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Neutron Radiation Effects Program (NREP) at the Indiana University Cyclotron Facility

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Abstract

The Low Energy Neutron Source (LENS) at Indiana University Cyclotron Facility delivered first neutrons in December of 2004. Neutrons are produced via Be(p,nx) reactions at 7 MeV. The neutron spectrum covers the range from thermal to ~ 5 MeV. The neutron spectrum inside the moderator cavity has been characterized using foil activation in the thermal range and sulfur pellets in the fast range. Measured neutron intensities are compared to MCNPX calculations. A set of transistors with a known response to neutrons was irradiated inside the moderator cavity. The transistor gain as a function of neutron fluence serves as an independent verification of the foil and pellet activation measurements. The first microcircuit with 150 nanometer feature size was tested for single event upsets at LENS. No upsets were induced by the neutrons.

1. Introduction

Studies of neutron induced radiation effects in electronic devices are part of the future research program at LENS. As semiconductor technology continues to scale down into the “nano” regime (feature sizes less than 100 nanometers), the sensitivity to single event effects (SEE) from energetic particles (alpha particles, protons, neutrons, galactic cosmic rays, etc.) will continue to increase [1]. Neutron induced SEE effects are a concern for avionics and military applications of electronic devices. Neutrons produced in cosmic ray showers in the atmosphere affect onboard electronics of aircraft while electronic devices for military applications need to be designed to survive the radiation environment generated by nuclear explosions. To date, testing for neutron SEE susceptibility has been conducted primarily at reactor based facilities. An accelerator based facility like LENS offers the advantage of fewer security concerns and easier access.

A detailed description of LENS can be found in [2]. Protons are accelerated to 7 MeV by a radio frequency quadrupole followed by a drift tube linac. The linac was run at a peak beam current of 6 mA, a pulse width of 200 μs, and a repetition rate of 15Hz (the average beam current was 18 μA). Neutrons are produced via Be(p,nx) reactions up to an energy of ~5MeV. The existing target/moderator (TMR) configuration will eventually be optimized for applications using cold neutrons. Pending funding, a second TMR dedicated to the neutron radiation effects program (NREP) will be built. The existing TMR is useful to obtain experimental data as input to the design of the dedicated NREP TMR. For the present work the neutrons were moderated by a room-temperature polyethylene slab instead of the planned cryogenic methane moderator. Using the polyethylene moderator the neutron spectrum extends down to 10^{-3} eV. Details about the neutron spectrum can be found in [3].

2. Transistor damage

Fast neutrons contribute to the bulk damage in silicon through the displacement of silicon atoms while thermal neutrons cause damage by triggering nuclear reactions in which energetic fragments are produced. In pure silicon the damage is primarily caused by fast neutrons. This so-called displacement damage results in a change of the transistor gain as a function of the neutron fluence (# neutrons/cm^2). Commonly, the neutron fluence from a source is characterized in terms of an equivalent monoenergetic neutron source. By convention, 1MeV is chosen as the reference energy [4].

While the initial gain and the response to irradiation vary from transistor to transistor the change in reciprocal gain $\Delta 1/h_{FE}$ is always proportional to the 1 MeV equivalent fluence if the collector current is kept constant. This behavior can be written as [5]:

$$\frac{1}{h_{FE\phi}} - \frac{1}{h_{FE0}} = K_\tau \phi(1MeV) \tag{2.1}$$

Here, h_{FE0} and $h_{FE\Phi}$ are the transistor gains before and after irradiation respectively. K_τ is the so-called damage factor and $\Phi(1MeV)$ is the 1 MeV equivalent fluence. If the transistor is made from silicon, the 1MeV equivalent fluence is calculated by evaluating the expression

$$\phi(1MeV) = \frac{\int_0^\infty \phi(E) F_{D,Si}(E) dE}{F_{D,Si}(1MeV)} \tag{2.2}$$

Here, $F_{D,Si}$ is the damage function (MeV·mb) and $\Phi(E)$ is the energy dependent fluence of the neutron source. $F_{D,Si}(1MeV)$ is defined to be a reference value of 95 MeV·mb [4]. The damage function for silicon is largest for fast neutrons ($\geq$ 1MeV).

3. Experiment

NAVSEA Crane supplied PNP and NPN transistors for this test. Transistors of the same lot were previously irradiated at the White Sands fast burst reactor to fluences of up to $3\cdot 10^{13}$ neutrons/cm^2. Thus, the response of the transistors is known and they serve as an independent method to determine the neutron fluence. Prior to irradiation the gain h_{FE0} was determined for each transistor using a device tester. A total of 15 transistors (9 NPN and 6 PNP) were irradiated inside the TMR cavity.

The transistors were mounted on both sides of a 5x5 cm^2 foam board and inserted 97cm deep into the moderator cavity, thus positioning the devices at a distance of about 10cm from the target.

The neutron flux was measured concurrently with the transistor irradiations. Activation foils and sulfur pellets were mounted on the same foam board. Gold foils and cadmium covered gold foils as well as indium foils and cadmium covered indium foils (for the shorter irradiations) were used to determine the thermal neutron flux. Sulfur pellets were used to measure the fast neutron flux (> 1 MeV) via the $^{32}S(n,p)^{32}P$ reaction. The sulfur pellets were evaluated at Sandia laboratory[6].

In addition, the neutron flux was monitored using a low efficiency (nominally η=.001) ^{3}He transmission detector. The ^{3}He detector was mounted in the collimated neutron beam ~130 cm from the target. Also monitored were the gamma and neutron background in the room.

The activation foils and the ^{3}He detector measure the thermal neutron flux, which we take to be neutrons below 0.5eV. The sulfur pellets and the transistors are sensitive to fast neutrons above 1 MeV. The measured thermal neutron flux was $4\cdot 10^7$ neutrons/s/cm^2 and the measured fast neutron flux was $2\cdot 10^7$ neutrons/s/cm^2. The thermal flux determined from the foils and the ^{3}He detector agree within 10%. We estimate the error of the fast neutron flux measurement to be 30%.

The energy dependent flux is compared to an MCNPX calculation [3]. The measured thermal flux (from activation foils and the ^{3}He monitor) is 30% of the simulated value and the fast flux (from the sulfur pellet activation) is 60% of the simulated value.

After each irradiation the transistor gain $h_{FE\Phi}$ was measured for several collector currents using the device tester. In order to compare the reciprocal gain shift of the transistors with the existing data from reactor irradiations it is necessary to calculate the 1MeV equivalent fluence Φ(1MeV) for the LENS neutron spectrum. Since the measured ratio of fast to thermal neutron flux is larger than in the simulation we scaled the simulated spectrum by 0.3 below 1 MeV and by 0.6 above 1 MeV before calculating Φ(1MeV). The overall scaling of the fluence for each run was derived from the ^{3}He detector.

Fig. 1 shows $1/h_{FE\Phi}$ for NPN and PNP transistors as a function of Φ(1MeV). The gains of transistors of the same type were averaged. The triangles represent irradiations at LENS, and the diamonds represent irradiations at the reactor. The green, yellow, pink and blue sets of data points correspond to different collector currents I_{CE}. As can be seen from Fig.1 the LENS data and reactor data agree quite well. The agreement between the two data sets supports our measurement of the neutron flux.

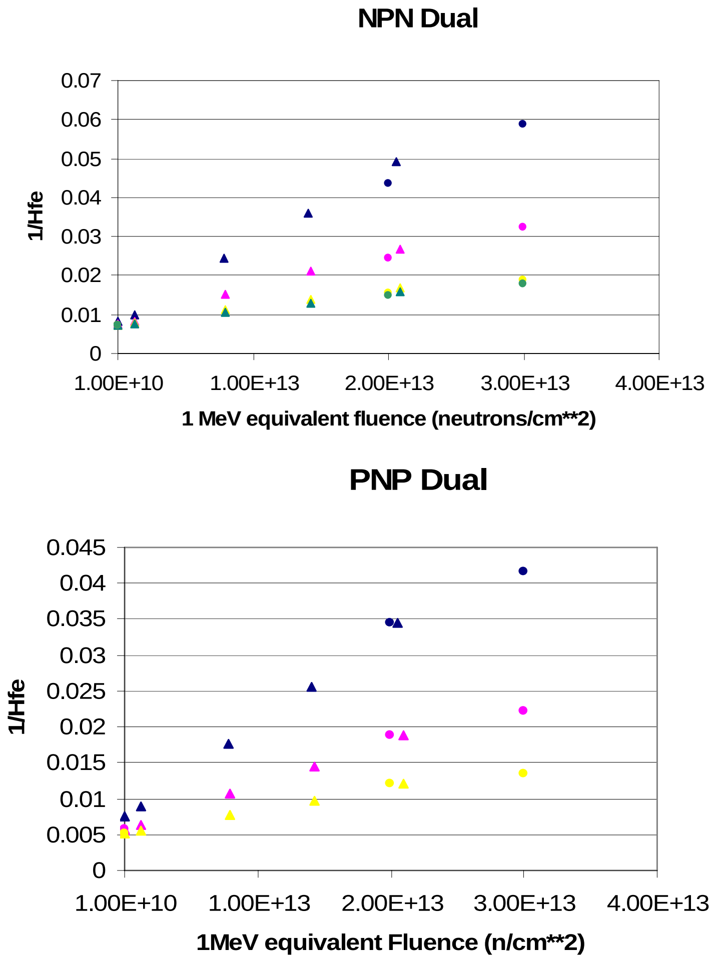

Figure 1: Inverse transistor gain as a function of fluence. The triangles represent irradiations with LENS, and the diamonds represent irradiations with a fast-burst reactor. The different color data points indicate different collector currents.

5. A first device test

We have also used the LENS beam to conduct a first SEE measurement of a microcircuit board with 150 nm feature size (see Fig. 2). The device was inserted into the moderator at the same position as the transistors. The device had first been demonstrated to be susceptible to upset from 50 MeV protons in the IUCF RERP beamline [7]. No upsets were induced in the device with the 5 MeV (maximum) neutrons produced by the current LENS configuration.

Figure 2: A microcircuit board is prepared for single event effect (SEE) testing at LENS.

Conclusions

LENS has been used for first radiation effects measurements in electronic devices. Radiation induced gain degradation in transistors indicate that the damage induced is comparable to that produced by nuclear reactors which have been the classical sources used to test military devices. Reactors are becoming less available in the United States as simulators. LENS promises to be a viable alternative to reactors for such device testing. The addition of a second, dedicated target station for radiation effects studies in electronics is anticipated.

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