proton direct ionization for a 45-nm SRAM. SRIM simulations have been performed to better understand the results. The results suggest that high-energy proton radiation sources may be useful for identification of devices sensitive to proton direct ionization; however, this needs to be validated on a wider range of devices. The hardness assurance implications of these results are discussed.

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