Radiation Damage and Single Event Effect Results for Candidate Spacecraft Electronics

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Abstract

We present data on the vulnerability of a variety of candidate spacecraft electronics to proton and heavy-ion induced single-event effects and proton-induced damage. We also present data on the susceptibility of parts to functional degradation resulting from total ionizing dose at low dose rates (0.003-0.33 Rads(Si)/s). Devices tested include optoelectronics, digital, analog, linear bipolar, hybrid devices, Analog to Digital Converters (ADCs), Digital to Analog Converters (DACs), and DC-DC converters, among others.

I. INTRODUCTION

Recent experience in satellite design has shown a continuation, if not an acceleration, of the trend toward the use of commercial parts. 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), Co-60 total ionizing dose (TID) and proton-induced damage has assumed ever greater importance. Recent experience in satellite design has also emphasized the increased susceptibility of bipolar devices to damage from Total Ionizing Dose (TID) at low-dose-rates (0.001-0.01 Rads (Si)/s). This paper discusses the results of low-dose-rate (0.003-0.33 Rads(Si)/s) testing of a variety of devices representing several different vendors and fabricated in many different technologies.

The studies discussed here were undertaken to establish the sensitivities of candidate spacecraft electronics to heavy-ion and proton induced single-event upsets (SEU), single-event latchup (SEL), single event transient (SET), TID, and proton damage (ionizing and non-ionizing).

II. TEST TECHNIQUES AND SETUP

A. Test Facilities

All SEE and proton-induced damage tests were performed between February 1999 and February 2000. TID tests were performed between February 1998 and February 2000. TID testing was performed using a Co^{60} source at the Goddard Space Flight Center Radiation Effects Facility (GSFC REF). Heavy-Ion experiments were conducted at the Brookhaven National Laboratories Single-Event Upset Test Facility (SEUTF). The SEUTF uses a Tandem Van De Graaf accelerator that can provide ions and energies suitable for SEU testing. Test boards containing the device under test (DUT) were mounted within a vacuum chamber. The DUT was irradiated with ions with linear energy transfers (LETs) of 1.1 to 120 $MeV \cdot cm^2 mg^{-1}$, with fluences from $1x10^5$ to $1x10^7$ $particles \cdot cm^{-2}$. Fluxes ranged from $1x10^2$ to $1x10^5$ $particles \cdot cm^{-2}$ per second, depending on the device sensitivity. The ions used are listed in Table 1. LETs between the values listed could be obtained by changing the angle of incidence of ion beam onto the DUT, thus changing the path length of the ion through the DUT. Energies and LETs available varied slightly from one test date to another.

Proton SEE and damage tests were performed at four facilities: the University of California Davis (UCD) Crocker Nuclear Laboratory (CNL), TRI-University Meson Facility (TRIUMF), and the Indiana University Cyclotron Facility (IUCF). Proton test energies are listed in Table 2. Typically, the DUT was irradiated to a fluence from $1x10^{10}$ to $1x10^{11}$ $particles \cdot cm^{-2}$, with fluxes of $1x10^8$ $particles \cdot cm^{-2}$ per second.

Table 1: BNL Test Heavy Ions

Ion	Energy, MeV	LET in Si, MeV•cm²/mg	Range in Si, micronmeters
C^{12}	102	1.4	193
F^{19}	141	3.4	126
Si^{35}	186	7.9	85.3
Cl^{35}	210	11.4	65.8
Ti^{48}	227	18.8	47.5
Ni^{58}	266	26.6	41.9
Br^{79}	290	37.2	39
I^{127}	320	59.7	34
Au^{197}	350	82.3	27.9

Table 2: Proton Test Facilities

Facility	Particle	Particle Energy, (MeV)
University of California at Davis (UCD) Crocker Nuclear Laboratory	Proton	26.6-63
TRI-University Meson Facility (TRIUMF)	Proton	50-500
Indiana University Cyclotron Facility (IUCF)	Proton	54-197

B. Test Method

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

Dynamic – the DUT was exercised continuously while being exposed to the beam, and the errors were counted, generally by comparing DUT output to a unirradiated reference device or other expected output. Different device modes and clock speed may affect SEE results.

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

Biased (SEL only) – the DUT was biased and clocked while ICC (power consumption) was monitored for SEL or other destructive effects.

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.

Proton damage tests were performed on biased devices with functionality and parametrics being measured either continually during irradiation or after step irradiations (for example, every 10 krad (Si)).

TID testing was performed using a Co-60 source at the Radiation Effects Facility at Goddard Space Flight Center. The source is capable of delivering dose rates from 0.003-1.1 Rad(Si)/s, with dosimetry being performed by an ion chamber probe. TID testing used method 1019.5 as a guide.

Pre-irradiation electrical characterization was undertaken on all controls and test devices by means of functional and parametric tests. The parts were then irradiated in steps from 1 to 20 kRad(Si) and tested after each step for parametric degradation and functionality.

Displacement damage test guidelines are currently under development. Optocoupler characterization approaches used in this study are found in [2].

Unless otherwise noted, all tests were performed at room temperature and nominal power supply voltages.

III. Test Results Overview

SEE test results are summarized in Table 3. Displacement damage effects test results are summarized in Table 4. Abbreviations for principal investigators are listed in Table 5. TID test results are summarized in Table 6. This paper is a summary of results. Complete test reports are available online at http://radhome.gsfc.nasa.gov [1].

These tables use the following abbreviations and conventions:

H = heavy ion test
P = proton test (SEE)
LET = linear energy transfer (MeV•cm²/mg)
LET_{th} = linear energy transfer threshold (the minimum LET value to cause an effect at a fluence of 1×10^7 particles/cm²) in MeV•cm²/mg
LETmax = highest tested LET
SEU = single event upset
SEL = single event latchup
SET = single event transient
DD = displacement damage
< = SEE observed at lowest tested LET
> = No SEE observed at highest tested LET
PD = proton damage (both ionizing and non-ionizing)
TID = total ionizing dose
σ = cross section (cm²/device, unless specified as cm²/bit)
σ_{SAT} = saturation cross section (cm²/device, unless specified as cm²/bit)
LDC = lot date code
VOS = offset voltage
Vrms = root mean squared voltage
I_{SS} = V_{SS} current
I_{DD} = V_{DD} current
I_{IL} = low current
I_{IH} = high current
I_{DOFF} = V_{DD} current off
I_{SOFF} = V_{SS} current off
R_{ON} or RDS_{ON} = resistance
VGS = gate source voltage
VDS = drain source voltage

Unless otherwise noted, all LET_{th}s are in (MeV•cm²/mg) and all cross sections are in cm²/device.

Table 3: Summary of SEE Test Results

Part Number	Function	Manufacturer	Particle: (Facility)P.I.	Testing Preformed	Summary of Results
Power Devices:					
TL7702B	Power Supervisor	Texas Instruments	H: (BNL)RR P: (IUCF)KL	SEE and P: SEE	H: SEL LET_{th} > 73, SET LET_{th} ~ 5-7, $\sigma_{SAT}=5x10^{-5}$, results application specific P: No SEU, SETs observed
TL7705B	Power Supervisor	Texas Instruments	H: (BNL)RR P: (IUCF)KL	SEE and P: SEE	H: SEL LET_{th} > 73, SET LET_{th} ~ 2.7-3.3, $\sigma_{SAT}=1x10^{-4}$, results application specific P: No SEU, SETs observed
TL7770-5	Power Supervisor	Texas Instruments	H: (BNL)RR	SEE	H: SEL LET_{th} > 73, SET observed but not measured
TLC7705	Power Supervisor	Texas Instruments	H: (BNL)RR	SEE	H: SEL LET_{th} > 73, SET LET_{th} ~ <3.3, $\sigma_{SAT}=1.5\,x10^{-4}$, results application specific
ADC/DAC:					
MX7225UQ	8 bit DAC	Maxim	H: (BNL)RR	SEL	SEL LET_{th} > 90
AD571S	A/D Converter	AD	H: (BNL)RR/JH	SEL	SEL LET_{th} > 60
LTC1419	A/D Converter	Linear Tech	H: (BNL)RR/JH	SEL	SEL LET_{th} > 60
DAC08	Digital to Analog Converter	AD	H: (BNL)JH	SEL/SEU	SEL LET_{th} > 60, maybe SEU's at LET=60 and +/-15V and FF input, SEU/SEL LET_{th} >119.6 (application specific)
Memories:					
R29793	PROM	Fairchild	H: (BNL)JH	SEE	SEL LET_{th} > 37.4, two types of SEUs were observed, SEU LET_{th}~3, $\sigma_{SAT}=3x10^{-3}$
Digital Signal Processors:					
RH21020	DSP	Lockheed-Martin	P: (UCD)KL	P: SEE	$\sigma = 7.64x10^{-11}$
TSC21020F	DSP	Temic Semiconductor	P: (UCD)KL	P: SEE	$\sigma = 9.9x10^{-13}$
Logic Devices:					
10502	ECL Multiple NOR Gate	Motorola	H: (BNL)JH	SEL/SEU	SEL LET_{th} > 60, SEUs with LET_{th} ~ 26 and σ_{SAT}=~$1x10^{-6}$
MC74LCX08	2 INP and Gate	Motorola	H: (BNL)RR/JH	SEL	SEL LET_{th} > =60
Fiber Optic Links:					
HFBR-53D5	Transceiver	HP	P: (UCD)PM	P: SEE	Proton induced SETs observed, No destructive conditions observed to ~25 krads(Si) of 63 MeV protons
TTC-155M4	Transceiver	Lasermate	P: (UCD)PM	P: SEE	Proton induced SETs observed, No destructive conditions observed to ~25 krads(Si) of 63 MeV protons
TTC-155M2	Transceiver	Lasermate	P: (UCD)PM	P: SEE	Proton induced SETs observed, No destructive conditions observed to ~25 krads(Si) of 63 MeV protons
Linear Bipolar Devices:					
CLC449	OP AMP	National Semiconductor	H: (BNL)RR	SET; SEL	No SEL or SET to LETmax=60; SET result is application specific
PA07	High Power OP AMP	APEX	H: (BNL)RR	SET; SEL	SEL and SET are application specific. No SEL or SET to LETmax=37
LMC6081	Precision OP AMP	National Semiconductor	H: (BNL)JH	SEL	No SEL to LETmax=60
HS139	Comparator	Harris	H: (BNL)JH	SET; SEL	SETs observed, No SELs observed
LM139	Comparator	National Semiconductor	P: (UCD)JH H: (BNL)JH	P: SET HI: SET; SEL	No SETs observed with test setup used; SET LET_{th}=20; $\sigma_{SAT}=2x10^{-4}$ SEL LET_{th}>59.8
MAX962	Comparator	Analog Devices	H: (BNL)JH	SEL	No SEL to LETmax=60

Part Number	Function	Manufacturer	Particle: (Facility)P.I.	Testing Preformed	Summary of Results
Linear Bipolar Devices (Cont.):					
AD783SQ	Sample and Hold Amplifier	Analog Devices	H: (BNL)RR	SET; SEL	SEL LET_{th} > 90, SET LET_{th} ~ 7, $\sigma_{SAT}=1x10^{-4}$ cm^2
A250	Charge Sensitive Amp	Amptek	H: (BNL)RR	SET; SEL	No SEL or SET to LETmax=60; SET is application specific
MSA0670	MMIC Amplifier	HP	H: (BNL)JH	SET; SEL	No SEL or SET to LETmax=85
Optocouplers:					
OLH5601	Optocoupler	Isolink	P: (TRIUMF)RR	SET	Proton induced transients were observed, no significant degradation
6N134	Optocoupler	Micropac	P: (TRIUMF)RR	SET	Proton induced transients were observed, no significant degradation
Others:					
DS1670E	System Controller	Dallas Semiconductor	H: (BNL)RR	SEL	SEL LET_{th}~15
SN54LVTH16244A	Buffer/Drivers	Texas Instruments	H: (BNL)RR/JH	SEL	No SEL to LETmax=60
CGS74LCT2524	Clock Driver	National Semiconductor	H: (BNL)RR/JH	SEL	No SEL to LETmax=60
MIC4423	MOSFET driver	Micrel	H: (BNL)RR	SET; SEL	No SEL or SET to LETmax=60; SEL and SET are application specific
MC74HC4538A	Multivibrator	Motorola	H: (BNL)RR/JH	SEL	No SEL to LETmax=60
DS1803	Dual Digital Potentiometer	Dallas Semiconductor	H: (BNL)RR	SEL; SEU	LET_{th}>20; SEL observed at LET <37

Table 4: Summary of Displacement Damage Test Results

Part Number	Function	Manufacturer	Particle: (Facility)P.I.	Testing Preformed	Summary of Results
Linears Bipolar Devices:					
LM111	Comparator	National Semiconductor	P: (UCD)JH (IUCF)JH	DD	Saw enhanced damage from Protons vs Co-60
Optocouplers:					
OLH249	Optocoupler	Isolink	P: (UCD)KL	DD	CTR degradation observed. See [2]
66099	Optocoupler	Micropac	P: (UCD)RR	P: DD	CTR measurements for 63 MeV; Vce=5V
Optoelectronics:					
OD800	LED	Optodiode	P: (UCD)RR/PM	DD	60% light output degradation at $2.7x10^{10}$
HFE-4080	Linear feedback shift register	Honeywell	P: (UCD)CM	DD	

Table 5: List of Principal Investigators

Principal Investigator (PI)	Abbreviation
Kenneth LaBel	KL
Robert Reed	RR
Jim Howard	JH
Paul Marshall	PM
Cheryl Marshall	CM

Table 6a: Summary of NASA GSFC TID Test Results - Comparator

Manufacturer & Part Number.	Part Type	LDC	Test Level (krads)	Effective Dose Rate (rads)/s	Param. Degrad. Level (krads)	Radiation Sensitive Parameters	Report Number	Comments
Maxim MX913	TTL Comparator	9704	100	0.0035-0.174	>100	None	PPM-98-018	
AD CMP01 (V_{CC}= 5 V)	Voltage Comparator	9729	200	0.33	>200	None	PPM-98-015	
AD CMP01 (V_{CC}= 15 V)	Voltage Comparator	9729	200	0.33	>60	I_{ib}, CMRR, I_{OS}	PPM-98-015	Improved after 240 hr @ 25 °C anneal
AD PM139	Comparator	9720A	200	0.33	>200	None	PPM-98-010	

Table 6b: Summary of NASA GSFC TID Test Results - Operational Amplifiers

Manufacturer & Part Number.	Part Type	LDC	Test Level (krads)	Effective Dose Rate (rads)/s	Param. Degrad. Level (krads)	Radiation Sensitive Parameters	Report Number	Comments
NSC LMC6464	CMOS Op Amp	9722	5.0, 10.0	0.03	N/A	Multiple parameters	PPM-99-041	Catastrophic failure at 5-10 krads(Si)
NSC (Comlinear) CLC502	Op Amp	Not marked	5-100	0.035-0.174	100	N/A	PPM-98-018	
AD AD783SQ	Sample & Hold Amp.	9702	2.5-50	0.04	N/A	N/A	PPM-99-040	Passed all tests to 50 krads(Si)
AD AD620	Inst. Op Amp	9815	5.0-25	0.04	5-10	Bias currents	PPM-99-029	
AD AD845	CBFET Op Amp	9846	2.5-50	0.04	>20	Multiple parameters	PPM-99-026	
AD OP-07	Op Amp	9723B	10-40	0.14	>10 krads(Si)	Offset voltage	PPM-99-017	Some recovery after anneal
AD OP-07	Op Amp	9724A	5-40	0.14	~20	Offset voltage	PPM-99-016	Some recovery after anneal
AD OP-07	Op Amp	9724	20-200	0.14 and 0.58	~20	Multiple parameters	PPM-99-001	Degradation worse for higher rate. Lot had outliers in Vos
AD OP-07	Op Amp	9723B	20-200	0.33	~20	Offset voltage, then multiple parameters	PPM-98-011	Lot had outliers in Vos.
AD AMP01	Inst. Amp.	9818A	2.5-50	0.02	>5	Offset voltages, gain errors	PPM-99-015	
AD OP467	Op. Amp.	9812A	2.5-50	0.04	>10	Bias currents	PPM-99-004	
AD OP400	Op. Amp	9814A	2.5-50	0.04	>5	Bias currents, slew rate, gain	PPM-99-003	
AD OP270	Op. Amp.	9815	2.5-50	0.04	>5	Bias currents	PPM-98-029	
AD OP27	Op. Amp.	9721A	20-200	0.333	<20-40	Offset voltages	PPM-98-009	
AD OP15	Op. Amp.	9722A	20-200	0.333	20-40	Offset voltage, leakage currents	PPM-98-008	
AD AD585	Sample &Hold Amp.	9648	5-100	0.035-0.174	>30	Common-mode rejection ratio, offset voltage	PPM-98-006	
AD AD524	Inst. Amp.	9650A	5-100	0.072	>20	Offset voltages	PPM-98-005	
LT LF155A	Op. Amp. JFET input	9811	2.5-30	0.04	>10	Bias currents	PPM-99-035	
LT LT1010	Pwr. Buffer	9808	2.5-100	0.08	>100	N/A	PPM-99-010	
LT LF198	Sample & Hold Amp.	9129	20-200	0.33	>200	N/A	PPM-99-009	
LT LF147	Op. Amp.	9803	2.0-10 (low-dose rate) 2.5-50	0.004 0.02	See * in comments section	Multiple parameters	PPM-99-002	Low-rate tests, no significant degradation to 10krads(Si) * High rate: 5 krads showed sig. Degradation; not seen at lower rate
Burr- Brown INA117SM	Diff. Amp.	9837	10-50	0.06	>17.5	Offset voltage	PPM-99-033	
Apex PA07M	Power Op. Amp.	9918	10-50	0.06	>17.5	Offset voltage	PPM-99-032	
Amptek A250	Preamplifier	9902	10-100	0.07	>100	N/A	PPM-99-031	
Maxim MAX494	Op. Amp.	9639	5-100	0.06	>10	Bias currents	PPM-98-019	
Omnirel OM11725SMX	Op. Amp.	9735	5-75	0.043	>20 krads(Si)*	Line voltages	PPM-98-002	Note: catastrophic functional failure 15-75 krads(Si)

Table 6c: Summary of NASA GSFC TID Test Results - Analog-to-Digital and Digital-to-Analog Converters

Manufacturer & Part Number.	Part Type	LDC	Test Level (krads)	Effective Dose Rate (rads)/s	Param. Degrad. Level (krads)	Radiation Sensitive Parameters	Report Number	Comments
AD AD7821	8-Bit ADC	9727	2.5-50	0.04	>30	Missing codes, integral nonlinearity	PPM-99-045	
AD AD7885	16-Bit ADC	9827	2.5-50	0.06	>50	N/A	PPM-99-039	
AD AD571	10-Bit ADC	9746	20-200	0.33	>200	N/A	PPM-98-024	
AD AD976	16-Bit ADC (BiCMOS)	9723	5-100	0.033	<5	Missing codes, integral and differential nonlinearity	PPM-98-001	Note parts may exhibit low-dose-rate susceptibility
AD DAC08	8-Bit DAC	9831	10-50	0.05	>25	Power supply sensitivity	PPM-99-036	
AD AD7535	14-Bit DAC	9812	10-25	0.05	>10	Integral and differential nonlinearity	PPM-99-027	
AD AD7545	12-Bit DAC	9807	2.5-30	0.07	>5	Integral and differential nonlinearity; leakage currents	PPM-99-022	
AD AD8222	12-Bit DAC	9738	GroupA: 2.5-5; Group B: 1-10	Group A: 0.004 Group B: 0.003	A: <2.5 B: <1	Multiple parameters	PPM-99-006	
Maxim MX7225	8-Bit DAC	9321	2.5-30	0.04	>10	Multiple parameters	PPM-99-042	
Maxim MX536	RMS-DC Converter	9817	2.5-100	0.06	>10	VOS, Vrms	PPM-99-008	
Micronetworks MN5295	16-bit DAC	9549 9540	5-35	0.019	>15	Missing codes, integral and diff. Nonlinearity	PPM-99-018	

Table 6d: Summary of NASA GSFC TID Test Results - Voltage Regulators and Voltage References

Manufacturer & Part Number.	Part Type	LDC	Test Level (krads)	Effective Dose Rate (rads)/s	Param. Degrad. Level (krads)	Radiation Sensitive Parameters	Report Number	Comments
Linfinity PIC7527	Switching Regulator	9450	2.5-50	0.06	>50	N/A	PPM-99-038	
NSC LM117K	Voltage Regulator	9808	10-30	0.08	>10	Line voltages	PPM-99-034	
NSC LM117H	Voltage Regulator	9727	20-200	0.33	>20	Line voltages	PPM-98-026	No improvement after anneal
NSC LM117HVK	Voltage Regulator	9732	20-200	0.33	>/~20	Line voltages	PPM-98-021	
NSC LM117HVH	Voltage Regulator	9727	20-200	0.33	>20	Line voltages	PPM-98-020	
Omnirel OM3914	Neg. Voltage Reg.	9909	2.5-50	0.05	>10	Ref. Voltage, line reg.	PPM-99-028	
Omnirel OM1850STM3	Voltage Regulator	9912	2.5-50	0.04	>10	Ref. Voltage, line reg.	PPM-99-024	
AD AD588	Voltage Reference	9814	2.5-100	0.05	>15	Minor shifts in voltage levels	PPM-99-014	
AD AD780	Voltage Reference	9728	2.5-100	0.08	>100	N/A	PPM-99-011	

Table 6e: Summary of NASA GSFC TID Test Results - Memories

Manufacturer & Part Number.	Part Type	LDC	Test Level (krads)	Effective Dose Rate (rads)/s	Param. Degrad. Level (krads)	Radiation Sensitive Parameters	Report Number	Comments
Samsung KM48C800AS-6U	8MBx8 DRAM	Multiple wafer lots	Batch1: 2.5-100 Batch2: 20-100	Batch 1: 0.09 Batch 2: 0.06	>20	Supply currents, functional	PPM-99-030	
Samsung KM684002AJ-17	512Kx8 SRAM	9826	2.5-100	0.05	>30	Leakage currents, functional failure	PPM-99-014	
SEEQ/ATMEL 28C256	256K EEPROM	9133	1-25	0.01	>20	Functional failure	PPM-98-023	
Fairchild/Raytheon R29773	2Kx8 PROM	9347	20-200	0.33	>200	N/A	PPM-98-013	

Table 6f: Summary of NASA GSFC TID Test Results - Analog Switches and Multiplexers

Manufacturer & Part Number.	Part Type	LDC	Test Level (krads)	Effective Dose Rate (rads)/s	Param. Degrad. Level (krads)	Radiation Sensitive Parameters	Report Number	Comments
Maxim DG412	Analog Switch	9829	15	0.006	<2.5	I_{SS}, I_{DD}, I_{IL}, I_{IH}, I_{DOFF}, I_{SOFF}	PPM-99-012	Functional to >15 krads
Maxim DG403	Analog Switch	9810	5-10	0.02, 0.003	<2.5	I_{DD}, I_{SS}, I_{IH}, I_{IL} and R_{ON}	PPM-99-007	Failed functionality at 7.5-20 krads
Harris HI300	Analog Switch	9816	5-50	0.03	<2.5	I_{IH}, I_{IL}, and (for >30 krad) I_{SS}, I_{DD} and R_{ON}	PPM-99-005	Parts annealed at 5.0 and 50 krad; functional despite parametric degradation
Harris HI506	Multiplexer	9745	50	0.04	>50	N/A	PPM-98-028	

Table 6g: Summary of TID Test Results - Power Devices

Manufacturer & Part Number.	Part Type	LDC	Test Level (krads)	Effective Dose Rate (rads)/s	Param. Degrad. Level (krads)	Radiation Sensitive Parameters	Report Number	Comments
Lambda/ Advanced Analog ATR2815TF	DC-DC Converter	9907	5-25	0.022	>10	Efficiency, line reg	PPM-99-020	
Interpoint MTR2815	DC-DC Converter	9830	2.5-100	0.09	15-50	Input current	PPM-98-031	
Interpoint MTR2805	DC-DC Converter	9828	2.5-100	0.09	>50	Multiple parameters	PPM-98-030	
Linfinity SG1846	Pulse-Width Modulator	9715	20-200	0.33	>80	Error-amp section parameters	PPM-98-022	

Table 6h: Summary of TID Test Results - Miscellaneous

Manufacturer & Part Number.	Part Type	LDC	Test Level (krads)	Effective Dose Rate (rads)/s	Param. Degrad. Level (krads)	Radiation Sensitive Parameters	Report Number	Comments
NSC 54ABT245A	Transceiver	9736	10-50	0.05	17.5	Leakage currents	PPM-99-037	
Micrel MIC4424	Dual MOSFET Driver	9832	5-75	0.058	20	Functionality	PPM-99-019	
Q-Tech QT22AC10M	36 MHz Xtal Osc.	9842	5-100	0.08	>100	N/A	PPM-99-021	
National DS7830	Diff. Line Driver	9749	20-200	0.33	>200	N/A	PPM-98-025	
National 54AC74	Dual Flip-Flop	9610	5-100	0.16	>5	Power supply voltages	PPM-98-027	
Omnirel OM20P10	P-Channel MOSFET	9735	2.5-20	0.03	>10	Threshold VGS, VDS, RDSon	PPM-99-025	
Harris 2N7225	N-Channel MOSFET	9827	2.5-50	0.06	>10	Threshold VGS	PPM-99-023	
Solitron 2N5115	PJFET	9430	5-100	0.089	5-15	Leakage currents	PPM-98-004	One failure after 5 krads
Motorola 2N4858	NJFET	9333	5-100	0.072	>100	N/A	PPM-98-003	

IV. SEE TEST RESULTS AND DISCUSSION

A. Power Devices

1) TL7702B, TLC7705, and TL7705B Heavy Ion Testing

Texas Instruments power supply supervisors TL7702B, TLC7705, and TL7705B were tested for SEE at BNL. Figure 1 gives the measured (uncorrected) high-to-low SET cross section versus the linear energy transfer (LET) for TCL7705. Heavy ion-induced SET measured cross section data for TL7705B is shown in Figure 2, and data for TL7702B is shown in Figure 3. These tests were application specific. Details of the test techniques can be found in the test synopsis [2]. We visual observed that the SETs were typically 25ms in duration and the dropout was all the way to ground. Considering corrections for application specific test factors, the value of the cross section measured with the automated collection system could be low by an order of magnitude. No low to high SETs were observed.

The TLC7705 did not experience any SELs for the test setup used.

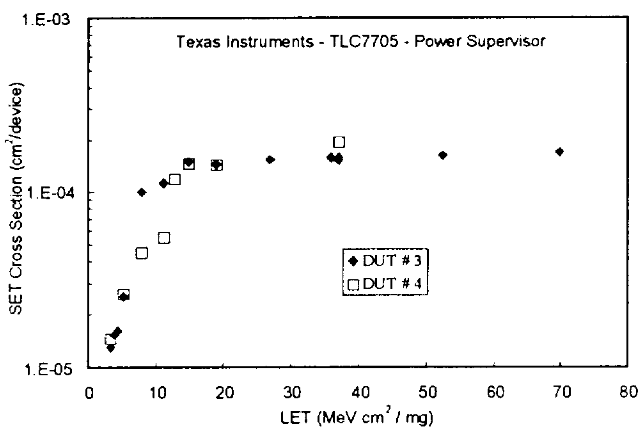

Fig. 1. Heavy ion-induced SET measured cross section data for two devices. The actual cross section is unknown and could be as high as an order of more large than the measured cross section.

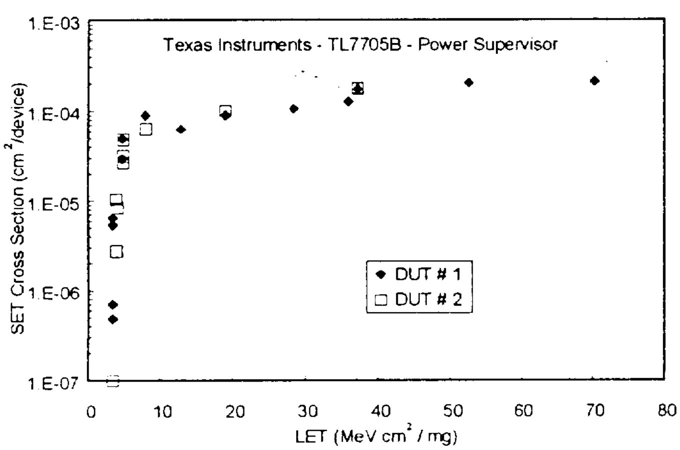

Fig. 2. Heavy ion-induced SET measured cross section data for two devices. The actual cross section is unknown and could be as high as an order of more large than the measured cross section.

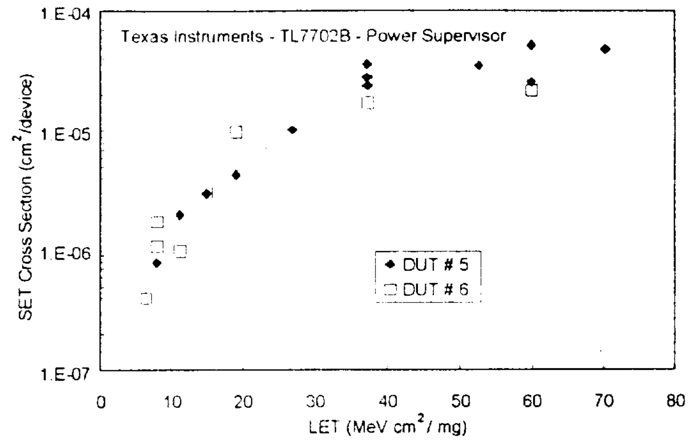

Fig. 3. Heavy ion-induced SET measured cross section data for two devices. The actual cross section is unknown and could be as high as an order of more large than the measured cross section.

2) TL7770-5 Heavy Ion Testing

Radiation-induced SET and SEL susceptibility of the Texas Instruments TL7770-5 Dual Power-Supply Supervisors was performed at BNL Single Event Upset Facility. Output of the device was monitored for radiation induced errors. Only undervoltage conditions were tested. The power supply current was monitored for large current increase and the device functionality was monitored.

The TL7770-5 did not experience any SELs for the test conditions and circuit configuration used, see test synopsis [3] for details of testing conditions). High to low SETs were observed, however, they were too short in duration to be captured by the automated data collection system. They were <2μs in duration and the pulse height varied from just visible on the digital oscilloscope to going all the way to ground. No low to high SETs were observed.

3) TL7702B and TL7705B Proton Testing

Proton induced degradation testing on Texas Instruments power supervisors TL7702B and TL7705B was performed at IUCF.

No errors, anomalies, or destructive conditions were observed on 2 test samples of the TL7702B at a cumulative fluence of 6.56×10^{11} protons/cm^2 (40 krads (Si) of TID). Thus, the limiting device cross-section is 1.52×10^{-12} cm^2/device. No obvious degradation due to TID or displacement damage was observed.

No errors, anomalies, or destructive conditions were observed on 2 test samples of the TL7705B at a cumulative fluence of 6.56×10^{11} protons/cm^2 (40 krads (Si) of TID). Thus, the limiting device cross-section is 1.52×10^{-12} cm^2/device. No obvious degradation due to TID or displacement damage was observed.

B. ADC/DAC

1) Maxim MX7225 8-bit digital to analog converter

Testing was performed at BNL to determine the radiation-induced latch-up sensitivity of the Maxim MX7225 and to measure sensitivity as a function of supply voltage.

The MX7225 did not experience any SELs for the application specific test conditions used. Details of the test setup can be found in [4]. Thus, the DUT has an LET_{th} > 84.7 MeV•cm²/mg with a limiting cross-section $<1\times10^{-7}$ cm². No SETs were observed.

2) Analog Devices AD571S analog to digital converter

The device was monitored for latchup induced high power supply currents by exposing it to a number of heavy ion beams at BNL. Supply current was monitored for an increase or decease. No SELs were observed for the AD571S analog to digital converter up to LET of 60 MeV•cm²/mg.

3) Linear Technologies LTC1419 analog to digital converter

The Linear Technologies LTC1419 was monitored for latchup induced high power supply currents by exposing it to a number of heavy ion beams at BNL [5]. Supply current was monitored for an increase or decease.

No SELs were observed on 3 devices of each type tested under bias conditions of 7 volts at all ion LETs to a fluence of 1×10^{7} p/cm².

4) Analog Devices DAC08 digital to analog converter

The Analog Devices (AD) DAC08 digital to analog converter was tested at BNL to determine the single event transient and latch-up sensitivity. Tests were performed to screen for the possibility of upset and latch-up and measure sensitivity as a function of input code (output voltage) and particle LET. The DAC was operated in a dc mode as required by the application specific test (dc output mode only).

The devices were exposed to a fluence of 10^{7} particles/cm² of Titanium, Bromine and Iodine ions with no single event upsets or latchup. An occasional trigger on the digital scope was seen, indicating a possible upset. Upon review of the data it was determined that these events were just noise. The upset window was kept intentionally small to catch even upsetting the LSB so temporary fluctuations of noise could trigger the scope. The events seen were very infrequent (approximately 15 events in 2 x 10^{8} ions) and not considered to have a detrimental impact to the testing. The Analog Devices (AD) DAC08 Digital to Analog Converter is considered to have an LET_{th} for upsets and latchup greater than 119.6 MeV•cm²/mg. This latchup result is valid for generic use, but since this testing was dc output mode only, the upset portion of this testing is application specific to operation in the dc output mode [6].

C. Fairchild R29793 Programmable Read Only Memory (PROM)

Test conditions included the nominal case level for the Supply Voltage (Vs = 5 Volts) and a checkerboard pattern (55AA) while the device operated at a frequency of 1 MHz.

The devices were exposed to a fluence of 5×10^{5} to 1×10^{6} particles/cm² of Bromine and various fluences of the Carbon, Silicon, and Chlorine ions with no single event latchups. The Fairchild R29793 PROM is considered to have an LET_{th} for latchup greater than 37.4 MeV•cm²/mg.

Upsets, on the other hand, were common. During the testing, it became apparent that there were actually two modes of upsets. These were single cell upsets and massive-device-failure upsets (where approximately all storage locations would read incorrectly). For the single cell upsets the approximate LET_{th} is 3 MeV•cm²/mg and the device saturation cross section is 3×10^{-3} cm². For the massive error events, approximate LET_{th} is 5 MeV•cm²/mg and the device saturation cross section is 1×10^{-4} cm².

For the massive error events, the ion beam flux was allowed to continue until the error counter jumped, nearly instantaneously, to in excess of 70,000 errors. On occasion, before the beam could be stopped, a second massive event was observed as the counter jumped to in excess of 140,000. From Figure 4, it can be seen that for both normal and angled incident Carbon ion beams, no massive upset events were observed. At the higher LETs of 7.88 and 11.4, all the devices experienced these errors at a highly variable rate [7].

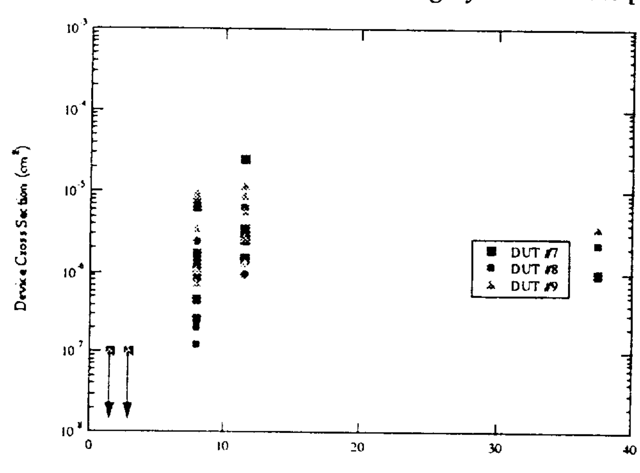

Fig. 4. Device Cross Section as a function of Effective LET for the massive error events. Data points with a down-pointing arrow indicate that no events were observed under those conditions.

D. Digital Signal Processors

1) Lockheed-Martin RH20120

Lockheed-Martin RH21020s were tested for SEU under irradiation by proton beams in both dynamic and static modes [8]. Outputs from the DUT were compared to those from an identical, non-irradiated reference chip and logged as errors when they did not match. The DUTs were operated at 15 MHz (50% derated) and a power supply voltage of 5 volts. They were irradiated with proton fluences up to 1.4×10^{12}

particles per cm^2 at fluxes ranging from $8.6x10^7$ – $1.7x10^9$ particles/cm^2 per second. The total upset cross section of the DSP for protons was measured to be $7.64x10^{-11}$ cm^2 per device. The total device cross section broke down as $5.64x10^{-11}$ cm^2 per device for the Data Address Generator registers and $2.29x10^{-11}$ cm^2 for the General Purpose Registers. No upsets were observed for the Multiplier Registers, System Registers, Interrupt Registers or I/O portions of the device, implying a proton upset cross section less than $7.14x10^{-13}$ cm^2 per device for these portions of the chip. Table 7 below summarizes the SEE test results for both the Lockheed-Martin RH21020 and the Temic Semiconductor TSC21020F. No latchup events were observed, consistent with the results of heavy-ion upset and latchup test results reported previously [9].

2) Temic Semiconductor TSC21020F

Temic Semiconductor TSC21020Fs were tested for SEU under irradiation by proton beams in both dynamic and static modes [8]. They were irradiated with proton fluences up to $1.4x10^{12}$ particles per cm^2 at fluxes ranging from $8.6x10^7$ – $1.7x10^9$ particles/cm^2 per second. The total upset cross section of the DSP for protons was measured to be $9.9x10^{-13}$ cm^2 per device. The cross section for the I/O is $9.9x10^{-13}$ cm^2 per device. No upsets were observed for the Data Address Generator registers, Multiplier Registers, System Registers, or Interrupt Registers portions of the device, implying a proton upset cross section less than $9.9x10^{-13}$ cm^2 per device for these portions of the chip.

It was noted during irradiation that some anomalous current signatures on the TSC21020F DSP occurred. No functionality of the DUT appeared to be impaired. The two samples of the TSC21020F that were exposed to the proton beam began showing increases in power supply leakage current at ~100krads (Si) with excessive levels (out of specification) appearing at >125 krads (Si).

Table 7 below summarizes the SEE test results for both the Lockheed-Martin RH21020 and the Temic Semiconductor TSC21020F. All errors observed on both device types were data errors only. No errors requiring reset pulses were observed to maximum test fluences.

Table 7: Proton SEE RH21020 and TSC21020F Area Test Results

Type of Error	Cross-section in cm^2/device LMFS RH21020	Cross-section in cm^2/device Temic TSC21020F
Overall DUT	$7.93x10^{-11}$	$9.90x10^{-13}$
Data Address Generator		
(DAG) Registers	$5.64x10^{-11}$	$4.95x10^{-13}$*
General Purpose Registers (GPS)	$2.29x10^{-11}$	$4.95x10^{-13}$*
Multiplier Registers	$7.14x10^{-13}$*	$4.95x10^{-13}$*
System Registers	$7.14x10^{-13}$*	$4.95x10^{-13}$*
Interrupt Registers	$7.14x10^{-13}$*	$4.95x10^{-13}$*
I/O errors	$7.14x10^{-13}$*	$9.90x10^{-13}$

* indicates limiting cross-sections measured: no upsets observed in these areas of the device to the maximum test fluence

E. Logic Devices

1) Motorola 10502 ECL Multiple NOR Gate

The Motorola 10502 ECL Multiple NOR Gate was screened for the possibility of upset and latch-up and measure sensitivity as a function of particle LET. Test conditions included the nominal and worst case levels for the supply voltage (Vs = -5.2 and -7 Volts). One input to the NOR gate was maintained at ground potential while the other was clocked at 100 kHz (as required by the HST application). A fluence of at least $1x10^7$ ions/cm^2 was used at each test condition. The beam flux range of $2.5x10^4$ to $1.1x10^5$ particles/cm^2/s resulted in individual exposures of about between 1.6 and 6.7 minutes.

The input voltage conditions were evaluated at 7 different values of Linear Energy Transfer (LET). Testing began with a normal incident LET of 59.8 MeV•cm^2/mg obtained with Iodine ions. Following this, the Bromine beam provided a normal incident LET of 37.3 MeV•cm^2/mg. Finally, the Nickel beam provided a normal incident LET of 26.6 MeV•cm^2/mg. Angle of incidence was used to obtain the seven effective LETs used. Four samples from the same lot and date code were tested under overlapping sets of conditions.

From Figure 5, it can be seen that for most LET conditions, the cross section data is fairly constant, but this is likely due to the statistical variations. At the lower LET values between 20 and 40, there are cases where no events were observed. For all cases with effective LET greater than 40, upsets were seen.

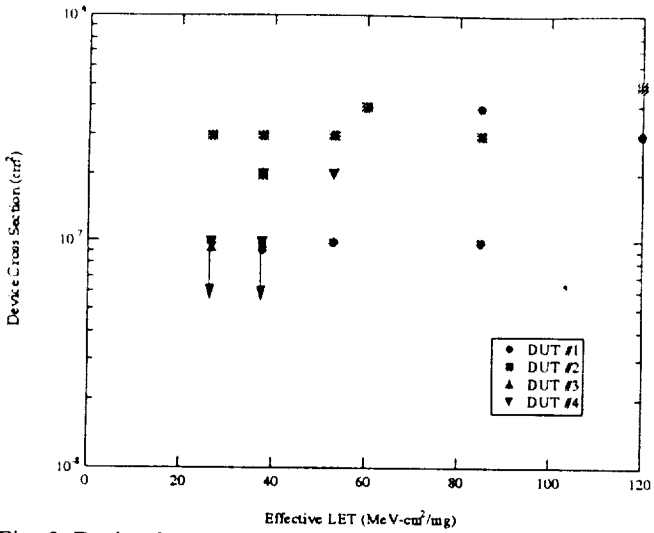

Fig. 5. Device Cross Section as a function of Effective LET. Data points with a down-pointing arrow indicate that no events were observed under those conditions.

The Motorola ECL Multiple NOR Gate is considered to have an LET_{th} for latchup greater than 119.6 MeV•cm^2/mg and the approximate LET_{th} for upset is 20 MeV•cm^2/mg with a device saturation cross section is 5 x 10^{-7}cm^2. This latchup result is valid for generic use, but since this testing was done at a slow clock speed (100 kHz) and one grounded input, the upset portion of this testing is application specific to this operational mode only [10].

2) Motorola MC74LCX08 2INP and Gate

The device was monitored for latchup induced high power supply currents by exposing it to a number of heavy ion beams at BNL. Supply current was monitored for an increase or decease. No SELs were observed for the MC74LCX08 up to LET of 60 MeV•cm^2/mg.

F. Fiber Optic Links

1) HP HFBR-53D5 Transceiver

We conducted extensive proton single event effects testing of the optical fiber-based HP HFBR-53D5 Gigabit Ethernet Transceiver with 850 nm VCSEL, Si PIN detector and a Si bipolar transimpedance amplifier (TIA). Throughout all tests the proton energy incident on the package was 63 MeV to assure penetration and knowledge of the proton energy at the circuit location. Test variables included proton angle of incidence, optical power incident on the receiver, data rate up to 1100 Mbps, and part to part variation. Results indicated large cross-sections for the receiver with characteristics consistent with transients in the photodiode. The cross-section tended approximately linearly with data rate and was also reduced at higher optical powers up to approximately 10x for a 10 dB increase in received power. Significant increases were noted in the cross section at grazing angle of incidence to the receiver photodiode. Under some test conditions, this exceeded two orders of magnitude as compared to normal incidence. Negligible change was noted after an integrated 63 MeV proton fluence of over 3.8x10^{12} cm^{-2}.

The test configuration had two transceivers on a card with an optical fiber cable connecting them and ECL in/out connectors to the BCP bit error rate tester (BERT). The bit error cross sections were characterized using a pseudo-random sequence as a function of optical power and data rate at various incident angles, and the radiation susceptibility of both the transmitter and receiver circuitry was monitored.

No catastrophic failures were observed to an exposure level of ~25 krads (Si) at 63 MeV. Figure 6 illustrates representative data captured during these experiments.

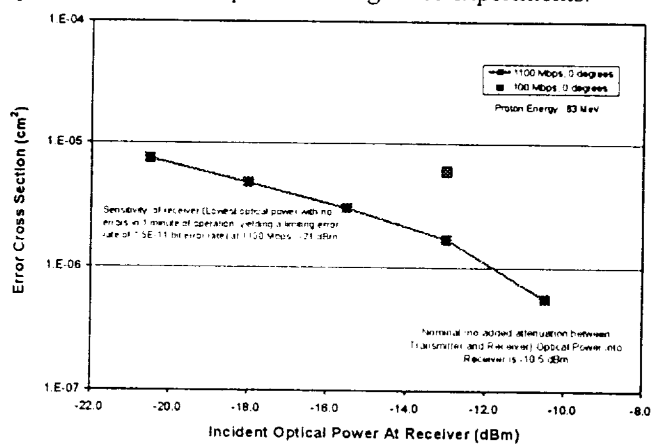

Fig. 6. shows the effect of received optical power and data rate on radiation-induced error cross section for the HFBR-53D5 device.

2) Lasermate TTC-155M2 & TTC-155M4

We conducted extensive proton single event effects testing of the optical fiber-based 155 Mbps transceivers TTC-155M4 (850 nm VCSEL transmit/1300 nm receive) and TTC-155M2 (850 nm VCSEL transmit/850 nm Si PIN receive) fiber optic link hardware. Throughout all tests the proton energy incident on the package was 63 MeV to assure penetration and knowledge of the proton energy at the circuit location. Test variables included proton angle of incidence, optical power incident on the receiver, data rate up to 1100 Mbps, and part to part variation. Results here also indicated large cross-sections for the receiver with characteristics consistent with transients in the photodiode. The cross-section tended approximately linearly with data rate and was also reduced at higher optical powers up to approximately 20x for a 17dB increase in received power. Significant increases were noted in the cross section at grazing angle of incidence to the receiver photodiode. Under some test conditions, this exceeded two orders of magnitude as compared to normal incidence. Negligible change was noted after an integrated 63 MeV proton fluence of over 4.8x10^{11} cm^{-2}.

The test configuration had two transceivers on a card with an optical fiber cable connecting them and ECL in/out connectors to the BCP bit error rate tester (BERT). The bit error cross sections were characterized using a pseudo-random sequence as a function of optical power and data rate at various incident angles, and the radiation susceptibility of both the transmitter and receiver circuitry was monitored.

No catastrophic failures were observed to an exposure level of ~25 krads (Si) at 63 MeV protons. Figure 7 illustrates representative data captured during these experiments.

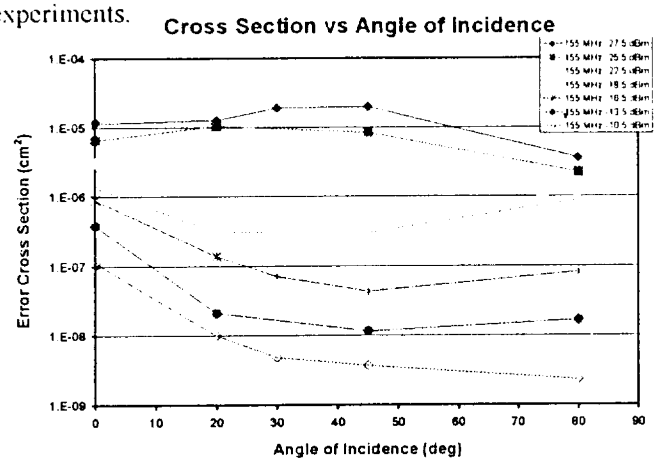

Fig. 7. Shows the measured effect of angular incidence and optical power on error cross section for the Lasermate TTC-155M4.

G. Linear Bipolar Devices

1) National Semiconductor CLC449Ultra-Wideband Monolithic Operational Amplifier

Tests were performed to screen for the possibility of latch-up and measure sensitivity as a function of supply voltage and particle LET. Test conditions included a supply voltage (Vs) levels of ±5V and ±5.5 V. Supply currents were automatically monitored. The normally incident fluence was at least 9.5×10^6 ions/cm^2. The beam flux ranged from 1.2×10^4 to 1.0×10^5 particles/cm^2/s resulted in individual exposures between 95 and 790 seconds. The DUT was loaded with 100 ohm resister. For all cases, the input was 2 Vpp and the output was 4 Vpp. The typical input frequency was 200 MHz, the test setup limited the input frequency to 500 MHz.

Application specific SELs were observed. The CLC449 did not experience any SELs up to LET of 60 MeV•cm^2/mg.

2) APEX PA07 High Power OP AMP

The APEX PA07 was monitored for latchup induced high power supply currents by exposing it to a number of heavy ion beams at BNL. Supply current was monitored for an increase or decease. No SELs were observed up to LET of 60 MeV•cm^2/mg.

3) National Semiconductor LMC6081 Precision OP AMP

The National Semiconductor LMC6081 was monitored for latchup induced high power supply currents by exposing it to a number of heavy ion beams at BNL. Supply current was monitored for an increase or decease. No SELs were observed up to LET of 60 MeV•cm^2/mg.

4) Harris HS139 and National Semiconductor LM139 Comparators

A study has been undertaken using linear comparators from two vendors (Harris, now Intersil, and National Semiconductor) to collect a sufficient amount of data under many operational conditions in an attempt to understand the SET generation and characteristics. This information is to be utilized in the development of this test methodology for comparators and possibly other linear devices.

Both LM-139 and HS-139 comparators produce SETs on their outputs. The cross sections and threshold LETs for the comparators are only slightly sensitive to the applied bias. However, the LM-139 cross section and threshold LET has a strong dependence on the input differential voltage, first reported in [ ]. The HS-139 has an LET threshold of approximately 8-10 and a cross section of 3 x10-4 cm2. The LM-139 has an LET threshold and cross section that vary with the input voltage differential from 1-10 (LET) and 1 x 10-5 to 3 x10-4 cm2 (cross section). It should also be noted that the output transient characteristics (peak height and pulse width) of the LM-139 are also a strong function of input differential voltage.

5) National Semiconductor LM139 Comparator (Application Specific testing)

LM139 devices were exposed to a fluence of 1×10^6 to 1×10^7 particles/cm^2 of the Chlorine, Titanium, Nickel, Bromine and Iodine ions with no single event latchups. The National Semiconductor LM139 is considered to have an LET threshold for latchup greater than 59.8 MeV•cm^2/mg. For single event transients, the approximate LET threshold for high output is 20 MeV•cm^2/mg and the device saturation cross section is 2×10^{-4} cm^2. The approximate LET threshold of 20 MeV•cm^2/mg and device saturation cross section of 1×10^{-4} cm^2 is seen for the low output conditions. It must be noted that these results are application specific [11]. Test conditions were: V_{cc} = ±7 Volts and maintaining a two volt differential between the input voltages, V_+ = 3 Volts, V- was set to 1 Volt, or vice versa.

6) Analog Devices MAX962 Comparator

The MAX962 was monitored for latchup-induced, high power-supply currents by exposing it to a number of heavy ion beams at BNL. Supply current was monitored for an increase or decease. No SELs were observed up to LET of 60 MeV•cm^2/mg.

7) Analog Devices AD783SQ Sample and Hold Amplifier

The AD783 did not experience any SELs up to LET_{th} >90 MeV•cm^2/mg. Exposures were performed to a fluence of 1×10^7 p/cm^2 or greater. Figure 8 gives the results of SET application specific testing results on the Analog Devices AD783. The data is plotted as the SET cross section versus the linear energy transfer (LET). During testing we observed that the SETs were typically <2µs in duration. The height was typically somewhere between 0.4V and 1V, however we did observe some that were larger, maybe as large as 2-3V.

This is a qualitative summary of the data observed during the exposures [12].

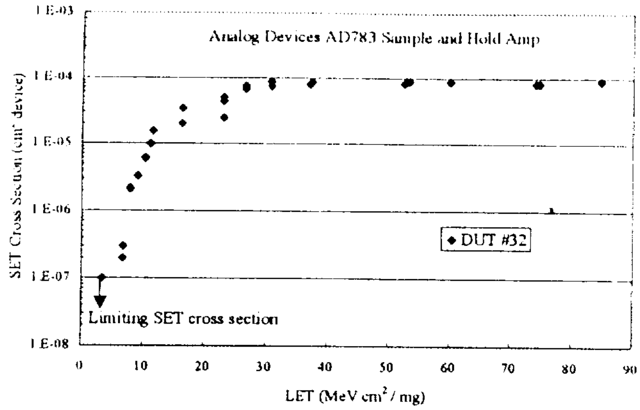

Fig. 8. Heavy ion SET cross section for AD783.

8) Amptek A250 Charge Sensitive Amplifier

The Amptek A250 was monitored for latchup induced high power supply currents by exposing it to a number of heavy ion beams at BNL. Supply current was monitored for an increase or decease. No SELs were observed up to LET of 60 MeV•cm²/mg.

9) MSA-0670 MMIC Amplifier

The Hewlett Packard MSA-0670 MMIC was tested for susceptibility to SET and SEL under irradiation with heavy ions (265.9 MeV Ni ions with LET=26.6 MeV•cm²/mg and 343 MeV I ions with LET=59 MeV•cm²/mg). The device was tested for both nominal (7.93 volts) and worst-case (8.03 volts) supply voltages, and with V_{in} = 0.5 V @ 150 MHz. No SET or SEL events were seen for ion fluences of at least 10^7 particles/cm² at fluxes from 4.6×10^4 to 1.1×10^5 with effective LETs up to 84.6 MeV•cm²/mg [13].

H. Optocouplers

1) Isolink OLH5601

Proton SET testing was performed at TRIUMF at 68,103, 160, 225 MeV and CNL 63 MeV. We observed SETs for various angles of incidence relative to the photodiode. The cross section increased with angle as it was swept around grazing angle for the photodiode for the 103, 63 and the 68 MeV beam. The angular effect was not observed for the higher energies.

2) Micropac 6N134

Proton SET testing was performed at TRIUMF at 68,103, 160, 225 MeV. We observed SETs for various angles of incidence with the cross section increasing the angle was near grazing angle for the photodiode at all energies.

I. Others

1) Dallas Semiconductor DS1670E System Controller

The DS1670E experience several SELs with several ions at several angles of incidence. The latchup current ranged from 40 to 109 mA. During the latchup condition the device was not functional, however the device recovered after a power cycle.

Figure 10 shows the device cross section for an SEL at various LETs. The incident particle beam angle relative to the die was changed to obtain effective LETs between those listed in the table. The 3.3 V exposures are indicated by open circles, and the 3.6 V exposures are denoted by the solid triangles. The data crossed by a solid horizontal line indicate that no events where observed during the exposure, i.e. limiting cross section [14].

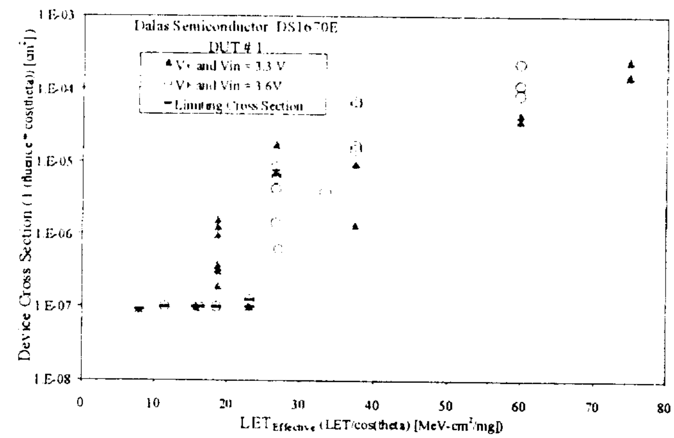

Fig. 10. Heavy Ion SEL cross section for DS1670E.

2) TI SN54LVTH16244A Buffer/ Drivers

Texas Instruments SN54LVTH16244A was monitored for latchup induced high power supply currents by exposing it to a number of heavy ion beams at BNL. Supply current was monitored for an increase or decease. No SELs were observed up to LET of 60 MeV•cm²/mg.

3) National Semiconductor CGS74LCT2524 Clock Driver

The CGS74LCT2524 was monitored for latchup-induced, high power-supply currents by exposing it to a number of heavy ion beams at BNL. Supply current was monitored for an increase or decease. No SELs were observed up to LET of 60 MeV•cm²/mg.

4) Micrel MIC4423 MOSFET Driver

Tests were performed to screen for the possibility of latch-up and measure sensitivity as a function of input voltage, input frequency, case temperature, and particle LET. A normally incident fluence at least 1×10^7 ions/cm² was used at each test condition. A beam flux of 8.2×10^5 to 1.4×10^5 particles/cm²/s resulted in individual exposures between 75 and 130 seconds. A 100 kHz signal was placed on the input oscillating between −5V and +12V. DC input signals of +12V and −5V was also used. For all cases the supply voltage (V_s) was level of 12V. The MIC4423 did not experience any SELs for the test conditions described and circuit configuration described above. Detailed test conditions for each exposure can be found it reference [15].

5) Motorola MC74HC4538A Multivibrator

The Motorola MC74HC4538A was monitored for latchup-induced, high power-supply currents by exposing it to a number of heavy ion beams at BNL. Supply current was monitored for an increase or decease. No SELs were observed up to LET of 60 MeV•cm²/mg.

6) Dallas Semiconductor DS1803 Addressable Dual Digital Potentiometer

Tests were performed on the DS1803 to screen for susceptibility to latch-up and measure sensitivity as a function of supply voltage and particle LET. Test conditions included nominal and worst-case levels for the supply voltage (V_{cc}) of 3.3 V and 5.5 V. A normal incidence fluence of at least 1×10^7 ions/cm² was used at each test condition unless an SEL occurred. A beam flux range of 2×10^2 to 1.3×10^5 particles/cm²/s resulted in individual exposures between 10 second and 13 minutes. Both input voltage conditions (3.3 V and 5.5 V) were evaluated at 4 different ions and a several angles of incidence.

Device functionality was monitored by observing the resistance of the potentiometer. If the device current experienced a sudden increased larger than I_L, the power was cycled and the DUT was checked for functionality, we called this an SEL. The DUT functionality information was not saved to a file. From time to time during the exposure, but before an SEL, the device was monitored for changes in the output (this is known as a single event upset SEU). A description of our observation is provided below. This information is provided as a cursory look at the SEU susceptibility of the device. The number of SEUs were not captured. Therefore the rate of occurrence in a space flight application can not be predicted.

The DS1803 experienced several SELs with several ions at several angles of incidence. The latchup current ranged from 51 to 57 mA. During the latchup condition the device was not functional, however the device recovered after a power cycle [16].

Figures 11 shows the device cross section for an SEL at various LETs. The 3.3 V exposures are indicated by open circles, and the 5.5 V exposures are denoted by the filled in triangles. The data crossed by a solid horizontal line indicate that no events where observed during the exposure, i.e. limiting cross section.

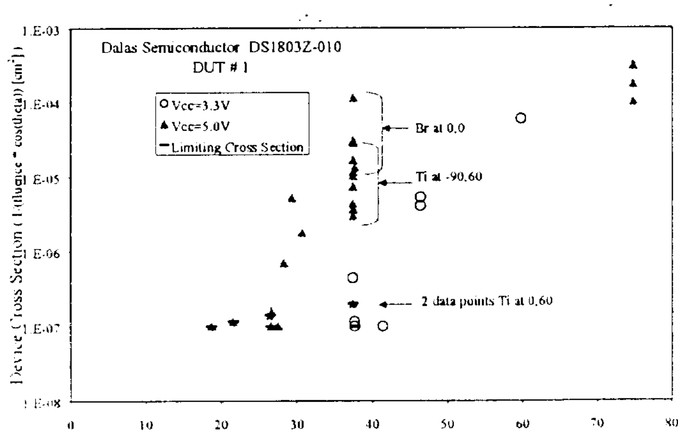

Fig. 11. DS1803 cross section for an SEL at various LETs

V. Displacement Damage Test Results and Discussion

A. National Semiconductor LM-111 Comparator

It has been demonstrated that some linear devices are susceptible to enhanced degradation when exposed to proton environments as compared to Cobalt-60. In an effort to understand this effect and develop an efficient test procedure, National Semiconductor Corporation (NSC) LM-111 Comparators have been exposed to proton environments at Indiana University (IU) and University of California at Davis (UCD) cyclotrons. The initial parameter investigated and the most sensitive is the input current. For consistency, this current was measured at what is termed the crossover point (one input is held at a voltage while the other is swept from the negative to positive side of that voltage. The crossover current is the point where the two input currents are equal).

To develop a complete data set for this investigation, rail voltages of ± 15 Volts, ± 10 Volts, ± 5 Volts and + 15/0 Volts were used. For all of these bias conditions, a crossover current was measured on six devices at input voltages from – 3 to +3 Volts at 1 Volt increments. Examples of the data set are shown in figures 12 and 13. As can be seen, significant bias dependence is observed for both the rail bias and the input conditions.

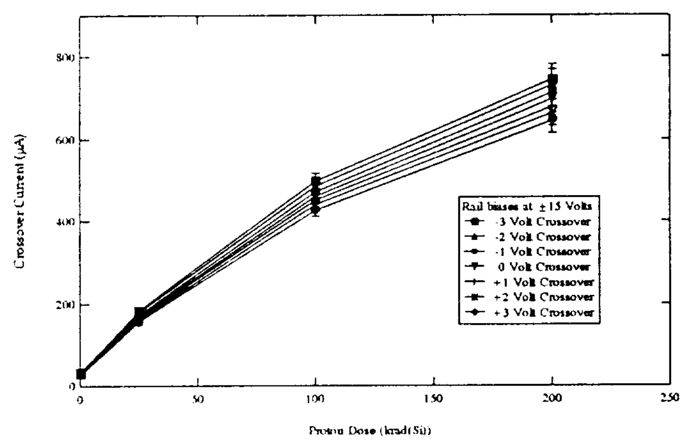

Figure 12. Crossover currents as a function of proton dose with a rail bias of ±15 Volts. The data points are the average response of six parts and the error bars represent one sigma variation.

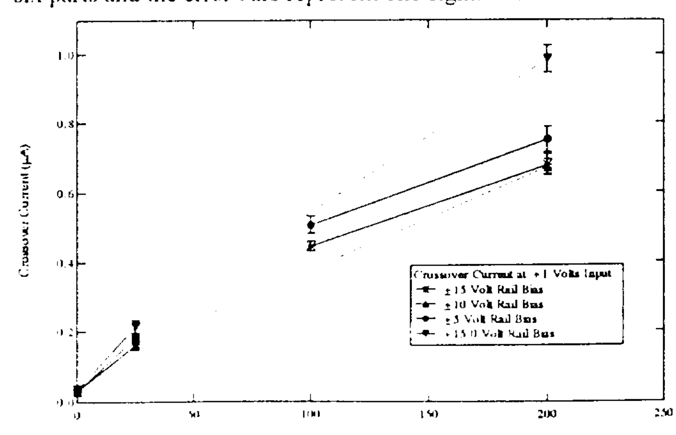

Figure 13. Crossover currents as a function of proton dose with crossover measured at +1 Volts at the inputs. The data points are the average response of six parts and the error bars represent one sigma variation.

B. Optocouplers

1) Isolink OLH249

The OLH249 was irradiated with 195MeV protons at IUCF. IF was swept from 4 to 26mA with V_{CE} = 5V. CTR degradation was observed at $6x10^{11}$p/cm^2.

2) Micropac 66099

Proton effects characterization of the Micropac 66099 optocoupler were made at Crocker Nuclear Laboratory at the University of California at Davis using 63 MeV protons. Three devices (DUTs 1,2,3) were used for a quick set of measurements to ensure that reasonable choices were made for the proton fluences. A very detailed set of measurements were completed for an additional 3 devices (DUTS 4,5,6). The quick look was designed to be a worse case look and was performed for a no load condition with I_f at 1 mA and 5 mA. The detailed measurements performed on a second set of 3 devices included CTR measurements at various loads (0, 430 Ω, 970 Ω, and 2.7 Ω) on the output for I_f from 0.5 to 20 mA (in 0.5 mA increments) for each V_{CE}. V_{CE} itself was varied from 0 to 10 V in 1 V increments. Corresponding transistor measurements were also made. It is important to note that of the 6 devices tested, one exhibited anomalous behavior, and performed significantly worse under irradiation.

There was a range of initial CTRs observed and the spread in values was dependent on the operating conditions. Figure 9 shows a typical data set for the CTR as a function of proton fluence for various operating conditions.

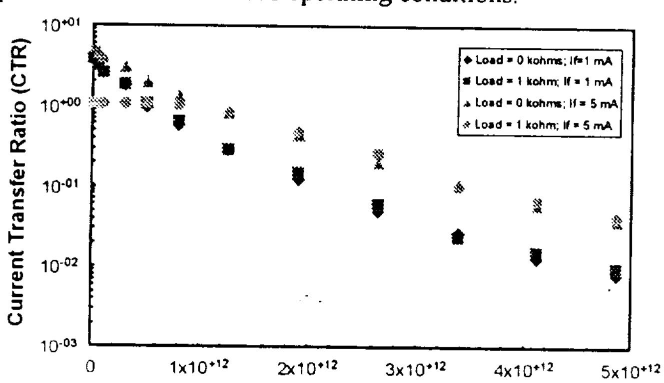

Fig. 9. CTR and transistor characteristics for the Micropac 66099.

C. Optodiode OD800 LED

Proton-induced degradation testing of the Optodiode OD800 light emitting diode was performed. LEDs were exposed to proton irradiations at University of California at Davis Crocker Nuclear Laboratory. The light output and I-V characteristics of the device were monitored for radiation-induced degradation at various fluence levels. The Optodiode OD800 is a GaAs Double Heterojunction light emitting diode. Figure 14 shows the degradation (P/P_o) of the all the DUTs at each exposure level (fluence) for I_f = 4mA. The measured output power (P) for each DUT at each fluence is normalized to the pre-irradiation output power (P_o). Figure 15 shows the I-V curves measured for DUT #18. The solid dark line is the pre-irradiation values, the dash line is the post-irradiation values after an exposure $2.6x10^{11}$ p/cm^2. For the most part the post- and pre-rad values are the same. In the configuration used, the current resolution of the parametric analyzer is thought to be ~1nA. Measurements below 1 nA should be considered to have large error bars. These data presented in Figure 2 are consistent with results on DUTs 13-17, I-V curves were not measured for DUTs 1-12. See Reed et al., "Energy Dependence ... [17].

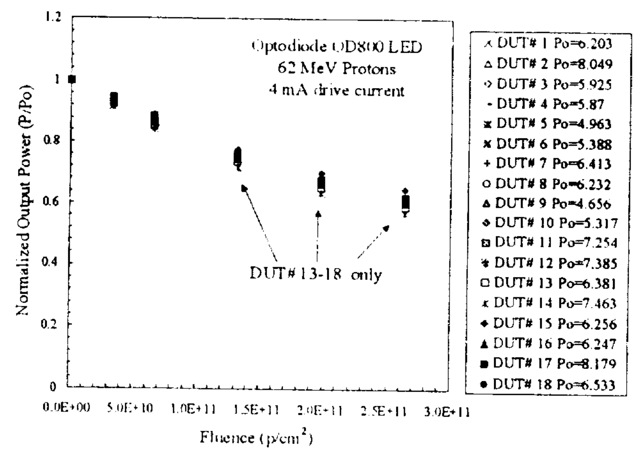

Fig. 14. Proton degradation of light output for 6 Optodiode OD800W. The output power was normalized to the pre-rad values.

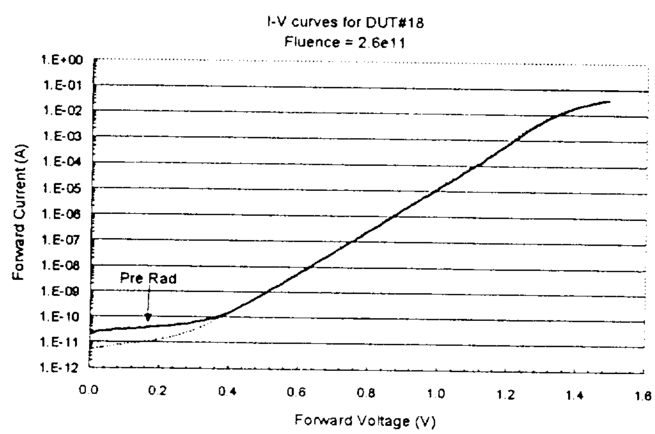

Fig. 15. Typical Optodiode OD800 DUT#17 post and pre-rad I-V curves.

D. Honeywell HFE-4080 a Vertical Cavity Surface Emitting Laser (VCSEL)

The Honeywell HFE-4080 ion-implanted 850 nm VCSELs were exposed unbiased to Cobalt-60 gamma irradiation to ~1.8 Mrad(Si) to ensure that the Ultem lens in the package would not darken and obscure the proton test results. No significant gamma radiation-induced changes were observed.

Proton tests were performed at TRIUMF in May 1999, and the Crocker Nuclear Laboratory (CNL) in June 1999. The VCSELs were irradiated unbiased which is a worse case since there is no concurrent forward biased annealing. As expected the primary effect of proton exposure was an increase in the threshold drive current. For example, the initial threshold currents of ~5 mA increased to ~7 mA after a 63 MeV exposure of 5e13 cm^-2. At the higher proton exposure levels, we also see a decrease in the slopes of the light output versus drive current curves (i.e. the differential quantum efficiency).

Additional 850 nm oxide-confined VCSELs with different aperture sizes were also underwent proton characterization. The smallest threshold current shifts were observed for the small aperture oxide-confined VCSELs. For example, the threshold current of the 4 micron squared oxide aperture VCSEL remained almost unchanged at ~0.5 mA after a 63 MeV fluence of 5313 cm^{-2}.

In summary, the VCSELs are very robust to gamma and proton irradiation and are suitable for most space applications.

VI. TID Test Results and Discussion

A. Comparators

TID evaluations of three different comparators, Maxim's MAX913 and Analog Devices' (AD) CMP01 and PM139, revealed varying susceptibility. In addition to functionality, parametric measurements of quantities such as power supply current (I_{CC}), input bias current (I_{ib})offset voltage and current (V_{OS} and I_{OS}), common-mode rejection ratio (CMRR), power supply rejection ratio (PSRR) and gain (A_{ol}), were performed at each step during the irradiation and annealing processes.

B. Actel A1280A FPGA

Actel A1280A CQ172B FPGAs (5962-9215601MYC) were irradiated at a rate of 0.01 rad(Si)/s using a Co^{60} source. The parts were irradiated under bias to levels of 3.0, 5.0, 10.0 and 15.0 krad(Si). At levels above 5 krad(Si), supply currents were seen to increase above specified levels. Substantial improvement in these parameters was seen after a 168 hour anneal at 25°C.

C. Operational Amplifiers

The Radiation Effects and Analysis Group undertook 27 TID evaluations on 23 different amplifiers, 12 from Analog Devices (AD), 4 from Linear Technologies (LT), 2 from National Semiconductor (NSC) and one each from Burr Brown, Apex, Amptek, Maxim and Omnirel. Failure levels ranged from less than 5 krads(Si) to over 200 krads(Si). Functional and parametric tests were performed at every irradiation step.

D. Analog-to-Digital and Digital-to-Analog Converters

The Radiation Effects and Analysis Group undertook evaluations on 4 ADCs and 4 DACs from Analog Devices and on one DAC each from Maxim and Micronetworks. There was also one RMS-DC converter from Maxim. Parametric failure levels ranged from >200 krads(Si) to <1 krad(Si). For these devices, functional failures may be seen even before significant parametric degradation. At least one part (Analog Devices AD976) may exhibit ELDRS.

E. Voltage References and Voltage Regulators

Voltage references and regulators exhibit a wide range of susceptibilities to radiation damage. The 4 voltage regulators and 2 voltage references tested by the Radiation Effects Branch are consistent with this observation.

F. Memories

The speeds and capacities of commercial memories make them attractive to designers. They exhibit a broad range of radiation tolerances.

G. Analog Switches and Multiplexers

Parts were irradiated in steps from 2.5 krad to 5 krad. Prior to irradiation and after each step, tests were performed to measure supply currents, I_{DD} and I_{SS}, input leakage currents with inputs high and low, I_{IH} and I_{IL}, on-resistances, R_{ON}, and so on. The HI506 multiplexer showed no significant functional or parametric degradation for dose levels up to 50 krad(Si), as well as after a 168 hour, 25 °C anneal.

H. Power Devices

With the exception of the Linfinity PWM, the power devices tested were hybrid DC-DC converters, and they exhibit a range of radiation tolerances. The PWM exhibits good radiation tolerance.

I. Miscellaneous Devices

The devices in this category do not fit neatly into any of the other categories. They include discrete FETs, drivers, a crystal oscillator, a transceiver and a logic device. The failure levels are as diverse as the device types.

VII. Summary

We have presented recent data from SEE, Co-60 total ionizing dose (TID), and proton-induced damage on mostly 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.

VIII. Acknowledgements

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