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Test procedures for proton-induced single event effects in space environments

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35 WORD ABSTRACT:

Proton SEL data shows no significant difference in SEL cross-section with proton angle of incidence at high proton energies. Hardness assurance test procedures for proton-induced SEU and SEL are proposed.

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Introduction

Recently, it has been shown that proton induced SEL and SEU testing can be more challenging than heavy-ion single event testing. The manner in which protons induce single event effects is considerably different than for heavy ions. In general, protons do not have high enough LETs to cause either SEU or SEL by direct ionization. Instead, protons induce single-event effects by generating secondary particles with much higher LETs. The properties of secondary particles generated during proton irradiation are very dependent on the energy of the incident proton and the materials available in the device with which the protons can interact. For example, it has been recently shown that high energy protons interacting with high-Z materials can produce secondary ions with very high LETs [1,2]. Indeed, some SRAMs were shown to only exhibit latchup when irradiated with high energy protons greater than 300 MeV [2]. A proposed mechanism for this effect was the interaction of high energy protons with tungsten, generating high LET secondary particles. Although these secondary particles (heavy ions) can have relatively high LETs (~35 MeV-cm^2/mg), their energies are much lower than the energies of the ions routinely used for heavy-ion single event hardness assurance testing. Because of this, the sensitive volume for proton-induced single event effects can be much different than the sensitive volume for heavy-ion induced single event effects. In addition, during heavy-ion testing, changing the angle of incidence directly changes the direction of the ion track. Because charge is deposited along the path of the ion, changing the angle of incidence also directly changes the path where charge is deposited. This is not true for proton irradiation. For protons, changing the angle of incidence will directly change the path of the protons. However, because the secondary particles produced by proton-material interactions can be emitted in any direction, changing the proton angle of incidence does not uniquely define the direction of secondary particles and hence the path of deposited charge. Moreover, low energy secondary ions produced during irradiation with low energy protons have recently been shown to significantly impact the single event latchup response for devices irradiated with protons at large angles of incidence [1].

In addition to single event effects, protons can also induce significant total dose degradation in devices. From a hardness assurance perspective, it has been shown that some devices can exhibit increased SEU sensitivity during mission lifetime (buildup of total dose damage) [3]. This correlation of total dose degradation to SEU sensitivity has important implications for space applications where the total dose is due to either electrons or protons.

Although the SEU and SEL proton sensitivity has recently been explored in detail experimentally, proton single event hardness assurance test guidelines have not been clearly defined. In this summary we present some additional high-energy proton results to further explore the effects of angle of incidence on proton induced SEL. Based on these results and results published over the past few years, we propose proton single event hardness assurance test guidelines for qualification of devices in proton dominated space environments.

Experimental Details

Several SRAMs from multiple vendors were irradiated at proton energies from ~50 to ~500 MeV, at temperatures of 25 and 75°C, and at angles of incidence from 0 (normal) to 85 degrees (grazing). The proton irradiations were performed at the TRIUMF proton irradiation facility. Proton 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 greater than 105 MeV were obtained by varying the primary energy of a second beamline with a maximum proton energy of 500 MeV.

During latchup testing, the SRAMs were irradiated in their preferred power-up logic state, i.e., no pattern was written to the memory array. The power supply current was continuously monitored during exposure using a computer controlled HP power supply. A latchup threshold current was set a few mA above the steady-state current of the part. When the power supply current increased above the latchup threshold a latchup was recorded and the power supply voltage was removed for 0.5 s to clear the latchup state. For a given particle flux, this limits the maximum latchup rate that can be accurately measured. The latchup current was limited to 100 mA to limit any potential damage to the part during the high current latchup state.

Because some ICs were exposed to high fluence levels and were repeatedly triggered into a latched state, the SEL cross sections of SRAMs were measured before and after repeated SEL characterizations under similar conditions. Within experimental uncertainty, the same SEL cross sections were measured before and after repeated characterization, indicating that proton-induced displacement damage and total ionizing dose effects were negligible. In addition, there were no observable latent effects caused by repeated latchup testing [4]. The

SRAMs were electrically tested before and after latchup testing to ensure that they were functional during latchup testing.

Experimental Results

Proton induced SEL depends on several factors such as characterization temperature, the energy of the protons, and the angle of incidence of the protons [5]. This is illustrated in Fig. 1 for SRAMs from vendor C. These are 1-Mbit SRAMs fabricated in a 0.15-µm technology. The nominal voltage for these devices is 3.3 V, so the SEL characterization was performed at 3.6 V. Fig. 1 is a plot of the SEL cross section for devices characterized at room temperature (squares) and 75°C (circles) at angles of incidence of 0 (blue) and 85 (red) degrees at proton energies from 50 to 495 MeV. At low proton energies, these devices exhibit a moderate temperature dependence, but a fairly large dependence on the angle of incidence. To see this, consider the data at a proton energy of 105 MeV. Comparing the room temperature data to the elevated temperature data at either normal incidence or grazing angle, we observe that the devices irradiated at 75°C have a ~40% increase in latchup cross-section compared to the 25°C data. On the other hand, the SEL cross-section for a given temperature at grazing incidence compared to normal incidence, is ~80% larger. Thus, the effect of angle of incidence is approximately twice as large as the effect of temperature for this device type at 105 MeV. These data confirm that the worst-case condition for proton-induced SEL testing at low energies is maximum system temperature and grazing angle. For increasing proton energy (> 105 MeV), we observe that the impact of angle of incidence and temperature on the SEL cross-section decreases with increasing proton energy. At a proton energy of 495 MeV, we observe no significant difference in the SEL cross-section for devices characterized at normal incidence compared to devices characterized at grazing angle. These results are unexpected based on previously published low energy proton data (≤ 105 MeV) describing the effects of angle of incidence on the proton-induced SEL response of SRAMs [1,2].

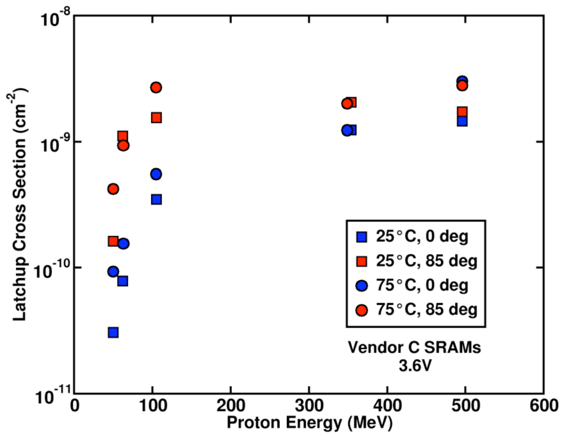

Fig. 1: Latchup cross section versus proton energy for vendor C SRAMs for angles of incidence of 0 and 85 degrees measured at a temperatures of 0°C and 75°C.

Fig. 2 is a plot of the SEL cross section for vendor B SRAMs characterized at a temperature of 75°C at angles of incidence of 0 and 85 degrees at proton energies from 50 to 495 MeV. The vendor B SRAMs are 1-Mbit devices, fabricated in a 0.14-µm technology. These devices have separate core and I/O voltage levels. The nominal voltages are 1.5 and 3.3 V for the core and I/O, respectively. The SEL testing was performed at worst-case bias conditions of 1.6 and 3.6 V. These data show the same general trends for the impact of angle of incidence and temperature as was observed for the Vendor C SRAMs (see Figure 1 and related discussion). However, these SRAMs show a much larger temperature effect than the devices in Fig. 1. At a proton energy of 105 MeV, the SEL cross-section at normal incidence is a factor of ~4 larger for devices characterized at 75°C than for devices characterized at room temperature. Similarly, for SRAMs characterized at grazing incidence the SEL cross-section is ~16 times larger at 75°C than devices tested at room temperature. This is an example of a device type for which the proton SEL cross-section is strongly dependent on temperature, angle of incidence, and proton energy. For the devices of Fig. 2, it appears that at high angles of incidence, the SEL cross section saturates at a much lower proton energy than at normal incidence.

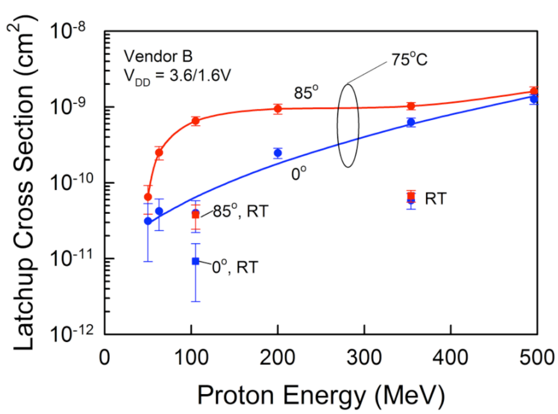

Fig. 2: Latchup cross section versus proton energy for vendor B SRAMs for angles of incidence of 0 and 85 degrees measured at a temperature of 75°C.

One of the main results of this work is that if SEL hardness assurance testing is performed at a facility with a low maximum proton energy, testing should be performed at grazing angle (in addition to normal incidence); whereas, if testing is performed at a facility with a high maximum proton energy (e.g., TRIUMF), testing need be performed only at normal angle. Note that there is an apparent small increase in the SEL cross section at very high proton energies. This increase in SEL cross section is close to experimental uncertainty.

However, it may also be due to the generation of very high LET secondary particles by proton interactions with high-Z materials (e.g., tungsten) increasing SEL sensitivity [1].

Discussion

The data of Figs. 1 and 2 demonstrate the challenges associated with developing a hardness assurance test method for qualifying parts for use in proton environments. The worst-case test conditions will depend on the proton energy of interest. For lower proton energy testing (≤ 105 MeV), parts need to be tested at maximum operating temperature and at both normal and grazing angles of incidence. For each device investigated (data for additional device types will be presented in the full paper), the effect of angle of incidence reached a maximum at a proton energy between 62 and 105 MeV for bulk silicon devices. Special considerations for other devices types (e.g., silicon on insulator devices) will also be discussed in the full paper. During testing at higher proton energies (> 100 MeV), it was determined the effect of angle of incidence continually decreased as the proton energy was increased. In fact, at 495 MeV, the effect of angle of incidence was negligible for all SRAMs investigated. This may be explained by the differences in the ranges and numbers of the secondary particles generated by high-energy protons compared to those generated by lower energy protons. In 2006, Schwank et al., showed that the mechanism for the effect of angle of incidence on SEL cross section is not due simply to the deposition of more energy in the sensitive volume caused by an increase in path length as the angle of incidence is increased [1]. Instead, the increased sensitivity is a consequence of the linear energy transfer (LET) and range distributions of secondary ions produced by proton-material interactions coupled with an increase in SEL sensitivity (decrease in LET threshold) as angle of incidence is increased. Considering this, our results may suggest that for high energy protons, there are enough high LET secondary particles such that the latchup cross section does not depend significantly on the angle of incidence of the proton or temperature.

Hardness Assurance Test Guidelines

Based upon our experimental results published over the past few years [1-3] and the results presented here, we propose a viable test procedure for SEE to qualify parts for use in proton-rich space environments. In the full paper we will discuss procedures for both SEL and SEU, however in this summary we will only present the procedure for SEL. Proton-induced SEL sensitivity is dependent on four factors; the power supply bias, the characterization temperature, the proton energy, and the angle of incidence of the protons. The effects of bias have been described in detail in the literature [5]. The maximum bias of the device under test is the worst-case test condition and will not be described here. Instead we will focus on the remaining three factors.

Fig. 3 is a flow chart diagram illustrating the proper test flow for qualifying parts for proton SEL. For SEL qualification, it is best to test the part at the maximum proton energy of the environment. For space applications the maximum proton energy of trapped protons is ~400 MeV [6]. Galactic protons can have higher energies, but the flux of these protons is very low. Therefore, for most systems a practical upper limit for proton testing is 400 MeV. If testing is performed at 400 MeV or above, it is likely that the full spectrum of secondary particles generated by proton high-Z material interactions will be covered. As shown by the left fork in Fig. 3, if it is practical to test at the maximum energy of the environment (≥400 MeV), then testing should be performed at the maximum bias, maximum temperature, and at normal incidence (0 deg.). As shown by the high energy data in Figs. 1 and 2 the distribution of high LET secondary ions is large enough that there is no significant difference between normal incidence and grazing angle incidence for the highest energy protons. Therefore, testing at normal incidence is sufficient, and preferred to ensure the protons reaching the die have the highest possible energy, and any issues associated with misalignment in the beam are minimized.

Even though SEL hardness assurance testing should ideally be performed at the maximum proton energy of the environment, unfortunately, the number of high-energy proton sources is limited, As shown by the right fork of the flow diagram in Fig. 3, if it is not practical to test at the maximum energy, there is an option to test at lower proton energies between 200 and 400 MeV protons. A minimum energy of 200 is required to ensure that the SEL cross section has saturated. If testing is to be conducted at energies less than 400 MeV, the part should first be tested at the maximum bias and temperature, and at a grazing angle of incidence between 80 and 90 degrees. Recall that as shown in Figs. 1 and 2, as well as in the literature for several other part types [1,2], normal incidence does not provide the worst-case test condition at 200 MeV. Although the amount of increase in SEL cross section with increasing angle of incidence varies from part to part, all devices examined to date show the worst case SEL cross section at grazing incidence for lower energy proton irradiation. If the response of the part is acceptable at grazing angle the part should also be tested at normal incidence to ensure that the incident protons cover the entire part, and there is less chance for issues associated with misalignment of the part in the beam. If

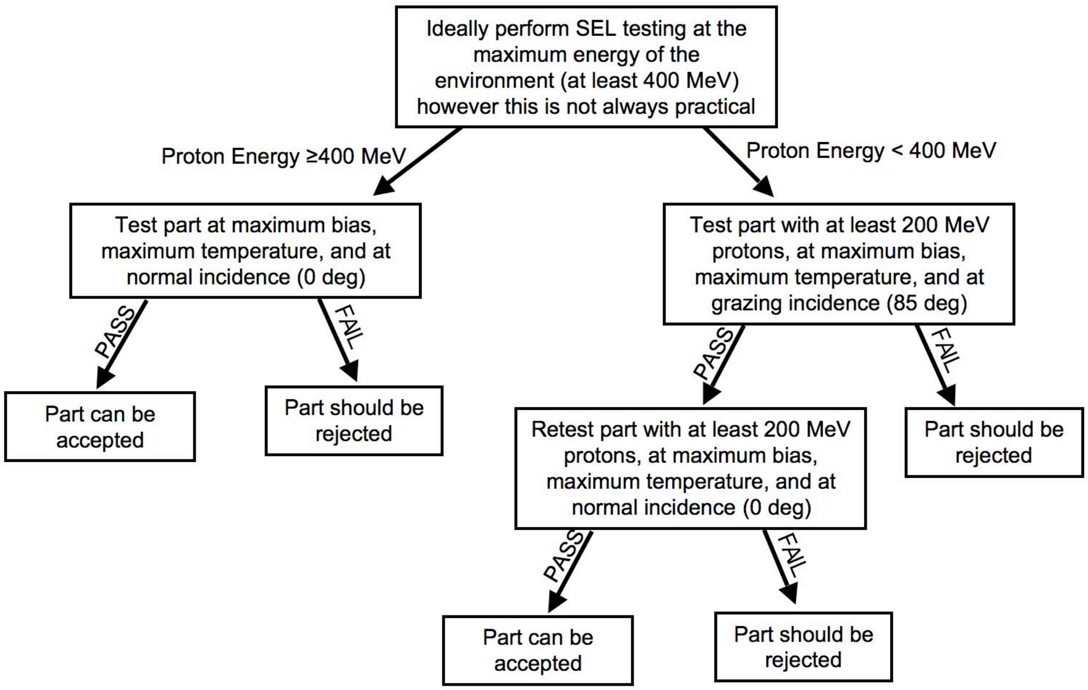

Fig 3 : Flow chart diagram showing the test procedure for SEL qualification of parts in a proton space environment.

the part fails either part of this SEL test procedure it should be rejected. Because of potentially large decreases in SEL cross section as proton energy is decreased, which can significantly affect the probability for detecting latchup [1], testing at maximum proton energies below 200 MeV is not recommended.

When qualifying a part for use in a proton environment, it is also important to consider what total fluence level should be tested. This decision should be based both on the expected fluence for the system, as well as the required confidence level of the measurement. Depending on flight path and mission duration, system proton fluences could vary over a large range. In addition, typically only 1 out of every ~10^5 protons interacts with the device materials to produce a secondary particle. Therefore, to achieve a very high level of confidence in the SEL test, it is necessary to irradiate the parts to sufficiently high fluence levels to ensure that enough secondary particles were generated during the test that if the part is latchup-sensitive a latchup would likely be detected. This requires engineering trade-offs between the time and cost of the test with consideration for impact on the system if the device under test were to latch up in a real scenario.

Summary and Conclusions

Over the past few years, we have performed a significant amount of work investigating proton-induced single event effects in bulk Si ICs. For this summary, we have taken additional high-energy proton SEL data. These new data show that at the highest proton energies observed in space environments, there is no significant difference between normal incidence and grazing incidence irradiation for proton-induced SEL. This work completes the picture for qualifying parts for use in a proton dominated space environment, enabling us to present guidelines for proton-induced single event hardness assurance testing. In this summary, we have presented a test flow for SEL testing based on the mechanisms for proton SEL illustrated by our results. Data for additional part types, as well as a test flow for proton SEU testing will be presented in the full paper.

References

[1] J. R. Schwank et al., *IEEE TNS*, **53**, pp. 3122 (2006).
[2] J. R. Schwank et al., *IEEE TNS*, **52**, pp. 2622 (2005).
[3] J. R. Schwank et al., *IEEE TNS*, **53**, pp. 1772 (2006).
[4] H. N. Becker et al., *IEEE TNS*, **49**, pp. 3009 (2002).
[5] A. H. Johnston et al., *IEEE TNS*, **44**, pp. 2367 (1997).
[6] E. G. Stassinopoulos et al., *Proc. IEEE*, **76**, pp. 1423 (1988).