Facility for fast neutron irradiation tests of electronics at the ISIS spallation neutron source

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(Received 22 January 2008; accepted 25 February 2008; published online 20 March 2008)

The VESUVIO beam line at the ISIS spallation neutron source was set up for neutron irradiation tests in the neutron energy range above 10 MeV. The neutron flux and energy spectrum were shown, in benchmark activation measurements, to provide a neutron spectrum similar to the ambient one at sea level, but with an enhancement in intensity of a factor of 10^7. Such conditions are suitable for accelerated testing of electronic components, as was demonstrated here by measurements of soft error rates in recent technology field programable gate arrays. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2897309]

The growing availability of integrated circuits featuring minimum dimensions of the order of tens of nanometers is affecting properties and design methodologies of digital systems. These digital devices are more susceptible to random faults, known as single event effects (SEEs), which can occur when a highly energetic particle (such as a neutron present in the environment) causes a disruption of their correct operation by striking sensitive regions of an electronic device.[1] SEEs have already been identified as a predominant threat to aircraft safety,[2] and the effects on electronic components from cosmic radiation is of significant importance for the semiconductor industry.[3]

The collision process of a neutron with a silicon nucleus can be either elastic or inelastic. At high energies (in the MeV region), inelastic collisions are more effective and may lead to a series of direct reactions, called intranuclear cascade, which are characterized by the ejection of individual nucleons (protons or neutrons as well as alpha particles) as well as of residual heavy ions that more likely induce SEE into the device. At lower energies, capture reactions may take place with the formation of a compound nucleus, which, in turn, decays to reach stability. A SEE can be induced when the energy released into the active medium by the charged particles causes the total number of ionization electron-hole pairs collected in a sensitive region of the device to exceed a critical value (which is characteristic of the device). These radiation-induced errors may be a concern in static random accessing memory (SRAM)-based field programable gate arrays (FPGAs), where bit flips in the configuration memory may alter the functionality of the implemented circuits.

A FPGA is a semiconductor device containing logic components and interconnects that can be programed "in the field" by the designer, without requiring dedicated manufacturing steps to implement the desired functionality.[4] Applications of FPGAs include a growing number of areas from signal processing to aerospace and defense systems. The logic components inside the FPGA can be used to realize complex combinatorial or sequential functions. The FPGA configuration, i.e., the information describing the implemented circuit, is stored in a memory (configuration memory) that can be of different types: antifuse, flash, or SRAM. If the data in the configuration memory become corrupted, the functionality of the implemented circuit can be altered, possibly leading to computation errors or even functional interruptions. SRAM-based FPGAs are the most versatile and inexpensive devices but, at the same time, the most sensitive to neutrons and ionizing particles.

As a matter of fact, commercial off-the-shelf devices are becoming popular in mission- or safety-critical applications since they satisfy the designers' need for high-performance computing at moderate prices. However, to exploit such devices, fault-tolerant design techniques must be employed, and extensive analyses are needed in order to qualify the robustness of the devices and systems. Experiments with atmospheric neutrons at different altitudes can be carried out, but due to low intensity, they require very long periods of data acquisition.[5] In this context, neutron sources represent an opportunity due to the availability of high intensity fluxes, which allow accelerated irradiation experiments.

Currently, semiconductor industries perform irradiation tests, for example, at the Los Alamos Neutron Science Center[6] (LANSCE) and TRIUMF (Ref. 7) neutron sources. LANSCE is a multidisciplinary facility for science and technology. Los Alamos Meson Physics Facility (LAMPF), the heart of the facility, is an 800 MeV high-power linear accelerator that can accelerate both protons and negative hydrogen ions with pulsed beam time patterns, which suits a wide variety of experiments. The facility consists of three major experimental areas, of which the Weapons Neutron Research (WNR) is mainly focused to applied research and for testing semiconductor devices. The WNR uses a H^- beam, chopped and bunched before acceleration to give an adjustable pulse-to-pulse separation, typically 1–8 ms, and accepts a small adjustable fraction of the 1 mA LAMPF beam on its neutron-producing target. An unmoderated white neutron beam with useful energies from 100 keV up to above

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600 MeV is produced by the interaction of the proton beam with a tungsten target. The neutron beam pulse width is approximately 125 ps, allowing for high-resolution neutron time-of-flight measurements.

Irradiation tests of semiconductors are performed at the Irradiation of Chips and Electronics (ICE House), where the neutron spectrum is rather similar to that of neutrons produced in the atmosphere by cosmic rays, but with a neutron flux 10^8 times higher than the natural one at sea level. This large flux allows users from many countries to use the WNR high-energy-neutron source to characterize electronic components at greatly accelerated rates and study various failure modes caused by neutron irradiation.

Irradiation tests of semiconductor devices are also performed at the Neutron Irradiation Facility (NIF) of TRIUMF, Vancouver, Canada. NIF is mainly dedicated to testing avionics and ground-based electronic systems. The neutrons are produced by an intense proton beam from a 500 MeV cyclotron, striking an aluminum beam stop immersed in a tank of cooling water. The neutron beam is then incident in the testing station, where the device under test is lowered into the path of the neutron beam. NIF has an energy spectrum well matched to the atmospheric one, although somewhat softer than that at LANSCE, and can simulate the radiation effects of ten years of atmospheric exposure in just a few minutes. The neutrons produced at TRIUMF have energies up to 400 MeV, with the additional feature that thermal neutrons from the water moderator are also present. Similar to TRIUMF and LANSCE, the Research Center for Nuclear Physics facility in Japan also provides a white neutron spectrum of up to 400 MeV energy suitable for SEE studies.[8]

The availability of a neutron test facility located in Europe would provide increased test opportunities at different geographical locations for the benefit of those industries for which access to WNR or NIF is not convenient. This letter assesses the effectiveness of the ISIS spallation source[9] located at the Rutherford Appleton Laboratory (Chilton, UK), to serve as a reliable European facility for accelerated irradiation tests of electronics. This is done by presenting measurements of the neutron spectrum available on the VESUVIO beam line[10] used for this experiment and by comparing it to the one of the LANSCE. Experimental results obtained in a series of benchmark irradiation experiments on recent technology semiconductors (SRAM-based FPGA) are presented and compared to results obtained at LANSCE.

The neutron production at ISIS relies upon spallation reactions induced by 800 MeV proton bunches accelerated through a synchrotron. The beam makes about 10^4 orbits inside the synchrotron as it is accelerated before being kicked in a single revolution into the extracted proton beam line, delivering 4 μC of protons in "two 100-ns-long pulses" to a spallation target (W/Ta). The entire acceleration process is repeated 50 times/s, so that a mean current of 200 μA is delivered to the target, with a neutron yield of about 30 n/proton. Although the VESUVIO instrument is mainly for the purpose of spectroscopy with neutrons in the low-eV range, the beam line has been used for irradiation experiments of electronic chips, taking advantage of the availability of high energy neutrons (in the MeV range). VESUVIO has a primary flight path of 11.055 m and a water moderator at ambient temperature that provides a pulsed neutron beam whose spectrum is peaked at about 30 meV and is known to decrease as $1/E^{\alpha}$, with $\alpha \approx 0.9$, in the epithermal energy region (above 0.5 eV). The undermoderation of the neutrons results in the presence of an intense flux of neutrons above 1 MeV. The beam diameter at the sample position is about 4.5 cm.

TABLE I. List of the nuclides used for the foil activation analysis and their threshold energies.

Nuclide	E_{th} (MeV)
^{27}Mg	5
^{24}Na	8
^{206}Bi	25
^{11}C	30
^{205}Bi	40
^{204}Bi	45
^{203}Bi	55
^{202}Bi	70
^{201}Bi	80
^{200}Bi	95

In order to evaluate the high energy component of the VESUVIO neutron spectrum, a Monte Carlo *N*-Particle extended (MCNPX) spectrum model was made to simulate the differential neutron flux as a function of energy.[11] The MCNPX input model was based on the protoengineering description. This model has individual components for the moderators and their containment vessels, the decoupling layers (B_4C and Cd), and the target Ta clad and W plates. On the other hand, the Be rod reflector, which is cooled with interstitial D_2O, and the target service areas were calculated from homogenized components. These approximations add a systematic error decreasing from about 15% at low energies (meV) down to about 5% at the highest energies (MeV). The spectrum from a window tally placed at the entrance at the VESUVIO guide was resampled to take into account the octagonal guide transport (first stage). This model was benchmarked with two independent measurements. First, neutron activation measurements were performed by irradiating selected foils of aluminium, carbon (as graphite), gold, and bismuth in the VESUVIO beam for up to 24 h. The threshold energies E_{th} of the reactions used are listed in Table I.

The induced activity was measured in a calibrated gamma spectrometer using two collection times for each foil. This method allowed for the identification of the activated nuclide since both the half life and the gamma spectrum were measured. The induced activation for each identified nuclide was corrected for the decay, absorption, and dead time and was normalized to the proton current. These results were then compared to the estimated activities derived from the MCNPX model, taking into account the mass of the foil and a start time correction that allows for the decay that occurs in the time taken to irradiate and to move the foils from the VESUVIO beam line to the gamma spectrometer. Figure 1 shows the normalized ratio of the measured activity (for each threshold energy) to the corresponding value obtained by the MCNPX model. It can be noticed that the overall agreement between the two determinations is satisfactory within the experimental uncertainties, thus confirming the reliability of the model used to extract the neutron flux. A consistent ratio between the measured and calculated activity for the range of reaction thresholds gave an integrated intensity above 10 MeV of the VESUVIO beam of $(5.82 \pm 1.05) \times 10^4$ n cm^{-2} s^{-1} at 180 μA proton current and

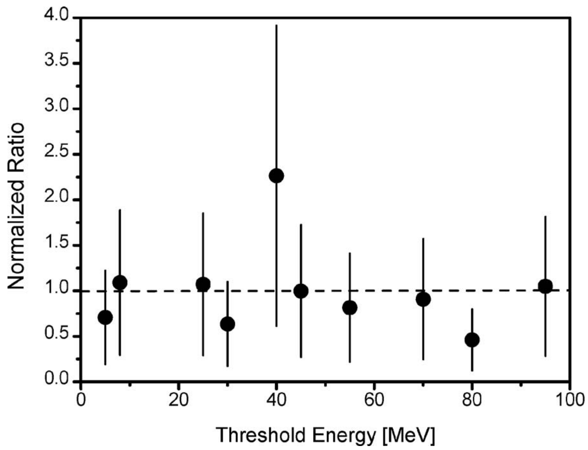

FIG. 1. Normalized ratio of the measured activity (for each threshold energy) to the one obtained from the MCNPX model. The dashed line is the normalized activity of the MCNPX model.

indicated that the MCNPX spectrum was a reasonable model of the differential flux (Fig. 2).

The second benchmark measurement was based on the event rate in a charge-coupled device detector[12] that provides a relative measure of the neutron beam intensity. Direct comparison of the observed event rate with that generated when the same detector was put into the beam at LANSCE provides a value for the LANSCE equivalent flux. The LANSCE equivalent flux is defined as the flux of the LANSCE beam that would be required to induce the same rate of events in the same detector.[13]

This method of characterizing a beam takes into account the energy dependence both of the neutron spectrum and also of the cross section for the generation of events. It therefore provides a measure of the effectiveness of the beam in inducing SEE. Conventionally, SEE cross sections measured at LANSCE are normalized to the portion of the LANSCE fluence, which is above 10 MeV, even though neutrons below 10 MeV can cause SEE in many devices. The flux at the optimum irradiation position at LANSCE is $4.1 \times 10^5\ n\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ above 10 MeV at a typical proton current of 1.8 μA. The LANSCE-equivalent flux at the irradiation position used at VESUVIO is $7.4 \times 10^4\ n\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ for 180 μA proton current.[14] This means that the fast neutron flux on VESUVIO is 0.18 times as effective at inducing SEE events as the LANSCE beam. Taking account of the softer spectrum at VESUVIO and the potential for neutrons below 10 MeV to cause SEE, this independent measurement is consistent with that derived from the activation analysis.

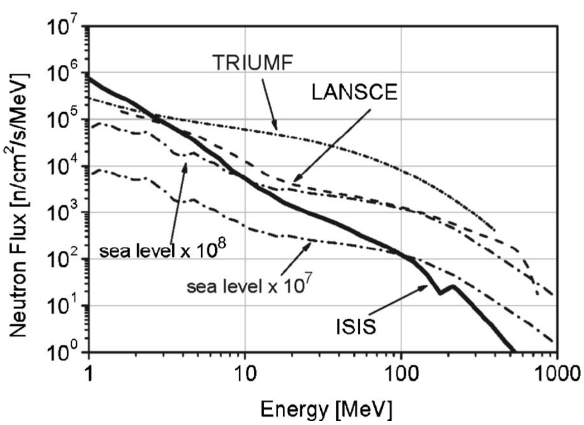

FIG. 2. Neutron energy spectrum at VESUVIO (solid line). Also shown for comparison are the neutron energy spectra at LANSCE and TRIUMF facilities, as well as the terrestrial one at sea level, multiplied by 10^7 and 10^8.

A series of benchmark measurements were performed on semiconductor chips of recent technology. The aim of the tests was to assess the neutron sensitivity of commercial off-the-shelf SRAM-based FPGAs through a measurement of the static cross section. This is defined as the ratio of SEU/bit (SEU denotes single event upset) of the FPGA configuration memory to the total received neutron fluence and represents a generic measure of the FPGA neutron sensitivity. Measurements were made on a Xilinx Spartan-3 XC3S200. The LANSCE-equivalent fluence incident on the device was $2.32 \times 10^9\ n\ \mathrm{cm}^{-2}$. We determined the LANSCE-equivalent static cross section to be $3.3 \times 10^{-14}\ \mathrm{cm}^2/\mathrm{bit}$, with estimated standard uncertainty approximately $\pm 13\%$. These results are consistent with the range of values obtained by independent measurements made on similar devices at LANSCE.[5] As LANSCE is considered as the standard site for this kind of tests, the results from VESUVIO at ISIS indicate its usefulness as an irradiation facility.

Following the demonstration tests reported here, a dedicated setup has been made available on VESUVIO for user-proposed experiments on fast neutron irradiation tests of electronic chips. Work is in progress at ISIS to design and build a dedicated irradiation beam line with optimized spectral conditions.

We acknowledge the Consiglio Nazionale delle Ricerche (CNR)-Italy for financial support within the CNR-CCLRC agreement.

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