Single Event Effects Compendium of Candidate Spacecraft Electronics for NASA

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Abstract— **We present the results of single event effects testing and analysis investigating the effects of radiation on electronics. This paper is a summary of test results.**

Index Terms—**Single event effects, spacecraft electronics, digital, linear bipolar, and hybrid devices.**

I. Introduction

In order to meet the demands of reduced cost, higher performance and more rapid delivery schedules imposed by the space flight community, spacecraft designers are increasingly turning to commercial and emerging technology devices to meet these needs. The importance of ground-based testing of such devices for susceptibility to single event effects (SEE) is critical to ensure reliable performance of these devices. The novel utilizations of some of these devices highlight the need for application specific testing to ensure their proper operation and the ability to meet mission goals.

The studies discussed here were undertaken to establish the sensitivities of candidate spacecraft electronics to heavy ion and proton-induced single event upset (SEU), single event latchup (SEL), and single event transients (SET). For total ionizing dose (TID) and displacement damage results, see a companion paper submitted to the 2009 IEEE NSREC Radiation Effects Data Workshop entitled: "Total Ionizing Dose and Displacement Damage Compendium of Candidate Spacecraft Electronics for NASA" by D. Cochran, et al. [1].

II. Test Techniques and Setup

A. Test Facilities

All SEE tests were performed between February 2008 and February 2009. Heavy ion experiments were conducted at Texas A&M University Cyclotron (TAMU) [2] and at the NASA Space Radiation Laboratory (NSRL), a heavy ion facility located at Brookhaven National Laboratory (BNL).

The TAMU facility uses an 88 inch cyclotron and is suitable for providing a variety of ions over a range of energies for testing. The device under test (DUT) was irradiated with heavy ions having linear energy transfers (LETs) generally ranging from 0.59 to 120 MeV•cm^2/mg. Fluxes used generally range from 1×10^2 to 1×10^7 particles/cm^2/s, depending on the device sensitivity. Representative ions used are listed in Table I. LETs between the values listed were obtained by changing the angle of incidence of the ion beam with respect to the DUT, thus changing the path length of the ion through the DUT and the "effective LET" of the ion [3]. Energies and LETs available varied slightly from one test date to another.

At the NSRL facility, heavy ions are accelerated using one of the two BNL tandem Van de Graaff accelerators and sent down a 700 m beam line to the Booster synchrotron. The beams are accelerated further in the Booster and then delivered to the NSRL. Because the tandems serve as the ion source, the number of beams available at the NSRL is presently limited to hydrogen, carbon, oxygen, silicon, chlorine, titanium, and iron. However, with the commissioning of the electron beam ion

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source in 2010, all ions from hydrogen to uranium will be available and at higher fluxes.

The NSRL beam itself is well-controlled and focused by two sets of magnetic lenses that can produce a “square” beam spot of up to 20 cm × 20 cm with a uniformity of 2%. The staple energy tune at the NSRL is 1 GeV/u, though the energy can be changed in about 15 minutes as long as the operators have advanced notice. The energy range is approximately 0.1 GeV/u to 1 GeV/u, which is the energy at the DUT, not the extraction energy of the Booster synchrotron. At lower energies the beam is less uniform, with a dip in intensity at the center of the beam spot. The ions are delivered to the target room in 300 ms spills approximately every 3.7 s. Real-time dosimetry is achieved with a calibration ion chamber manufactured by Far West Technologies in conjunction with larger secondary ion chambers. The secondary ion chambers are used to measure integrated dose and cut the beam off when a specific dose has been reached. The dosimetry unit is rad(H_2O) and must be converted to rad(Si) and then scaled by the LET of the incident beam in order to calculate the particle fluence. [4]

Proton SEE tests were performed at three facilities: the University of California at Davis (UCD) Crocker Nuclear Laboratory (CNL) [5], the Indiana University Cyclotron Facility (IUCF) [6], and at a 2 MeV Van de Graaff particle accelerator. Proton test energies incident on the DUT are listed in Table II.

Laser SEE tests were performed at the pulsed laser facility at the Naval Research Laboratory (NRL) [7, 8]. The laser light had a wavelength of 590 nm resulting in a skin depth (depth at which the light intensity decreased to 1/e - or about 37% - of its intensity at the surface) of 2 µm. A nominal pulse rate of 100 Hz was utilized.

TABLE I: HEAVY ION TEST FACILITIES AND TEST HEAVY IONS

	Ion	Energy (MeV)	Surface LET in Si ($MeV \cdot cm^2/mg$) (Normal Incidence)	Range in Si (µm)
TAMU	^{20}Ne	300	2.6	316
	^{40}Ar	599	8.0	229
	^{63}Cu	944	18.7	172
	^{84}Kr	1259	26.6	170
	^{109}Ag	1634	40.3	156
	^{129}Xe	1934	49.3	156
	15 MeV per AMU tune			
	^{22}Ne	545	1.8	799
	^{40}Ar	991	5.5	493
	^{84}Kr	2081	19.8	332
	^{139}Xe	3197	38.9	286
	25 MeV per AMU tune			

TABLE I: HEAVY ION TEST FACILITIES AND TEST HEAVY IONS (CONT.)

	Ion	Energy (MeV)	Surface LET in Si ($MeV \cdot cm^2/mg$) (Normal Incidence)	Range in Si (µm)
NSRL	^{56}Fe	5600	3.8	3.7×10^3
	100 MeV per AMU tune			
	^{56}Fe	28000	1.5	5.3×10^4
	500 MeV per AMU tune			
	^{56}Fe	56000	1.2	1.5×10^5
	1000 MeV per AMU tune			

TABLE II: PROTON TEST FACILITIES

University of California at Davis (UCD) Crocker Nuclear Laboratory (CNL), energy ranged from 5 to 63 MeV, flux ranged from 8×10^7 to 1×10^9 particles/cm²/s.
Indiana University Cyclotron Facility (IUCF), energy ranged from 63 to 198 MeV, flux ranged from 5×10^5 to 3×10^9 particles/cm²/s.
A 2MeV Van de Graaff particle accelerator facility, energy ranged from 0.8 to 1.4 MeV, flux ranged from 10^6 to 10^8 particles/cm²/s.

TABLE III: LASER TEST FACILITY

Naval Research Laboratory (NRL) Pulsed Laser SEE Test Facility
Laser: 590 nm, 1 ps pulse width, beam spot size ~1.2 µm

B. Test Method

Unless otherwise noted, all tests were performed at room temperature and with nominal power supply voltages. We recognize that high-temperature and worst-case power supply conditions are recommended for single event latchup (SEL) device qualification.

1) SEE Testing - Heavy Ion:

Depending on the DUT and the test objectives, one or more of three SEE test methods were typically used:

Dynamic – the DUT was exercised continually while being exposed to the beam. The events and/or bit errors were counted, generally by comparing the DUT output to an unirradiated reference device or other expected output (Golden chip or virtual Golden chip methods) [9]. In some cases, the effects of clock speed or device operating modes were investigated. Results of such tests should be applied with caution due to the application-specific nature of the results.

Static – the DUT was loaded prior to irradiation; data were retrieved and errors were counted after irradiation.

Biased – the DUT was biased and clocked while power consumption was monitored for SEL or other destructive effects. In most SEL tests, functionality was also monitored.

In SEE experiments, DUTs were monitored for soft errors, such as SEUs and for hard errors, such as SEL. Detailed descriptions of the types of errors observed are noted in the individual test results [10].

SET testing was performed using a high-speed oscilloscope. Individual criteria for SETs are specific to the device being tested. Please see the individual test reports for details [10].

Heavy ion SEE sensitivity experiments include measurement of the Linear Energy Transfer threshold (LET_{th}) and cross section at the maximum measured LET. The LET_{th} is defined as the maximum LET value at which no effect was observed at an effective fluence of 1×10^7 particles/cm^2. In the case where events are observed at the smallest LET tested, LET_{th} will either be reported as less than the lowest measured LET or determined approximately as the LET_{th} parameter from a Weibull fit. In the case of SEGR experiments, measurements are made of the SEGR threshold Vds as a function of LET at a fixed Vgs.

2) SEE Testing - Proton

Proton SEE tests were performed in a manner similar to heavy ion exposures. However, because protons cause SEE via indirect ionization of recoil particles, results are parameterized in terms of proton energy rather than LET. Because such proton-induced nuclear interactions are rare, proton tests also feature higher cumulative fluences and particle flux rates than heavy ion experiments.

3) Pulsed Laser Facility Testing

The DUT was mounted on an X-Y-Z stage in front of a 100x lens that produced a spot size of about 1.2 µm at full-width half-maximum (FWHM). The X-Y-Z stage can be moved in steps of 0.1 µm for accurate positioning of SEU sensitive regions in front of the focused beam. An illuminator together with a charge coupled device camera and monitor were used to image the area of interest, thereby facilitating accurate positioning of the device in the beam. The pulse energy was varied in a continuous manner using a polarizer/half-waveplate combination and the energy was monitored by splitting off a portion of the beam and directing it at a calibrated energy meter.

III. Test Results Overview

Abbreviations and conventions are listed in Table IV. Abbreviations for principal investigators (PIs) are listed in Table V, and SEE results are summarized in Table VI. Unless otherwise noted, all LETs are in MeV•cm^2/mg and all cross sections are in cm^2/device. This paper is a summary of results. Complete test reports are available online at http://radhome.gsfc.nasa.gov [10].

TABLE IV: ABBREVIATIONS AND CONVENTIONS:

LET = linear energy transfer (MeV•cm^2/mg)
LET_{th} = linear energy transfer threshold (the minimum LET value for which a given effect is observed for a fluence of 1x10^7 particles/cm^2 – in MeV•cm^2/mg)
< = SEE observed at lowest tested LET
> = no SEE observed at highest tested LET
σ = cross section (cm^2/device, unless specified as cm^2/bit)
$\sigma_{max\ measured}$ = cross section at maximum measured LET (cm^2/device, unless specified as cm^2/bit)
ADC = analog to digital converter
App. Spec. = application specific
CMOS = complementary metal oxide semiconductor
DUT = device under test
FPGA = field programmable gate array
H = heavy ion test
I/O = input/output
L = laser test
LDC = lot date code
LSB = least significant bit
MSPS = Mega Samples Per Second
P = proton test (SEE)
PI = principal investigator
Q_{crit} = critical charge
QWIP = Quantum Well Infrared Photodetector
ROIC = Readout Integrated Circuit
SDRAM = synchronous dynamic random access memory
SEB = single event burnout
SEBE = single event burst error
SEE = single event effect
SEFI = single event functional interrupt
SEGR = single event gate rupture
SEHE = single event hard error
SEL = single event latchup
SET = single event transient
SEU = single event upset
SiGe = silicon germanium
SOI = silicon on insulator
Vgs = gate-source voltage
Vds = drain-source voltage

TABLE V: LIST OF PRINCIPAL INVESTIGATORS

Principal Investigator (PI)	Abbreviation
Melanie Berg	MB
Steve Buchner	SB
Michael Campola	MC
Dakai Chen	DC
Hak Kim	HK
Ray Ladbury	RL
Jean-Marie Lauenstein	JML
Cheryl Marshall	CM
Paul Marshall	PM
Timothy Oldham	TO
Jonathan Pellish	JP
Anthony (Tony) Sanders	AS
Michael Xapsos	MX

TABLE VI: SUMMARY OF SEE TEST RESULTS

Part Number	Manu-facturer	LDC	Device Function	Tech-nology	Particle: (Facility/Date) P.I.,	Test Results LET in MeV•cm²/mg σ in cm²/device, unless otherwise specified	App. Spec. Test (Y/N)	Supply Voltage	Sample Size (Number Tested)	Test Report
Linear Devices:										
MAX997	Maxim Integrated Products	0531	Voltage Comparator	Bipolar	H: (TAMU08DEC) DC	H: SEL LETth > 84.1 @ 85ºC; SET LETth < 2.7; SET σ increases for wide transients (>20 ns) at higher temperature. Tested at room temperature and at 85ºC.	Y	4.3V	2	T121408_MAX997 [11]
DG390	Maxim Integrated Products	9149	Analog Switch	CMOS	H: (TAMU08FEB) RL	H: SEL LETth>87.6; SET LETth>87.6; Tested at room temperature and at 85ºC.	N	+/-15V	3	T022508_MAX367_DG390 [12]
SG1845	Microsemi Corp.	0006	Pulse Width Modulator	Bipolar	H: (TAMU08FEB) RL	H: SEL LETth>53; SET LETth<2.8; SET $\sigma_{max\ measured}$ =1.9x10^{-3} cm^2 (at LET=53)	Y	12V; 28V	3	T022608_SG1845 [13]
SG1846	Microsemi Corp.	0122	Pulse Width Modulator	Bipolar	H: (TAMU08FEB) RL	H: SEL LETth>53; SET LETth<2.8; SET $\sigma_{max\ measured}$ =1.5x10^{-3} cm^2 (at LET=53)	Y	14V	4	T022608_SG1846 [14]
AD822	Analog Devices	0741	Operational Amplifier	Bipolar	H: (TAMU08JUN) RL	H: SEL LETth>53 SEL LETth <2.8; Both positive and negative transients were observed, some negative transients with durations as long as a few microseconds.	Y	+/-12V; 0V/30V	3	T061808_AD822 [15]
LM124	National Semi-conductor	036AD	Operational Amplifier	Linear Bipolar	L: (NRL08AUG) DC	L: SET pulse width increases with increasing temperature, pulse amplitude did not change significantly with temperature. Tested at room temperature and up to 120ºC.	Y	+/- 5V	1	NRL082608_LM124 [16] [17 - Chen tns09 PA-5]
LM139	Texas Instruments	0535F	Operational Amplifier	Linear Bipolar	L: (NRL09MAR) DC	L: SET amplitude increases with increasing temperature. Device slew rate degrades with increasing temperature. Tested at room temperature and up to 120ºC.	Y	5V	1	NRL031009_LM139 [18]
ADG526A	Analog Devices	0704	Analog MUX	LC^{2}MOS	H: (TAMU08JUN) MC	H: SEU LET_{th} ~ 20.7 SEL LET_{th} > 123.6	Y	15V	5	T062208_ADG526A [19]
UC1708	Texas Instruments	0529A	MOSFET Driver	Bipolar	L: (NRL08AUG) RL	L: SETs observed with a steady-state input. Most SETs were short pulses and were seen only for moderate to high laser intensities. Tested at both room temperature and 80°C.	Y	12V	2	NRL082508_UC1708 [20]
RH1086	Linear Technology	9714A	Voltage Regulator	Bipolar	L: (NRL08NOV) SB	L: Worst case SETs were captured for an application specific configuration, where "worst case" refers to the transients generated with very high equivalent LETs; i.e. LETs > 100.	Y	5V	1	NRL110608_RH1086 [21]
Power Devices:										
RI7113	International Rectifier	0142	Power MOSFET Driver	CMOS	H: (TAMU08FEB) RL	H: SEL LET_{th} >106; 8.6 < SET LET_{th} < 17.2; SET $\sigma_{max\ measured}$ =4x10^{-5} cm^2 (at LET=108)	Y	14V; 28V	4	T022508_IR7113 [22]
APT50M38PLL	Microsemi Corp.	0735	Power MOSFET	MOS 7® family n-channel VD MOSFET	H: (TAMU08SEP; TAMU08NOV; TAMU08DEC) JML	H: SEGR last pass/first fail Vds: at LET=28.8 (Kr) 225V/250V; at LET=43.6 (Ag) 150V/160V	N	0Vgs	7	T090608_APT50M38PLL [23]
IRH7250	International Rectifier	Q911729	Power MOSFET	Gen 4 n-channel VD MOSFET	H: (TAMU08DEC) JML	H: SEGR last pass/first fail Vds: LET=28.1 (Kr) 190V/195V at 0Vgs, 125V/130V at -12Vgs; LET=41.3 (Ag) 80V/85V at 0Vgs, 50V/55V at -12Vgs	N	0Vgs; -12Vgs	10	T121508_IRH7250 [24]

Part Number	Manu-facturer	LDC	Device Function	Tech-nology	Particle: (Facility/Date) P.I.,	Test Results LET in MeV•cm²/mg σ in cm²/device, unless otherwise specified	App. Spec. Test (Y/N)	Supply Voltage	Sample Size (Number Tested)	Test Report
AFL12028	International Rectifier	0718	DC-DC converter	Hybrid	H: (TAMU08JUN) HK	H: SEL LET_{th} <41.5 (70% loading); No SEL seen at 30% loading up to LET 41.5; SET LET_{th} >41.5 (30% loading)	Y	28V	2	T061808_AFL12028 [25]
ADC/DAC Devices:										
ADC14155W-MLS	National Semi-conductor	0824	ADC	CMOS	H: (TAMU08JUN) SB (w/K. Kruckmeyer)	H: SELth > 58.69 at 25ºC; SETth <1.8; SETs consisted of bursts of errors and temporary clock losses.	N	3.3V; 1.8V	1	T061808_ADC14155WG-MLS [26]
ADS5424	Texas Instruments	5962 0725A	ADC	BiCMOS	H: (TAMU08JUN) MB P: (IU08APR) MB	H: SEL LET_{th} >55 (room temperature and 85°C); SEFI LET_{th} >55; SEU LET_{th} <8.5 P: No SEL observed at both 89 and 195 MeV protons. SEU observed at both 89 and 198 MeV protons.	N	5V supply; 3.3V output	2	T111207_ADS5424_V2 [27]
Memory Devices:										
MT29F4G08AAAWP	Micron	0744	4 Gbit NAND Flash Memory	CMOS	H: (TAMU08NOV) TO/AS	H: SEL LETth <54.8; Bit error LETth ~2.8; Bit errors, SEFIs, and destructive failure were observed at LET 8.4.	Y	3.3V for SEU; 3.6V (3.3+ 10%) for SEL	4	T110308_ MT29F4G08AAAWP [28]
K9F4G08U0A	Samsung	0840; 0843; 0846; 0901	4 Gbit NAND Flash Memory	CMOS	H: (TAMU09MAR) TO/AS	H: SEL LETth >87; Bit error LETth ~2.8; Write mode failures were observed at 70ºC at LET 54.8.	N	3.3V for SEU, 3.6V (3.3 +10%) for SEL	3 from 0840; 5 from 0843; 2 from 0846; 4 from 0901	T030809_K9F4G08U0A [29] [30 - Oldham nsrec09 W-9]
EDS5108ABTA	Elpida	0805	3DPLUS 512M SDRAM	CMOS	L: (NRL08OCT) AS (w/J. Benedetto); (NRL09FEB) RL/JP H: (TAMU08NOV) RL/AS	H: SEL LETth >60 SEFI>20 (limiting cross section $<1\times10^{-4}$ cm²); SEU<2.7 (Limiting cross section ~0.5 cm²); Block errors<2.7 (limiting cross section ~0.5 cm²); L: No SEL or other destructive modes were seen. A single SEFI requiring a power cycle for recovery was seen during both laser and heavy-ion testing.	N	3.3V	2	NRL100808_NRL020209_T110308_ EDS5108ABTA [31]
Test Structure (no part number)	IBM	No LDC (test chip)	SRAM (test structure)	65 nm SOI	P: (UCD08MAY) PM	SEU measured under static conditions with various patterns, and results indicate relatively low Q_{crit} exhibiting sensitivity to direct ionization from low energy protons.	Y	0.8 V; 1.2 V	1	(no test report)

Part Number	Manu-facturer	LDC	Device Function	Tech-nology	Particle: (Facility/Date) P.I.,	Test Results LET in MeV•cm^2/mg σ in cm^2/device, unless otherwise specified	App. Spec. Test (Y/N)	Supply Voltage	Sample Size (Number Tested)	Test Report
Test Structure (no part number)	Texas Instruments	No LDC (test chip)	SRAM (test structure)	65nm CMOS	H: (NSRL09MAR) JP 56 GeV ^{56}Fe LET = 1.9 (MeV•cm^2)/mg Range(Si) = 15 cm H: (TAMU07DEC; TAMU08FEB; TAMU08JUN) MX P: (UCD08JAN; VDG08FEB; IU08APR) MX	H: (NSRL) SEU LETth < 1; plus grazing angle data [32- Pellish RADECS09] H: (TAMU07DEC; TAMU08FEB; TAMU08JUN) SEU, MBU and SEL all strongly depend on angle of incidence and test board orientation; Irradiations were performed for discrete angles and solid angles using new goniometer set-up. Largest SEU/MBU susceptibilities were observed when ions were incident parallel to well direction. P: (UCD08JAN) Nuclear reaction induced SEU and MBU observed for E > 10 MeV; (VDG08FEB) Direct ionization SEU observed for E < 2 MeV; (IU08APR) No angular dependence observed at 200 MeV.	N	1.2V	1 at NSRL; 4 at TAMU, UCD, and NVDG	[32 -Pellish RADECS09] T121007_T022508_x1886 [33] D012808_I042208_x1886 [34]
Other Devices:										
LX25 XC4VLX25-10FF668	Xilinx	0553	Virtex IV FPGA	90nm CMOS	P: (UCD08NOV) MB	P: SEUs observed >2 MeV protons.	Y	Core 1.2V; I/O 3.3V	5	D111208_LX25 [35]
MAX367	Maxim Integrated Products	0731	Circuit Protector	CMOS	H: (TAMU08FEB) RL	H: SEL LETth>87.6; SET LETth>87.6; Tested at room temperature and at 85ºC.	N	+10V; -0V	3	T022508_MAX367_DG390 [12]
HMP1-155TRX	Space Photonics Inc. (SPI)	No LDC (test chip)	Fiber Optic Transceiver	Hybrid	H: (TAMU08JUN) PM P: (UCD08JAN) PM/CM (w/M. Leftwich)	H: Bit error LETth >2.8; Bit error $\sigma_{max\ measured}$ =1.5x10^{-1} cm^2/device for receivers. P: Under all conditions, no loss of synchronization or LU observed. SEE bit and burst errors observed. SEE sensitivity on orbit will be low. Receiver more susceptible to SEE than the transmitter.	Y	3.3V; with LU testing 3.3V; 3.15V; 3.45V	3	D012808_T061808_HMP155TRX [36]
ISC 9803 Standard 640 and custom QWIP	Indigo Systems (9803) and NASA GSFC (QWIP)	No LDC (custom chip)	Readout Integrated Circuit (ROIC) hybridized to infrared sensor array	CMOS 8.6 micron AlGaAs QWIP In bump bonded to bulk 0.6 micron AMI C5 Si process chip	P: (UCD08NOV) CM	P: Large positive-going transients were seen to occur with the probability of ~10^{-6} per incident 63.3 MeV proton, corresponding to the approximate probability for a proton nuclear reaction event. These large transients produce a large positive single-pixel event followed by a smaller negative shift in all the trailing pixels of that column within a given frame. The trailing negative shift in affected columns is largely, but apparently not completely, restored by the beginning of the next frame due to the routine between frame commands sent to the ROIC. The residual offset appears to integrate over time, but can be reset by a power cycle.	Y	5.5V	2	D111908_TIRS-QWIP_Indigo-9808 [37]

IV. Test Results and Discussion

As in our past workshop compendia of GSFC test results, each DUT has a detailed test report available online at http://radhome.gsfc.nasa.gov [10] describing in further detail the test method, SEE conditions/parameters, test results, and graphs of data.

This section contains a summary of testing performed on a selection of featured parts.

1) International Rectifier AFL12028 DC-DC Converter

This study was undertaken to characterize the SEL and SET sensitivity levels for the AFL12028 DC-DC Converter from International Rectifier. The AFL12028SX/CH is a 120V in 28V single output DC to DC converter featuring high power density with a 4 A (112 W) minimum full load output current in a 2.5” ×1.5” ×0.38” steel case. The DUT was monitored for SEE and for potentially destructive events induced by exposing it to a heavy ion beam at TAMU.

The device is a hybrid component, containing a number of active components, such as an operational amplifier, MOSFET, and voltage reference. All the active components are scattered over the part and could not all be irradiated at the same time since radiation beam spot size is only 1” diameter. Three areas that were irradiated separately are indicated in the Figure 1.

The parts were irradiated in air. The distance between the beam output and the DUT was 7 cm. Three input voltages were used (80, 120, and 160) and a minimum of three loads conditions were investigated.

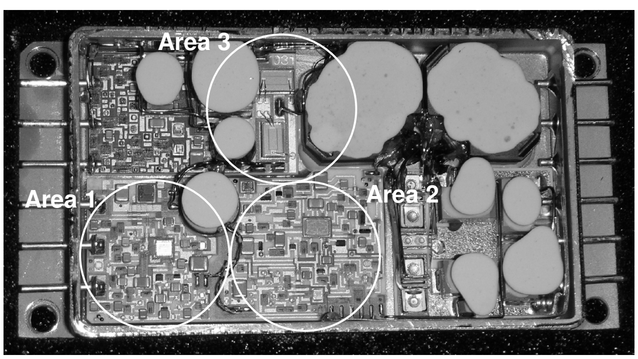

Fig. 1. Picture of a de-lidded DC-DC converter and identification.

No Single Event Transient (SET) was observed with all three ions and with all output loads. The maximum fluence was 10^7, 5×10^6, and 10^6 particles/cm^2 for Ar, Kr and Xe respectively.

Destructive failures with Xe ion were observed when Area 3 was irradiated. DUT1 had a destructive failure at $1.5\text{x}10^5$ particles/cm^2 fluence with 100% load and DUT2 showed the failure at 1.5×10^4 particle fluence with 70% load. Device output of 28V dropped to near ground level when the failure happened and the output never recovered. Figure 2 depicts the output wave form at the time of failure. All failures happened with 120V input voltage.

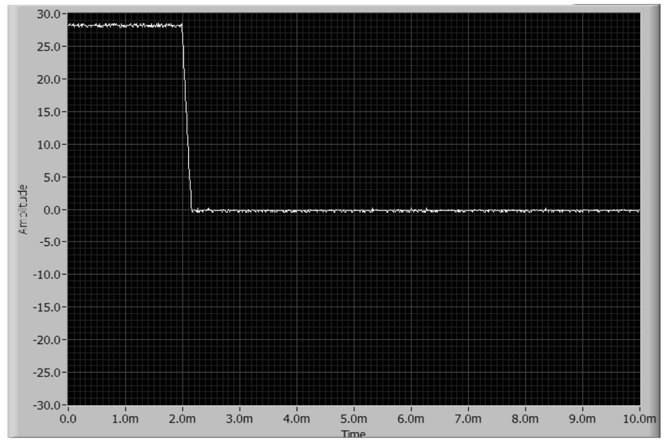

Fig. 2. Output at the time of destructive failure.

After the DUT was removed from the radiation beam, the input power was recycled in an effort to bring the DUT back to a normal operating condition. However, the device still drew more than triple the nominal current. It was only limited by the power supply. After the DUT was taken out of the irradiation room, visible inspection revealed that there was a burnt spot in Area 3. Figure 3 shows the DUT after the failure.

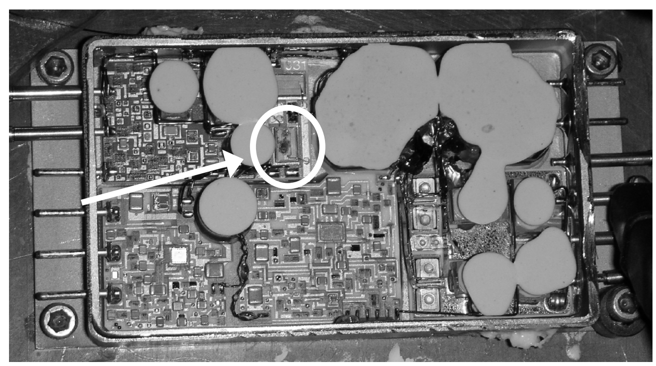

Fig. 3. Burnt Spot Observed.

Even though there was no SET monitored up to 10^6 Xe particles/cm^2 with a 30% output load, there was a destructive failure with low fluence of Xe (as low as 1.5×10^4 particles/cm^2) with a 70% load. The threshold of destructive failure conditions are yet to be determined since the device was not tested with other output loads between 30% and 70%, and test with a LET between 21 MeV•cm^2/mg (of Kr) and 41.5 MeV•cm^2/mg (of Xe) was not performed. Responses to various input voltages should also be studied in more detail. [25]

2) Microsemi Corp. APT50M38PLL Power MOSFET

This study was undertaken to determine the single event burnout (SEB) and gate rupture (SEGR) susceptibility of the APT50M38PLL power MOSFET under heavy ion irradiation. The device is an 88 amp, 500 volt commercial n-channel vertical power MOSFET with an aluminum metal gate structure in an interdigitated layout. It features a very low drain-source on-state resistance of 0.042 Ω. Tests were conducted at normal incidence (worst-case), and at a 45° angle of incidence to the surface normal either along the gate interdigitation or perpendicular to it. SEGR was the predominant failure mode: all seven devices tested at normal incidence and three of the four devices tested at angle experienced gate rupture. One device suffered SEB when tested at 45° incidence along the gate interdigitation. Table VI and this summary refer to data for the worst-case normal incidence testing only.

All devices were biased at or near a zero gate-source voltage (Vgs), and the drain-source voltage (Vds) was incremented between beam runs until device failure was observed. Currents were monitored at the gate and drain nodes during testing. Following each run, a gate electrical stress test was performed to check for latent damage, and the gate threshold voltage was measured. Devices were irradiated at TAMU with either 15 MeV/amu Kr or Ag ions having ranges above 100 µm in order to fully penetrate the sensitive epilayer.

SEGR occurred at half the rated Vds for the device when irradiated with Kr ions having a surface LET of 28.8 MeV•cm^2/mg, and at one third the rated Vds under Ag irradiation with an LET of 43.6 MeV•cm^2/mg. See Table VI for more details.

The gate threshold voltage (Vth) shifted dramatically during testing despite the low 1×10^5 ions/cm^2 maximum fluence per run. Under silver ion irradiation, Vth fell below vendor specification after less than 100 rads (Si) – the dose delivered during one or two beam runs. This finding is remarkable considering that the actual accumulated dose is much less due to the significant columnar recombination that occurs under the minimal oxide field created by the applied Vds (recall Vgs = 0V). Two tests were conducted in order to ensure that the drain biases at which SEGR occurred were not impacted by this heavy-ion dose induced threshold voltage shift. One pristine device was irradiated at the first-fail drain-source bias and experienced gate rupture. This test suggests that the threshold drain-source bias for SEGR was not artificially lowered. Two additional devices were pre-irradiated with silver ions while biased in the off state with 0 Vgs and a Vds well below the SEGR threshold, until the gate threshold voltage had degraded to less than half its initial value (well below vendor specification). Subsequently, SEGR testing was performed. No effect was seen on the minimum Vds required for SEGR. These heavy-ion dose effect tests suggest that the data presented in Table VI may be applicable to the relatively low heavy-ion dose conditions of typical space missions; however, further studies would be needed to explore the possibility of competing effects of heavy-ion dose versus Vth degradation-induced device turn-on. The SEGR threshold Vds as a function of heavy-ion dose is shown in Figure 4 for all devices tested at normal beam incidence. [23]

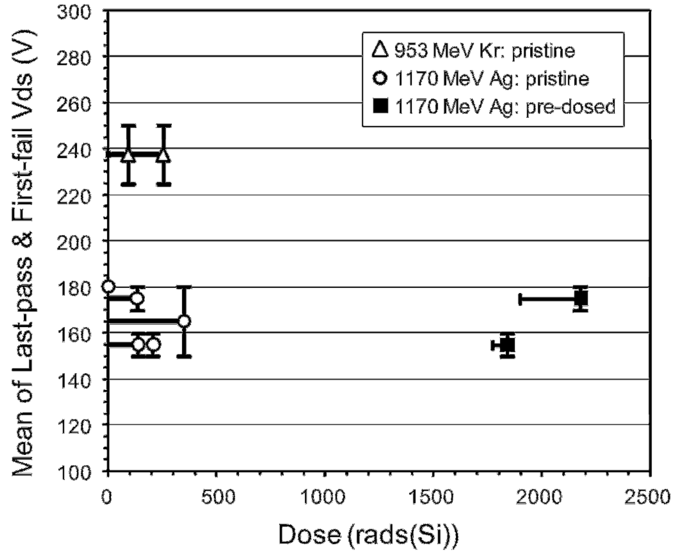

Figure 4. Mean drain-source threshold voltage for SEGR as a function of accumulated heavy-ion dose. Y-bars show measurement error; x-bars indicate dose accumulated during SEGR testing. Open markers indicate initially pristine-device data; filled markers show SEGR test results for the devices initially exposed to 1170 MeV silver ions.

3) National Semiconductor ADC14155W-MLS ADC

The ADC14155WG-MLS, manufactured by National Semiconductor (NS) is a 14-bit ADC designed to operate at 155 MSPS. Testing was conducted on June 2008 at the Texas A&M Cyclotron Institute using the 25 MeV/amu beam. The part was mounted on an evaluation board manufactured by NS and modified to make it compatible with NASA's "Low Cost Test System" motherboard.

SET characteristics were compared for three different sampling modes. For the one-point method, the input sine-wave was sampled once every clock cycle, always at the same amplitude. As a result, the point on the sine wave at which the signal is read does not change and the digital output has the same value for each reading. Readings were taken for 10 MSPS and 100 MSPS. For the two-point method, the clock frequency is set just a little faster than the input signal frequency so that each reading is separated by about 6 LSBs. For the four-point method, the input signal (25 MHz) was sampled four times during a single clock cycle, which was set to 100 MHz. The same four points were read on every clock cycle. When an error was detected at any of the four points, the values of all four were recorded. The usefulness of this approach is that, because it samples the sine wave at four different points instead of just one, it provides more information about the SET characteristics.

Bursts of SETs and clock losses were the only disturbances captured in all three methods. Figure 5 shows the distribution of SET length for different ion LETs for the single-point method. Figure 6 shows the cross-section as a function of ion LET for different SET amplitudes.

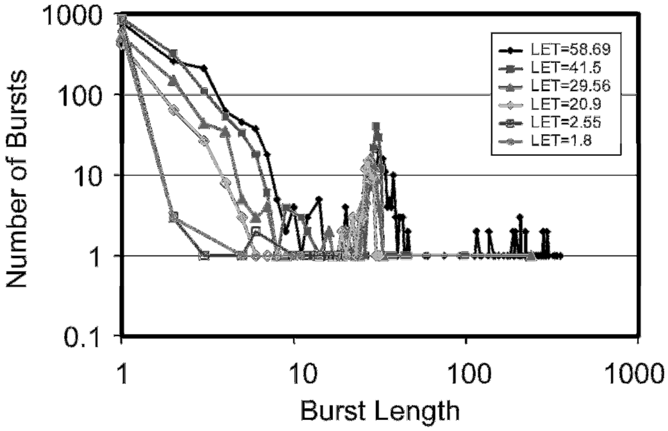

Figure 5. Number of bursts as a function of burst length (in clock cycles) for different LETs at a frequency of 100 MHz for the one-point method.

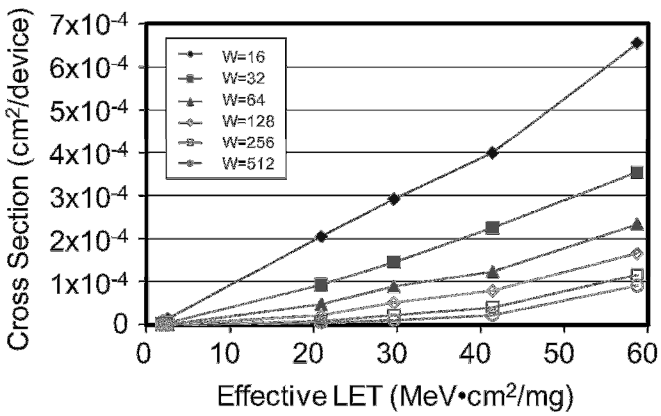

Figure 6. Cross-section for SETs as a function of ion LET for different SET amplitudes for the one-point method at 100 MHz.

Figure 7 shows the usefulness of the four-point method in capturing the shapes of the SETs. The figure shows the presence of large deviations from the expected values for only two of the four points sampled. The presence of additional points increases the likelihood of detecting SETs. Figure 8 shows the SET cross-section for the four-point method. [26]

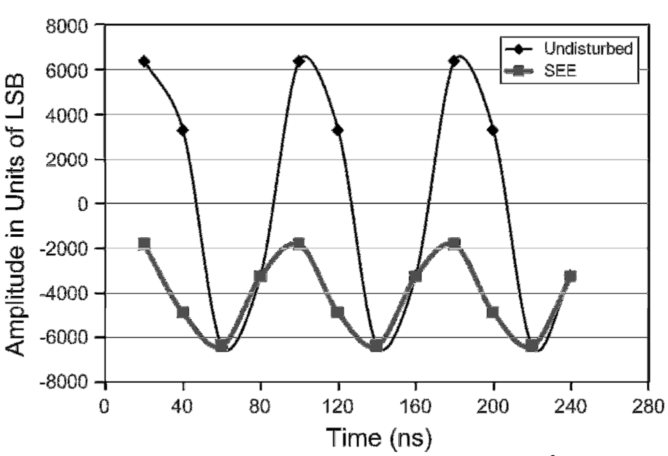

Figure 7. Example of a transient for a LET of 29.6 MeV•cm^2/mg. All four points were outside the window, and the resulting SET amplitude was smaller than that of the undisturbed sine wave.

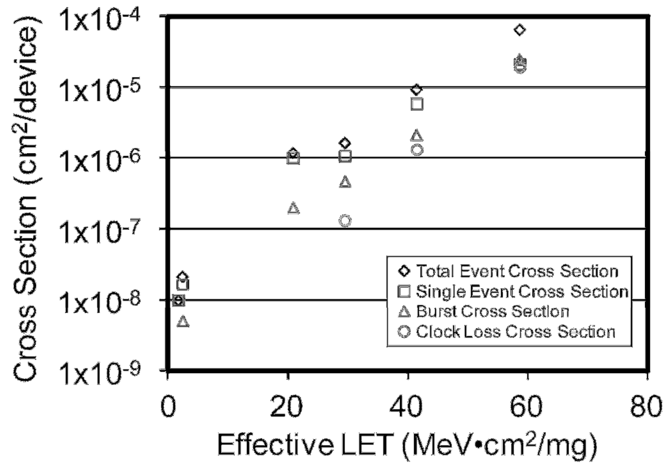

Figure 8. SET cross-section as a function of effective LET for four-point measurements for singles, bursts, clock losses and the sum of all events.

V. SUMMARY

We have presented recent data from SEE testing on a variety of mainly commercial devices. It is the authors' recommendation that this data be used with caution. We also highly recommend that lot testing be performed on any suspect or commercial device.

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