NASA Goddard Space Flight Center's Recent Radiation Effects Test Results

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

I. INTRODUCTION

NASA spacecraft are subjected to a harsh space environment that includes exposure to various types of radiation. The performance of electronic devices in a space radiation environment is often limited by its susceptibility to single-event effects (SEE), total ionizing dose (TID), and displacement damage dose (DDD). Ground-based testing is used to evaluate candidate spacecraft electronics to determine risk to spaceflight applications. Interpreting the results of radiation testing of complex devices is quite difficult. Given the rapidly changing nature of technology, radiation test data are most often application-specific and adequate understanding of the test conditions is critical [1].

These test results show sensitivities of candidate spacecraft and electronic devices to SEE including single-event upset (SEU), single-event functional interrupt (SEFI), single-event latchup (SEL), single-event transient (SET), TID, and DDD effects. All tests were performed between March 2021 and February 2022.

II. TEST TECHNIQUES AND SETUP

A. Test Method

TID testing was performed using MIL-STD-883, Test Method 1019.9 [2] unless otherwise noted as research. All tests were performed at room temperature and with nominal power supply voltages, unless otherwise noted. Based on the application, samples would be tested in a biased and/or unbiased configuration. Functionality and parametric changes were measured after step irradiations (for example: every 10 krad(Si)).

Unless otherwise noted, SEE testing was performed in accordance with JESD57A test procedures [3]. Depending on the Device Under Test (DUT) and the test objectives, one or two SEE test methods were typically used:

a) *Dynamic* – The DUT was exercised and monitored continuously while being irradiated. The type of input stimulus and output data capture methods are highly device- and application-dependent. In all cases the power supply levels were actively monitored during irradiation. These results are highly application-dependent and may only represent the specific operational mode tested.

b) *Static/Biased* – The DUT was provided basic power and configuration information (where applicable), but not actively operated during irradiation. The device output may or may not have been actively monitored during irradiation, while the power supply current was actively monitored for changes.

In SEE experiments, DUTs were monitored for soft errors, such as SEUs, and for hard errors, such as SELs. Detailed descriptions of the types of errors observed are noted in the individual test reports.

SET testing was performed using high-speed oscilloscopes controlled via National Instruments LabVIEW® [4]. Individual criteria for SETs are specific to the device and application being tested. Please see the individual test reports for details.

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

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B. Test Facilities – TID

TID testing was performed using a gamma source [5]. Dose rates used for testing were between 10 mrad(Si)/s and 2.6 krad(Si)/s.

C. Test Facilities – DDD

Proton DDD tests were performed at the University of California at Davis Crocker Nuclear Laboratory (UCD - CNL) [6] using a 76" cyclotron and energy of 64 MeV.

D. Test Facilities – SEE

Heavy ion experiments were conducted at the Texas A&M University Cyclotron (TAMU) [7] and Lawrence Berkeley National Laboratory (LBNL) 88-inch cyclotron [8]. Energies and Linear Energy Transfers (LETs) available varied slightly from one test date to another.

III. TEST RESULTS OVERVIEW

Principal Investigators (PIs) are listed in Table I. Abbreviations and conventions are listed in Table II. Table III is a summary of the SEE, TID, and DDD test results for all parts tested between March 2021 and February 2022. Please note that these test results can depend on operational conditions.

TABLE I
LIST OF PRINCIPAL INVESTIGATORS

Principal Investigator (PI)	Abbreviation
Jonathan Barth	JB
Melanie Berg	MB
Thomas Carstens	TAC
Megan C. Casey	MCC
Matthew Joplin	MBJ
Jean-Marie Lauenstein	JML
Edward (Ted) Wilcox	TW

TABLE II
ACRONYM LIST

Acronym	Definition
σ	cross section (cm^2/device, unless specified as cm^2/bit)
ADC	Analog-to-Digital Converter
BiCMOS	Bipolar Complementary Metal Oxide Semiconductor
CMOS	Complementary Metal Oxide Semiconductor
DDD	Displacement Damage Dose
DUT	Device Under Test
ELDRS	Enhanced Low Dose Rate Sensitivity
FD-SOI	Fully Depleted Silicon On Insulator
FPGA	Field Programmable Gate Array
GSFC	Goddard Space Flight Center
HDR	High Dose Rate
HEMT	High Electron Mobility Transistor
$I_{C(ON)}$	On-state Collector Current
IRAD	Internal Research & Development Program
LBNL	Lawrence Berkeley National Laboratory
LDC	Lot Date Code
LDR	Low Dose Rate
LED	Light Emitting Diode
LET	Linear Energy Transfer
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
NEPP	NASA Electronics Parts and Packaging
Op Amp	Operational Amplifier
PGOOD	Power Good Signal
PI	Principal Investigator
REAG	Radiation Effects & Analysis Group
SEB	Single-Event Burnout
SEE	Single-Event Effect
SEFI	Single-Event Functional Interrupt
SEGR	Single-Event Gate Rupture
SEL	Single-Event Latchup
SET	Single-Event Transient
SEU	Single-Event Upset
SRAM	Static Random-Access Memory
TAMU	Texas A&M University
TID	Total Ionizing Dose
TPU	Tensor Processing Unit
TTM	Time-To-Market
UCD-CNL	University of California at Davis Crocker Nuclear Laboratory
$V_{(BR)CEO}$	Collector-Emitter Breakdown Voltage
$V_{(BR)ECO}$	Emitter-Collector Breakdown Voltage
V_{DS}	Drain-Source Voltage
V_{GS}	Gate-Source Voltage

TABLE III
SUMMARY OF TEST RESULTS

Part Number	Manufacturer	LDC; (REAG ID#)	Device Function	Technology	PI	Sample Size	Test Env.	Test Facility (Test Date)	Test Results (Effect, Dose Level/Energy, Results)
66212-301	Micropac	2051; (19-047)	Optocoupler	Hybrid	TW	12	Protons	UCD (Oct 2021)	DDD and TID, No failures up to 2.2 x 10^{11} protons/cm^2 or TID equivalent 29.3 krad(Si). [9]
FBG20N18	EPC Space	Y003; (21-018)	HEMT	GaN	JML	7	Heavy Ions	LBNL (Jun 2021)	No SEB with 10 MeV/n Xe (LET = 59 MeV•cm^2/mg(Si)) at V_{GS} = -4V & V_{DS} = 200V 185 V_{DS} < SEB threshold < 190 V_{DS} at -4 V_{GS} with 10 MeV/n Au (LET = 86 MeV•cm^2/mg(Si)).
FBG30N04	EPC Space	T047; (21-019)	HEMT	GaN	JML	5	Heavy Ions	LBNL (Jun 2021)	No SEB at 300 V_{DS} & -4 V_{GS} with 10 MeV/n Au (LET=86 MeV•cm^2/mg(Si)). I_D degradation onset ~250 V_{DS} but I_{DSS} remained in manufacturer spec after 10^7 cm^{-2} Au ions.
JANS2N2907AUB	Semicoa	2026; (21-005), 2012A; (21-006), 2028; (21-007), 1921; (21-008)	Transistor	Bipolar	TW	88	Gamma	GSFC (Jun 2021)	TID, LDR, No parametric failures ≤ 30 krad(Si). [10]
JANS2N5339	Semicoa	1747; (21-010)	Transistor	Bipolar	TW	10	Gamma	GSFC (Sep 2021)	TID, LDR, No functional failures ≤ 36 krad(Si).
JANSR2N7593U3	Microchip	C2052; (21-020)	MOSFET	Si	JML	3	Heavy Ions	LBNL (Jun 2021)	No SEB/SEGR up to 10 MeV/n Au (LET = 86 MeV•cm^2/mg) at V_{DS} = 250V & V_{GS} = 0V; No SEB/SEGR with 10 MeV/n Ag (LET = 48 MeV•cm^2/mg) at V_{DS} = 250V & V_{GS} = -20V.
LIFCL-40-8BG400CE82 (CrossLink)	Lattice Semiconductor	2048; (21-016)	FPGA	28nm FD-SOI	MB	2	Gamma	GSFC (Mar 2021)	TID, HDR, 330 krad(Si), A "first look" test, New dial-down approach was used to measure internal delay paths. DUT4 saw input-rise to output-rise delay measurements increase by 6ns over dose. The voltage regulator died after 275 krad(Si). DUT5 saw input-rise and output-rise delay measurements increase by 6ns over dose. The voltage regulator died at 330 krad(Si). Further studies are in progress.[11]
LT3482	Analog Devices	n/a; (21-024)	DC/DC Converter	Bipolar	JB	2	Gamma	GSFC (Jul 2021)	TID, HDR (No ELDRS consideration), 100 krad(Si), Output voltage showed < 0.5% decrease from pre-irradiation values at 100 krad(Si). [12]
LTC1604	Linear Technology	1537; (21-025)	ADC	CMOS	MBJ	3	Heavy Ions	LBNL (Sep 2021)	SEL: 49 < LET_{th} < 53 and 40 deg C. SEL saturated σ~1x10^{-6} cm^2. [13]
LTC2054	Linear Technology	2034; (21-022)	Op Amp	Bipolar	MBJ	10	Gamma	GSFC (Jul 2021)	TID, LDR, 100 krad(Si), All device parameters stayed in specification up to a dose level of 80 krad(Si). Degradation in biased devices were observed in input offset voltage variance, high voltage swing, quiescent current, and slew rate variance. Biased input offset voltage lower bound went out of datasheet specification between 80 krad(Si) and 90 krad(Si). Biased quiescent current upper bound went out of datasheet specification between 90 krad(Si) and 100 krad(Si). Degradation in unbiased (grounded) devices was observed in high voltage swing measurement. Grounded device parameters remained in datasheet specifications up to 100 krad(Si). [14]

Part Number	Manufacturer	LDC; (REAG ID#)	Device Function	Technology	PI	Sample Size	Test Env.	Test Facility (Test Date)	Test Results (Effect, Dose Level/Energy, Results)
MSK130	M. S. Kennedy/TTM Technologies	n/a; (21-024)	Differential Amplifier	BiCMOS	JB	2	Gamma	GSFC (Jul 2021)	TID, HDR (No ELDRS consideration), Current draw had increased by an order of magnitude and the part was not functional at 10 krad(Si). [12]
MT29F16G08ABABAWP	Micron	1642; (22-003)	Flash	CMOS	TW	6	Heavy Ions	LBNL (Feb 2022)	See Section IV, B for the full results. [15]
OMT1090	TT Electronics	M2047; (21-012)	Opto-electronics	Hybrid	TAC	10	Protons	UCD (Oct 2021)	DDD, 64 MeV, No effects were seen up to 4 krad(Si) or 3.01 x 10^{10}, $V_{BR(CEO)}$ went out of specification at 6 krad(Si) or 4.52 x 10^{10} protons/cm^2 for biased DUTs, DUT 2 failed at 6 krad(Si). Collector current went below specification after 7 krad(Si). [16]
PIC18F4685T	Microchip	n/a; (21-032)	Microcontroller	CMOS	TW	5	Heavy Ions	LBNL (Jun 2021)	SEL was observed; no parts damaged in testing SEL LET_{th} < 2.4 MeV•cm^2/mg (1.25x10^{-6} cm^2) $\sigma_{max\ measured}$ 2.68x10^{-3} cm^2 @ LET 25 MeV•cm^2/mg, 3 parts irradiated with LET 76.7 MeV•cm^2/mg at 85°C to at least 1x10^7/cm^2 with no permanent failures.
RM3100	PNI	n/a; (21-017)	Sensor	CMOS	TW	2	Heavy Ions	LBNL (May 2021)	SEL, LET_{th} > 76 MeV•cm^2/mg at 3.3 V and 85 deg C, 3.7 < SEFI LET_{th} < 7.3 MeV•cm^2/mg, SEFI $\sigma_{max\ measured}$ ~1x10^{-5} cm^2 @ LET = 38.9 MeV•cm^2/mg
Si5345	Silicon Labs/Sky Works	n/a; (21-024)	Clock Synthesizer	CMOS	JB	2	Gamma	GSFC (Jul 2021)	TID, HDR, 100 krad(Si), Less than 1% decrease of output voltage over dose. [12]
SY88422L	Microchip	n/a; (21-024)	Laser Driver	SiGe	JB	2	Gamma	GSFC (Jul 2021)	TID, HDR, 100 krad(Si), No radiation induced degradation of timing performance for 10 ns input pulses during testing was observed. [12]
Edge Accelerator Module	Google	n/a; (22-001)	Tensor Processing Unit (TPU)	CMOS	MCC	12	Gamma	GSFC (Dec 2021)	TID, HDR, 30 krad(Si), biased DUTs were unable to connect via USB. PGOOD was checked and voltage was nominal indicating the on-board voltage regulator is functioning normally. Grounded DUTs survived to 75 krad(Si). [17]
Neural Compute Stick 2	Intel	n/a; (22-002)	Vision Processing Unit	CMOS	MCC	12	Gamma	GSFC (Dec 2021)	TID, HDR, 20 krad(Si), 3 of the 6 grounded DUTs were unable to connect via USB. All 6 biased DUTs were unable to connect via USB at 25 krad(Si). Remaining 3 unbiased DUTs were also unable to connect at 30 krad(Si). [17]

IV. TEST RESULTS AND DISCUSSION

As in our past workshop compendia of GSFC test results, most devices under test have a detailed test report available online at http://radhome.gsfc.nasa.gov [18] and at http://nepp.nasa.gov [19] 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. OMT1090, TT Electronics, Opto-electronics

The OMT1090 is a 50V slotted optical switch with a gallium aluminum arsenide LED and a silicon phototransistor. Phototransistor switching takes place when an opaque object passes through the slot.

A displacement damage test was performed at Crocker Nuclear Laboratory on the campus of The University of California at Davis with a proton energy of 64 MeV. Five devices were irradiated under bias and five were unbiased. There were two control devices. Parametric measurements were made after each run outside the irradiation chamber.

The forward voltage was un-affected by dose for the biased and unbiased cases. The $V_{(BR)CEO}$ remained constant for the unbiased case. However, the $V_{(BR)CEO}$ of the biased case went out of specification after a dose of 6 krad(Si) (64 MeV equivalent fluence of 4.52 x 10^{10} protons/cm^2). In particular, DUT (2) failed after 6 krad(Si). The $V_{(BR)ECO}$ increased slightly with dose for unbiased case but stayed above the specification minimum. On the other hand for the biased case the $V_{(BR)ECO}$ failed after a dose of 6 krad(Si) (64 MeV equivalent fluence of 4.52 x 10^{10} protons/cm^2). This was caused by DUT 2 failing.

After the first irradiation step, the on-state collector current ($I_{C(ON)}$) saw a significant decrease. At a dose of 6 krad(Si) (64 MeV equivalent fluence of about 4.52 x 10^{10} protons/cm^2), $I_{C(ON)}$ was below specification according the design application of 1mA. This is shown in Figure 1. The control DUTs were not measured the last two dose steps due to time constraints. Once again DUT 2 was the first to fail.

In summary the optical switches showed variability before irradiation. This variability was only exacerbated by dose effects. Based on the test results radiation negatively impacts the phototransistor more than the photodiode.

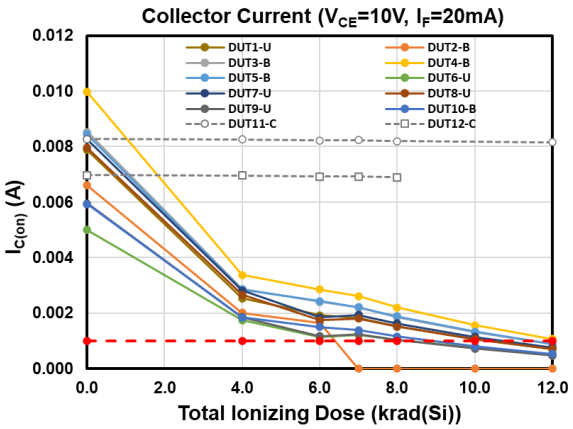


Fig. 1. On-state Collector Current (A) vs. Dose (krad(Si)) for each DUT.

B. MT29F16G08ABABAWP, Micron, Flash Memory

A 16Gb commercial NAND flash device was tested for single-event effects as part of a flight project anomaly investigation to evaluate any impacts to device reliability after repeated power cycles to mitigate single-event functional interrupts (SEFI). The devices tested were part of the original flight lot (LDC 1642) assembled and screened by a third-party vendor. Testing conducted at the Lawrence Berkeley National Laboratory's 88-inch cyclotron served to demonstrate two goals: first, that a lifetime's worth of SEFI events would not adversely affect device operation; and second, that allowing the devices to dwell in a SEFI condition for at least 24 hours would not degrade the expected lifetime of the device. SEFI observed during testing were classified into two groups: block SEFI, in which a localized block of flash memory was non-functional without intervention; and complete SEFI, in which the entire device was non-responsive.

To satisfy the first objective, three flash devices identified as device #1, #2, and #3 were each subjected to 52, 59, and 53 total SEFI events, respectively. The LET used to trigger SEFI varied run-to-run, but ranged from 5.1 to 19.3 MeV•cm^2/mg. The high number of SEFI/recovery cycles was made possible by the use of an automated test script and a NASA-supplied shutter mechanism to reliably block the heavy ion beam (verified experimentally) within approximately 10-20 ms of a detectable SEFI event, yielding very precise fluence-to-failure data. Power was automatically disconnected from the flash with an on-board solid-state relay, I/O pins were held at 0V, and after a one-second delay power was restored, the device reset, and operations resumed until the target number of SEFI events accumulated. The number of events was application-specific, pre-determined to be significantly greater than the number of SEFI expected for any given flash die within the system for the mission's lifetime.

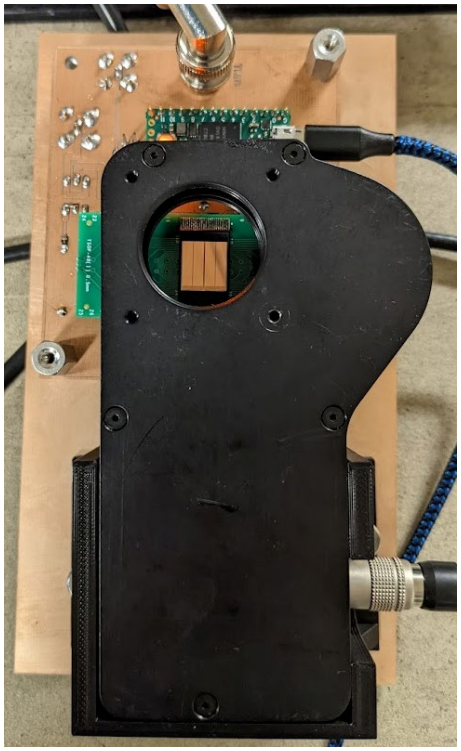


Fig. 2. A Thorlabs SH1 shutter was mounted above the device under test, activated as part of an autonomous SEFI test controlled by an ARM Cortex-M4 microcontroller visible at the top edge.

To satisfy the second objective, three flash devices (#4, #5, #6) were irradiated until a SEFI condition occurred (specifically, an event where more than one block, but less than the whole memory, was inoperable). For this experiment, a beam with effective LETs of 19.3, 5.1, and 29.1 MeV•cm^2/mg was used on the devices under test, respectively. The devices were maintained on a power supply without interruption while being maneuvered out of the cave to a temporary test cart. Here, the samples were allowed to dwell for 72 hours in the SEFI condition before power was removed and the parts placed in storage until such time that they could be released by the radiation physicist and returned to Goddard. Note that none of the SEFI encountered showed abnormally high power supply current while in this condition. A summary of SEFI cross-section data is provided in Table IV for block SEFI, and in Table V for complete SEFI. Note that for this testing, no attempt was made to identify the underlying cause of the SEFI nor the minimum recovery steps necessary.

Table IV. Test data for localized block SEFI

Device #	LET (MeV•cm^2/mg)	Total Fluence (/cm^2)	Block SEFI Count
4	2.6	1.08x10^7	1
3, 5	5.1	2.28x10^6	35
4	8.2	3.16x10^5	10
4, 5	19.3	1.51x10^5	29
6	29.1	1.82x10^5	8

Table V. Test data for device-wide complete SEFI

Device #	LET (MeV•cm^2/mg)	Total Fluence (/cm^2)	Complete SEFI Count
6	2.6	1.99x10^7	1
2, 6	5.1	2.92x10^7	8
1, 6	8.2	1.71x10^7	11
1, 2	19.3	4.74x10^7	101
6	29.1	1.36x10^7	43

All devices remained fully functional upon return to Goddard. No unrecoverable functional failures were ever observed. Two samples of each test objective were heated under bias to +125 C for 168 hours after testing to accelerate any possible latent damage effects caused by either the SEFI cycling or SEFI dwell. After latent damage testing, all parts remained fully functional as before. No indication of damage due to the repeated SEFI events nor the 72-hour SEFI dwell was observable.[15]

V. SUMMARY

We have presented data from recent radiation tests on a variety of devices including several commercial parts. It is the authors' recommendation that this data be used cautiously as many tests were conducted under application- or lot-specific test conditions. We also highly recommend that lot-specific testing be performed on any suspect or commercial device.

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