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Thermal neutron induced upsets in 28nm SRAM

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Abstract. In this work, we present the first results of static tests in a 28nm SRAM under thermal neutron irradiation from the IPEN/IEA-R1 research reactor. The SRAM used was the configuration memory of a Xilinx Zynq-7000 FPGA and the ECC frame was used to detect bit-flips. It was obtained a SEU cross-section of $9.2(21) \times 10^{-16}$ cm^2/bit, corresponding to a FIT/Mb of 12(5), in accordance with expected results. The most probable cause of SEU in this device are ^{10}B contamination on tungsten contacts.

1. Introduction

Single-event effects on eletronic devices are described as system events triggered by a single particle's charge deposition in a sensitive node of a device. This charge deposition may cause a current-pulse transient in a transistor that can lead to a bit-flip in a digital system, or even trigger a high-current state capable of destroying the device. Single-event effects are caused mainly by heavy-ions and protons [1], although there are also observations with electrons and neutrons [1, 2].

In the case of electronic components of aerospace use, embedded control devices used in avionics are exposed to a neutron spectrum from the interaction of cosmic rays with the atmosphere. This neutron spectrum is fairly intense around 10 MeV in the region of the South Atlantic Anomaly [3].

Laboratory irradiation of devices allow the study of the effects of single events (SEE) caused by neutrons, such as bit-flips in digital devices [4], or even effects of displacement damages of atoms in the crystalline lattice, which alter the electrical characteristics of the devices, like solar cells whose gain factor changes after neutron exposure. Controlled studies in each range of neutron energies provide better prediction capability of failures and optimization of embedded system designs. In recent years, the observation of single-event burnout, a destructive effect, caused by neutrons is also a concern for high-reliability applications [5]

Due to the absence of electrical charge, neutron-induced effects are result of neutron interactions with nuclei present in the medium. For neutrons with energies ranging from thermal (25 meV) up to tens of MeV, the most commom reactions are the neutron capture reactions, suceeded in most cases by gamma or beta emissions. However, in the presence of ^{10}B the $^{10}B(n,\alpha)^7Li$ reaction may take place, with cross-section values as large as 3838 barn, and which

products alpha particle (1.78 MeV and 1.47 MeV[1]) and lithium recoil (about 1 MeV) are much more capable of triggering an effect [1].

For semiconductor devices, it was common the presence of insulating layers made of borophosposilicate-glass (BPSG), which contains ^{10}B in natural abundance of 19.9%, and, as its location was very close to the sensitive nodes, was a serious issue for soft errors in digital circuits. Despite the manufacturers have eliminated the presence of BPSG layers, the interconnect processing method uses B_2H_6 carrier gas, resulting in an accumulation of ^{10}B in the sidewalls of tungsten contact holes [6, 7].

In order to improve manufacturing processes and/or mitigation techniques, it is crucial to understand all the process involved in neutron soft-error generation and precise measurements of neutron SEU cross-sections.

This paper presents some of the first results of thermal neutron irradiation studies at IEA-R1 research reactor, where the thermal neutron single-event upset cross-section for 28nm SRAM was determined.

2. Experimental Procedure

Nuclear reactors are strong sources of thermal, epithermal and fast (up to 5-10 MeV) neutrons. The nuclear fission process produces fast neutrons in the few-MeV range, and the reactor moderator (usually water) reduces the neutrons' energies by means of scattering progressively until they reach thermal equilibrium with the medium (with energies around 0.025 eV). These neutrons can be then extracted from the reactor pool through *beam holes* and these neutron beams can then be filtered and/or separated from the accompanying gamma-rays by using different materials. One of the most effective ways to do so is to use crystal monochromators, where neutrons with the right energy are diffracted towards the sample.

The device under test was irradiated in the monochromatic low-energy facility installed at IEA-R1 research reactor at IPEN, where the neutron flux is $\sim 6{\times}10^4 cm^{-2}{\cdot}s^{-1}$, for approximately 7 hours. Figure 1 shows the beam exit and sample holder.

The testing was carried out in a 28 nm configuration SRAM (CRAM) of a Xilinx Zynq-7000 FPGA. An aleatory pattern of "0"s and "1"s was loaded in the CRAM and the device was configured to report bit-flips detected by the Error Correction Code instance by means of a logic signal in a digital output. A scaler was used to count the bit-flips.

3. Results and Discussion

To determine device's sensitvity, single-event upset cross-section and failures in time (FIT/Mb) were calculated. SEU cross-section is given by equation 1, were N represents the number of events observed with fluence Φ. Uncertainties are calculated assuming a Poisson distribution for single-event upsets. Failures-in-time represents the expected number of events recorded for one billion device-hours of operation, per megabit, and it is expressed in terms of cross-section as in equation 2, where ϕ is the neutron flux ($[n/s/cm^2]$) and N_{bits} is the total number of memory bits.

$$\sigma = \frac{N}{\Phi} \tag{1}$$

$$FIT/Mb = \frac{\sigma \times \phi \times 3.6 \times 10^{12}}{N_{bits}} \tag{2}$$

Were observed 24 bit-flips under a $\sim 10^9$ n/cm^2 fluence, resulting in a SEU cross-section of $9.2(21) \times 10^{-16}$ cm^2/bit and FIT/Mb of 12(5), in accordance with the expected order of magnitude, although somewhat below the reported value of 29(3) FIT/Mb [8].

[1] Corresponding to lithium recoil in ground and excited states, respectively.

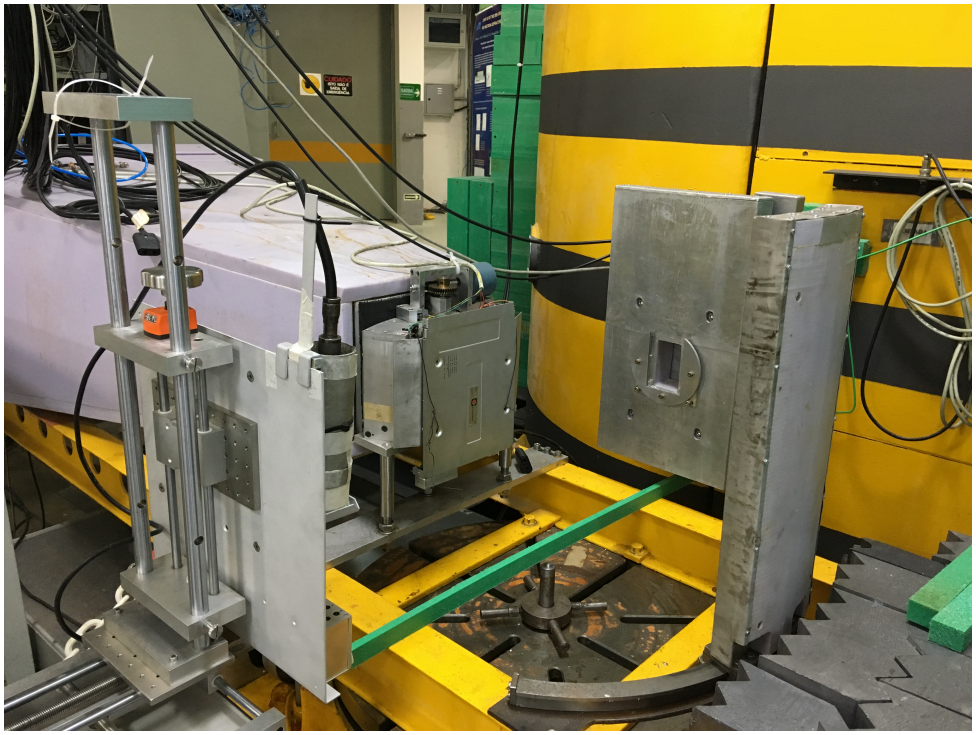

Figure 1. Thermal neutron irradiation setup

In order to determine the boron content present in the sample, Rutherford Back-Scattering and Nuclear Reaction Analysis were performed at LAMFI-USP, with alpha and proton beams at several energies. For NRA, proton energies from 2.0 to 3.2 MeV and detection angle of 170°, and the reaction considered was $^{11}B(p,\alpha)^8Be$[2] The data were analyzed using MultiSIMNRA software [9], and the boron content was below the detection limit of the setup, estimated in about 10^{17} $atoms/cm^2$. The complex structure of the device also has influenced on the analysis. The absence of detectable amount of boron together with information on manufacturing processes leads to the conclusion that contaminant boron in tungsten contacts is responsible for the SEU observed, in accordance to ref. [6], which also states that such boron content should be detectable only by secondary-ion-mass-spectrometry (SIMS) technique. Dopping boron concentration should not be an issue in modern devices [1]. Further analysis are being conducted.

4. Conclusions

In this work we measured the thermal neutron upset cross section for a 28nm SRAM using the ECC frame of a Zynq-7000 SRAM FPGA and thermal neutrons from a setup installed in IPEN/IEA-R1 research reactor. The results obtained were a SEU cross-section of $9.2(21) \times 10^{-16}$ cm^2/bit and FIT/Mb of 12(5). More studies should be made to determine the composition of the FPGA and the upset cross-section for different voltage/neutron energy configurations.

Acknowledgments

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[2] ^8Be is an unbound nucleus and decays in two alfa particles, but only the alfa particle from the reaction (p,α) has a defined energy from reaction Q-value and kinematics - around 6.0 MeV for the experimental condition.

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