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Hardness Assurance for Low-Energy Proton-Induced Single-Event Effects

Final report for LDRD Project 173134

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Abstract

This report briefly summarizes three publications that resulted from a two-year LDRD. The three publications address a recently emerging reliability issue: namely, that low-energy protons (LEPs) can cause single-event effects (SEEs) in highly scaled microelectronics. These publications span from low to high technology readiness levels. In the first, novel experiments were used to prove that proton direct ionization is the dominant mechanism for LEP-induced SEEs. In the second, a simple method was developed to calculate expected on-orbit error rates for LEP effects. This simplification was enabled by creating (and characterizing) an accelerated space-like LEP environment in the laboratory. In the third publication, this new method was applied to many memory circuits from the 20-90 nm technology nodes to study the general importance of LEP effects, in terms of their contribution to the total on-orbit SEE rate.

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1. SUMMARY OF PUBLICATIONS

All of the work performed under this LDRD Project has been thoroughly documented in three complementary peer-reviewed publications. Rather than duplicate the information at length, we now provide references and summarize the findings of these three publications.

One of these publications received the "Best Paper" award at the 2014 IEEE Nuclear and Space Radiation Effects Conference (NSREC); the largest and most competitive conference in this field. The other two publications were recently presented at the 2015 NSREC, and are both finalists for the 2015 "Best Paper" award. Therefore, experts in this field have identified all three of these publications as high-impact and high-quality papers.

1.1. Summary of Reference [1]

Low-energy proton SEU data are presented in which energy loss, energy straggle, flux attrition, and angular scattering have been minimized by removing the SOI SRAM's silicon substrate. By minimizing these common sources of experimental interference, these data give deeper insight into SEU mechanisms than previous datasets.

Results show that grazing angles are the worst case for LEP-induced SEUs in these SOI circuits. (A different LEP angular response was seen for bulk Si circuits in [3].) Angular scattering is shown to affect the measured LEP cross sections to a small degree, even in these circuits with very thin intervening materials. Effective LET in the sensitive volume is shown to be adequate to predict the SEU cross section, even when using protons, alphas, and heavy ions at many different angles and energies, proving that proton direct ionization is the dominant mechanism for LEP-induced SEUs in these circuits. Finally, the LEP error rate calculation method developed in [2] is shown to be accurate.

1.2. Summary of Reference [2]

The physics of proton energy loss in matter cause the sub-3-MeV proton energy spectra of all shielded space environments to have the same shape. Simulations and energy spectroscopy measurements show that this shape can be reproduced in the laboratory by degrading a high-energy proton beam. We exploit this phenomenon to develop an accurate PDI error rate prediction method that is more practical than those developed previously. Unlike previous methods, this method can be applied at high-energy proton facilities, on encapsulated parts, without knowledge of the IC design, and with little or no computer simulations required. This method is used to predict that PDI significantly contributes to the total error rate for a 65-nm SOI SRAM under the conditions investigated. Results from 65-nm, 45-nm, and 32-nm SOI SRAMs suggest that scaling has little effect on the per Mbit PDI error rates across these technologies.

Cross sections from PDI are shown to be highest at large angles of incidence for the three SOI technologies investigated. This occurs because proton effective LET increases as a function of angle. Therefore, hardness assurance methods for PDI must account for angular effects to be conservative, which is more easily done using the proposed method than methods developed previously. We present how this angular dependence can be used to quickly identify whether an IC is susceptible to PDI effects.

1.3. Summary of Reference [3]

This is the most comprehensive study to date on the contribution of LEPs to the total on-orbit SEU rate. Low- and high-energy proton tests were performed on many circuits from the 20 to 90 nm technology nodes. Every effort was made to predict LEP error rates that are conservatively high. Even so, LEPs were found to contribute less to the total SEU rate than some have feared. Across all the environments and circuits considered and when operating within 10% of nominal VDD, LEPs were found to increase the total SEU rate to be up to 4.3 times as high as it would have been in the absence of LEPs. This contribution was for the unusually harsh Geo Worst Day solar flare environment, behind only 100 mils Al shielding. Across the other seven environments considered, LEPs were found to less than double the total error rate. These findings suggest that the best approach to account for LEP effects is to calculate the total error rate from high-energy protons and heavy ions, and then multiply it by a safety margin of 5. If that error rate can be tolerated then our findings suggest that it justified to waive LEP tests. This approach is not justified in certain situations, which have been described.

Trends were observed in the LEP angular responses of the circuits. Grazing angles were the worst case for the SOI circuits. The bulk Si circuits showed a complex dependence on the roll and tilt angles, with the worst-case angle being at or near normal incidence. These worst-case angles must be used for conservative LEP error rate predictions.

The transport model used by CREME-96, UPROP, is shown to underpredict the flux of LEPs by up to 25× for certain environments dominated by galactic cosmic rays. Fortunately, LEPs are a negligible contributor to the total error rate in these environments, so this model can still be used for accurate calculations of the total SEU rate.

2. References

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