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Fast neutron irradiation tests of flash memories used in space environment at the ISIS spallation neutron source

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This paper presents a neutron accelerated study of soft errors in advanced electronic devices used in space missions, i.e. Flash memories performed at the ChipIr and VESUVIO beam lines at the ISIS spallation neutron source. The two neutron beam lines are set up to mimic the space environment spectra and allow neutron irradiation tests on Flash memories in the neutron energy range above 10 MeV and up to 800 MeV. The ISIS neutron energy spectrum is similar to the one occurring in the atmospheric as well as in space and planetary environments, with intensity enhancements varying in the range 10^8- 10^{9} and 10^6- 10^{7} respectively. Such conditions are suitable for the characterization of the atmospheric, space and planetary neutron radiation environments, and are directly applicable for accelerated tests of electronic components as demonstrated here in benchmark measurements performed on flash memories. https://doi.org/10.1063/1.5017945

INTRODUCTION

The study of Single Event Effects (SEE), occurring when a highly energetic charged or neutral particle causes a disruption of the correct operation of an integrated circuit, is of great importance to assess the robustness of electronic devices and provide indications to protect them from environmental ionizing radiation. The phenomenon is well known in the aerospace community: the possibility of single-event upsets, firstly postulated by Wallmark and Marcus in 1962,[1] became an established field of research and development in the late 1970s; in 2004 the work of J.F. Ziegler suggested that cosmic rays were a substantial contributor to electronic reliability mechanisms,[1] thus the impact of atmospheric neutrons on electronic devices became a relevant issue as well.

Energetic particles, including neutrons, are naturally present in the earth's atmosphere - at sea level and even more abundant at aircrafts altitudes, in avionic and space environments. Neutrons are generated as a secondary component from the interaction of primary cosmic ray particles with nuclei in the molecules composing the atmosphere, aircraft and spacecraft components, or the surface of planets.[2] The advent of spallation neutron sources, with neutron energy spectra extending up to 3 GeV

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and intense fluxes of fast neutrons, has opened up new opportunities to fulfill the need for testing of electronic devices under fast neutron irradiation.

Seminal studies on SEE process by fast neutrons in FPGAs were performed in 2007[3,4] using VESUVIO spectrometer at the ISIS spallation neutron source.[5] ISIS produces neutrons by using 800 MeV protons, extracted from the synchrotron on two extraction lines and colliding on tungsten targets. VESUVIO is primarily tailored to neutron spectroscopic studies in materials research in the eV energy range (epithermal neutrons). Its design, optimized for epithermal neutrons flux, provides an "under-moderated" spectrum with a tail of high energy neutrons. The latter is being exploited for SEE testing of microelectronics since 2007.[3] VESUVIO delivers a pulsed neutron beam with a fast neutron (E_n > 10 MeV) fluence rate in the order of $5.8 \cdot 10^4$ $cm^{-2}s^{-1}$. The high energy neutron spectrum extends in principle up to 800 MeV. High fluence and high energy are both needed for SEE studies.[3,4]

Up to now several are the irradiation experiments carried out on VESUVIO on a large variety of electronic devices. This experimental activity triggered the development of the new irradiation station ChipIr. (ChipIr beamline was realized with the support of STFC and the CNR (PANAREA project), the latter within the CNR-STFC agreements 2008-2014 and 2014-2020.) Figure 1 shows how the ChipIr neutron spectrum is optimised to match the atmospheric one for E_n >10 MeV. One hour exposure of electronic devices in the its neutron beam is equivalent to hundreds to thousands of years in the real environment. Figure 1 also shows that the VESUVIO neutron spectrum is somewhat softer than the atmospheric one. However this feature does not prevent one to test and validate on VESUVIO the experimental and computational techniques that are being adopted for accelerated SEE tests on ChipIr.

The spallation processes that generate neutrons in ISIS target are similar to those occurring in space and planetary environments, and as such they are relevant for the characterization of the space and planetary neutron radiation environments involving manned and unmanned missions, as well as for satellites. Primary cosmic rays interact with nuclei of the materials of the spacecraft (such as the spacecraft's structures, payload, etc.) or any planetary atmosphere and surface. Neutrons components in space environment are mostly generated as secondary radiation with large penetration depths up to ~ m.

Thus fast neutron spectra from ISIS beam lines extend to high energy as in space and planetary environments, but with much increased intensity.

Figure 1 shows that the fast neutron spectra from ISIS are similar to and extend to high energy as in space and planetary environments, but with much higher intensity.[3,4,6–11] In this energy range

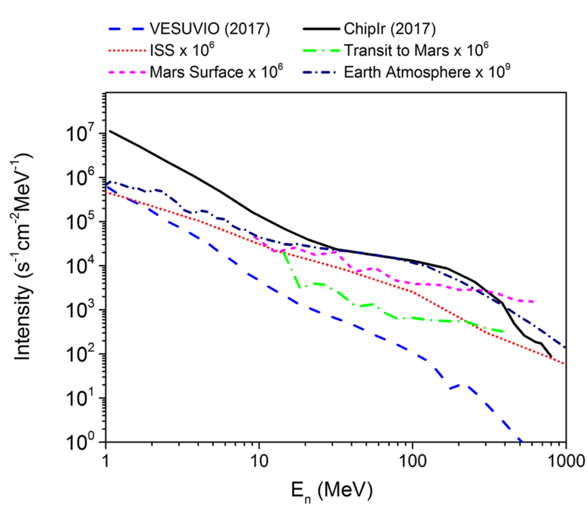

FIG. 1. The neutron spectra of VESUVIO (dotted blue line)[3,4,6] and ChipIr (black continuous line)[7,8] are compared to space environment spectra, i.e. the International Space Station (dotted red points),[9] Transit to Mars (green dotted line),[10] Mars Surface (purple line)[11] and Earth Atmosphere (black dotted line).[9]

(E_n >10 MeV) ChipIr has a flux of $5.6 \cdot 10^6$ $cm^{-2}s^{-1}$ which is about a hundred times more intense than VESUVIO.

This paper addresses the study of electronic and accelerated measurements in neutron fields of Flash memories used in space environment, provided by Thales Alenia Space using both VESUVIO and ChipIr at ISIS. Flash memories are the electronic component in which the feature size has scaled more rapidly and which have the largest capacity among semiconductor devices.

Currently Flash memories, based on Floating Gate (FG) cells, dominate the market of non-volatile memories. These devices, besides being used in many mainstream applications, such as mobile phones, MP3 players, and digital cameras, are increasingly used also in safety-critical applications such as automotive and biomedical. One of the aspects addressed here is to evaluate the reliability of Flash memories in terms of their susceptibility to atmospheric neutrons. Flash memory manufacturers are becoming more and more concerned by the neutron threat, both at ground level and at aircrafts altitudes. Until few years ago, it was very unlikely that a single neutron strike could affect data stored in the FG, due to the large amount of charge stored in the floating electrode; only heavy ions with high Linear Energy Transfer (LET) were able to affect the amount of stored charge to an extent large enough to create a digital error. From 2008, using VESUVIO[3,4,6] and ChipIr[7,8] beam lines it was shown that FG cells are also sensitive to lighter ionizing particles, such as those produced by nuclear reactions resulting from atmospheric neutrons interacting with chip materials.[4]

EXPERIMENT

Six Flash memories with two different architectures (single level cell, SLC and multiple level cell, MLC) and feature size (25 and 20 nm) have been irradiated on VESUVIO and six nominally-identical samples on ChipIr. The samples were programmed before the exposure, irradiated in unbiased conditions, and then read back after the irradiation. This procedure was made possible by the non-volatility of the devices and was chosen as the goal of the measurements was to assess the single event upset rate of the cells in the floating gate array, and not SEE related to the peripheral circuitry.

A total fluence of $1.86 \cdot 10^{10}$ n/cm^2 (E_n >10 MeV) is delivered on VESUVIO in about 6 days of beam time, corresponding to a Proton Accelerator integrated current of 16598 μAh, whereas a total fluence of $4.59 \cdot 10^{10}$ n/cm^2 (E_n >10 MeV) is delivered on ChipIr in about 2 hours of beam time. Both on VESUVIO and ChipIr, the proton fluence was monitored using single crystal diamond detector used in pulse mode.[12,13]

Results are shown in Figure 2: Single Event Upset (SEU) cross sections are consistent with previous measurements[14,15] and in agreement with a mechanism based on charge loss from the floating gate,[16] and to a much smaller extent charge trapping in the tunnel oxide.[17,18] MLC devices are more sensitive than SLC devices, as predicted by the models developed by the University of Padova.[14]

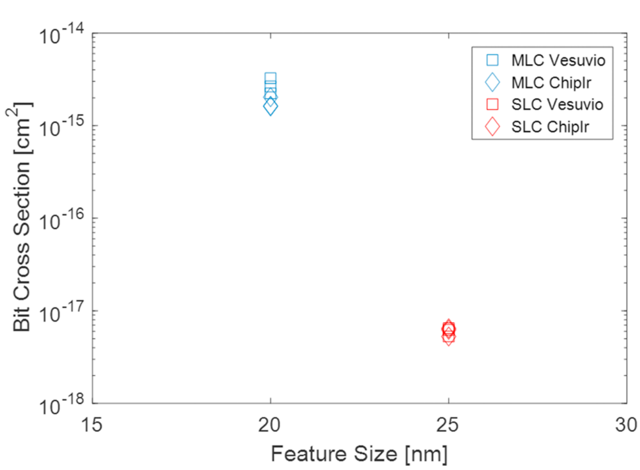

FIG. 2. SEU Cross sections for SLC and MLC Flash memories irradiated at ISIS.

No retention issues related to radiation[19] were observed and the memories could be reprogrammed without any issue after the neutron exposure, implying that no permanent damage was produced in the oxides. The agreement between VESUVIO and ChipIr measurements show that the hardness of the neutron spectrum is not so important for devices and effects having a low linear energy transfer threshold, as in the case of single event upsets in deeply scaled Floating gate devices.[20]

Overall the agreement in the values of the cross sections measured on VESUVIO and ChipIr is good and the small differences can be attributed to either experimental uncertainties and to the effect of the different spectrum of the two beam lines.

These results show the accuracy of the experimental method and suggests that the cross section of these devices does not have a strong energy dependency in the fast neutron range.

CONCLUSIONS

Neutron spectra conditions on VESUVIO and ChipIr are suitable for performing accelerated testing of electronic components. A benchmark experiment was designed to perform accelerated tests of Flash memories of interest for Thales Alenia Space for space applications where neutrons fluxes are demanding. The experiment assesses the neutron sensitivity of commercial Flash memories through a measurements of the static cross section. Results show that the SEU Cross sections for SLC and MLC devices are successfully obtained.

The matching of high energy neutron spectra from Vesuvio and ChipIr beamlines and space environment spectra opens up at the ISIS facility the possibility of performing routinely accelerated neutron radiation testing of electronic devices used in space.

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