Study of Single Event Upset Phenomena Induced by Muons and Protons in 65-nm Planar Bulk SRAMs

鄧, 亦凡

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氏　　名　：Deng Yifan

Name

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Title　　　（ 65 nm プレナーバルク型 SRAM のミューオン及び陽子誘起シングルイベントアップセット現象に関する研究 ）

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Category

論 文 内 容 の 要 旨

Thesis Summary

Industrial needs for highly reliable integrated circuits are in various applications, including medical, aerospace, automotive, networking, nuclear engineering and supercomputers. For circuit reliability, the problem of cosmic ray induced soft errors occurring inside the Very Large-Scale Integrations (VLSIs) in a terrestrial radiation environment has been recognized as a significant threat to electronics. Among the cosmic rays at ground level, neutrons have always been considered a main radiation source for Single Event Upsets (SEUs) in terrestrial environments. As the supply voltage and cell size are reduced with each technological generation, the critical charge of SRAM cells continues to decrease, making the cell more vulnerable to more types of particles. Thus, with the miniaturization of semiconductors and low operating voltages, there is a growing interest in whether large amounts of muons may also be another source of SEUs through the direct ionization process and nuclear capture reaction for negative muons. As our concern for muon SEUs is growing, many more experiments need to be performed.

However, the SEU cross-sections and the SER (Soft Error Rate) predictions from acceleration tests highly depend on the experimental conditions. Since muons pass through different thicknesses and materials before reaching the Sensitive Volume (SV) in cases of varying irradiation sides, i.e., package side (PS) and board side (BS), the varying peak incident energy and energy straggling degree will influence the muon-induced SEUs. Therefore, the first primary objective of this study is to investigate the impact of irradiation side on muon-induced SEU in 65 nm bulk SRAMs through muon-accelerating test, and then explain this effect through simulation-based analysis.

On the other hand, the minimal muon test facilities worldwide make it challenging to conduct muon irradiation tests, and such muon-accelerating tests are often financially expensive. As the Low Energy Proton (LEP) induced SEU and its contribution to the SER have been investigated widely and reported to need to be considered at ground level, this study also seeks to establish a method for predicting muon SEUs using a combination of proton testing and Monte Carlo simulation, after comparing positive muon and proton-induced SEU in 65 nm bulk SRAM. Because LEP and positive muons have the same positive charge and the relationship of stopping power with kinetic energy, and they deposit energy and produce SEUs in devices primarily through direct ionization.

The last object of this study is to investigate the impact of muon irradiation sides for SRAM devices on the SER prediction. Moreover, since the incident angle dependence of muon-induced SEUs is reported, it is

of interest to evaluate the muon-induced SER under a realistic environment considering the zenith angle distribution of muon flux.

Chapter 1 of this thesis introduces the background and motivation of this work. The mechanism of radiation-induced SEU in SRAM, the fundamentals of cosmic rays in the terrestrial environment, the physical properties of positive and negative muons and protons, and the straggling in energy deposition are introduced. At the end of this Chapter, a brief review of past muon and proton-induced SEU works is explained.

Chapter 2 presents the re-analysis of measurements on muon SEU cross-sections in different irradiation side. The negative and positive muon acceleration tests were performed for 65-nm bulk SRAMs at the Muon Science Facility (MUSE) in Materials and Life Science Experimental Facility (MLF), Japan Proton Accelerator Research Complex (J-PARC). In the experiment period, both package side (PS) irradiation and board side (BS) irradiation tests were done, while the results of PS irradiation have not been wholly analyzed nor published. Therefore, this chapter first describes the previous tests' experimental facilities, devices, and setups. Then, the muon beam intensity in PS irradiation is newly analyzed using the image luminance of the beam profile monitor. After that, the measured SEU cross sections in the PS irradiation tests are derived and compared with the previously published results for BS irradiation. About twice the SEU cross-section differences were observed between PS and BS irradiations.

Chapter 3 gives a simulation analysis of measurement results. The simulation method is introduced first, including the simulation tools (Geant4), physical process, geometry model, beam source, and SEU determination in simulation. Then, the critical momentum dependence of SEU cross sections for positive and negative muons in BS irradiation are analyzed to determine the critical charge so that the simulation reproduces the measurement well. The momentum dependent SEU cross sections for positive and negative muons in PS and BS irradiations are derived using the simulation and compared with the measurement. At the end of the Chapter, a quantitative assessment of the impact of energy straggling on SEU is established based on the concept of effective SEU fluence. The effective SEU fluence has proved essential for understanding that the magnitude of the peak SEU cross-sections is different by a factor of about two between the PS and BS irradiations with both positive and negative muons.

Chapter 4 compares positive muon-induced SEU in BS irradiation with proton-induced ones by simulation. The peak energy of the proton SEU cross sections is 17.1 MeV, which is larger than the peak energy of 6.63 MeV for the muon SEU ones. The peak cross-section of the proton is about 15 times that of the positive muon. This difference is explained by the different characteristics of the energy deposition process between proton and positive muon, using effective SEU fluences. Then, a new method was developed to predict the positive muon-induced SEU using proton tests and Monte Carlo simulation. The muon SEU cross-section predicted by this method was found to reproduce the experimental muon SEU data reasonably well.

Chapter 5 gives the SER estimations for positive and negative muon in 65 nm bulk SRAMs based on the measured data in PS and BS irradiations. For both positive and negative muons, the estimated SERs for the BS irradiation are slightly larger than those for the PS irradiation. The difference is at most 21%, indicating the irradiation side's impact on SER prediction is relatively weak. Then, the SERs were predicted under a more realistic environment by considering the zenith angle distribution of muon flux. As a result, the predicted SER was found to have no significant difference from that without zenith angle distribution. Therefore, the experimental data from conventional irradiation tests in which a device board is placed perpendicular to the incident beam are expected to be useful in estimating muon-induced SERs on the ground.

Finally, Chapter 6 gives a summary and conclusions, and the perspectives of the future work are also described.