Test Results of Single-Event Effects Conducted by the Jet Propulsion Laboratory

Farokh Irom and Tetsuo F. Miyahira

***Abstract*-- This paper reports recent single-event effects results for a variety of microelectronic devices that include ADC, DAC, DDS, MOSFET driver, analog switch, oscillator, and zero delay buffer. The data was collected to evaluate these devices for possible use in NASA spacecraft. Six of ten devices under study were sensitive to SEL, and the latchup was destructive.**

***Index Terms*—Cyclotron, heavy ion, SEE, Latchup**

I. Introduction

Electronic devices used in satellites and other spacecraft are exposed to cosmic radiation. To insure reliability of these devices, the effects of radiation should be carefully studied. The primary method used to evaluate the radiation reliability of an electronic device is to measure its single event effect (SEE) cross section as a function of ionizing power of the ion beam. Many SEE results for space applications have been published previously [1-4].

The studies discussed in this paper were undertaken to establish the sensitivity, of the electronic devices, to single event latchup (SEL) and single event upset (SEU). SEE measurements were performed on ten different types of CMOS devices including ADC's, DACs, analog switches, MOSFET drivers, digital synthesizers, delay buffers and crystal oscillators.

II. EXPERIMENTAL PROCEDURE

A. Test Facilities

Heavy ion SEU measurements were performed at two facilities. The SEU Test Facility located at the Brookhaven National Laboratory (BNL) and the Radiation Effects Facility located at the Cyclotron Institute Texas A&M University (TAM). The BNL facility uses a twin Tandem Van De Graaff accelerator while the TAM facility uses an 88" cyclotron. Both facilities provide a variety of ion beams over a range of energies for testing. Ion beams used in our measurements are listed in Table I for BNL and Table II for TAM. LET and range values are for normal incident ions. At both facilities, test boards containing the device under test (DUT) were mounted to the facilities test frame. Tests at BNL were done at vacuum with normal incident beam. Tests at the TAM facility were done in air with normal incident beam. Some of the parts were tested at both facilities. The tests at TAM facility can be done in air because of the higher energy ions available at this facility. The beam flux ranged from $1x10^3$ to $2x10^4$ ions/cm^{2}sec.

Table I. List of the ion beams used in our measurements at BNL.

Ion	**Energy** (MeV)	**LET** (MeV-cm^2/mg)	**Range** (μm)
F^{19}	141	3.4	122
Si^{28}	182	8.0	74
Si^{28}	117	10.0	42
Cl^{35}	199	11.7	59
Ti^{48}	193	19.8	40
Ni^{58}	265	26.6	42
Br^{81}	279	37.5	36
I^{127}	320	59.7	31

Table II. List of the ion beams used in our measurements at TAM.

Ion	**Energy** (MeV)	**LET** (MeV-cm^2/mg)	**Range** (μm)
Ar^{40}	519	8.5	186
Cu^{63}	757	19.9	129
Kr^{84}	1886	20.4	290
Xe^{129}	2814	40.3	244
Ho^{165}	1808	70.0	114
Au^{197}	2127	86.3	112

B. Experimental Methods

In general, the test setup consisted of a computer, power supplies, and test boards specially designed for the device to be tested. A computer-controlled HP6629A power supply provides precision voltage control, current monitoring and latchup protection. Single event latchups were detected via

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Farokh Irom is with the Jet Propulsion Laboratory, California Institute of technology Pasadena, CA 91109 (telephone: 818-354-7463, e-mail: farokh.irom@jpl.nasa.gov.

Tetsuo F. Miyahira is with the Jet Propulsion Laboratory, California Institute of technology Pasadena, CA 91109 (telephone: 818-354-2908, e-mail: tetsuo.f.miyahira@jpl.nasa.gov.

the test system software. The software controls the power supply voltage and monitors the supply current. The software also provides a strip chart of power supply measurements. In some cases a separate computer was used to monitor functionality of the test board.

At both facilities, DUTs were tested at room temperature as well as at an elevated temperature. The elevated temperature depended on the DUT specification [5]. To determine each cross section point, either a minimum of fifty latchup events were accumulated or a beam fluence of 10^7ions/cm^2 was used.

The SEU measurements included the saturation cross sections and the linear energy transfer (LET_{th}) threshold. The LET_{th} is the minimum LET value necessary to cause a SEU at a fluence of $1x10^7$ ions/cm^2.

III. Test Results and Discussion

A) *LTC1604*

The Linear Technology LTC1604 is a 333ksps, 16-bit Analog to Digital Converter, (ADC), that draws 220mW from ±5V supplies.

Two of the available supplies on the HP6629 were used to power the DUT. One supply was used for $V_{digital}$, and one supply for V_{analog}. Both supplies were set to +5.25V. A third supply was used to power a support circuit, Demonstration Circuit 718 (DC718), provided by Linear Technology. The DC718 is a computer-hosted digital data acquisition system that when used with the evaluation software, QuickEval-II, provided the functionality feedback used during the test.

The measurements were performed at the TAM facility. The LTC1604 was tested at room temperature and at 85ºC. SELs were observed at a LET of 70.0 MeV-cm^2/mg but no latchups were observed at a LET of 55.0 MeV-cm^2/mg. The latchup LET threshold is between 55 and 70 MeV-cm^2/mg. In figure 1, we compare the result of room temperature measurements with that of the heated measurements. As one might expect, the latchup cross section is higher for the heated device [5].

Previously, SEL measurements were performed on the LTC1604 at BNL facility [6]. In these measurements one device (different date code) was tested. The I^{127} ion beam at 3 different incident angles was used to perform the measurements. Incident angles of 0, 37 and 60 degrees resulted in an effective LET of 59.5, 74.5 and 119.1 MeV-cm^2/mg which corresponds to the range of 29.5, 23.6 and 14.75 μm. No SEL event was detected for LTC1604 up to a LET 119.1 MeV-cm^2/mg. The discrepancy between the BNL and TAM data is caused by the fact that LTC1604 is a commercial part and there might be variation in the radiation characterization from different date codes. Furthermore, the range of the ion used in the BNL measurements is not enough to cause latchup in a CMOS device. In general, SEL involves deeper regions in the CMOS device (greater than 40 μm) as contrasted with Single event Upset (SEU). The ion ranges used in the BNL measurements were below 29.5 μm and at highest LET (119.1 MeV-cm^2/mg) it was 14.75 μm.

Our latchup measurements indicate that LTC1604 is not highly sensitive to latchup. The cross section is relatively small, and rises to about 10^{-6} at high LETs. The LTC1604 was tested for destructive latchup by turning off latchup protection. When the device went into a latchup state, the supply current increased to 600mA. The lack of an output signal from the device indicated that the device was not functioning in this high current state. To determine if this condition was recoverable, the beam was turned off and the device was power cycled. The device did not recover, after power cycling, indicating that device had been destructively failed.

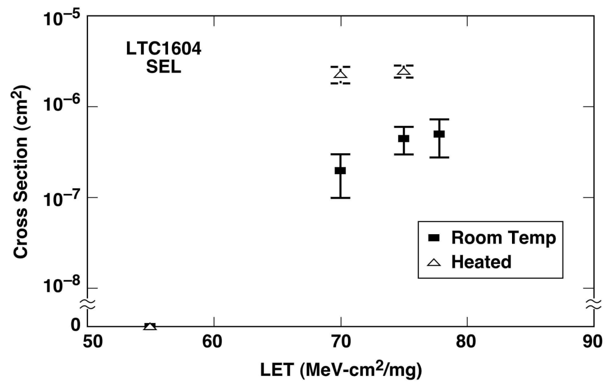

Fig. 1. Comparison of data obtained at room temperature with the heated measurement for LTC1604. Measurements were performed at the TAM.

B) *LTC1609*

The Linear Technology LTC1609 is a 200ksps, serial 16-bit ADC that draws 65mW from ±5V supplies.

The LTC1609 serial ADC was tested for SEL at both facilities. For the test at the BNL facility, we used an in-house fabricated PC board. This board provides necessary voltages, clock, input signal to the DUT and monitors output signal. Two devices were tested. Both devices were tested at room temperature and one of the two devices was also tested at an elevated temperature of 85ºC. At room temperature, the latchup LET threshold is between 8.0 and 11.7 MeV-cm^2/mg. For the heated device, the latchup LET threshold is between 5.3 and 8.0 MeV-cm^2/mg. Figure 2 shows the results obtained at the BNL facility for the two devices that were tested at room temperature. This data indicates that LTC1609 is sensitive to latchup, and has an LET threshold of about 10 MeV-cm^2/mg. The cross section is relatively small, at low LETs, and gradually increases to about $5x10^{-4}$ at high LET (saturation cross section).

Also, the LTC1609 was tested for latchup at the TAM facility using the manufacturer's evaluation board.

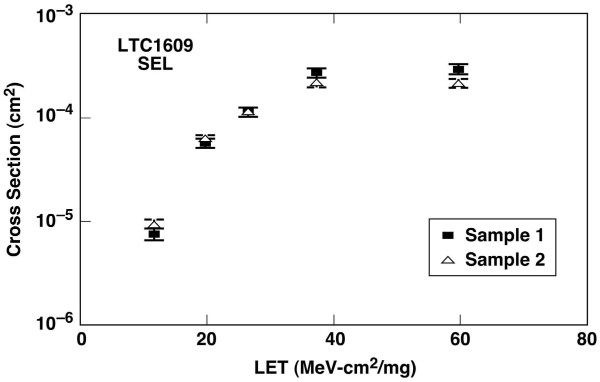

Fig. 2. Comparison of data obtained for two samples at room temperature for LTC1609. Measurements were performed at the BNL.

For the test at the TAM facility, only one of the four supplies available on the HP6629 was needed to provide the 5.25 V required by the evaluation board. Another of the four supplies was used to power a support circuit, a DC718, provided by Linear Technology.

In figure 3, we compare room temperature measurements and heated measurement taken at both facilities. The square symbols represent the room temperature measurements taken at the BNL and the TAM facilities. The triangle symbols represent the heated measurements taken at the BNL and the TAM facilities. Although, the TAM facility ions have longer range, there is very little difference between the two sets of data. As one might expect, the latchup cross section is higher for the heated measurements. There was a factor of 1.5 - 2 increase in latchup cross section for the heated device which is much less than the increase between heated and room temperature for LTC1604.

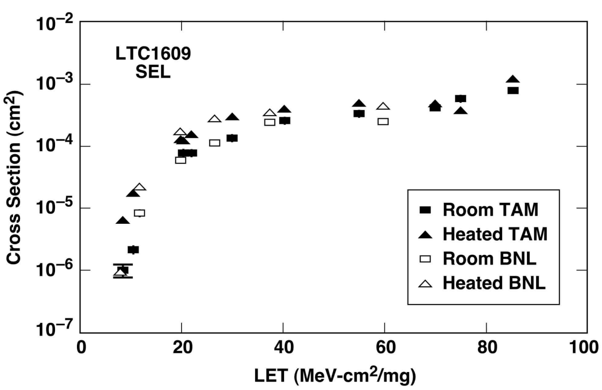

Fig. 3. Comparison of data obtained at TAM facility and BNL facility for both room temperature and heated measurement for LTC1609.

We tested LTC1609 for destructive latchup. During the irradiation, with latchup current protection turned off, the supply current increased to 1.2A and the lack output signal from the device indicated that the device was not functioning. To determine if this condition was recoverable, the beam was turned off and the device was power cycled. The device did not recover and therefore had been destructively damaged.

C) LTC1595

The Linear Technology LTC1595 is a 16-bit serial Digital to Analog Converter (DAC). A printed circuit board was fabricated to test the device. This board provides necessary voltages and a serial input to the DUT. Two devices were tested at room temperature. One of the two devices was also tested while heated to 85ºC. At room temperature, the latchup LET threshold is between 10.0 and 11.7 MeV-cm^2/mg. For the heated device the latchup LET threshold is between 8.0 and 10 MeV-cm^2/mg.

In figure 4, we show our results for two devices that were tested at room temperature. This data indicates that LTC1595 is sensitive to latchup, and has an LET threshold of about 10 MeV-cm^2/mg. The cross section is relatively small at low LETs, gradually increasing to about 10^{-4} at high LET (saturation cross section).

In figure 5, we compare the average result of two room temperature measurements with the heated measurements. As one might expect, the latchup cross section is higher for the heated measurements. There was a factor of 1.5 to 2 increase in latchup cross section for the heated device.

We tested LTC1595 for destructive latchup. When the device was irradiated without latchup protection the device destructively failed.

D) LTC1864

The Linear Technology LTC1864 is a 250ksps, 16-bit ADC.

One of the supplies available on the HP6629 was needed to provide the 15V required by the evaluation board. The second of the four supplies was used to power DC718 support circuit, provided by Linear Technology.

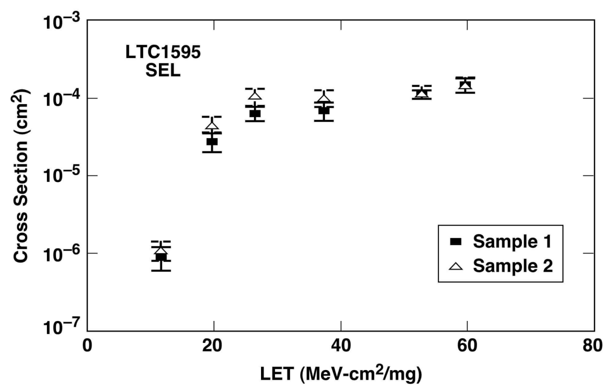

Fig. 4. Comparison of data obtained for two samples at room temperature for LTC1595. Measurements were performed at the BNL.

Latchups were observed at a LET of 8.5 MeV-cm^2/mg with the device at room temperature. The latchup saturated cross section was $5x10^{-5}$ cm^2.

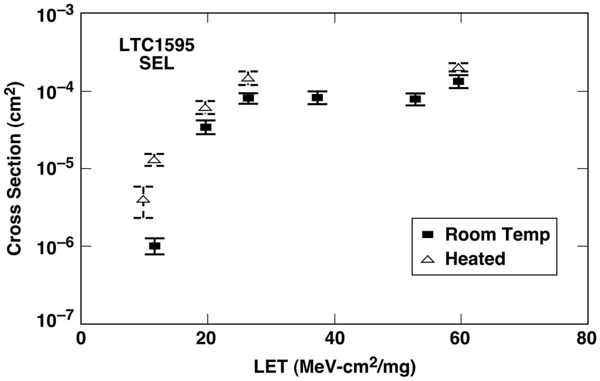

Fig. 5. Comparison of data obtained at room temperature with the heated measurement for LTC1595.

We tested the LTC1864 for destructive latchup. The device destructively failed when tested without latchup protection.

E) AD9858

The Analog Devices AD9858 is a direct digital synthesizer (DDS).

Evaluation boards and related software supplied by the manufacturer, Analog Devices, was used to interrogate the registers and monitor device functionality. The AD9858 was tested at the TAM facility for SEU and SEL.

1- SEU Test Results

The device exhibited SEU in the registers that change the operating conditions of the device. The effect of the SEU in the working registers was a change in the output waveform of the device. The LET threshold of the device was 7.5 MeV-cm^2/mg while the saturation cross section was 8.8×10^{-5} cm^2. Two samples were tested at the TAM facility and showed statistically identical results. In figure 6, we show the SEU results for the two samples.

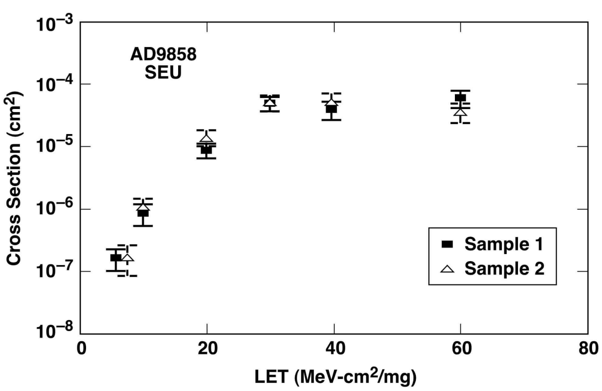

Fig. 6. Comparison of data obtained for two samples at room temperature for AD9858. Measurements were performed at the TAM.

2- SEL Test Results

Two devices were tested for latchup at the TAM facility. These devices experienced SEL at a LET of 10 MeV-cm^2/mg with a saturation cross-section of 4×10^{-5} cm^2. The result of the SEL measurements for two samples is shown in figure 7. The latchup was seen to be non-destructive in all cases and conditions. The device was left in the latchup state for 24 hours with no obvious degradation in operation once removed from latchup state.

We note that recent SEE measurements of the older DDS devices, AD9850 and AD9851[7], provided similar results in terms of the SEU and SEL cross sections compared to our measurements for AD9858.

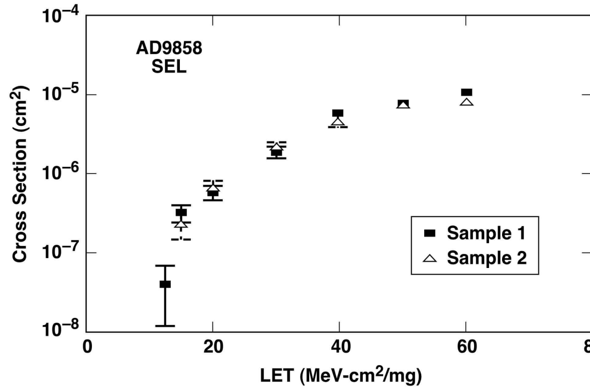

Fig. 7. Comparison of data obtained for two samples at room temperature for AD9858. Measurements were performed at the TAM.

F) TC4423

The Microchip TC4423 is a 3A, dual output buffers/MOSFET driver.

Printed circuit boards were fabricated to mount the test devices as well as the resistors, and bypass capacitors used to configure the test circuit.

Two devices were tested at room temperature and one device was tested at an elevated temperature of 125ºC. The TC4423 was tested at both TAM and BNL facilities. No latchups were observed for either the heated or the non-heated devices up to a LET of 86.3 MeV-cm^2/mg.

G) DG412 and DG413

The Maxim DG412 and DG413 are quad, single-pole/single-throw (SPST) analog switches.

The four analog switches were daisy-chained together so that an input signal could be fed into the first switch and the signal sequentially fed into the other three switches. Printed circuit boards were fabricated to test the devices. This board provides necessary voltages and input signal buffer to the DUT. This board also, provides visual feedback that allows the DUT to be monitored during testing. The DG412 and DG413 were tested at both TAM and BNL facilities. Two devices were tested at room temperature and one of the two devices was also tested at an elevated temperature of 125ºC. No latchups were observed for either the heated or the non-heated devices up to a LET of 86.3 MeV-cm^2/mg.

H) CY23FS08 Failsafe Buffer

The Cypress CY23FS08 is a Zero Delay Failsafe Buffer. A printed circuit board was fabricated to test the device. This board provides necessary voltages, clocks to the DUT and monitors its functionality. Two devices were tested at the TAM facility. Both devices were tested at room temperature and one was also tested at an elevated temperature of 85ºC.

Latchups were observed at a LET of 70 MeV-cm^2/mg at an elevated temperature of 85ºC. Latchups were observed at a LET of 86.3 MeV-cm^2/mg at room temperature and an elevated temperature of 85ºC.

In figure 8, we compare the results from room temperature measurements with that of heated measurements. The latchup LET threshold for room temperature is between 75 to 86 MeV-cm^2/mg. The latchup LET threshold for the heated measurements is between 55 to 70 MeV-cm^2/mg.

The device was tested for destructive latchup by turning off the latchup protection. During irradiation, the device current went up to 220mA. After stopping the irradiation and power cycling, the current went down to 7mA and the device was functioning. This device did not experience destructive latchup.

This device shows extreme sensitivity to SEU, even at a low LET such as 8.5 MeV-cm^2/mg.

I) VPC1 Crystal Oscillator

The VPC1 programmable crystal-controlled oscillators operate at 160 MHz while providing a jitter as low as 7 ps.

The crystal, which was placed on top of the IC, was moved to the side to allow the ions to strike the IC unimpeded (without having to pass thought the crystal). The VPC1 was tested at the TAM facility. Two devices were tested at room temperature and one was also tested at an elevated temperature of 85° C. No latchups were observed for either the heated or the non-heated devices. The V+ and V- supply voltage was increased to 3.6 V and latchup measurements were repeated. Again, no latchups were observed for either the heated or the non-heated devices at a LET of 86.3 MeV-cm^2/mg.

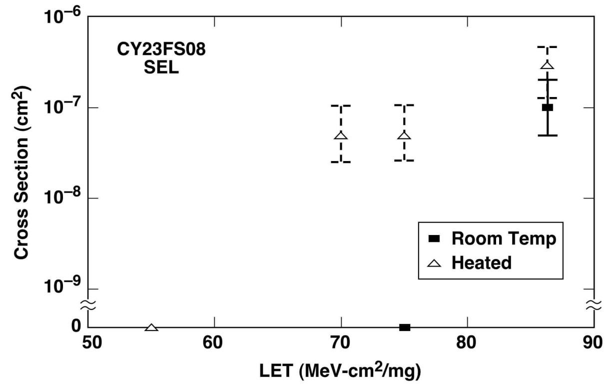

Fig. 8. Comparison of data obtained at room temperature with the heated measurement for CY23FS08. Measurements were performed at the TAM.

IV. Summary

We have presented SEE data for a variety of commercial CMOS devices. The latchup measurements were performed at room temperature and an elevated temperature. The latchup cross section is higher for the heated measurements. Latchups were destructive for the following parts; LTC1604, LTC1609, LTC1595 and LTC1864, except for the AD9858 and CY23FS08. The TC4423, DG412, DG413 and VPC1 were latchup immune up to a LET of 86.3 MeV-cm^2/mg. We summarized our SEE test results in table III.

Table III. Summary of SEE test results.

Part Number	Manufacture	Device Function	Test Results LET in MeV-cm^2/mg; σ in cm^2/device
LTC1604	Linear Technology	Parallel 16-bit ADCs	SEL $LET_{th} > 55$; $\sigma_{SAT} \sim 1x10^{-6}$
LTC1609	Linear Technology	Serial 16-Bit ADCs	SEL $LET_{th} > 8$; $\sigma_{SAT} \sim 5x10^{-4}$
LTC1595	Linear Technology	Serial 16-Bit Multiplying DACs	SEL $LET_{th} \sim 10$; $\sigma_{SAT} \sim 1x10^{-4}$
LTC1864	Linear Technology	Serial 16-Bit ADCs	SEL $LET_{th} < 8.5$
TC4423	Microchip Technology	Dual High-Speed Power MOSFET Drivers.	SEL $LET_{th} > 86.3$
DG412	Maxim	Quad Analog Switch	SEL $LET_{th} > 86.3$
DG413	Maxim	Quad Analog Switch	SEL $LET_{th} > 86.3$
AD9858	Analog Devices	Direct Digital Synthesizer	SEU $LET_{th} \sim 7.5$; $\sigma_{SAT} \sim 9x10^{-5}$ SEL $LET_{th} < 10$; $\sigma_{SAT} \sim 4x10^{-5}$
CY23FS08	Cypress	Zero Delay Buffer	SEL $LET_{th} \sim 70$; $\sigma_{SAT} \sim 1x10^{-7}$
VPC1	VITE	*Crystal Oscillator*	SEL $LET_{th} > 86.3$

I. References

[1] M. V. O'Bryan, et al., "Current Single Event Effects Results for Candidate Spacecraft Electronics for NASA," 2004 IEEE Radiation Effects Data Workshop Record, pp. 10-18, 2004.

[2] L. Z. Scheick, "SEE Evaluation of Digital Analog Converters for Space Applications," 2001 IEEE Radiation Effects Data Workshop Record, pp. 62-66, 2001.

[3] M. V. O'Bryan, et al., "Single Event Effects Results for Candidate Spacecraft Electronics for NASA," 2003 IEEE Radiation Effects Data Workshop Record, pp. 65-76, 2003.

[4] J. R. Coss, "Device Susceptibility Update 1999-2000," 2001 IEEE Radiation Effects Data Workshop Record, pp. 106-126, 2001.

[5] A. H. Johnston, B. W. Hughlock, M. P. Baze and R. E. Plaag, "Effect of Temperature on Single-Particle Latchup," IEEE Trans. Nucl. Sci., Vol 38, pp. 1435-1441, Dec. 1991.

[6] Steven S. McClure, private communication.

[7] J. L. Wert et al., "Single Event Effects Test and Analysis Results from the Boeing Radiation Effects Laboratory (BREL)," 2005 IEEE Radiation Effects Data Workshop Record, 2005.