Results of Single-Event Latchup Measurements Conducted by the Jet Propulsion Laboratory

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***Abstract*-- This paper reports recent single-event latchup results for a variety of microelectronic devices that include an digital, analog, and CMOS. The data was collected to evaluate these devices for possible use in NASA spacecraft.**

I. INTRODUCTION

Radiation-induced latchup has been studied for many years [1-5]. The susceptibility to single event latchup (SEL) exists in all junction-isolated or bulk CMOS processes. The latchup is triggered when a charged particle strikes in the well substrate junction (the region with the largest charge collection depth) and deposits sufficient charge. If the voltage drop within the well due to the charge particle strike is above approximately 0.6 V, then it is possible for the vertical transistor to turn on. The amplified current from the vertical transistor then flows through the substrate region, making it possible to turn on a second parasitic bipolar transistor and initiate SEL. Regenerative feedback between the two sustains the latchup state.

Electronic devices used in satellites and other spacecraft are exposed to cosmic radiation. To insure reliability of these devices, the effects of radiation, in particular SEL should be carefully studied. Many SEL results for space applications have been published previously [6-10].

The studies discussed in this paper were undertaken to establish the sensitivity of the electronic devices to SEL. SEL measurements were performed on eight different types of CMOS devices including ADC's, line drivers and receivers, analog switches, logic phase-locked loop, multiplexers, transceivers, buffer/driver and digital isolators.

II. EXPERIMENTAL PROCEDURE

A. Test Facilities

Heavy ion SEL measurements were performed at two facilities. The Cyclotron Institute Texas A&M University (TAM) and the Test Facility located at the Brookhaven National Laboratory (BNL). The TAM facility uses an 88" cyclotron while the BNL facility uses a twin Tandem Van De Graaff accelerator. 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 TAM and Table II for BNL. 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 the TAM facility were done in air with normal incident beam. The tests at TAM facility can be done in air because of the higher energy ions available at this facility. Tests at BNL were done at vacuum with normal incident beam. 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 TAM

Ion	**Energy** (MeV)	**LET** (MeV-cm^2/mg)	**Range** (µm)
Xe^{129}	2814	40.3	244
Pr^{141}	1716	57.5	127
Ho^{165}	1808	70.0	114
Ta ^{181}	2183	76.4	125
Au^{197}	2127	86.3	112

Table II
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

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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. SELs were detected via 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 [11]. 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 SEL 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 SEL at a fluence of 1x10^7 ions/cm^2.

III. TEST RESULTS AND DISCUSSION

A. Linear Technology LTC1419

The LTC1419 is a 800ksps, 14-bit sampling A/D converter that draws only 150mW from ±5V supplies.

An HP6629A quad power supply was used to power the LTC1419. Three of the four available supplies on the HP6629 were used. One supply for AV$_{dd}$, one supply for V$_{ss}$, and one supply for DV$_{dd}$. All three supplies were set to +5.25V. The power supply clamp currents were set to 50, 100 and 40mA and threshold currents were set to 25, 50 and 20mA for AV$_{dd}$, V$_{ss}$, and DV$_{dd}$ supplies respectively.

The SEL measurements were performed at the TAM facility. The LTC1419 was tested at room temperature, application temperature of 50 and at 85°C. The sample size was 3. No Latchup was observed at room and application temperature of 50°C. At evaluated temperature of 85°C latchups were observed at LET of 68.3 MeV-cm^2/mg but no latchup was observed at LET of 64.0 MeV-cm^2/mg. The latchup threshold at the elevated temperature of 85°C is therefore between an LET of 64.0 MeV-cm^2/mg and an LET of 68.3.0 MeV-cm^2/mg. In Fig. 1, we show the result of the SEL measurements at 85°C.

Our latchup measurements indicate that LTC1419 is not highly sensitive to latchup. The cross section is relatively small, and rises to about 3x10^{-6} at high LETs. The LTC1419 was tested for destructive latchup by turning off latchup protection. When the device went into a latchup state, the supply current increased to ~1.2A. 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 destructively failed.

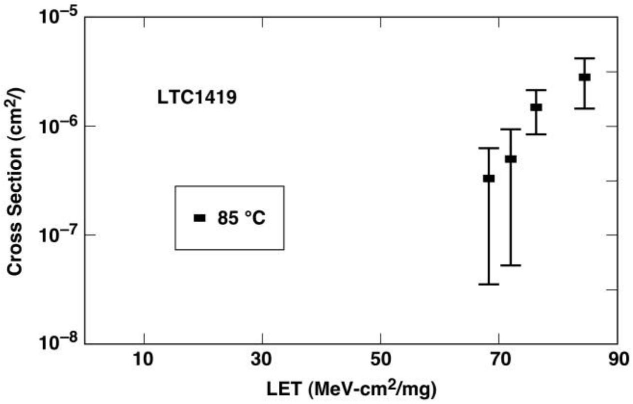

Fig. 1. SEL measurements for LTC1419 at 85°C. Measurements were performed at the TAM.

Latchup rates for the LTC1419 are calculated for interplanetary space GCR and on the surface of Mars. The interplanetary space environment is taken to be during solar minimum (worst case for GCR) and behind 100 mils of aluminum (but GCR rates are insensitive to spacecraft shielding). The GCR environment on the surface of Mars is affected by atmospheric shielding and has not yet been accurately modeled. A rough estimate of the effects from this shielding was done in the past and has produced a simple algorithm, which has the same accuracy and reliability as the original calculations that produced the algorithm. The algorithm starts with the interplanetary space solar maximum GCR environment, which is the environment that remains after many of the lower energy particles are removed from the solar minimum environment, i.e., the solar maximum environment is less intense but more skewed towards the higher energies. Roughly half of these particles make it through the atmosphere. Divide by another factor of two for shielding by the planet below. The rate on Mars is then calculated by calculating the rate in interplanetary space solar maximum GCR and then dividing by four. The rate on Mars is the same during solar maximum as during solar minimum because the lower energy particles that distinguish between the two environments are stopped in the atmosphere [12].

Latchup rates for the LTC1419 for interplanetary space GCR and on the surface of Mars are presented in Table III. Two models are used to obtain two rate estimates for each environment. One is the Best Estimate model for directional effects, which is a guess that is probably close to reality but is not guaranteed. The other is the Worst Case model for directional effects, which is the recommended model for design purposes. Note that for very hard parts (such as this one) there is a very large spread between the two estimates, which reflects the uncertainty in the rates. Additional test data that measure directional effects might remove some of the uncertainty, but there are experimental difficulties with large-angle testing, so additional data may or may not help depending on the angles at which the cosine law begins to fail [12].

Table III
LTC1419 Latchup Rate at elevated temperature of 85 °C (per Device) from GCR

Environment	Best Estimate Rate	Worst Case Rate
Inter. space (solar min. GCR)	9.0x10^{-6}/year	7.9×10^{-5}/year
On Mars (solar max. inter. space GCR÷4)	3.5×10^{-7}/year	4.4×10^{-6}/year
Flare Heavy Ion (1AU, Inter. space, worst week)	6.9×10^{-5}/flare	3.8×10^{-4}/flare

B. *Texas Instrument 55LBC174/55LBC175*

The 55LBC175 and 55LBC174 are a monolithic quadruple differential line receiver and driver with 3-state outputs, respectively.

An HP6629A power supply was used to power the test device. The tests were done at V_{dd} of 5.25V, which is the highest manufacturer specified operating voltage for this device. The highest specified operating voltage is used because it is expected to be the worst case test condition for SEL.

The SEL measurements were performed at the TAM facility. The 55LBC174 and 55LBC175 were tested at room temperature and at 85°C. The sample size for each part was 3. For both parts latchups were observed at room temperature at LET of 69.1 MeV-cm^2/mg but no latchup was observed at LET of 65.0 MeV-cm^2/mg. The latchup threshold at room temperature is therefore between an LET of 65.0 MeV-cm^2/mg and an LET of 69.1 MeV-cm^2/mg. The latchup threshold at 85°C is also between an LET of 65 MeV-cm^2/mg and an LET of 69.1 MeV-cm^2/mg.

In Fig. 2, we show the average result SEL measurements at room temperature. This data indicates 55LBC175 and 55LBC174 were not highly sensitive to latchup, and have an LET threshold between an LET of 65.0 and 69.1 MeV-cm^2/mg. Furthermore, at room temperature the cross section is relatively small, and gradually rising to about 10^{-6} at high LET's (saturation cross section).

In order to determine if latchup for these devices could be destructive, we removed latchup protection by increasing the current clamps to 1.9A and current threshold to 2.0 A. During the irradiation, the supply current increased to ~1.8A and device failed destructively.

The probability of SELs from GCR is about 8.4x10^{-4} SEL events per device per year. The SEL rate from solar flare is about 5.5x10^{-5} per device per flare. The SEL rate from GCR at the surface of Mars is about 2.8x10^{-5} per device per year [12].

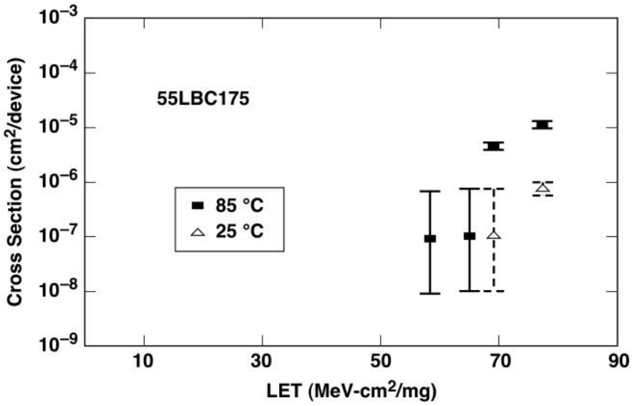

Fig. 2. SEL measurements for 55LBC175 at room temperature. Measurements were performed at the TAM.

C. *Texas Instrument CD54HCT4046*

The CDHCT4046A is high-speed CMOS logic phase-locked loop.

An HP6629A quad power supply was used to power the CD54HCT4046. Only one of the four supplies was used to provide power for $V_{cc.}$ Testing was done using power supply voltages for V_{cc} of +5.5V. The current was about 0.4mA. The power supply current clamp was set to 40mA and threshold currents were set to 20mA.

For functionality monitoring, a 10 kHz, 0.1V/4.0V square wave was fed to the SIG_IN pin and the VCO_OUT pin was monitored during the test.

The SEL measurements were performed at the TAM facility. The CD54HCT4046 was tested at room temperature and application temperatures of 60 and at 85°C. The sample size was 3. No Latchup was observed at room temperature. At elevated temperature of 60°C, SELs were observed at a LET of 73.0 MeV-cm^2/mg but no latchups were observed at a LET of 69.1 MeV-cm^2/mg. The latchup LET threshold is, therefore, between 69.1 and 73.0 MeV-cm^2/mg at elevated temperature of 60°C. At elevated temperature of 125°C SELs were observed at a LET of 69.1 MeV-cm^2/mg but no latchups were observed at a LET of 51.5 MeV-cm^2/mg. The latchup LET threshold is, therefore, between 51.5 and 69.1 MeV-cm^2/mg at elevated temperature of 125°C. In Fig. 3, we compare the result of the two heated measurements. As one might expect, the latchup cross section is higher for higher temperature [11].

In order to determine if latchup for these devices could be destructive, we increased the current clamps to 1.9A and current threshold to 2.0A. During the irradiation, the supply currents increased to 600 and 300mA and there was no output signal on the scope**.** After power cycling, with the beam off, the currents went back to about 0.4mA and device was functional. Therefore, the latchup was not destructive.

Latchup rates for the CD54HCT4046 for interplanetary space GCR and on the surface of Mars are presented in Table IV.

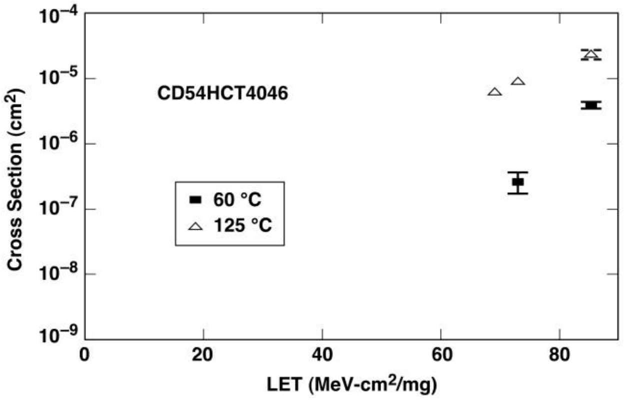

Fig. 3. SEL measurements for CD54HCT4046 at elevated temperature of 60°C and 125°C.

Table IV.
CD54HCT4046 Latchup Rate at elevated temperature of 125°C (per Device) from GCR

Environment		Rate using **Best Estimate** Directional model	Rate using **Worst Case** Directional model
Inter. Space (100 mils, 1AU)	GCR	2.1E-4/device-year	6.9E-3/device-year
	Flare	1.5E-3/device-flare	3.4E-2/device-flare
On Mars	GCR	7.6E-6/device-year	3.5E-4/device-year

D. Intersil HI-507

*The HI-507 monolit*hic CMOS multiplexers include an array of eight analog switches, a digital decoder circuit for channel selection, voltage reference for logic thresholds, and an enable input for device selection when several multiplexers are present.

An HP 6629A quad power supply was used to power the HI-507. Three of the four available supplies on the HP6629 were used. One supply for V_{dd}, one supply for V_{ss}, and one supply to power the logic inputs, V_{logic}. The voltage for all three supplies were set to +16.5V. The power supply clamp currents were set to 40mA and threshold currents were set to 20mA for all three supplies.

The HI-507 was tested for SEL at TAM. Three HI-507 devices were tested at room temperature as well as an elevated temperature of 125°C. No Latchup was observed at either room temperature or at 125°C.

E. Intersil ISL43110

The Intersil ISL43110 is a precision, high performance analog switch that is fully specified for 3.3V, 5V, and 12V operation, and feature improved leakage, Icc, and switching time specifications.

An HP6629A quad power supply was used to power the ISL43110. Two of the four available supplies on the HP6629A were used. One supply was used for V_{dd} and one supply was used to provide a logic input to the IN pin. Because this device can operate at supply voltages of from +2.4V to +13V, the test was done at two V_{dd} voltages. The voltage for the logic input pin was set at 5.0V for all tests. Testing was done using power supply voltages for V_{dd} of +5.5V and +13V. The power supply clamp currents were set to 40mA and threshold currents were set to 20mA for both supplies.

For functionality monitoring, the analog switch COM pin was fed with a 1 kHz, 0.2V/4.0V sine wave and the NO pin was monitored, by comparing the input signal into the NO pin against the output signal, from the COM pin.
The Intersil ISL43110 was tested for SEL at TAM. Four ISL43110 devices were tested at room temperature as well as an elevated temperature of 85°C. No Latchup was observed at either room temperature or at 85°C up to LET 77.3 MeV-cm^2/mg.

F. Intersil UT63M147

The monolithic UT63M147 transceivers are complete transmitter and receiver pairs for MIL-STD-1553A and 1553B applications.

An HP6629A power supply was used to power the test device during SEL measurements. The tests were done at an input voltage of 5.5V.

The UT63M147 was tested for SEL at TAM. Two devices were tested at room temperature and one device was tested at both room temperature as well as an elevated temperature of 125ºC. No latchups were observed for either the heated or the non-heated devices up to LET 77.3 MeV-cm^2/mg.

G. Texas Instrument 54LVTH244

The 54LVTH244 is designed specifically for low voltage (3.3V) Octal Buffer/Drive, but with the capability to provide a TTL interface to a 5V system environment.

An HP6629A power supply was used to power the test device. The tests were done at an input voltage of 3.6V.

Printed circuit daughter cards were fabricated that were used for SEL tests. The two output enable pins, on the 54LVTH244, were grounded to place the device in the output enable state. Only one of the eight inputs was driven, with an input signal, and the corresponding output was monitored for functionality. The monitored input was loaded with a 510 Ω resistive load and was fed with 1kHz, square wave for device functionality monitoring during the SEL tests. The other seven inputs were grounded and the corresponding outputs were left open. The daughter cards were, in turn, mounted onto a generic test board that provides the necessary power and input signals to the daughter card. The generic test board also has line buffers used to avoid loading the output of the test device. The line driver drives the coaxial cables that connect the DUT to the scope used to monitor for functionality.

Three devices were tested at room temperature and an elevated temperature of 125ºC. No latchups were observed for either the heated or the non-heated devices up to LET 77.3 MeV-cm^2/mg.

H. Analog devices ADuM1401

The ADuM140 is a 4-channel digital isolator based on Analog Devices, Inc. iCoupler® technology. Combining high speed CMOS and monolithic air core transformer technology, these isolation components provide outstanding performance characteristics superior to alternatives such as optocoupler devices.

An HP6629A quad power supply was used to power the ADuM1401. Two of the four available supplies on the HP6629 were used. One supply was used for V_{dd1}, and one supply was used for V_{dd2}. Both supplies were set to +5.5V. The power supply clamp currents were set to 40mA and threshold currents were set to 20mA for both supplies.

The ADuM1401 was tested for SEL at BNL. The ADu1401 was tested at room temperature and at an elevated temperature of 105°C. The sample size was 5. The parts showed destructive latchup at LETs as low as 8 MeV-cm2/mg. The normal operating current was 1.5 and 1.1mA for Vdd1 and Vdd2, respectively. The supply current went up to 40mA (current clamp) on both supplies and the current remained in this high current state, 40mA, after power cycling with the ion beam turned off. The current remained high after repeated power cycling with no beam on the device. The device was destructively damaged.

IV. SUMMARY

We have presented SEL 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; LTC1419, 55LBC175, 55LBC174, and ADuM1401 except for the CD54HCT4046. The HI-507, ISL43110, UT63M147 and 54LVTH244 were latchup immune up to a LET of 86.3 MeV-cm^2/mg. We summarized our SEE test results in table V.

Table V.
Summary of SEE test results

Part Number	**Manufacturer**	**Device Function**	**Test Results** **LET in MeV-cm^2/mg; σ in cm^2/device**
LTC1419	Linear Technology	Parallel 14-bit ADCs	SEL $LET_{th} > 64$; $\sigma_{SAT} \sim 3x10^{-6}$ at 85°C
55LBC174/55LBC175	Texas Instrument	Line receiver and driver	SEL $LET_{th} > 65$; $\sigma_{SAT} \sim 1x10^{-6}$
CD54HCT4046	Texas Instrument	High-speed CMOS logic phase-locked loop	SEL $LET_{th} > 61.5$; $\sigma_{SAT} \sim 1x10^{-5}$ at 125°C
HI-507	Intersil	CMOS multiplexer	SEL $LET_{th} > 86.3$
ISL43110	Intersil	Precision analog switch	SEL $LET_{th} > 86.3$
UT63M147	Intersil	Transceiver	SEL $LET_{th} > 86.3$
54LVTH244	Texas Instrument	Octal Buffer/Drive	SEL $LET_{th} > 86.3$
ADuM1401	Analog Devices	Digital isolator	SEL $LET_{th} < 8$

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