Compendium of Single Event Effects Results for Candidate Spacecraft Electronics for NASA

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***Abstract*— Susceptibility of a variety of candidate spacecraft electronics to proton and heavy ion induced single event effects is studied. Devices tested include digital, linear bipolar, and hybrid devices.**

***Index Terms*—Single Event Effects, spacecraft electronics, digital, linear bipolar, and hybrid devices.**

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I. Introduction

As spacecraft designers use increasing numbers of commercial and emerging technology devices to meet stringent performance, economic and schedule requirements, ground-based testing of such devices for susceptibility to single event effects (SEE) has continued to assume ever greater importance.

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 transient (SET). For proton displacement damage (DD) and total ionizing dose (TID) results, a companion paper submitted to the 2006 IEEE NSREC Radiation Effects Data Workshop entitled: "Compendium of Total Ionizing Dose Results and Displacement Damage Results for Candidate Spacecraft Electronics for NASA" by D. Cochran, et al. [1] should be referenced.

II. Test Techniques and Setup

A. Test Facilities

All SEE tests were performed between February 2005 and February 2006. Heavy Ion experiments were conducted at the Brookhaven National Laboratories' (BNL) Single Event Upset Test Facility (SEUTF) [2], Texas A&M University Cyclotron (TAMU) [3], and at the Single-Event Effects Test Facility (SEETF) at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University (MSU) [4]. The BNL SEUTF uses twin Tandem Van De Graaf accelerators while the TAMU facility uses an 88" Cyclotron. The NSCL MSU facility uses tandem K500 and K1200 cyclotrons to deliver ions with energies up to 125 MeV/n to the target. All three facilities are suitable for providing a variety of ions over a range of energies for testing. At all facilities, test boards containing the device under test (DUT) were mounted in the test area, but note that at BNL SEUTF, testing was performed in a vacuum chamber, while TAMU and NSCL SEETF are open-air facilities. For heavy ions, the DUT was irradiated with ions with incident linear energy transfers (LETs) ranging from 0.59 to 120 MeV•cm^2/mg. Fluxes ranged from $1x10^3$ to $1x10^5$ particles/cm^2 per second, depending on the device sensitivity and ion being used. 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 on the DUT, thus changing the path length of the ion through the DUT and the "effective LET" of the ion [5]. Energies and LETs available may have varied slightly from one test date to another.

Proton SEE tests were performed at two facilities: the University of California at Davis (UCD) Crocker Nuclear Laboratory (CNL) [6], and the Indiana University Cyclotron Facility (IUCF) [7]. Proton test details are listed in Table II.

Laser SEE tests were performed at the pulsed laser facility at the Naval Research Laboratory (NRL) [8] [9]. 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•cm^2/mg (Normal Incidence)	Normal Incidence Range in Si, µm
BNL	C-6	1.45-1.46	99.6	180.43
	F-9	3.5	142	118.88
	Si-14	7.8-11.3	187	77.16
	Cl-17	11.3-11.5	212	64.41
	Ti-22	19.6-19.8	232	47.8
	Ni-28	27.9	270	44.56
	Br-35	41.3	287	37.5
	I-53	66.9	322	32.54
MSU	Xe-136	17360	25	~ 3300
TAMU	Ne-22	262-266	2.8-2.9	256-267
	Ar-40	496-497	8.6-8.7	174-180
	Cu-63	953	20.3-20.7	123
	Kr-84	912	28.5-29.9	108-122
	Xe-129	1291	52.7-55.6	102-108
	15 MeV per nucleon tune			

TABLE II: PROTON TEST FACILITIES

University of California at Davis (UCD) Crocker Nuclear Laboratory (CNL), energy 63 MeV, flux ranged from 8x10^7 to 1x10^9 particles/cm^2/s.
Indiana University Cyclotron Facility, energy ranged from 63 to 200 MeV, flux ranged from 4x10^7 to 8x10^8 particles/cm^2/s.

TABLE III: OTHER TEST FACILITIES

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 DUT output to an unirradiated reference device or other expected output (Golden chip or virtual Golden chip methods). 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 I_{CC} (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 maximum measured cross sections and the LET threshold (LET_{th}). The LET_{th} is defined as the maximum LET value at which no effect was observed at an effect fluence of 1x10^7 particles/cm^2. In the case where events are observed at lower fluences for 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.

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 fluence and particle flux rates than do 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 full-width half-maximum (FWHM). The X-Y-Z stage could 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 (CCD) 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, SEE test result categories are summarized in Table VI, SEE results are summarized in Table VII, and SEL results are featured in Table VIII. 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:

H = heavy ion test
P = proton test (SEE)
L = laser test
Cat = category
Samp = sample
P.I. = principal investigator
LDC = lot date code
DUT = device under test
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)
SEE = single event effect
SEU = single event upset
SEL = single event latchup
SET = single event transient
SEFI = single event functional interrupt
SEB = single event burnout
SEGR = single event bate rupture
BERT = bit error rate test or tester
MBU = multi-bit upset
SEBE = single event burst error
SHE = single event hard error
DIP = dual inline package
LCDT = low-cost digital tester
WC = worst case
ADC = analog to digital converter
ALU = arithmetic logic unit
ASIC = application specific integrated circuit
CCD = charge collection device
CMOS = complementary metal oxide semiconductor
DAC = digital to analog converter
FET = field effect transistor
FPGA = field programmable gate array
MSB = most significant bits
NVM = non-volatile memory
Op Amp = operational amplifier
PROM = programmable read-only memory
PWM = pulse width modulator
RAM = random access memory
SDRAM = synchronous dynamic random access memory
SRAM = static random access memory
DDR = double data rate
SSPC = solid state power controller
DAC = digital to analog converter
ADC = analog to digital converter
Op Amp = operational amplifier
FPGA = field programmable gate array
Epi = epitaxy
APS = active pixel sensor
FOCUTS = Flipped Optical Chip Ultra Thin Silicon-on-Sapphire
NAND = not and (electronic logic gate)
V_{IN} or V_{OUT} = input voltage or output voltage
I/O = input/output

TABLE V: LIST OF PRINCIPAL INVESTIGATORS

Principal Investigator (PI)	Abbreviation
Steve Buchner	SB
Melanie Berg	MB
Ryan Flanigan	RF
Jim Howard	JH
Scott Kniffin	SK
Ray Ladbury	RL
Kenneth LaBel	KL
Paul Marshall	PM
Timothy Oldham	TO
Christian Poivey	CP
Wes Powell	WP
Anthony (Tony) Sanders	TS

TABLE VI: LIST OF CATEGORIES

Following ground SEE irradiation, devices generally are categorized into "useability" categories for spacecraft interest. Recommendations for SEE are color coded according to the following key:

Category	Implications
1:	Recommended for usage in all NASA/GSFC spaceflight applications
2:	Recommended for usage in NASA/GSFC spaceflight applications, but may require mitigation techniques
3:	Recommended for usage in some NASA/GSFC spaceflight applications, but requires extensive mitigation techniques or hard failure recovery mode (may require latent damage screening)
4:	Not recommended for usage in any NASA/GSFC spaceflight applications
RTV	Research Test Vehicle - Please contact the P.I. for further details

TABLE VII: SUMMARY OF SEE TEST RESULTS

Part Number	Manufacturer	LDC	Technology/ Device Function	Process	Particle: (Facility) P.I.,	Test Results LET in MeV•cm^2/mg σ in cm^2/device, unless otherwise specified	SEE Usage Cat.	Supply Voltage	Samp. Size	Test Report
Memories										
K4H1G-438 1Gb SDRAM	Samsung	0546	1 Gbit DDR SDRAM	90 nm minimum feature size CMOS	H: (MSU) RL/ JH/KL	SEUs, MBUs and SEFIs seen at the lowest LET tested (LET 24) $\sigma_{max\ measured}$=0.03 for SEU, 0.013 for MBU and 1.76×10-5 for SEFI; SEL 37 <LET_{th}<62 (only at 85 °C); SEL σ~2.35×10^{-5}	3	2.5 V	1	M120205_KH41G0X38
Test Parts - SDRAM	Maxwell	No LDC (test chip)	256 Mbit SDRAM	CMOS	H: (BNL; TAMU) RL/JH	SEU LET_{th}<1.45; SEFI: LET_{th}~10	3	3.3 V	2	T031205_Maxwell_SDRAM
MT29F2G08B	Micron	0524	NAND Flash Memory	CMOS	H: (MSU) TO/RL; H: (TAMU) TO	SEU, SEFIs, SHE: LET_{th} <20; Page Errors, and Stuck Bits LET_{th} <20	3	3.3 V	5	M120205_MT29F2G08B; T031206_MT29F2G08B; I032706_MT29F2G08B
CMOS Test Chips										
Test Parts - Shift Register	IBM	No LDC (test chip)	0.13µm CMOS bulk shift register	CMOS	H: (BNL) KL/MB/RL	SEU LET_{th} varied by design from 1.5 to <28.44	RTV	1.2 V	1	B061605_RHBD
G FLX Logic Chip Test Vehicle	LSI Logic	0528	0.11µm CMOS, Bulk & Epi Logic Chip	CMOS	H: (TAMU) CP	SEL LET_{th} >107; SEU LET_{th} ~2; SEU σ ~2 x 10^{-7} cm^2/flip-flop	Buried Layer: 2, Bulk: 3	Core: 1.2V, I/Os: 3.3V	Buried Layer: 2; Bulk: 2	T080805_Gflx_Qchip
G FLX SRAM Test Chip	LSI Logic	0528	0.11µm CMOS; Bulk & Epi 4Mbit SRAM	CMOS	H: (TAMU) CP	SEL LET_{th} >107; SEU LET_{th} <2.8; SEU $\sigma_{max\ measured}$ 8 x 10^{-8} cm^2/bit; Bulk: micro latchup event LET_{th}<2.8; part recovers functionality after a power cycle	Buried Layer: 2, Bulk: 3	Core: 1.2V, I/Os: 2.5 V	Buried Layer: 2; Bulk: 2	T080805_Gflx_SRAM
Converters										
AD565	Analog Devices	0236	12-Bit DAC	Bipolar	H: (TAMU) SB/CP	SET LET_{th} <8.57	2	15 V	1	T121805_AD565
AD650	Analog Devices	0518A	2.5 µm bipolar Voltage to Frequency Converter	Bipolar	H: (TAMU) CP	SEL LET_{th} > 10^7; SET LET_{th} <2.8; SET σ 5.0 x 10^{-3} @ LET 10^7	2	+/-10 V	2	T080805_AD650
Linear Devices										
OP11	Analog Devices	0412	Op Amp Linear Device	Bipolar	H: (TAMU) SB/RL	SET LET_{th} <8.57; For ΔV>100mV; 28.8 <SEB LET_{th} <53	3	15 V	2	T121805_OP11
RHFL4913	ST Microelectronics	0510A	Bipolar LVDO Regulator	Bipolar	H: (TAMU) CP	SEL LET_{th}>75; SET LET_{th} <2.8; SET $\sigma_{max\ measured}$ 1.5 x 10^{-3} @ LET 75; WC I_{out}=1.6A	3	3-5 V	2	T121805_RHFL4913
MSK5900	MS Kennedy	0442	Adjustable Positive Voltage Regulator	Hybrid	H: (TAMU) CP	SEL LET_{th} >75; SET LET_{th} ~12; SET $\sigma_{max\ measured}$ ~3 x 10^{-4} @ LET 75; WC V_{in}=3.8V I_{out}=100mA	2	3.6 V	2	T121805_MSK5900
MSK5920	MS Kennedy	No LDC (cage code 51651)	Dropout Voltage Regulator	Hybrid	H: (TAMU) CP	SEL LET_{th} >80; SET LET_{th} <10; SET $\sigma_{max\ measured}$ ~1 x 10^{-3} @ LET 80	2	3.3 V	2	T080905_MSK5920
RH1013	Linear Technology	0343A	Op Amp	Bipolar	H: (TAMU) SB	SET LET <8.47	2	15 V	2	T121805_RH1013
FPGAs										
Virtex II Pro XQ2VP40	Xilinx	0425	FPGA	CMOS	P: (IU) JH/WP	SEFIs observed with 200 MeV protons; SEFI σ ~1x10^{-8} @ LET 40	3	1.5 V	2	I101705_V2Pro
RTAX-S	Actel	0506 and 0543	0.15µm CMOS FPGA	CMOS	H: (TAMU) MB P: (UCD) KL/MB	SEU LET_{th} <8.5 (will be higher if running at a slower frequency)	2	Core: 1.5 V, I/O: 3.3 V	10	T110405_RTAX
RTSXSU	Actel	0501	0.25µm CMOS FPGA	CMOS	H: (TAMU) MB	SEU LET_{th} ~8.5	2	Core: 2.5 V, I/O: 5 V	2	T110305_RTSXSU
Eclipse FPGA	Aeroflex	No LDC (markings WF01G/ QL1082)	0.25µm CMOS shift register	CMOS	H: (TAMU) MB/TO	8.5< SEU LET_{th} <12	2	I/O: 3.3 V, Core: 2.5 V	10	T022205_Aeroflex_ Eclipse
Miscellaneous Devices										
Star1000	Fill Factory	No LDC (test chip)	CMOS Mixed APS Image Sensor	CMOS	P: (UCD) CP	SETs observed; No SEL or SEFI up to a fluence of 8x10^{10} with 63 MeV protons	3	5 V	3	D120506_ STAR1000
PE97201	Peregrine Semiconductor	No LDC (markings Rev B 24)	FOCUTS Fiber Optic Module	Hybrid	P: (UCD) SB/PM	SEBE observed with 63 MeV protons; Tested at 2.5 GHz data rate	2	3.3 V	1	D120505_PE97201
HTE721010G9AT00	Hitachi	No LDC (hard drive)	100 Gbyte E7K100 Hard Drive	Not Applicable	H: (TAMU) CP	SEL LET_{th} ~9 (destructive failure); SEFI LET_{th} ~2.8; SEFI σ ~1x10^{-3}	4	5 V	2	T022006_E7K100

TABLE VIII: SUMMARY OF SEL TEST RESULTS

Part Number	Manufacturer	LDC	Device Function	Process	Particle: (Facility) P.I.	Test Results LET in MeV•cm^2/mg σ in cm^2/device, unless otherwise specified	SEE Usage Cat.	Supply Voltage	Samp. Size	Test Report
EP1525	Altera Stratix	0401	FPGA	CMOS	H: (TAMU) TS/KL/CP	SEL LET_{th} <37; rise in current necessitated a power reset	4	3.3 V	2	T031405_Altera_FPGA
7809	Maxwell	No LDC (test chip)	16-bit ADC	Hybrid	L: (NRL) SK/SB	All devices remained functional. Two anomalies observed (exceeded specification limit). No latent damage.	1	5 V	5	NRL05JUL_7809
Spartan III D1327453A/4C and D1287920C/ 4C-ES	Xilinx	0441 UMC foundry	90 nm CMOS FPGA	CMOS	P: (IU 0605 & 10/05) MB/RF	No SEL observed with 200 MeV Protons	3	5 V	3	I101805_Spartan

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, 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) Analog Devices OP11 Operational Amplifier

The OP11 consists of four matched operational amplifiers in a DIP package. The object of the test was to determine the maximum amplitude and width of the SETs and to measure the cross-section as a function of LET to be able to calculate the SET rate for a specific NASA mission.

The part was mounted on a board in the exact configuration that will be used in space. A digital-to-analog (DAC) converter (AD565) was connected to the input of the OP11. A jumper on the board could be set so that the output of the DAC was at either +10V or –10V. Therefore, the input to the OP11 was +/-10V. The supply voltage was set at +/-15V.

A pulsed laser was first used to roughly gauge the sizes of the transients. SETs as long as 400 µs were observed when maximum laser pulse energy was used. Subsequent heavy ion testing was carried out at TAMU. Figure 1 shows that the largest transients had negative amplitudes of –25V and widths of less than 5 µs.

During heavy-ion testing the OP11 suffered destructive failure (SEB) when exposed to heavy ions with an LET of 75 MeV•cm^2/mg. No SEBs were observed at LET of 18.8.

The failure is tentatively attributed to burnout that occurred in the internal capacitor of the device. [11].

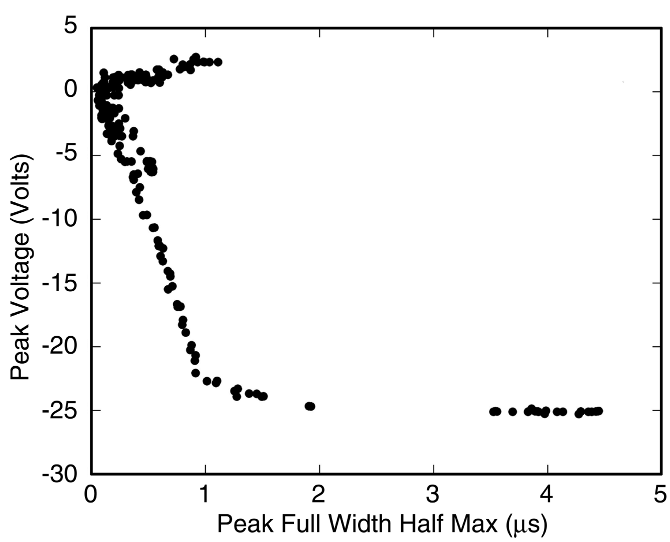

Fig. 1. Plot of amplitude vs width for SETs produced with 15 MeV Xe ions (LET = 75 MeV•cm^2/mg).

2) Voltage Regulators

As with other bipolar analog devices, voltage regulators are known to be sensitive to single event transients (SET). However, because typical applications use large output capacitors to provide noise immunity, SET amplitudes are generally less than 1V. These SET are a concern for low voltage applications. Overvoltages may cause destructive conditions. Undervoltage may cause functional interrupt and may also trigger electrical latchup conditions. SETs from voltage regulators may be especially critical in FPGA applications. For example, in the case of Actel FPGA RTAX family, core power supply voltage is 1.5V with a manufacturer absolute maximum rating of 1.6V and recommended operating conditions between 1.425V and 1.575V.

We tested two 1.5V low dropout voltage regulators for SET sensitivity, RHFL4913 from ST Microelectronics and MSK5900 from MS Kennedy.

Bias conditions of the RHFL4913 are shown in Figure 2. The device was tested with different load conditions, output currents and output capacitors. The device was also tested with and without a RC filter (highlighted in the figure) consisting of a 0.1 ohm resistor, and 200 µF capacitor. Input voltage is 3.3V +/-10%. Output Voltage is 1.5V.

The test circuit contains a power supply for the input voltage, an electronic load for drawing current, and a digital scope for capturing any output anomalies. Once the programmable output is present and the load conditions are set, the digital scope is set to trigger on voltages that are above or below a predetermined threshold of 70 mV.

Figure 3 shows the SET cross section curves for different load conditions, low and high output current and low and high output capacitor, without filter. We can see in Figure 3 that the output capacitor has little effect on SET cross section. However, output current does have an effect. The sensitivity is higher for high current loads.

Worst-case transients are shown in Figure 4. They were observed for the largest LET, the largest output current, and the lowest output capacitor. Larger output capacitor values reduce significantly the amplitude and duration of under-voltages. But there remain 200 mV amplitude over-voltage transients that last for up to 2 µs, and short duration, 200 ns, bipolar transients of 300 mV maximum amplitude.

The filter was effective in removing all long duration transients, but the short duration bipolar transients were not suppressed.

The MSK5900 was tested under similar conditions. Figure 5 shows the SET cross-section. We can see that the MSK5900 is significantly less sensitive than the RHFL4913. Maximum cross section is about one order of magnitude lower and LET threshold is higher than 15 MeV•cm^2/mg, compared with 2 MeV•cm^2/mg for RHFL4913. We can also see that the MSK5900 is most sensitive for the lowest current load of 100 mA.

Only one kind of transient was observed with MSK5900, 200 mV over-voltage transients with a worst-case duration of 4 µs. With the filter, the amplitude of transient is reduced to about 50 mV. Figure 6 shows typical transients with and without filter. [12], [13].

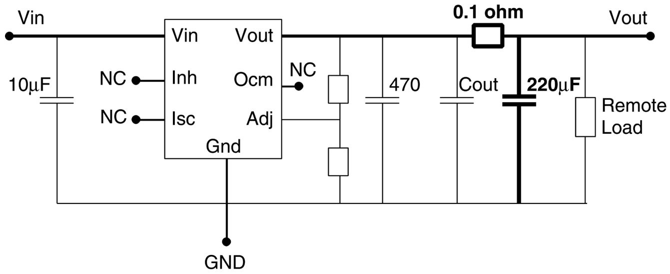

Fig. 2. RHFL4913 bias conditions.

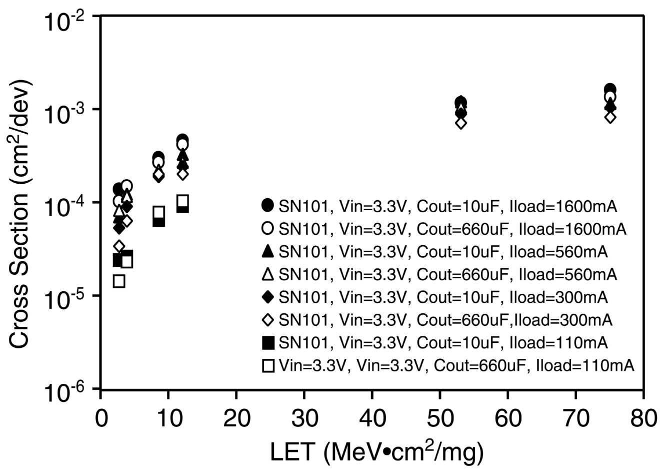

Fig. 3. RHFL4913, SET cross section curve.

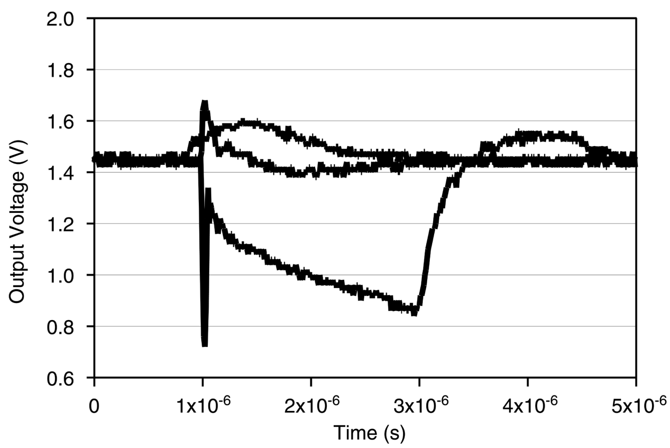

Fig. 4. RHFL4913 worst-case transients.

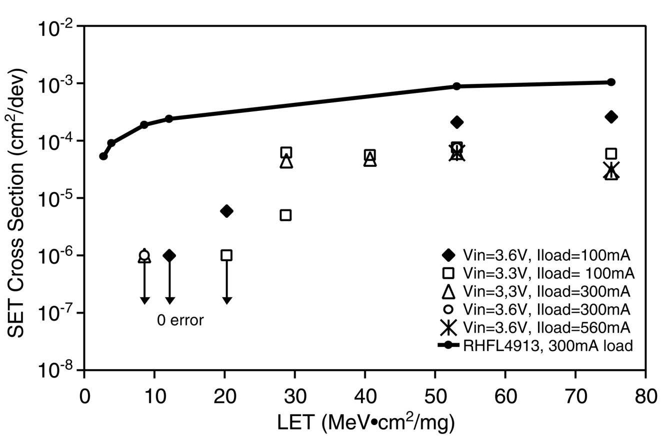

Fig. 5. MSK5900 SET cross-section curve.

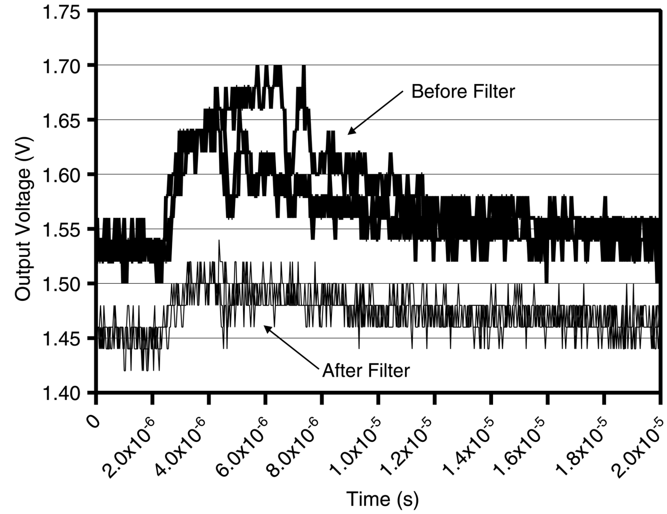

Fig. 6. MSK 5900, typical SETs, without filter (top) and with filter (bottom).

3) ACTEL RTAX-S FPGA

The RTAX-S devices were irradiated with Argon, Copper, Krypton, and Xenon beams at normal incidence (0) and 45 degrees (yielding effective LETs of approximately 8.5, 12, 28.5, 40.26, 52.7, 74.5 MeV•cm^2/mg) at TAMU. The ACTEL RTAX-S was configured as a shift register containing a windowed output [14]. The devices were manufactured on an advanced 0.15µm CMOS Antifuse Process Technology with 7 layers of metal. Test goals were to observe SEU, SEL, and SEBE pertaining to multiple types of design state-space variations: Frequency (15MHz-150MHz), Data Patterns (all '0', all '1', or alternating), and Architectural (varying levels of combinatorial logic between shift register flip-flops).

The NASA/GSFC low-cost digital tester (LCDT) was used to test the DUT [15]. The central component of the LCDT is a Xilinx Spartan 3 FPGA. It was configured to supply controls to the DUT and to perform DUT output data processing. A command processor was designed into the LCDT to provide user flexibility while driving tests. Thus the user could control the test frequency and data pattern (input to the DUT) without having to reconfigure or replace the test set-up (a significant cost savings).

The LCDT test vehicle provided a means for obtaining the first high-speed (150 MHz) radiation data for the RTAX-S devices. Because of the very high operational speeds of the LCDT, it is able to capture output data at every cycle. This provides accurate data encapsulation with additional insight to the possibility of burst data and its exact duration.

We were able to demonstrate that frequency, data pattern, and architectural effects exist for the RTAX-s FPGA. Please see Figure 7 for an overview of results. [16]

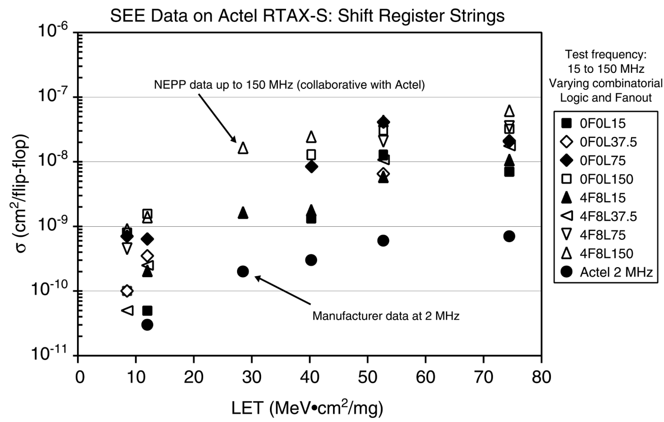

Fig. 7. Actel RTAX-S SEE Test Results: Includes Manufacturer 2 MHz Data.

V. SUMMARY

We have presented recent data from SEE 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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