Results of Recent 14 MeV Neutron Single Event Effects Measurements Conducted by the Jet Propulsion Laboratory

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Abstract-- **This paper reports 14 MeV neutron induced single-event effects results for a variety of microelectronic devices that include an ADC, operational amplifiers, optocoupler, flash memory, PowerPC microprocessor, SRAM, and SDRAM. Data were collected to evaluate these devices for possible use in NASA spacecraft.**

I. INTRODUCTION

Previous works have demonstrated that the single event upset (SEU) effects on microelectronic circuits seem to be comparable in the high energy range between neutrons and protons [1]-[2]. The use of more available protons in place of neutrons for energies above 50 MeV is thus commonly accepted. However, at lower energies (e.g. below 50 MeV), differences between protons and neutrons are expected to show up due to the Coulomb interaction between the proton and the nucleus. Therefore, the use of protons instead of neutrons at low energy below, 50 MeV, is incorrect due to their lower interaction cross-section which leads to an underestimate of the SEE cross-section [2]-[4].

When a neutron, being electrically neutral, hits a device, it does not deposit any energy by direct ionization. However, it interacts with an elemental nucleus, for example, a silicon nucleus in a device region, and oxygen nucleus in the oxide layer, or a copper nucleus in the metal layer. This neutron–nucleus event initiates a nuclear reaction. There are two main types of neutron reactions that can create recoils which induce an SEE: elastic scattering reactions and non-elastic reactions [inelastic scattering, and reactions yielding light nuclei other than neutrons, e.g., (n, α), (n, p), etc.].

The most probable reactions for which 14 MeV neutrons can induce SEE in silicon are elastic, inelastic scattering events, and the non-elastic reactions (n, p), and (n, α). In a (n, α) reaction, that also produces a Mg recoil, the α particle has a limited range (about 55- 80 μm), depending on the energy after the reaction (8.35-11.7 MeV). The energy of a recoil Mg can be up to 3.6 MeV. The maximum energy of a recoil Al from (n, p) reaction is about 2 MeV. The maximum energy of a recoil Si from elastic and inelastic scattering can reach up to 0.5 and 1.6 MeV, respectively.

As indicated, the maximum energy recoil created by a 14 MeV neutron in Si is 3.6 MeV. Since it takes 3.6 eV to generate an electron-hole pair in silicon, this is equivalent to generating a total charge of 0.16 pC. Assuming the charge collection depth is 2 μm, we obtain a charge deposition gradient of 0.08 pC/μm, which is also known as the linear energy transfer, LET. Dividing this by the density of silicon (2.3 g/cm^3) we obtain the LET in more conventional units as 7.8 MeV-cm^2/mg. Thus, based on a 2 μm collection depth, the Mg recoil created by the 14 MeV neutrons has a LET of 7.8 MeV-cm^2/mg. Therefore, devices with heavy ion SEE LET thresholds greater than ~8 MeV-cm^2/mg would not be susceptible to 14 MeV neutrons. However, if the heavy ion SEE LET threshold is less than ~8 MeV-cm^2/mg, the part might be susceptible to the 14 MeV neutrons.

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The test results discussed in this paper were undertaken to establish the sensitivity of the electronic devices to 14 MeV neutron induced SEEs. SEE measurements were performed on 11 different types of CMOS and bipolar devices including an Operational Amplifier, an ADC's, a Voltage Regulator, a Comparator, an Optocoupler, Flash Memories, a PowerPC microprocessor, a SRAM, and SDRAMs. Most of the devices under study were previously tested with heavy ions and have heavy ion LET threshold less than 10 MeV-cm^2/mg.

II. EXPERIMENTAL PROCEDURE

A. Test Facility

The experiments were performed at the Boeing Radiation Effects Laboratory (BREL). The BREL uses a Kaman Sciences A711 neutron generator to provide a beam of 14 MeV neutron beam.

The A-711 neutron generator is a pumped, drift tube accelerator that is used as a positive ion electron accelerator. Deuterons are accelerated into the titanium tritide target by applying a voltage that is typically 160 kV and achieving a beam current of < 3 mA. The nominal neutron source strength is 1x10^{11} neutron/sec, but experience has shown that even for a new tube, the source strength is less than this, approximately 7-8x10^{10} neutron/sec and it decreases further with use.

The neutron dosimeter used is the PDM-303 made by the Aloka Corporation in Japan. This neutron dosimeter has previously been used to monitor the neutron flux [5]. Two PDM-303 dosimeters were used for each test exposing the various devices under test (DUTs) to the neutrons. The equivalent neutron fluence was calibrated based on neutron fluxes measured with activation foils.

B. Device description

We performed the 14 MeV neutron induced SEE tests on the devices listed in Table I. Also, in this table for devices that heavy ion data is available, the corresponding LET threshold and saturated cross section are shown.

III. TEST RESULTS AND DISCUSSION

1) LTC2052 Op Amp

The part is a quad amplifier and consists of two die. Each die contains two amplifiers. A printed circuit board was fabricated to mount the test device as well as the resistors and the bypass capacitor. A series of 0.1µF bypass capacitors were used on the V_+ and V_- pins. All of the amplifiers were connected together in series so that the four amplifiers could be monitored for functionality during the test by observing the output of the last amplifier. A 1 kHz sine wave was fed into the first amplifier, because the amplifiers were connected in series, the signal passed through all four of the amplifiers. The output of the last amplifier was monitored using an oscilloscope. The monitored output was loaded with 2 kΩ resistors and connected to a high-speed buffer amplifier.

TABLE I
SUMMARY OF HEAVY ION SEE DATA FOR PARTS TESTED WITH 14 MEV NEUTRON

Device	Heavy Ion SEE LET Threshold (MeV-cm^2/mg)	Heavy Ion SEE Saturated Cross Section (cm^2)
LTC2052 Op Amp	$\mathrm{LET}_{th} < 8$ (SEL) [6]	1x10^{-4}
LTC1609 ADC	$5 < \mathrm{LET}_{th} < 8$ (SEL) [7]	1x10^{-3}
6N134 Optocoupler	$\mathrm{LET}_{th} \sim 0.5$ (SET) [8]	2.5x10^{-3} at LET = 30 MeV-cm^2/mg
LM139 Comparator	$\mathrm{LET}_{th} \sim 2$ (SET) for 20 mV Δ V [8]	3x10^{-3}
LM117HVH Voltage Regulator	$\mathrm{LET}_{th} < 3.5$ (SET) [9]	1x10^{-3}
K9F1G08UOM NAND Flash	$\mathrm{LET}_{th} \sim 3$ (SEU), $\mathrm{LET}_{th} \sim 10$ (SEFI) [10]	2x10^{-11} (SEU) per bit, 3x10^{-6} (SEFI) per device
S29JL0644 NOR Flash	$\mathrm{LET}_{th} \sim 8$ (SEU), $\mathrm{LET}_{th} \sim 8$ (SEFI) [11]	5.7x10^{-12} (SEU) per bit, 3x10^{-7} (SEFI) per device
UT8CR512K32 SRAM	$\mathrm{LET}_{th} \sim 1.5$ (SEU) [12]	5x10^{-9}
MPC7448 PowerPC	$\mathrm{LET}_{th} < 1.7$ (SEU), $1.7 < \mathrm{LET}_{th} < 3.5$ (SEFI) [13]	9.2x10^{-10} (SEU) per bit, 9x10^{-7} (SEFI) per device
K4S510432M SDRAM	No data available	No data available
MT48LC128M4A2 SDRAM	No data available	No data available

During irradiation, the current and voltage for V_+ and V_- power supplies were monitored and recorded. A Hewlett-Packard (HP) 6629A power supply was used to power the circuit. The V_+ voltage was set to 5.25 V and the V_- voltage was set to -5.25 V. The nominal current for the supplies were 4 mA and -4 mA, respectively. The power supply clamp currents for both supplies were set to 30 mA and latchup detection threshold currents were set to 20 mA. The power supply could shut down power within about 100 ms after a high-current condition occurred in either of the power supplies. The test system software was able to detect single event latchups (SELs).. The software controls the power supply voltage, and monitors the supply current to the device under test (DUT). The software provides automatic latchup detection and latchup counting. The software also records a strip chart of power supply currents and voltages.

The radiation testing was performed while the device was at an elevated temperature of 85^{o} C. The DUT distance from neutron source was 21 cm which provides a flux of 8x10^6 neutrons per cm^2 per second. No SEL events were detected for a fluence of 2x10^{10} neutrons per cm^2. The limiting cross section was calculated from the null result as 1.9 x 10^{-10} cm^2, based on 95% probability (approximately two standard deviations).

2) LTC1609 ADC

For the LTC1609 latchup test at BREL, we used an in-house fabricated printed circuit (PC) board as opposed to the manufacturer's evaluation board. This was done because of the difficulties of shielding the support electronics on the manufacturer's evaluation boards from neutron exposure. For the in-house boards, all of the support electronics were placed away from the direct neutron beam. This PC board provides necessary voltages, clock, input signal required by the DUT and provides a means of monitoring the output signal. A Hewlett-Packard 6629A quad power supply was used to power the test circuit. Two of the four supplies available on the HP6629 were used to power the LTC1609, one supply for $V_{digital}$, and one supply for V_{analog}. A third supply was used to power the support DAC. All three supplies were set to +5.25 V. The power supply clamp currents were set to 50 mA and threshold currents were set to 20 mA for all supplies. SELs were detected via the test system software.

The radiation testing was performed while the device was at an elevated temperature of 85^o C. The DUT distance from the neutron source was 21 cm which provided a flux of $8x10^6$ neutrons per cm^2 per second. No SEL events were detected after a fluence of $2x10^{10}$ neutrons per cm^2. The limiting cross section was calculated from the null result as 1.9 x 10^{-10} cm^2.

3) 6N134 Optocoupler

For this test, a -5 V power supply was connected to the GND pin and the V_{cc} pin was grounded. This arrangement allowed the output pull-up resistor to be connected to ground through a 50 Ω terminator thereby establishing an output voltage of approximately 5 V. The circuit configuration used for testing used a 2.4 k pull-up resistor that was connected to a terminated coaxial cable which eliminates effects of capacitive loading from a more conventional instrumentation (such as a line driver). This allowed very fast transients to be observed. However, the output circuit effectively functions as an attenuator, reducing the normal 5 V switched signal at the output by a factor of 50. Output transients were captured with a Tektronix TDS784 oscilloscope and stored on a computer for analysis. The effective threshold level for transient capture was 200 mV, taking the attenuation factor of 50 into account. The stored waveforms were examined later, applying various criteria to select a subset of the transients that were captured during testing. The radiation testing was performed at room temperature. A total of 1061 single event transient (SET) events were detected for $1.6x10^{10}$ neutrons per cm^2. The 14 MeV neutron SET cross section is $6.6x10^{-8}$ cm^2.

4) LM139 Comparator

The same approach as that used for the 6N134 was used to measure transients for the LM139. The input delta voltage for the LM139 was set to 20 mV. No SET events were observed for a fluence of $2.9x10^9$ neutrons per cm^2. This establishes a limiting cross section of 1.3 x 10^{-9} cm^2 for that device with a 20 mV input delta voltage.

5) LM117HVH Voltage Regulator

The LM117HVH, manufactured by National Semiconductor Inc, was tested for SETs. An input voltage of 30 V was used that was bypassed with a 10 μF tantalum capacitor. The output voltage was set to 5 V. The output was loaded with a 0.1 μF capacitor. A buffer amplifier was used to drive the coaxial cable between the output of the device and the oscilloscope. The supply current was about 5 mA. A heat sink was used. The oscilloscope trigger was set to trigger on deviation above 200 mV at the DUT. No SET events were observed for fluence of $1.3x10^{10}$ neutrons per cm^2. This establishes a limiting cross section of $2.9x10^{-10}$ cm^2.

6) K9F1G08UOM 1Gb NAND Flash Memory

The Samsung K9F1G08UOM is a 1Gb NAND flash memory organized as 128Mx8 bit.

The Avnet FPGA board with Xilinx Virtex 2PRO was used to test the 1 GB flash memory. The DUTs were erased / verified / programmed and read (EVPR) before exposing them to neutrons. Upon observing any single effect functional interrupt (SEFI), the power to the DUTs was recycled, and the EVPR sequence applied for the next run. The Avnet FPGA board was heavily shielded to prevent upsets from neutrons. The DUT distance from the source was 21 cm. Only one SEU was detected for a fluence of $3.45x10^{10}$ neutrons per cm^2. No SEFI was detected. Based on the observation of one event, the 14 MeV neutron SEU cross section is $2.9x10^{-20}$ per bit per cm^2. This establishes a limiting SEU cross section of $1.1x10^{-19}$ per bit per cm^2. The limiting SEFI cross section is $1.1x10^{-10}$ per cm^2 per device.

7) S29JL0644 64Mb NOR Flash Memory

Spansion S29JL0644 is a 64 Mb NOR flash memory. The Avnet FPGA board with the Trenz FPGA board (Spartan IIe) was used for testing. The DUTs were erased / verified / programmed and read (EVPR) before exposure to neutrons. Upon observing any single effect functional interrupt (SEFI), the power to the DUTs was recycled, and the EVPR sequence applied for the next run. The Avnet FPGA board was heavily shielded to prevent upsets from neutrons. No SEU event was detected after irradiating the DUT with $2x10^{10}$ neutrons per cm^2. The limiting SEU cross section is $2.9x10^{-18}$ per bit per cm^2 and the limiting SEFI cross section is $1.9x10^{-10}$ per device per cm^2.

8) MPC7448 PowerPC

The Motorola 7448 PowerPC is fabricated with SOI technology. It uses a partially depleted technology without body ties. It has a feature size of 90 nm with a silicon film thickness of 55 nm and internal core voltage of 1.3 V. It is packaged with "bump bonding" in flip-chip ball-grid array (BGA) packages. Radiation testing was done at a clock frequency of 1600 MHz using a commercially available evaluation boards manufactured by Motorola for each processor type. The test methodologies used to measure upset errors in the D-cache, registers and hangs are discussed in detail in [12]. A total of 63 D-Cache SEUs were observed while 1 SEFI was detected after irradiating the DUT to 1.91x10^{10} neutrons per cm^2. The 14 MeV neutron D-Cache SEU cross section is 1.3x10^{-14} cm^2 per bit. The limiting SEFI cross section is 2.7x10^{-10} per device per cm^2.

9) UT8CR512K32 16Mb SRAM

UTMC UT8Q512K32 is a 16Mb asynchronous SRAM organized as 524,288x32 bit. A test program was developed to use with the Trenz FPGA board with Xilinx Spartan IIe. To simulate the real application of SRAM devices, each DUT was programmed with a random pattern. The pattern was read back during irradiation to verify data retention. The Trenz FPGA board was heavily shielded to prevent upsets from neutrons. The DUT distance from the neutron source was 28 cm. A total of 60 SEUs was measured after irradiating the DUT with 9.5x10^9 neutrons per cm^2. No SEFI was detected. The 14 MeV neutron SEU cross section is 3.9x10^{-16} per bit per cm^2. The limiting SEFI cross section is 3.9x10^{-10} cm^2 per device.

10) K4S510432M 512 Mb SDRAM

Samsung K4S510432M is a 512Mb SDRAM organized as 128Mx8 bit The 3MTS general purpose tester was used to test the SDRAMs at 100 MHz. To mimic real life use of SDRAMs, a random pattern was applied to the DUTs during irradiation. The 3MTS was heavily shielded from neutrons.

The measurements were performed at room temperature. The DUT distance from neutron source was 28 cm. Only the first 64 Mb of the SDRAM were tested. A total of 14 SEUs were observed while 4 SEFIs were detected after irradiating the DUT to 1.27x10^{10} neutrons per cm^2. The 14 MeV neutron SEU and SEFI cross sections are 1.7x10^{-17} cm^2 per bit and 3.1x10^{-10} cm^2 per device, respectively.

11) MT48LC128M4A2 512 Mb SDRAM

Micron MT48LC128M4A2 is a 512Mb SDRAM organized as 128Mx8 bit. The 3MTS was used to test the SDRAMs at 100MHz. To mimic real life use of SDRAMs, a random pattern was applied to DUTs during irradiation.

The measurements were performed at room temperature. The DUT distance from the neutron source was 25 cm. Only the first 64 Mb of the SDRAM were tested. No SEUs were observed while 5 SEFIs were detected after 3.1x10^9 neutrons per cm^2. The 14 MeV neutron SEFI cross section is 1.6x10^{-9} cm^2. The 14 MeV neutron SEU is 1.9x10^{-17} per bit per cm^2.

IV. SUMMARY

We have presented 14 MeV neutron SEE data for a variety of commercial CMOS and bipolar devices including an Operational Amplifier, an ADC, a Voltage Regulator, a Comparator, an Optocoupler, Flash Memories, a PowerPC microprocessor, a SRAM, and SDRAMs. Most of the devices under study were previously tested with heavy ions and have heavy ion LET threshold less than ~10 MeV-cm^2/mg. Six of eleven devices under study did not produce upsets during 14 MeV neutrons tests. However, relatively low fluences approximately 1-2x10^{10} n/cm^2 were used for these tests, which is too low to produce upsets for devices that have low cross sectio results indicate that the devices with heavy ion threshold below ~8 MeV-cm^2/mg might be susceptible to 14 MeV neutron SEE's. We summarized our SEE test results in table II.

TABLE II
THE SUMMARY OF 14 MEV NEUTRON SEE MEASUREMENTS

Device	14 MeV Neutron SEE Cross Section (cm^2)	14 MeV Neutron SEFI Cross Section per device (cm^2)
LTC2052 Op Amp	1.6x10^{-10} (SEL)	NA
LTC1609 ADC	1.6x10^{-10} (SEL)	NA
6N134 Optocoupler	6.6x10^{-08} (SET)	NA
LM139 Comparator	1.3x10^{-09} (SET) for 20 mV Δ V	NA
LM117HVH Voltage Regulator	2.9x10^{-10} (SET)	NA
K9F1G08UOM NAND Flash	1.1x10^{-19} per bit (SEU)	1.1x10^{-10}
S29JL0644 NOR Flash	2.9x10^{-18} per bit (SEU)	1.9x10^{-10}
MPC7448 PowerPC	1.3x10^{-14} per bit (SEU)	2.7x10^{-10}
UT8CR512K32 SRAM	3.9x10^{-16} per bit (SEU)	3.9x10^{-10}
K4S510432M SDRAM	1.7x10^{-17} per bit (SEU)	3.1x10^{-10}
MT48LC128M4A2 SDRAM	1.9x10^{-17} per bit (SEU)	1.6x10^{-09}

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