Heavy-Ion Test Results of Several Commercial Components for Use in a JPL Class D Interplanetary Mission Payload

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Abstract — **This paper presents recent heavy ion single-event effects test results for commercial off the shelf devices. Data was taken in CY17 for device evaluation for use in a Class D NASA interplanetary mission payload.**

I. INTRODUCTION

IT is becoming common for experimental spacecraft payloads to be designed with existing commercial off the self (COTS) subsystems. Commercial modules easily meet the performance requirements for the mission but are not designed with spaceflight requirements for reliability, or radiation, in mind. This test effort started as a milestone on a path to approve a COTS subassembly for use on a Class D payload and eventually became a driver for the redesign of the module as a radiation tolerant variant.

This work outlines the efforts taken on a list of devices to assess for SEL sensitivity. Over 14 unique devices were tested: data converters, amplifiers, transceivers, accelerometers, oscillators, linear voltage regulators, motor drivers, synchronous converter Systems on Chip (SoC), and supervisory circuits.

It is common for COTS devices to be susceptible to Single-Event Latchup (SEL) and device testing is required to prove absence of SEL [1-4]. To test for SEL, devices are biased, monitored, and irradiated to look for beam-induced anomalies. If a device exhibits failure, we measure the cross section, for various linear energy transfer (LET) data points, in order to allow rate calculation in various environments.

II. EXPERIMENTAL PROCEDURE

A. Test Facilities

This effort used the high-energy heavy ions available at two test facilities: Brookhaven National Laboratory (BNL) in Upton, New York and the Radiation Effects Facility located at the Cyclotron Institute at Texas A&M University (TAMU) in College Station, Texas. BNL uses a Tandem Van De Graaff (TVDG) electrostatic accelerator while the TAMU facility uses an electrodynamic 88" cyclotron. BNL has the advantage of creating an ion cocktail they can easily, and quickly, switch between for the user. The ion beams used for our measurements are listed in Table I.

Tests at BNL were done in vacuum and tests at TAMU were performed in air. All testing was performed at normal incidence. Some of the parts were tested at both facilities. The beam flux ranged from $2x10^1$ to $1x10^5$ ions/cm^2·sec.

Table I. List of ion beams used for measurements.

Test Facility	Ion	Beam Energy (MeV)	LET 0° (MeV·cm^2/mg)	Range (µm)
BNL-TVDG	^{28}Si	187	7.8	74
BNL-TVDG	^{35}Cl	212	11.4	59
BNL-TVDG	^{48}Ti	232	19.7	40
BNL-TVDG	^{81}Br	287	37.5	36
TAMU	^{109}Ag	2954	42.8	113

B. Experimental Methods

Testing for SEL requires a test fixture to house the device under test (DUT), excitation equipment or circuitry, and monitoring equipment. An Ethernet controlled N6700 power analyzer provides voltage control, current monitoring and latchup protection. A Visual Basic test computer monitors for SEL. The Visual Basic software controls the power supply voltage, and monitors the supply current. The software also logs current and provides a graphical representation of each power channel current. For the cases where an excitation or monitoring PC was required for a complex DUT, a separate PC was used.

The DUTs were tested at room temperature as well as at an elevated temperature. Elevated temperature is between application temperature and recommended maximum for the integrated circuit (IC). Each cross section point was taken when greater than fifty latchup events were accumulated or when a beam fluence of $1x10^7$ ions/cm^2 was reached.

The SEL evaluation included measurements of the saturation cross-section and the Linear Energy Transfer threshold (LET_{th}) for each device. The LET_{th} is the minimum LET value necessary to cause a SEL at a fluence of 1x10^7 ions/cm^2.

Section III provides an in depth discussion on the SEL measurement results of four different parts.

III. TEST RESULTS AND DISCUSSION

1) SF1600S & MS1002A

The SF1600S and MS1002A are both extremely low noise MEMS accelerometers with analog outputs from Colibrys. The devices were tested in biased condition at maximum recommended voltages. Accelerometers require physical movement to verify functionality; much like an ADC requires stimulation, so the pursued test method was to measure analog output pre irradiation at +1g and -1g. Then we rotate the devices for beam positioning to approximately 0g (parallel to beam line but perpendicular to earth gravity, effectively placing device output voltage at the midscale) and monitoring device output in situ for single event transients.

At least two device serial numbers for each device were tested at room temperature and at elevated temperature (> 70°C). At elevated temperature for the MS1002A, SELs were observed at an LET of 19.7 MeV·cm^2/mg but no latchup was observed at an LET of 11.4 MeV·cm^2/mg. The latchup LET threshold for the MS1002A is between 19.7 and 11.4 MeV·cm^2/mg at elevated temperature. At elevated temperature for the SF1600S, SELs were observed at an LET of 11.4 MeV·cm^2/mg but no latchup was observed at an LET of 7.8 MeV·cm^2/mg. The latchup LET threshold for the SF1600S is between 11.4 and 7.8 MeV·cm^2/mg at elevated temperature.

Table II compares the results of the room temperature measurements with that of the heated measurements. For the purpose of rate calculation, elevated temperature data points are used.

Table II. Comparison of MS1002.A latchup cross-sections.

SN	Temp (deg C)	LET (MeV*cm2/mg)	# events	fluence (ions / cm2)	cross-section (cm2)
3	room	37.5	15	1.00E+07	1.50E-06
3	75	37.5	61	1.00E+07	6.10E-06
5	room	37.5	19	1.00E+07	1.90E-06
5	78	37.5	40	1.00E+07	4.00E-06
3	room	19.71	0	1.00E+07	0.00E+00
3	71	19.71	6	1.00E+07	6.00E-07

Both devices were tested for destructive latchup by turning off the power supply current limiting and holding a latchup state for greater than 60 seconds no less than 10 times. Then we power cycle the device to verify device current returns to nominal and devices operate as expected. When the device went into a latchup state, the supply current increased at both temperatures; to 232 mA from 23 mA nominal on the MS1002A and to 340 mA from 20 mA nominal on the SF1600S. During the latchup, the device output would transition to power rail; indicated output is no longer valid. The devices did recover after power cycling, indicating the devices did not destructively fail.

The SEL data for these devices, at both measured temperatures, is fit to a Weibull distribution and is presented in Fig. 1 and Fig. 2. Error bars plotted represent 95% Poisson confidence interval. Note lower LET_{th} and three orders of magnitude higher cross section on the SF1600S vs MS1002A by the same manufacturer.

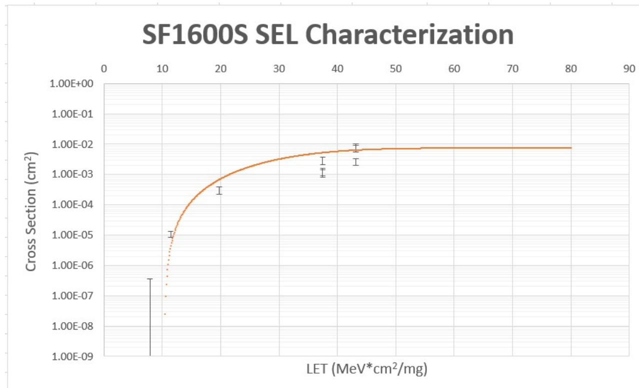


Figure 1. SEL cross section for SF1600S device

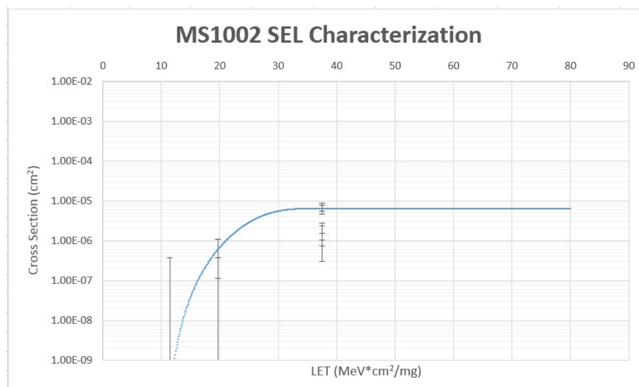


Figure 2. SEL cross section for MS1002A device

Both devices tested had sample device destructive cross sectioning performed to determine approximate depth to sensitive region of silicon; see Fig. 3 and Fig. 4. This gives a confirmation that the selected test ions limiting range of 36 µm were sufficient to penetrate to active region of silicon.

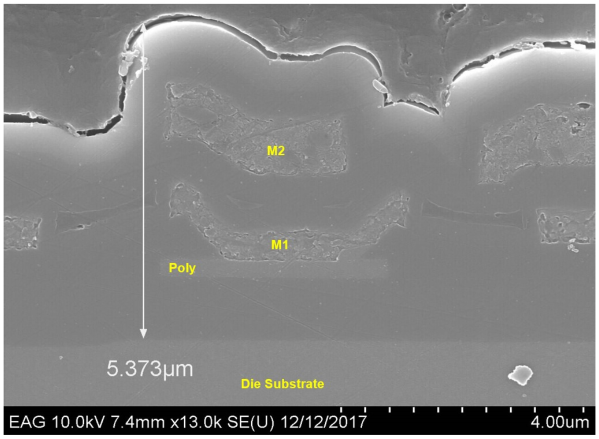
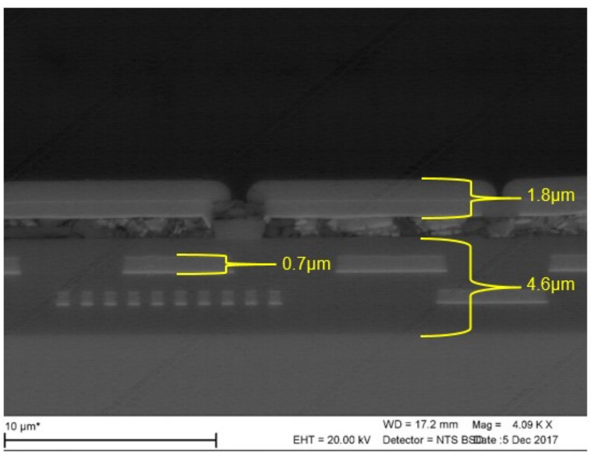


Figure 3. SF1600S device scanning electron microscope (SEM) measurement of distance to active region of silicon from top side of die.



Total patterned layer thickness is 7.4 microns

Figure 4. MS1002A device SEM measurement of distance to active region of silicon from top side of die.

2) EN5322QI

The Altera EN5322QI is a high efficiency synchronous buck converter Power SOC that integrates an inductor, PWM controller, MOSFETs, and compensation circuitry into a single 4mm x 6mm QFN package. See Figure 5 for device internal construction analysis.

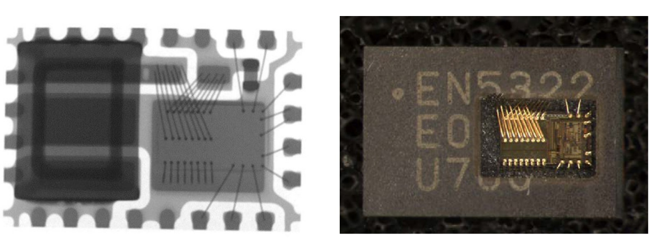


Figure 5. EN5322QI PowerSoC top view x-ray next to etched device with exposed silicon microcircuit

An evaluation board provided by the vendor was used for the SEL test. The SEL measurements were performed at TAMU.

Three devices were tested at room temperature and at 75 ±5 °C. At room temperature, SEL was observed at test LET of 42.8 MeV·cm^2/mg and test fluence of 7.5×10^6 ions/cm^2. In attempt to clear the SEL state, the device was power cycled. It was found the increase in device current is permanent, indicating destructive failure of the internal microcircuit. Another device was tested at same LET but at an elevated temperature and latchup was observed at test fluence of 4.2×10^6 indicating increased cross section with increase in temperature. This further supports the claim that damage is induced by latchup [5].

3) DRV8412

The Texas Instruments DRV8412 is an integrated dual full-bridge motor driver. The microcircuit includes temperature sense, overload protection, 4 MOSFET drivers, fault discrete outputs, and reset circuitry. This device is capable of 12A peak output current in parallel mode and incorporates a copper redistribution layer above the silicon. This can be seen in Fig. 6 and Fig. 7.

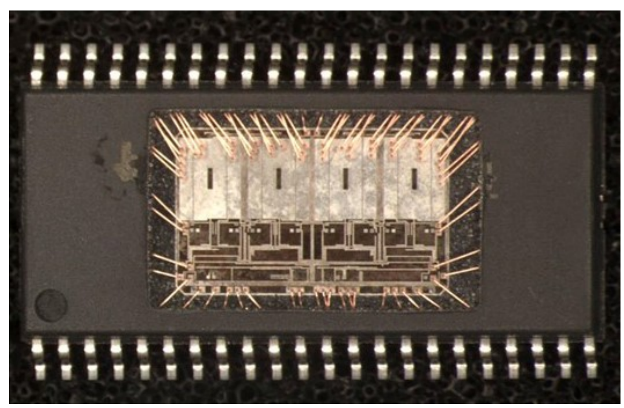


Figure 6. Etched microcircuit showing copper (Cu) bond wires and Cu redistribution layer (RDL).

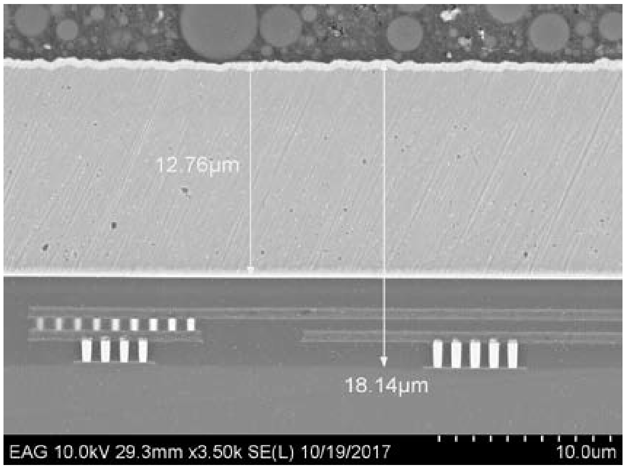


Figure 7. DRV8412 SEM measurement of distance from top of Cu RDL to active silicon region.

The Cu redistribution layer (RDL) in this device was cause for range concern at BNL. This layer increases beam energy required to ensure penetration through the entire active silicon region. There is a possibility of a false positive if devices are tested and ions cannot travel deep enough to cause the event. Fig. 8 is a Stopping Range in Matter (SRIM) plot of a hypothetical test at BNL-TVDG using 287 MeV Br-81 ions in an attempt to test the DRV8412 for SEL sensitivity. A DRV8412 target consisting of a 12.76 µm layer of Cu, 15 µm layer of Si, & 13 µm air is simulated. The expected range of the ion is ~17 µm, just under 2 µm from the active Silicon region.

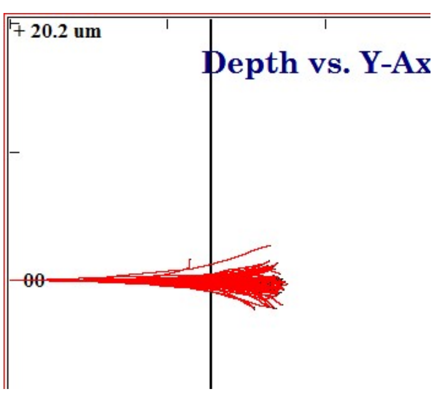


Figure 8. SRIM simulation of 287 MeV Br-81 ions into a simulated DRV8412 target. Ions have approximately 17 µm of range in the target. Note Figure 7. SEM yields range requirement of ~18 µm to active silicon region.

An evaluation board, available from Texas Instruments, was used for the SEL test. This device was tested in a biased condition with all outputs loaded with 2k ohm, static loads, and the test input stimulated with a +3.3V LVCMOS square wave at a 1.0 kHz operational frequency. Device was biased at +13 V (max recommended on VDD) and +13 V on PVDD. The maximum recommended voltage on PVDD is 52.5 V, it is recommended the device be retested at the application voltages, and application loads, for use on subsequent programs.

The SEL measurements were performed at TAMU using Ag-109 ions with 113 µm of range in Silicon. Two devices were tested at room temperature and at 90 ±5 °C. At room temperature and elevated temperature, no SEL was observed at test LET of 42.8 MeV·cm^2/mg and test fluence of 1.0x10^7 ions/cm^2. While device current remained at nominal throughout testing, it was noted the device output would stop operating as expected. This failure mode could be cleared with a power cycle. We suspect a single event functional interrupt (SEFI) due to protection circuitry. No permanent degradation was noted so this failure mode was not explored further.

ACKNOWLEDGEMENT

The authors wish to thank Brian Weltmer, Gerardo Ortiz, Scott Green, Sergeh Vartanian, Farokh Irom, Michael O'Connor, Gil Garteiz, & EAG Laboratories in Irvine, CA for their efforts in support of this work.

The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. This work was supported by a JPL flight project.

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IV. SUMMARY

Table III. Summary of SEL results for devices

Part Number	Manufacturer	Device Function	Test Results
SF1600S	Colibrys	MEMS Accelerometer	Non-destructive SEL, LET_{th} 7.88-11.44 MeV·cm^2/mg.
MS1002	Colibrys	MEMS Accelerometer	Non-destructive SEL, LET_{th} 11.44-19.71 MeV·cm^2/mg
LTC2440IGN	Linear Technology	24-Bit, Delta Sigma ADC	Destructive SEL
DRV8412	Texas Instruments	6A Motor Driver	No SEL under test conditions up to LET 42.8 MeV·cm^2/mg
TPS7A3001-EP	Texas Instruments	Ultra Low Noise Linear Regulator	No SEL under test conditions up to LET 42.8 MeV·cm^2/mg
TPS7A4700	Texas Instruments	Ultra Low Noise Low Dropout Linear Regulator	No SEL under test conditions up to LET 42.8 MeV·cm^2/mg
LMP2022	Texas Instruments	Operational Amplifier	No SEL under test conditions up to LET 42.8 MeV·cm^2/mg
LTC2904ITS8	Linear Technology	Precision Dual Supply Monitor	No SEL under test conditions up to LET 42.8 MeV·cm^2/mg
LTC6655BHLS8	Linear Technology	Low Drift Precision Reference	Destructive SEL
ECS-3961-040	ECS Inc.	4.00 MHz Crystal Oscillator	Destructive SEL
ASDMB-16.000MHZ-XY	Abracon	16.00 MHz MEMS Oscillator	Non-destructive SEL, LET_{th} 11.44-19.71 MeV·cm^2/mg
EN5322QI	Altera	. PowerSoC 2A Synchronous Buck Regulator	Destructive SEL
DS90LV032A	Texas Instruments	400 Mbps LVDS Quad Differential Line Receiver	Non-destructive SEL, LET_{th} < 42.8 MeV·cm^2/mg
DS90LV010A	Texas Instruments	Bus LVDS Transceiver	Non-destructive SEL, LET_{th} < 42.8 MeV·cm^2/mg