Current Total Ionizing Dose Results and Displacement Damage Results for Candidate Spacecraft Electronics for NASA

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Abstract-- We present data on the vulnerability of a variety of candidate spacecraft electronics to total ionizing dose and displacement damage. Devices tested include optoelectronics, digital, analog, linear bipolar devices, hybrid devices, Analog-to-Digital Converters (ADCs), and Digital-to-Analog Converters (DACs), among others.

I. INTRODUCTION

The space flight community will continue to utilize commercial and emerging technology devices to meet the increasing demands for higher performance, cost savings, and delivery schedules. With the use of these devices, the importance of ground testing for the effects of total ionizing dose (TID) and proton-induced degradation to qualify the devices for flight, can not be underestimated due to the inherent vulnerability of many of these devices.

The test results presented here were gathered to establish the sensitivity of the devices selected as candidate spacecraft electronics to TID and proton damage. Proton-induced degradation is a mix of ionizing (TID) and non-ionizing damage. This non-ionizing damage is commonly referred to as displacement damage (DD). This testing serves to determine the limit to which a candidate device may be used in space applications. For single event effects (SEE) results, see a companion paper submitted to the 2004 IEEE NSREC Radiation Effects Data Workshop entitled: "Current Single Event Effects Results for Candidate Spacecraft Electronics for NASA" by M. O'Bryan, et al. [1]

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II. TEST TECHNIQUES AND SETUP

A. Test Facilities - TID

TID testing was performed using a Co-60 source at the Goddard Space Flight Center Radiation Effects Facility (GSFC REF). The source is capable of delivering a dose rate of up to 0.5rads(Si)/s, with dosimetry being performed by an ion chamber probe.

B. Test Facilities – Proton

Proton DD/TID tests were performed at two facilities: The University of California at Davis (UCD) Crocker Nuclear Laboratory (CNL) that has a 76" cyclotron (maximum energy of 63 MeV), and the Indiana University Cyclotron Facility (IUCF) that has an 88" cyclotron (maximum energy of 205 MeV). Table I lists the proton damage test facilities and energies used on the devices.

Table I: Proton Test Facilities

Facility	Proton Energy, (MeV)
University of California at Davis (UCD) Crocker Nuclear Laboratory (CNL)	26.6-63
Indiana University Cyclotron Facility (IUCF)	54-205

C. Test Methods

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

1) TID Testing

TID testing was performed to the MIL-STD-883 1019.6 test method [2].

2) Proton Damage Testing

Proton damage tests were performed on biased devices with functionality and parametrics being measured either continually during irradiation (in-situ) or after step irradiations (for example: every 10 krads(Si), or every $1x10^{10}$ protons).

III. Test Results Overview

Abbreviations and conventions are listed in Table II. Abbreviations for principal investigators (PIs) are listed in Table III. Definitions for the categories are listed in Table IV. This paper is a summary of results. Please note that these test results can depend on operational conditions. Complete test reports are available online at http://radhome.gsfc.nasa.gov [3].

Table II: Abbreviations and Conventions:

ADC = analog to digital converter
ASIC = application specific integrated circuit
CCD = charge coupled device
CMOS = complementary metal oxide semiconductor
CTR = current transfer ratio
DAC = digital to analog converter
DD = displacement damage
DNL = differential non-linearity
DUT = device under test
GSFC REF = Goddard Space Flight Center Radiation Effects Facility
I_{bias} = bias current
I_f= forward current
I_{OS} = offset current
I_{READ} = Read current
LDC = lot date code
I_{CC} = power supply current
MeV = Mega electron volt
N/A = not applicable
op amp = operational amplifier
opto = optocoupler
p/cm^2 - $protons/cm^2$
PI = Principal Investigator
RHrFPGA = radiation hardened reprogrammable field programmable gate array
TID = total ionizing dose
V_{IL} = input saturation voltage
V_{LOAD} = load voltage
V_{OL} = output saturation voltage
V_{OS} = offset voltage

TABLE III: LIST OF PRINCIPAL INVESTIGATORS

Abbreviation	Principal Investigator (PI)
SB	Steve Buchner
JH	Jim Howard
SK	Scott Kniffin
KL	Ken LaBel
RL	Ray Ladbury
CM	Cheryl Marshall
PM	Paul Marshall
CP	Christian Poivey
RR	Robert Reed
AS	Anthony (Tony) Sanders

TABLE IV. LIST OF CATEGORIES

1	Passed to dose tested.
2	Degradation at >50 krads(Si)
3	Degradation at 20-50 krads(Si)
4	Degradation at 5-20 krads(Si)
5	Degradation at 5 or less krads(Si)
REV	Research Test Vehicle – Please contact the P.I. before utilizing this device for spacecraft applications.

TABLE V: SUMMARY OF TID TEST RESULTS

Part Number	Manufacturer	LDC	Function	Facility Date/P.I *(Co-60 source unless otherwise noted).*	Dose rate (rads(Si)/s)	Summary of Results	Degradation Level (krads(Si))	Cat.
Logic Devices:								
SN74LVC16244A	Texas Instruments	No LDC available; Markings: 31AX94k	Buffer/Driver	GSFC03/SB	~0.2	No parametric degradation to 20 krads(Si)	>20	1
SN74LVC16245A	Texas Instruments	No LDC available; Markings: 29E8Y5K	Transceiver	GSFC03/SB	~0.2	No parametric degradation to 20 krads(Si)	>20	1
CD54HC4052	Texas Instruments	0232	Multiplexer/Demultiplexer	GSFC04/JH	~0.2	I_{CC} exceeds specification limits after 18-25 krads(Si); Functional after 25 krads(Si) (max dose tested)	18-25	4
TC55257	Toshiba	0030	32kx8 SRAM	GSFC03JUN/SB	0.28	I_{READ}, I_{STDBY} exceeds specification limits after 30 krads(Si); Functional after 30 krads(Si) (max dose tested)	20-30	3
T36T-GAFE7	Agilent	Nov03	ASIC	GSFC04FEB/SK	0.03	No parametric degradation to 10 krads(Si)	>10	1
T36T-GARC3	Agilent	Nov03	ASIC	GSFC04FEB/SK	0.04	No parametric degradation to 10 krads(Si)	>10	1
Mixed Signal or Linear Devices								
ADC1175	National	Markings: EM04AB	8 bit ADC	GSFC03OCT/CP	~0.17	No parametric degradation to 48 krads(Si)	>48	1
MAX145	Maxim	0310	ADC	GSFC04/SK	0.03	No parametric degradation to 10 krads(Si)	>10	1
MAX494	Maxim	0229	Quad Op Amp	GSFC04/SK	0.03	One device experienced functional failure after 10 krad(Si). All others passed to 10 krads(Si)	10	4
MAX5121	Maxim	0134	DAC	GSFC04/SK	0.03	No parametric degradation to 10 krads(Si)	>10	1
MAX6325	Maxim	0037	Voltage Reference	GSFC03/RL/SK	0.03	Load Regulation exceeds specification limits after 4 krads(Si); Line Regulation exceeds specification limits after 12 krads(Si); VOUT measurements fell below specification limits after 20.5 krads(Si); Devices still functional after 24 krads(Si)	4	5
AD524	Analog Devices	0133	Instrument Amplifier	GSFC03JUL/SB	~0.46	$+I_{OS}$&$-I_{OS}$ exceeds specification limits after10 krads(Si); VOL exceeds specification limits after50 krads (Si); V_{IL} exceeds specification limits after 60 krads(Si); Functional after 90 krads(Si) (max dose tested)	10	4
AD587	Analog Devices	0213	Voltage Reference	GSFC03/RL/SK	0.03	No parametric degradation to 24 krads(Si)	>24	1
OP27	Analog Devices	0215	Op Amp	GSFC03JUL/JH	~0.2	No parametric degradation to 50 krads(Si)	>50	1

TABLE V: SUMMARY OF TID TEST RESULTS (CONT.)

Part Number	Manufacturer	LDC	Function	Facility Date/P.I *(Co-60 source unless otherwise noted).*	Dose rate (rads(Si)/s)	Summary of Results	Degradation Level (krads(Si))	Cat.
Mixed Signal or Linear Devices (continued):								
OP200	Analog Devices	9951	Op Amp	GSFC03AUG/JH	~0.2	No parametric degradation to 50 krads(Si)	>50	1
LT1024	Linear Technology	0114	Op Amp	GSFC03OCT/JH	~0.2	I_{bias} exceeds specification limits after 2 krads(Si); V_{OS} exceeds specification limits after 4 krads(Si); Functional after 30 krads (Si) (max dose tested)	2	5
UCC1806	Unitrode	0126	Pulse Width Modulator	GSFC03/JH	0.27	Functional failure between 20 and 30 krads(Si); No significant parametric degradation prior to failure	20-30	3
OP420	Analog Devices	9917	Quad Op Amp	GSFC03/SK/KL	~0.15	No parametric degradation to 15 krads(Si)	>15	1
DAC8408	Analog Devices	0020	Quad 8-bit DAC	GSFC03/SK/KL	~0.42	DNL exceeded specification limits after 6.7 krads(Si); Devices failed functionally after 10.7 krads(Si)	6.7	4
DC-DC Converters and Related Devices:								
AFL2803R3S	International	0351	DC-DC Converter	GSFC04/SK	0.03	No parametric degradation to 10 krad(Si)	>10	1
Optical Devices:								
F1D5	Fairchild	N/A	Optocoupler	GSFC03JUL/JH	~0.15	No parametric degradation to 50 krads(Si)	>50	1
HSDL-4420	Agilent	N/A	Infrared emitter	GSFC03/JH	0.2	No degradation in CTR at three If to 50 krads(Si) Note: HSDL-4420 and HSDL-5420 tested as a pair	>50	1
HSDL-5420	Agilent	N/A	Infrared PIN photodiode	GSFC03/JH	0.2	No degradation in CTR at three If to 50 krads(Si) Note: HSDL-4420 and HSDL-5420 tested as a pair	>50	1

TABLE VI: SUMMARY OF PROTON DD AND TID TEST RESULTS

Part Number	Manufacturer	LDC	Function	Facility Date/P.I.	Summary of Results	Cat.
Logic Devices						
SN74LVC16244A	Texas Instruments	No LDC available; Markings: 31AX94K	Buffer/Driver	IU03NOV/SB	No degradation to 3.27×10^{11} p/cm^2	1
SN74LVC16245A	Texas Instruments	No LDC available; Markings: 29E8Y5K	Transceiver	IU03NOV/SB	No degradation to 3.27×10^{11} p/cm^2	1
SiGe Devices						
5AM	IBM	N/A	SiGe 5AMSTC	UCD03OCT/RR/PM	No functional degradation after 2Mrad(Si) proton dose. [nsrec04_Marshall]	RTV
7HP	IBM	N/A	SiGe 127 bit SR	UCD03OCT/RR/PM	No parametric degradation after 150 krad(Si) proton dose (expect much higher) [nsrec04_Marshall]	RTV
8HP	IBM	N/A	SiGe	UCD03DEC/PM	No parametric degradation up to 1x10^12 63 MeV protons [nsrec04_Kuo]	RTV
9HP	IBM	N/A	SiGe	UCD03DEC/PM	No parametric degradation up to 7x10^12 63 MeV protons [nsrec04_Sutton]	RTV
Miscellaneous Devices						
UT54LVDS217	Aeroflex	0312	Serializer	IU03OCT/SB	No degradation to 1.5×10^{12} p/cm^2 (~94 krad(Si))	1
RHrFPGA	Honeywell	0314	FPGA	IU03OCT/TS	No degradation to 3.4×10^{13} p/cm^2	1
RHrFPGA	Teledyne	0312	Solid-State Relay (OPTO)	IU03OCT/SB	Functional failure after 5.01×10^{11} p/cm^2 (DUT 12) (~30 krads(Si); 6.68×10^{11} p/cm^2 (DUT 11)(~40 krads(Si))	3
OMR9701	International Rectifier	0313	Solid-State Relay (OPTO)	IU03OCT/SB	All four devices pass all tests up to 75 krads(Si) Significant degradation in V_{LOAD} in one device at 100 krads(Si)	2
JFET	Interfet	Markings: SNJ14AL 16	JFET	UCD03DEC/SB	Noise spectra functionally failed in some devices after 1 krad(Si)	5
WFC IV	E2V	N/A	CCD	UCD03OCT/CM/PM	5×10^9 p/cm^2; Hot pixel annealing studied as a function of temperature. [SPIE04_Polidan]	RTV
P-Channel (SNAP)	Dalsa & Berkeley	N/A	CCD	UCD03OCT/CM/PM	5.7×10^{10} p/cm^2; At -83C, the charge transfer efficiency is about an order of magnitude better than observed for n-CCDs. [SPIE04_Marshall]	RTV

IV. Test Results and Discussion

1) TC55257

The TC55257 32kx8 SRAM from Toshiba was tested to 30 krads(Si) at an average dose rate of 0.28rads(Si)/s. Testing was performed at the NASA GSFC REF Co-60 Facility. The devices were statically biased. All parts passed all tests to 20krads(Si), however there was significant degradation in the READ current in all three devices at 20krads(Si). After the 30krads(Si) exposure, the devices exceeded the specification limits for READ current, and Stand By current with readings of 3mA for both in all three. Two devices also displayed functional READ/WRITE failures after 30krads(Si). No annealing was performed on these devices. [T032803_TC55257]

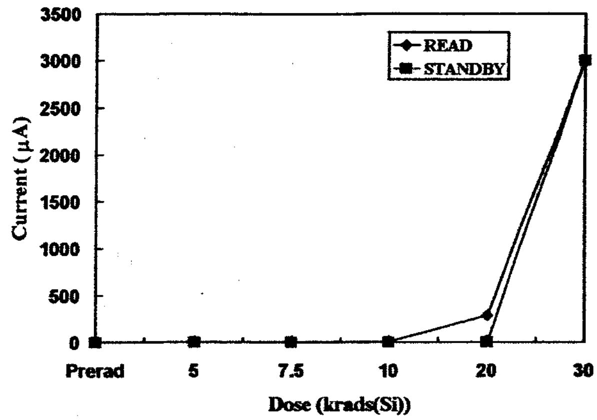

Fig. 1. TC55257 average current readings for READ and STANDBY.

2) MAX494

The MAX494 quad op amp from Maxim Semiconductor was tested to 10krads(Si) at an average dose rate of 0.03rads(Si)/s. Testing was performed at the NASA GSFC REF Co-60 Facility. The devices were statically biased. Two sets of 7 devices were irradiated. In the first set, all devices passed all tests to 7.5krads(Si). One device failed catastrophically after 10krads(Si) while the remaining 6 passed all parametric tests. After annealing the devices at room temperature for one week, no significant change was noted in any parameter in the 6 remaining devices. An extensive failure analysis was unable to determine the root cause of the one catastrophic failure due to the level of thermal damage internal to the device. The second set of 7 devices passed all tests to 10krads(Si). After annealing the devices at room temperature for one week, no significant change was noted in any parameter. [G2004_MAX494]

3) AD524

The AD524 op amp from Analog Devices was tested to 100krads(Si) at an average dose rate of 0.46rads(Si)/s. Testing was performed at the NASA GSFC REF Co-60 Facility. The devices were statically biased. After the 10krads(Si) exposure, all devices exceeded the specification limits for $+I_{OS}$ and $-I_{OS}$. After the 70krads(Si) exposure, there was significant degradation in the input offset voltage and some degradation in the output offset voltage. The devices were still functional after 100krads(Si). [G03OCT_AD587]

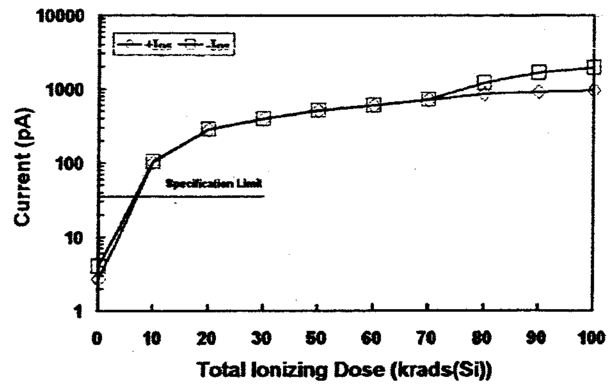

Fig. 2: Analog Devices AD524 +/- input offset currents.

4) LT1024

The LT1024 dual op amp from Linear Technology Corp. was tested to 30 krads(Si) at an average dose rate of 0.2rads(Si)/s. Testing was performed at the NASA GSFC REF Co-60 Facility. The devices were statically biased. After the 2krads(Si) irradiation step, all devices exceeded the specification limit for I_{bias}. After the 4krads(Si) irradiation step, all devices exceeded the specification limit for V_{OS} as well. The devices continued to function after 30krads(Si) although with significant further degradation in I_{bias} and VOS. [G101503_LT1024_TID]

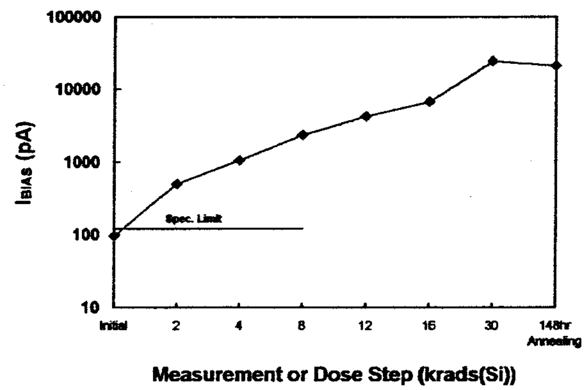

Fig. 3a. Linear Technologies LT1024 I_{BIAS} degradation.

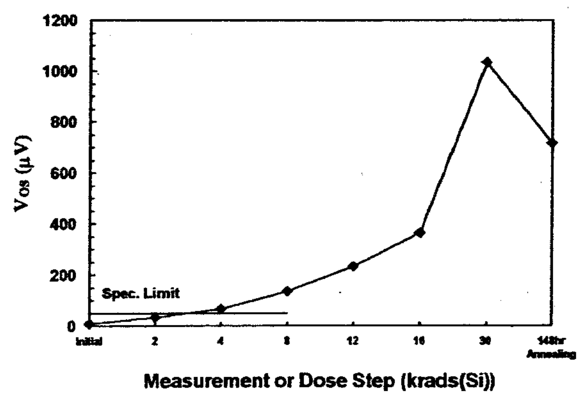

Fig. 3b. Linear Technologies LT1024 VOS degradation.

5) *RHrFPGA*

The RHrFPGA from Honeywell is a SOI based CMOS device. The devices were tested for DD and TID effects at IUCF with proton energy of 203 MeV. Each of the three devices was exposed to a fluence of 3.4×10^{13} p/cm^2 (DD dose ~ 2 Mrad(Si)). No parametric degradation was observed in the devices. [i103003_RHrFPGA_Honeywell]

V. Summary

We have presented data from recent TID and proton-induced damage tests on a variety of primarily 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.

VI. Acknowledgment

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VII. References

[1] M. O'Bryan, et al., "Current Single Event Effects Results for Candidate Spacecraft Electronics for NASA" submitted to the 2004 IEEE NSREC Radiation Effects Data Workshop.

[2] Department of Defense Test Method Microcircuits, MIL-STD-883 Test Method Standard, Microcircuits, MIL-STD-883 Test Method 1019.6, Dated: 07 March 2003, File name: std883not5.pdf, http://www.dscc.dla.mil/Downloads/MilSpec/Docs/MIL-STD-883/std883not5.pdf

[3] NASA/GSFC Radiation Effects and Analysis home page, http://radhome.gsfc.nasa.gov

[4] [nsrec04_Marshall] Paul Marshall, et al., "A Comparative Study of Heavy Ion and Proton Induced Bit Error Sensitivity and Complex Burst Error Modes in Commercially Available High Speed SiGe BiCMOS," submitted for publication to 2004 IEEE Trans. on Nucl. Sci., Dec 2004.

[5] [nsrec04_Kuo] Wei-Min Lance Kuo, et al., "Total Dose Tolerance of Monolithic Millimeter-Wave Transceiver Building Blocks Implemented in 200 GHz SiGe Technology," submitted for publication to 2004 IEEE Trans. on Nucl. Sci., Dec 2004.

[6] [nsrec04_Sutton] Akil K. Sutton, et al., "Proton Response of 4th-Generation 350 GHz UHV/CVD SiGe HBTs," submitted for publication to 2004 IEEE Trans. on Nucl. Sci., Dec 2004.

[7] [SPIE04_Polidan] Elizabeth J. Polidan, et al., "A study of hot pixel annealing in the Hubble Space Telescope Wide Field Camera 3 CCDs," submitted for publication to 2004 SPIE Astronomical Telescopes and Instrumentation.

[8] [SPIE04_Marshall] Cheryl Marshall, et al., "Comparisons of the proton-induced dark current and charge transfer efficiency responses of n- and p-channel CCDs," submitted for publication to 2004 SPIE Astronomical Telescopes and Instrumentation.

[9] [T032803_TC55257] Stephen Buchner and Jim Forney "Latchup Testing of the TC55257 Toshiba 32Kx8 SRAM," http://radhome.gsfc.nasa.gov/radhome/papers/T032803_TC55257.pdf, Mar. 2003.

[10] [G2004_MAX494] Scott Kniffin, "Radiation Report on MAX494 (Maxim) for the GLAST Project," http://radhome.gsfc.nasa.gov/radhome/papers/G2004_MAX494.pdf, 2004.

[11] [G03OCT_AD587] by Scott Kniffin and Christopher Palor, "Total Ionizing Dose (TID) Test Report for the AD587UQ (5962-8982503PA)," http://radhome.gsfc.nasa.gov/radhome/papers/G03OCT_AD587.pdf, Oct. 2003.

[12] [i103003_RHrFPGA_Honeywell] John Lintz,"Proton Single Event Effects Radiation Test Report for the RHrFPGA Radiation-Hardened Field-Programmable Gate Array," http://radhome.gsfc.nasa.gov/radhome/papers/i103003_RHrFPGA_Honeywell.pdf, Oct. 2003.

[13] [G101503_LT1024_TID] Hak Kim and Jim Howard, "Co-60 Total Ionizing Dose (TID) Test of LT1024 Operation Amplifier," http://radhome.gsfc.nasa.gov/radhome/papers/G101503_LT1024_TID.pdf, Oct. 2003.