Correlation of Neutron Dosimetry Using a Silicon Equivalent Proportional Counter Microdosimeter and SRAM SEU Cross Sections for Eight Neutron Energy Spectra

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***Abstract*—A silicon equivalent proportional counter microdosimeter (SEPCM) and 4 Mb SRAM were exposed to eight progressively hardened neutron energy spectra at the LANSCE ICE House facility. As the incident neutron energy spectra were hardened, the lineal energy spectra response from the SEPCM changed both in shape and in the number of lineal energy deposition events per incident neutron. The general trend of the 4 Mb SRAM single event upset (SEU) cross section was an increase for harder incident neutron energy spectra. Resulting dosimetric results were correlated to SEU cross sections.**

***Index Terms*—Neutron dosimetry, neutron radiation, silicon microdosimetry, single-event upsets (SEUs).**

I. INTRODUCTION

GALACTIC cosmic, solar particle, and trapped particle radiation produce neutrons in the atmosphere and also in spacecraft and aircraft structures and shielding [1], [2]. The neutron environment inside these crafts can produce single event upsets (SEUs) in onboard semiconductor devices [3]. Accurate dosimetric measurements are an important tool for understanding the rate of SEUs in semiconductor devices in neutron environments. Dosimetry experiments performed in this work measured the absorbed dose and the energy deposition spectrum of high energy neutrons to micrometer sized volumes of silicon that are similar in size to the sensitive volumes in modern integrated circuits.

The neutron energy spectrum produced at the Los Alamos Neutron Science Center (LANSCE) ICE House facility beamline is similar in shape to the neutron energy spectrum present in the atmosphere and inside aircraft and spacecraft [4]. Fig. 1 illustrates the similarity between the unmodified neutron energy spectrum used in these experiments at the ICE House and the neutron energy spectrum found in the atmosphere at 12 000 meters in altitude. Experiments were performed at the ICE House beamline using a silicon equivalent proportional counter microdosimeter (SEPCM). Also used in these experiments was a device under test (DUT) board containing a 4 Mb SRAM chip, and a remote computer that monitored the SEU rate induced by the incident neutrons. The DUT and the SEPCM were exposed to eight different (progressively hardened) neutron energy spectra at the ICE House "30L" beamline. Resulting dosimetric results were correlated to SEU cross sections. Previously published results correlated in-flight measurements of neutron fluence determined by a tissue equivalent proportional counter with in-flight SEU data [5]. To our knowledge the work presented here represents the first correlation of SEPCM measurements and SEU cross sections.

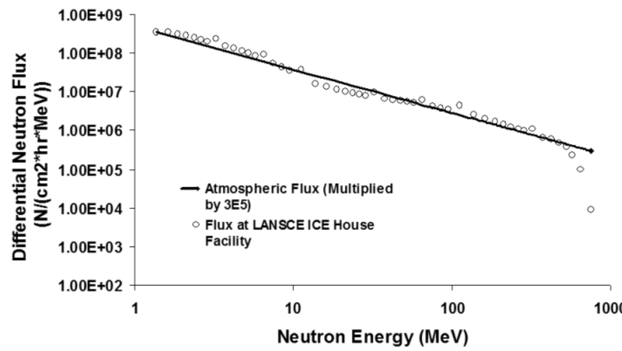

Fig. 1. Differential neutron flux at LANSCE ICE House facility, and neutron flux found in the atmosphere at an altitude of 12 000 m multiplied by 3×10^5.

II. MATERIALS AND METHODS

The neutron energy spectrum at the ICE House target area was generated by an 800 MeV pulsed proton beam that strikes a tungsten target causing spallation neutrons to be generated [6]. The absolute neutron intensities in the energy range from 1 MeV to 800 MeV were measured by a fission chamber and time of flight (TOF) system [7]. Fig. 2 illustrates the setup used in this series of experiments. The original neutron energy spectrum was modified using a polyethylene filter upstream of the sweep magnets on the flight path. After exposing the SEPCM and DUT to the original neutron energy spectrum, seven different thicknesses of polyethylene were used to harden the neutron energy spectra in a progressive fashion. The experimental

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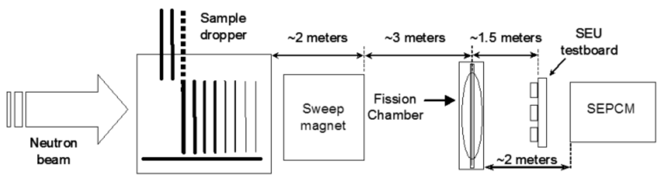

Fig. 2. Diagram of the experimental arrangement. During SEPCM measurements the DUT board was removed from the beamline.

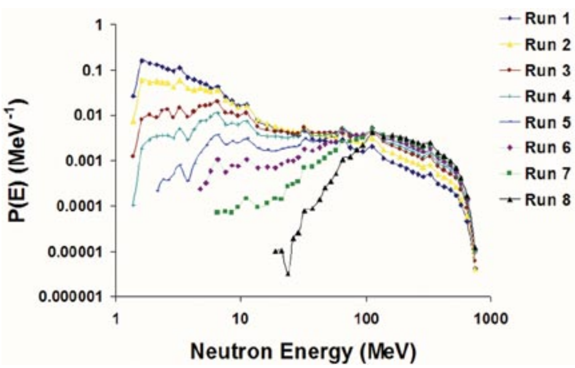

Fig. 3. Differential probability distribution of neutron energy spectra used in experimental Run 1 through Run 8.

runs were designated Run 1 through Run 8 with Run 1 using the unmodified spectrum, and Run 8 using the most hardened spectrum. The sweep magnet downstream of the polyethylene removed any secondary charged particles produced in the absorber, and the fission chamber TOF system determined each neutron energy spectrum (Fig. 3).

The SEPCM used in this series of experiments was a proportional counter that had a right cylindrical active volume 1.78 cm long and 1.78 cm in diameter. The walls of this right cylinder were fabricated from silicon and were 1.9 mm thick. The active volume of the SEPCM was filled with low-pressure propane gas. This low-pressure gas caused the active volume to simulate a right cylinder of silicon with a 2 micrometer diameter and length. This 2 micrometer diameter active volume can be treated like a Bragg–Gray cavity and absorbed dose can be accurately determined even if the low-pressure gas is not the exact same atomic composition as the silicon wall [8], [9]. An anode wire ran the length of the cylinder and was kept at a potential of 640 V relative to the cylinder walls. When energy was deposited in the SEPCM active volume by charged recoil particles produced by incident neutron collisions, charge was collected at the anode wire and the resulting signal was amplified.

During data analysis, the pulse height signals were combined to form a pulse height distribution. This distribution contained pulse height signals produced by the recoil silicon nuclei as well as lighter nuclei produced during neutron-silicon collisions. This distribution was then calibrated and converted into a lineal energy (y) deposition distribution (f(y) versus y). Lineal energy is defined as the energy deposited in the active volume by a single energy deposition event divided by the mean chord length through the active volume [10]. Units of lineal energy are keV/micrometer. Alpha particles from a Curium^{244} source deposited a known amount of energy in the active volume of the

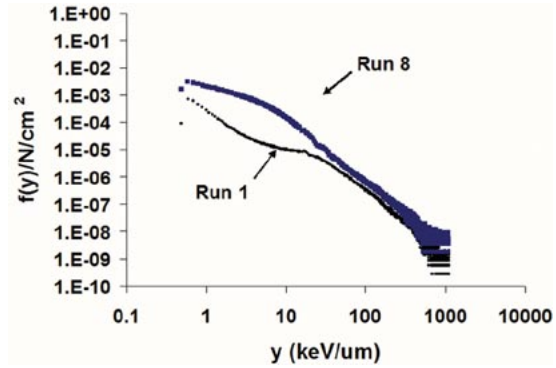

Fig. 4. Frequency distribution of SEPCM lineal energy spectra normalized per incident neutron per cm^2.

SEPCM and were used to calibrate the instrument before the neutron irradiations. The SEPCM measured a lineal energy (y) deposition spectrum ranging from 0.4–1024.0 keV/micrometer. Lineal energy spectra were produced by the SEPCM for each of the 8 incident neutron energy spectra in this experiment. The f(y) versus y spectrum was used to directly determine the correlation between SEU in the SRAM and the amount of energy deposition in a 2 micrometer diameter right cylinder of silicon. The f(y) versus y spectrum was also used to calculate the absorbed dose to silicon from the neutron radiation incident upon the SEPCM using

$$\text{Absorbed Dose} = \int C * yf(y)dy \tag{1}$$

where C is a constant to convert the energy deposited (keV/micrometer) into absorbed dose (Gy).

The dose mean lineal energy $\bar{y_D}$ was calculated by

$$\bar{y_D} = \frac{\int y^2 f(y)dy}{\int yf(y)dy}. \tag{2}$$

The dose mean lineal energy $\bar{y_D}$ (keV/micrometer) is the expectation value of the dose distribution of y. The dose distribution of y is a measure of the amount of dose delivered to the active volume by energy deposition events falling in a given lineal energy range [10].

The Motorola MCM6246 4 Mb SRAM was used to study the rate of SEUs by each of the incident neutron energy spectra. The SRAM was periodically scanned by a computer controlled software program to count the number of SEUs induced [11].

III. Results and Discussion

As the incident neutron energy spectra were hardened, the lineal energy spectra response from the SEPCM changed both in shape and in the number of lineal energy deposition events per incident neutron. The lineal energy spectra produced during Run 1 and Run 8 are shown in Fig. 4. The lineal energy spectrum from Run 8 (hardest incident neutron energy spectra) had a greater number of energy deposition events per incident neutron across the entire spectrum as compared to Run 1 (softest incident neutron energy spectra). The lineal energy spectrum from Run 8 also had a larger proportion of low lineal energy events compared to Run 1.

TABLE I
SUMMARY OF DATA CALCULATIONS.

Experimental Run Number	Expected Value of Neutron Energy Spectra (MeV)	AbsorbedDose/N/cm² (µGy/N/cm²)	Dose Mean Lineal Energy (keV/micron)
1	74.63	5.30E-06	144.89
2	112.85	7.55E-06	140.02
3	159.5	1.01E-05	127.79
4	180.85	1.18E-05	120.84
5	205.33	1.29E-05	116.88
6	222.96	1.39E-05	112.70
7	243.43	1.76E-05	101.73
8	265.45	2.30E-05	95.02

Table I presents the results of the absorbed dose and dose mean lineal energy calculations for each run, and also gives the expected value (weighted average) of the neutron energy spectrum for each respective run. Systematic error in the SEPCM was less than 10%. We note that absorbed dose per incident neutron increased with increasing beam hardness. For convenience, the increase in beam hardness is parameterized here by using the expected value of the incident neutron beam. This increase in absorbed dose per neutron for increasing beam hardness was caused by an increase in the number of events in the lineal energy spectra per incident neutron. The dose mean lineal energy $\bar{y_D}$ decreased as the beam hardness increased. Since $\bar{y_D}$ is the expected value of the dose distribution for each run, this means that as the incident neutron beam became harder, more of the absorbed dose to silicon was delivered by low lineal energy events. Modeling of neutron-silicon interactions for neutrons with incident energies of 50–2000 MeV have been published [12]. The results of this modeling predicted an increase in the number of high linear energy transfer (LET) particles produced and a proportionately larger increase in the number of low LET particles produced as the incident neutron energy increased [12]. These predictions are in excellent agreement with our experimental results.

The number of SEUs induced by each of the 8 incident neutron energy spectra were tallied and then normalized to determine the SEU cross section (#SEU/bit/total neutron fluence) in the DUT (Fig. 5).

The general trend of the SEU cross section was an increase for harder incident neutron energy spectra. A least squares regression was performed on the data points displayed in Fig. 5. It was found that an exponential function provided the best fit to the data. The regression line formula was

$$\frac{\frac{\frac{SEU}{\mathrm{N}}}{\mathrm{cm}^2}}{\mathrm{bit}} = (1 * 10^{-15})e^{0.0079}. \tag{3}$$

An SEU can be induced by the deposition of a sufficient amount of energy in a sensitive region of the DUT. This energy deposition can result in a charge being produced that is capable of causing an SEU. It has been estimated for devices similar to Motorola MCM6246 4 Mb SRAM that energy deposition of approximately 1000 keV/micrometer were needed to cause an SEU [13]. The number of events per incident neutron in the silicon equivalent microdosimeter lineal energy spectra above 1000 keV/micrometer was plotted for each of the 8 runs in Fig. 6. The general trend of the number of events with energy deposition above 1000 keV/micrometer was an increase for harder incident neutron energy spectra. A least squares regression was performed on the data points displayed in Fig. 6. The regression line formula was

$$\frac{\frac{\mathrm{Energy\ Deposition\ Events}}{\mathrm{N}}}{\mathrm{cm}^2} = (1 * 10^{-7})e^{0.0079}. \tag{4}$$

The regression fits for the data in Figs. 5 and 6 have R^2 values greater than 0.94 and the formulas differ only by the initial constant.

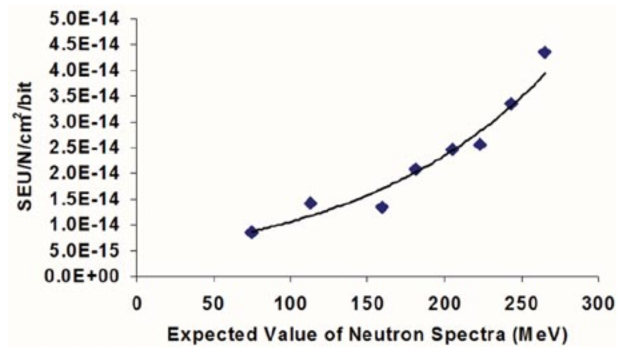

Fig. 5. SEU cross sections as a function of expected value of the incident neutrons energy spectra. The solid black line is the result of a least squares regression of the data points.

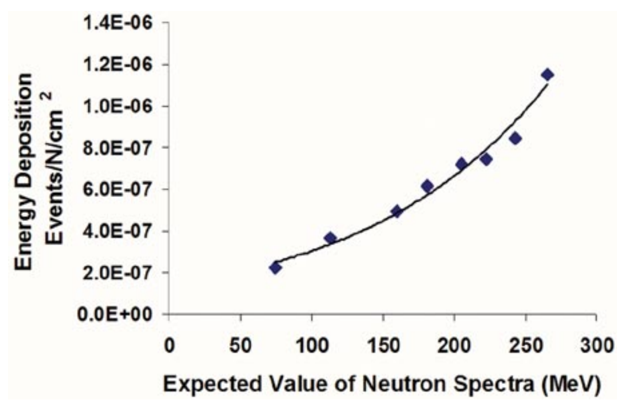

Fig. 6. Number of energy deposition events per neutron per cm^2 with lineal energy greater than 1000 keV/micrometer as a function of expected value of the incident neutrons energy spectra. The solid black line is the result of a least squares regression of the data points.

IV. Conclusion

Experiments were performed at the LANSCE ICE House facility. Microdosimetry and SEU data were obtained for eight progressively hardened neutron energy spectra. It was found that the absorbed dose per neutron to silicon increased as the neutron beam increased in average energy. The increase in absorbed dose was found to be caused by an increase in the number of energy deposition events in the detector active volume per incident neutron. It was further determined that the SEU cross section and the number of lineal energy events above 1000 keV/micrometer increased in value at a similar rate as the neutron beam increased in expected energy. This indicates that SEPCM instruments can be a useful tool in studying radiation effects on integrated circuits in neutron environments.

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