NASA Goddard Space Flight Center's Compendium of Recent Total Ionizing Dose and Displacement Damage Dose Results

Alyson D. Topper, Edward P. Wilcox, Megan C. Casey, Michael J. Campola, Noah D. Burton, Kenneth A. LaBel, Donna J. Cochran, Martha V. O'Bryan

***Abstract--* Total ionizing dose and displacement damage testing were performed to characterize and determine the suitability of candidate electronics for NASA space utilization. Devices tested include optoelectronics, digital, analog, linear bipolar devices, and hybrid devices.**

Index Terms- Displacement Damage, Optoelectronics, Proton Damage, Single Event Effects, and Total Ionizing Dose.

I. INTRODUCTION

Long term radiation-induced failure modes play a significant role in determining space system reliability. In order to determine risk to spaceflight applications, the effects of total ionizing dose (TID) and displacement damage dose (DDD) need to be evaluated through ground-based testing.

The test results presented here were gathered to establish the sensitivity of candidate spacecraft electronics to TID and/or DDD. Proton-induced degradation, dominant for most NASA missions, is a mix of ionizing (TID) and non-ionizing damage. The non-ionizing damage is commonly referred to as displacement damage. For similar results on single event effects (SEE), a companion paper has also been submitted to the 2018 IEEE NSREC Radiation Effects Data Workshop entitled: "NASA Goddard Space Flight Center's Compendium of Recent Single Event Effects Results," by M. O'Bryan, et al. [1]

II. TEST TECHNIQUES AND SETUP

A. Test Method

Unless otherwise noted, all tests were performed at room temperature and with nominal power supply voltages. Based on the application, samples were tested in a biased or unbiased configuration. Functionality and parametric changes were measured either continually during irradiation (in-situ) or after step irradiations (for example: every 10 krad(Si), or every $1x10^{10}$ protons/cm^2).

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B. Test Facilities – TID

TID testing was performed using MIL-STD-883, Test Method 1019.9 [2] unless otherwise noted as research. Dose rates used for testing were between 0.01 and 15.5 rad(Si)/s.

C. Test Facilities – Proton

Proton damage tests were performed on biased and unbiased devices. Table I lists the proton damage test facility and energy used on the devices.

TABLE I: PROTON TEST FACILITY

Facility	Proton Energy, (MeV)
University of California at Davis - Crocker Nuclear Laboratory (UCD - CNL)	63

III. TEST RESULTS OVERVIEW

Abbreviations for principal investigators (PIs) are listed in Table II. Abbreviations and conventions are listed in Table III. Summary of TID and DDD test results are listed in Table IV and VI. Please note that these test results can depend on operational conditions.

TABLE II: LIST OF PRINCIPAL INVESTIGATORS

Abbreviation	Principal Investigator (PI)
ADT	Alyson D. Topper
MCC	Megan C. Casey
MJC	Michael J. Campola

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TABLE III: ACRONYMS

A = Amp APL = Applied Physics Laboratory BiCMOS = Bipolar – Complementary Metal Oxide Semiconductor BJT = Bipolar Junction Transistor CMOS = Complementary Metal Oxide Semiconductor COTS = Commercial off-the-shelf CTR = Current Transfer Ratio DDD = Displacement Damage Dose DUT = Device Under Test FET = Field Effect Transistor GSFC = Goddard Space Flight Center HDR = High Dose Rate h_{FE} = Forward Current Gain I_{b+} = Positive Bias Current I_{Con} = On-State Collector Current I_{CE} = Collector-Emitter Current I_{CP} = Charge Pump Current IF = Intermediate Frequency I_{io} = Input Offset Current I_{os} = Offset Current I_{OUT} = Output Current JFET = Junction Field Effect Transistor	LDO = Low Dropout LED = Light Emitting Diode LDR = Low Dose Rate MeV = Mega Electron Volt mA = milliamp n/a = Not Available Op-Amp = Operational Amplifier PCB = Printed Circuit Board PI = Principal Investigator REAG = Radiation Effects & Analysis Group RF = Radio Frequency SEE = Single Event Effects SMD = Surface Mount Device Spec = Specification(s) TID = Total Ionizing Dose UCD-CNL = University of California at Davis – Crocker Nuclear Laboratory $V_{(BR)CEO}$ = Collector-Emitter Breakdown Voltage V_{CESAT} = Collector-Emitter Saturation Voltage VCO = Voltage Controlled Oscillator V_{OH} = Output Voltage High

TABLE IV: SUMMARY OF TID TEST RESULTS

Part Number	Manufacturer	LDC	Device Function	Technology	PI	Sample Size	Results	App. Spec (Y/N)	Dose rate (mrad(Si)/s)	Degradation Level (krad (Si))
OPERATIONAL AMPLIFIERS										
AD620SQ/883B	Analog Devices	1708D; (17-046)	Operational Amplifier	Bipolar	MJC	8	Input offset current out of specification at 3.3 krad(Si), positive bias current at 5.4 krad(Si), negative bias current at 8.5 krad(Si).	Y	10	$3.3 < I_{io} < 10$ $5.4 < I_{b+} < 9$ $8.5 < I_{b-} < 15$
OP484	Analog Devices	1553A; (17-072)	Operational Amplifier	Bipolar	MCC	10	All parameters within specification up to 50 krad(Si). V_{OH} dropped below the minimum specification at 75 krad(Si).	Y	10	$50 < V_{OH} < 75$
COMPARATORS										
LM193	Texas Instruments	0624A; (17-054)	Comparator	Bipolar	ADT	6	All parameters remained within specification.	Y	10	> 20
ADCMP600	Analog Devices	1639; (17-067)	Comparator	BiCMOS	MCC	10	All parameters remained within specification.	Y	10	> 100
ADCMP604	Analog Devices	1551; (17-068)	Comparator	BiCMOS	MCC	10	All parameters remained within specification.	Y	10	> 100
MISCELLANEOUS										
MT29F4G08ABADAWP-IT:D	Micron	1406; (16-034)	Flash Memory	CMOS	MJC	10	One unbiased part had block errors reading back after irradiation. No unrecoverable memory corruption.	Y	10 mrad(Si) and 15.5 rad(Si)	> 40
HS-4423BEH	Intersil	X1526ABBD; (17-071)	FET Driver	Bipolar	MCC	10	All parameters remained within specification.	Y	10	> 100
2N5154U3	Microsemi	E1624; (17-070)	NPN Transistor	Bipolar	MCC	10	h_{FE1} out of specification at 50 krad(Si).	Y	10	$h_{FE1} < 50$
ADF4252	Analog Devices	1637; (17-069)	Frequency Synthesizer	BiCMOS	MCC	10	Both RF and IF charge pumps failed at 92 krad(Si).	Y	10	$75 < I_{CP} < 92$
ISL71590	Intersil	1527; (17-073)	Temperature Transducer	Bipolar	MCC	10	Consistent linear decrease in output current. Maximum output value drift of 3.5 °C at 100 krad.	Y	10	$0 < x < 50$

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TABLE V: SUMMARY OF DDD TEST RESULTS

Part Number	**Manufacturer**	**LDC**	**Device Function**	**Technology**	**PI**	**Sample Size**	**Results**	**App. Spec (Y/N)**	**Proton Fluence (/cm^2)**
OPB847	OPTEK Technology	M1713A; (17-041)	Optical switch	Hybrid	MJC	10	On-State Collector Current out of specification at 2.18x10^{10} cm^{-2}, Collector-Emitter Saturation Voltage out of specification at 9.29x10^{10} cm^{-2}.	Y	I_{Con} < 2.18x10^{10}cm^{-2} V_{CESAT} < 9.29x10^{10}cm^{-2}
ACPL-785E	Avago	1649; (17-047)	Optocoupler	Hybrid	MJC	10	All parameters remained within specification.	Y	1.49x10^{11}
TUD69H1B	Sensor Electronics Technology, Inc.	n/a; (17-059)	LED	AlGaN	MCC	4	Glass darkening. No change in the forward I-V curve up to 9.4E^{11} cm^{-2}.	N	9.4x10^{11}
TUD89H1B	Sensor Electronics Technology, Inc.	n/a; (17-060)	LED	AlGaN	MCC	4	Glass darkening. No change in the forward I-V curve up to 9.4E^{11} cm^{-2}.	N	9.4x10^{11}
TCE49H1B	Sensor Electronics Technology, Inc.	n/a; (17-063)	LED	AlGaN	MCC	4	Glass darkening. No change in the forward I-V curve up to 3.3E^{13} cm^{-2}.	N	9.4x10^{11} 3 DUTs at 3.3x10^{13}

IV. TEST RESULTS AND DISCUSSION

As in our past workshop compendia of GSFC test results, each device under test has a detailed test report available online at http://radhome.gsfc.nasa.gov [3] and at http://nepp.nasa.gov [4] describing in further detail the test method, conditions and monitored parameters, and test results. This section contains a summary of testing performed on a selection of featured parts.

A. AD620SQ/883B, Analog Devices, Operational Amplifier

The AD620SQ/883B is an instrumentation amplifier featuring high accuracy and low noise. A gain range from 1 to 10,000 is programmable with an external resistor.

Eight AD620SQ parts were irradiated for TID testing at 10 mrad(Si)/s to a total dose of 25 krad(Si). Four parts were biased during irradiation and four were unbiased with two parts reserved as controls. Input offset current increased beyond specification at 3.3 krad(Si). Positive input bias current exceeded specification after 5.4 krad(Si). Negative input bias current and both power supply rejection ratios (gain at 1 and 10) failed at 8.5 krad(Si). After irradiation, the parts were annealed at room temperature for a total of 212 hours. The DUTs were unbiased at the 25.5 and 47.3 hour annealing measurements then were biased for the 93.8 and 212.3 hour measurement times. All measurements returned to specification or near specification after the 212 hour annealing period. Fig. 1 shows the input offset current over dose step and annealing. Fig. 2 displays the gain error at gain equal to ten over dose step and annealing.

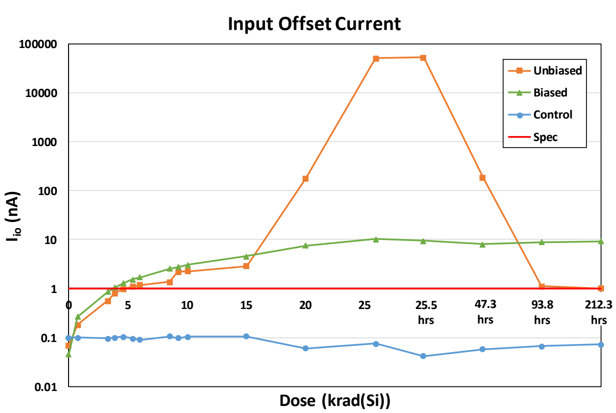

Fig. 1. Input offset current vs. dose (krad-Si) and annealing time.

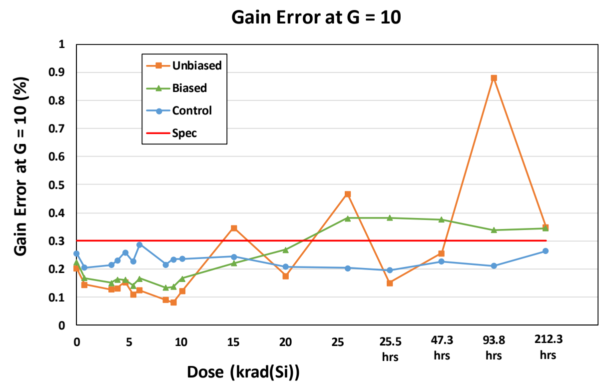

Fig. 2. Gain error at gain = 10 vs. dose (krad-Si) and annealing time.

B. OPB847, OPTEK Technology, Optical Switch

The OPB847 is a 110-V slotted optical switch with a gallium arsenide LED and silicon phototransistor. Ten parts were tested for displacement damage dose effects at Crocker Nuclear Laboratory at University of California at Davis (UCD-CNL). Five were biased and five were unbiased during irradiation, with two parts reserved as controls. On-state collector current (Ic_{ON}) showed an immediate decrease after the first fluence step. This parameter exceeded the manufacturer's specification, consistently across all parts, at 2.18 x 10^{10} p^+/cm^2. Collector-Emitter Saturation Voltage ($V_{CE(SAT)}$) and Collector-Emitter Breakdown Voltage ($V_{(BR)CEO}$) increased with proton fluence. Six DUTs exceeded the $V_{CE(SAT)}$ limit at 9.29 x 10^{10} p^+/cm^2 and all remaining parts except one failed at the next fluence step. DUT 6 failed at the final irradiation step of 1.49 x 10^{11} p^+/cm^2. Fig. 3 displays the Current Transfer Ratio over proton fluence. The unbiased parts were unmeasurable after 1.12 x 10^{11} p^+/cm^2 step.

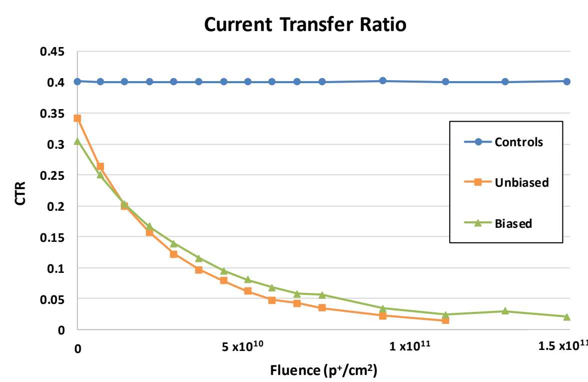

Fig. 3. CTR (Collector current divided by forward diode current) vs. fluence (p^+/cm^2).

C. ADF4252, Analog Devices, Frequency Synthesizer

The ADF4252 is a dual RF/IF frequency synthesizer for wireless receivers and transmitters, capable of multiplying or dividing an input reference signal to fully implement a phase-locked loop when paired with an external voltage controlled oscillator (VCO). The ADF4252 is programmed with an SPI-compatible serial interface which configures

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the on-chip mode registers. Fig. 4 shows a functional block diagram of the ADF4252.

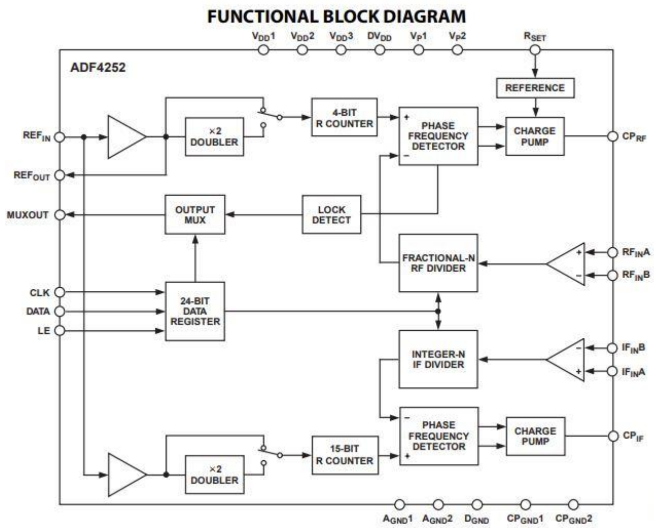

Fig. 4. ADF4252 block diagram from datasheet. [5]

Due to the small package size and external component requirements, each device was soldered to a custom-designed PCB (shown in Fig. 5) with a test circuit capable of measuring a typical set of performance and operational metrics. Ten identical test circuits are present on a single PCB, with individual power lines monitored via sense resistors. A total of twenty parts, with ten biased at nominal voltages and ten grounded, were irradiated at a rate of 10 mrad(Si)/s to a total dose of 100 krad(Si).

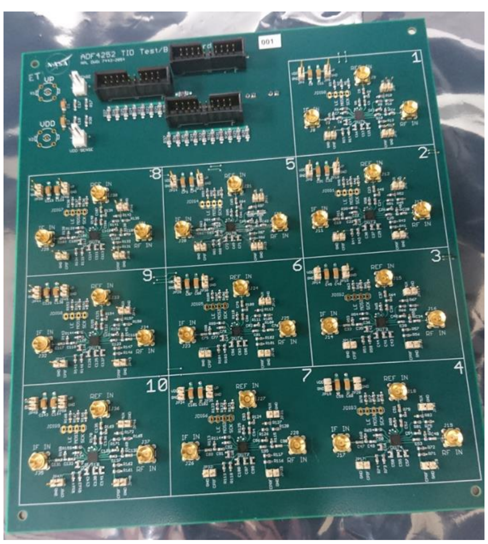

Fig. 5. ADF4252 Test PCB.

The logical high and low voltages, main supply voltage current, and the charge pump supply current showed no appreciable degradation during irradiation. Only degradation was seen during irradiation on the following parameters; quiescent supply current at 75 krad(Si) and charge pump supply current at 92 krad(Si).

Notably at 92 krad(Si), the charge pumps of the biased parts began to fail. By the 100 krad(Si) measurement, eight out of the ten biased DUTs were no longer functioning. Fig. 6 and 7 show the sudden current drop over dose of the biased devices.

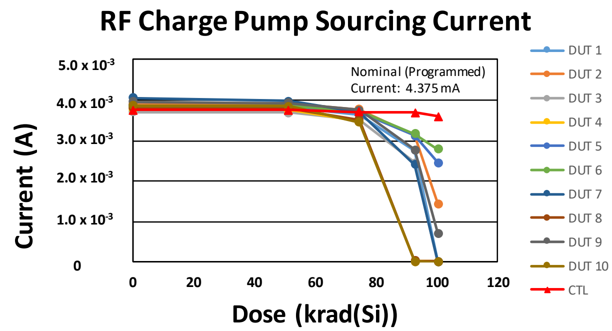

Fig. 6. RF charge pump sourcing current (biased DUTs) vs. dose.

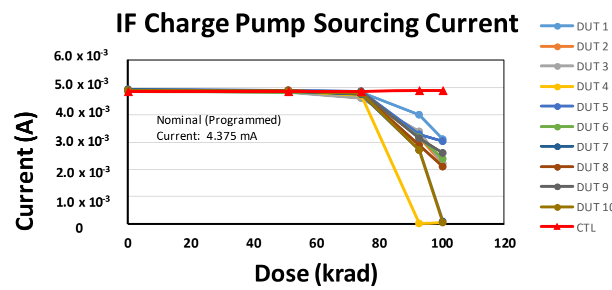

Fig. 7. IF charge pump sourcing current (biased DUTs) vs. dose.

The IF-side N-divider output frequency remained constant over dose. This proved that the ADF4252 was still programmed and setup properly. The RF-side N-divider output frequency also did not degrade during irradation as read on the MUX pin. However its amplitude was low and data fidelity was a recurring issue.

D. 2N5154, Microsemi, NPN Transistor

The 2N5154 NPN transistor was tested for TID response using the SMD-0.5 package. Ten parts were irradiated, five biased and five unbiased with two controls, up to 100 krad(Si) at a rate of 10mrad(Si)/s. All but one parameter stayed within specification during the entire irradiation. Forward current gain (h_{FE1}) with a collector current of 50 mA, decreased below specification for all devices at 50 krad(Si). h_{FE2} decreased as dose level increased but did not go below specification. Fig. 8 shows delta $1/h_{FE1}$ over dose. This parameter was used to show how the DUTs changed over dose. Since the control parts were not from the same lot or in the same package as the irradiated parts, the delta $1/h_{FE1}$ parameter allowed for a better comparison.

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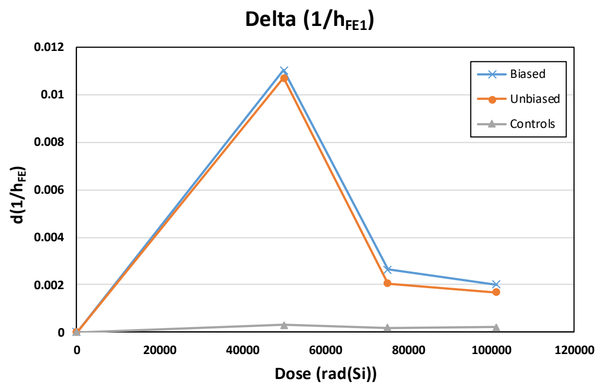

Fig. 8. Delta $1/h_{FE1}$ vs. dose (rad-Si).

V. SUMMARY

We have presented data from recent TID tests on a variety of primarily commercial devices. It is the authors' recommendation that this data be used with caution due to many application/lot-specific issues. We also highly recommend that lot testing be performed on any suspect or commercial device. As in our past workshop compendia of GSFC test results, each DUT has a detailed test report available online describing in further detail, test method, TID conditions/parameters, test results, and graphs of data [3].

VI. ACKNOWLEDGMENT

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VII. REFERENCES

[1] Martha V. O’Bryan, Kenneth A. LaBel, Edward P. Wilcox, Edward J. Wyrwas, Carl M. Szabo, Michael J. Campola, Megan C. Casey, Dakai Chen, Jean-Marie Lauenstein, Jonathan A. Pellish, and Melanie D. Berg, "NASA Goddard Space Flight Center’s Compendium of Recent Single Event Effects Results," submitted for publication in IEEE Radiation Effects Data Workshop, Jul. 2018.

[2] Department of Defense “Test Method Standard Microcircuits,” MIL-STD-883 Test Method 1019.9 Ionizing radiation (total dose) test procedure, June 7, 2013, https://landandmaritimeapps.dla.mil/Downloads/MilSpec/Docs/MIL-STD-883/std883.pdf.

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

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