Total ionizing dose results and displacement damage results for candidate spacecraft electronics for NASA

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Recent 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

In order to meet the demands of reduced cost, higher performance and more rapid delivery schedules imposed by the space flight community, commercial and emerging technology devices have assumed a prominent role in meeting these needs. With the skyrocketing increase in the use of such devices, the importance of ground based testing for the effects of total ionizing dose (TID) and proton displacement damage to qualify such devices for flight is paramount. The novel ways in which some of these devices are used also highlights the need for application specific testing to ensure their proper operation and ability to meet mission goals.

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 2005 IEEE NSREC Radiation Effects Data Workshop entitled: "Recent Single Event Effects Results for Candidate Spacecraft Electronics for NASA" by M. O'Bryan, et al. [1]

The Authors would like to acknowledge the sponsors of this effort: NASA Electronic Parts and Packaging Program (NEPP), and NASA Flight Projects.

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 the University of California at Davis Crocker Nuclear Laboratory (UCD-CNL) that has a 76" cyclotron (maximum energy of 63 MeV. Table I lists the proton damage test facility and energies used on the devices.

Table I: Proton Test Facilities

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

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 10krads(Si), or every $1x10^{10}$ protons).

III. TEST RESULTS OVERVIEW

Abbreviations for principal investigators (PIs) are listed in Table II. Definitions for the categories are listed in Table III. Abbreviations and conventions 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: LIST OF PRINCIPAL INVESTIGATORS

Abbreviation	Principal Investigator (PI)
SB	Steve Buchner
BD	Becky DiBari
SK	Scott Kniffin

TABLE III: LIST OF CATEGORIES

1	Not tested to failure.
2	Degradation at >50krads(Si)
3	Degradation at 20-50krads(Si)
4	Degradation at 5-20krads(Si)
5	Degradation at 5krads(Si) or less
REV	Research Test Vehicle – Please contact the P.I. before utilizing this device for spacecraft applications.

TABLE IV: ABBREVIATIONS AND CONVENTIONS:

ACRONYM	DEFINITION	ACRONYM	DEFINITION
ADC	analog to digital converter	LDC	lot date code
ASIC	application specific integrated circuit	LED	light emitting diode
CCD	charge coupled device	I_{CC}	power supply current
CMOS	complementary metal oxide semiconductor	MeV	mega electron volt
DAC	digital to analog converter	N/A	not applicable
DD	displacement damage	op amp	operational amplifier
DNL	differential non-linearity	p/cm^2	$protons/cm^2$
FET	field effect transister	PI	Principal Investigator
GSFC REF	Goddard Space Flight Center Radiation Effects Facility	PT	photo transistor
I_b	bias current	TID	total ionizing dose
I_C	collector current	UCD-CNL	University of California at Davis Crocker Nuclear Laboratory
I_f	forward current	V_{OL}	output saturation voltage
I_{OS}	offset current	V_{out}	output voltage
I_{STDBY}	standby current	V_{ce}	collector emitter voltage

TABLE V: SUMMARY OF TID AND DD 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))	Test Report	Cat.
Data Converters									
MAX529	Maxim	0101, 0126	8-Bit DAC	GSFC04MAY/SK	0.51	All parts passed all tests up to 5.0krads(Si).	>5	G04May_MAX529_TID.pdf	1
AD574	Analog Devices	9245, 9248, 9442	12-Bit ADC	GSFC04SEP/SK	0.17	All parts passed all tests up to 20krads(Si). After 30krads(Si) and higher, all devices exceed the specification limit for INL (greater than 1lsb).	30	G04SEP_AD574_TID.pdf	3
AD7545	Analog Devices	0503A	12-Bit ADC	GSFC05JAN/BD	0.15	Functional failure at 5krad (Si), no recovery observed after annealing.	5	G05JAN_AD7545_TID.pdf	5
AD7846SQ	Analog Devices	Q0408A	16-Bit DAC	GSFC05FEB/BD	0.42	DNL exceeds specification limit at 10krads(Si). Functional failure at 15krads(Si), recovered after 168 hour annealing., parametric degradation continues. Devices were taken to 20krads(Si) and no functional failure was observed. After 25krads(Si), functional failures were again observed.	10	G05FEB_AD7846_TID.pdf	4
Operational Amplifiers									
OP27	Analog Devices	0402F	Op Amp	GSFCFEB05/BD	0.6	All parts passed all tests up to 20krads(Si).	>20	G05FEB_OP27_TID.pdf	1
OP27A	Analog Devices	9347, 9407	Op Amp	GSFC04SEP/SK	0.17	All parts passed all tests up to 30krads(Si). Degradation was seen in $+I_b$ and $-I_b$ from 50 to 100krads(Si). After annealing two of the devices return to within specification limits.	50	G04SEP_OP27A_TID.pdf	3
OP200	Analog Devices	2C0347G	Op Amp	GSFC05JAN/BD	1.13	All parts passed all tests up to 5krads(Si). I_{os} exceeds specification limits after 10krads(Si). After annealing, all devices returned to within specification limits.	10	G05JAN_OP200_TID.pef	4
OP42AZ	Analog Devices	2C0345G	Op Amp	GSFC05JAN/BD	1.07	$+I_b$ exceeded specification limits at 10krad(Si).	10	G05JAN_OP42_TID.pdf	4
OP400	Analog Devices	2B0404F	Op Amp	GSFC05JAN/BD	1.13	All devices pass all tests after 1 krad(Si). $+I_b$ exceeded specification limits after 5krads(Si).	5	G05JAN_OP400_TID.pdf	5
OP77	Analog Devices	3B0402F	Op Amp	GSFC05MAR/BD	1.13	$+I_b$ exceeded specification limits after 10krads(Si).	10	G05MAR_OP77_TID.pdf	4
AD744	Analog Devices	0000G	BiFET Op Amp	GSFC05FEB/BD	0.71	All parts passed all tests up to 5krads(Si). After 10krads(Si), all devices exceeded the specification limit for $+I_b$. After annealing, all devices remain above the specification limit.	10	G05FEB_AD744_TID.pdf	4

TABLE V: SUMMARY OF TID AND DD 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))	Test Report	Cat.
DC/DC Converters and Related Devices									
AFL2803R3S	Advanced Analog (IR)	0351	3.3V, DC/DC Converter	GSFC04JUN/SK	0.028	All parts passed all tests up to 10krads(Si).	>10	G04JUN_AFL2803R3S_TID.pdf	1
MAX724ECK	Maxim	0342	DC/DC Regulator	GSFC04NOV/SK	0.23	All parts passed all tests up to 20krads(Si).	>20	G04NOV_MAX724ECK_TID.pdf	1
Logic Devices									
54ACTQ16245	National Semiconductor	0409	16-Bit Transceiver	GSFC04NOV/SK	0.23	Some VOL measurements exceeded specification limits after 10krads(Si), however these parameters were within specification after this step. All 8 ICC measurements exceeded specification limits after 15krads(Si) and 20krads(Si). Significant changes occurred following annealing, see report.	10	G04NOV_54ACTQ16245_TID.pdf	4
HN58C1001T15	Renesas	0433	EEPROM	GSFC05JAN/SB	0.8	All parts passed all tests up to 100krads(Si).	>100	G05JAN_HN58C1001T15_TID.pdf	1
Other Linear Devices									
AD584	Analog Devices	0348B, 0413D	Voltage Reference	GSFC05JAN/BD	0.7	V_{OUT}(10V) exceeded specification limits after 15krads(Si). No recovery was noted after annealing.	15	G05JAN_AD584_TID.pdf	4
AD822	Analog Devices	0029B	Low Power FET	GSFC04MAY/SK	0.04	All parts passed all tests up to 10krads(Si).	>10	G04MAY_AD822_TID.pdf	1
Optical Devices									
LXA0387	LSI Logic	0414	ASIC/512k SRAM	GSFC04AUG/CP	1.3	Parametric degradation at ~90krads(Si). Functional failure at ~270krads(Si).	~90	G04AUG_LXA0387.pdf	
Custom C-2 LED (InGaN blue)	Micropac (AXT Opto)	N/A	LED	CNL 04NOV/SK	$1x10^{10}$ p/cm^2 to $1x10^{12}$ p/cm^2	No degradation was seen up to $3x10^{11}$ p/cm^2. A small decrease in I_c was seen after $5x10^{11}$ p/cm^2 and $1x10^{12}$ p/cm^2.	$5x10^{11}$ p/cm^2	D04NOV_C2LED.pdf	2
Custom TCM405 (GaN UV)	Micropac (III-V Components)	N/A	LED	CNL04NOV/SK	$1x10^{10}$ p/cm^2 to $1x10^{12}$ p/cm^2	No degradation was seen up to $1x10^{12}$ p/cm^2.	>$1x10^{12}$ p/cm^2	D04NOV_C2LED.pdf	1
62087-301 (LED), 61055-305 (PT)	Micropac	N/A	LED/PT Encoder	CNL04JAN/SK	$1x10^{10}$ p/cm^2 to $1x10^{12}$ p/cm^2	No degradation was seen up to $5x10^{10}$ p/cm^2. Uniform degradation occurs from $1x10^{11}$ p/cm^2 to $1x10^{12}$ p/cm^2. Degradation is dependent on LED forward current. See report.	$1x10^{11}$ p/cm^2	D04JAN_61055_62087.pdf	1

IV. Test Results and Discussion

1) *OP27A*

The OP27A operational amplifier from Analog Devices was tested to 100krads(Si) with an average dose rate of 0.17rads(Si)/s. The two LDCs tested were 9347 and 9407. The devices were statically biased. For both $+I_b$ and $-I_b$, three devices exceeded the specification limits after 40krads(Si); all devices exceeded specification limits for both parameters after 50krads(Si) and continued to degrade through 100krads(Si). There was significant recovery in these parameters with two devices having readings within specification limits following annealing. Both LDCs of devices behaved similarly in terms of degradation; however, LDC 9407 did perform slightly better overall. See Figures 1 and 2 for comparisons of lot-to-lot 1_b degradation.

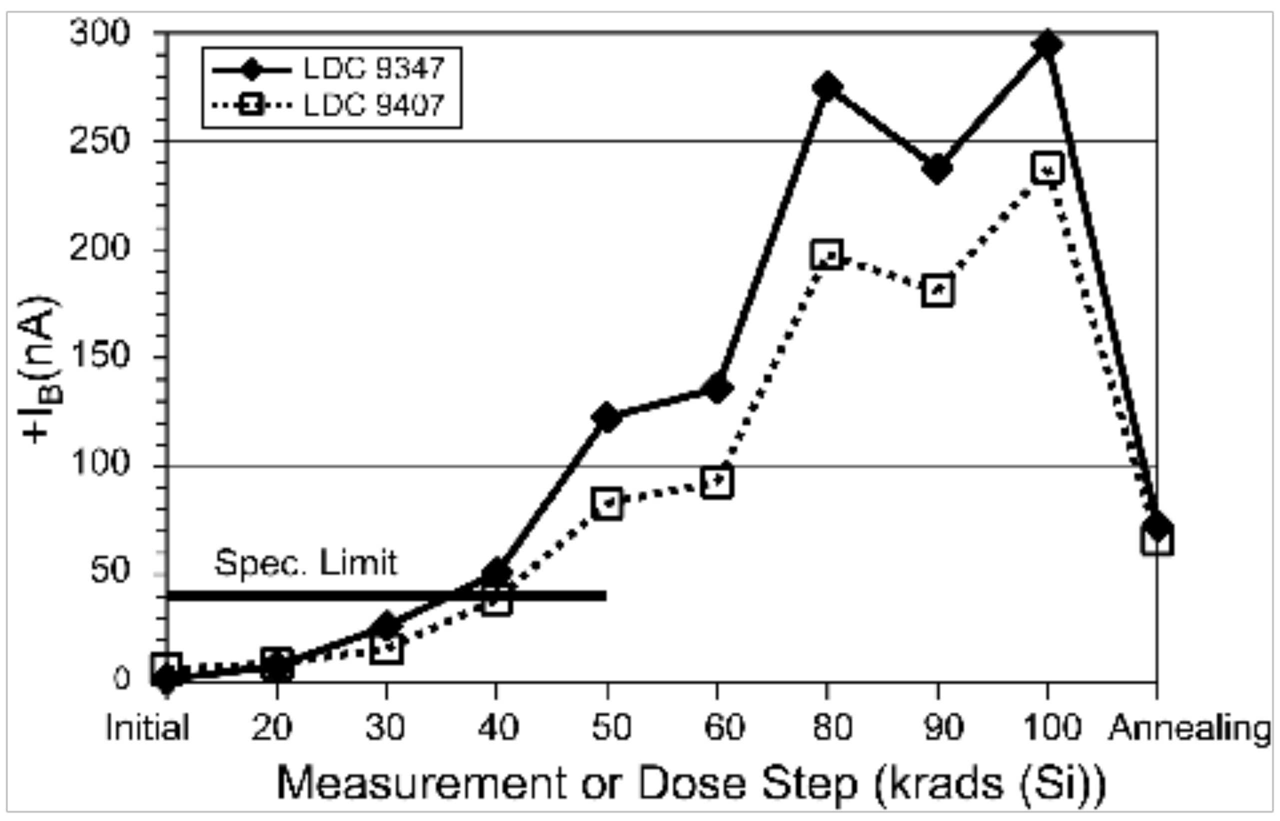

Fig. 1. Analog Devices OP27A $+I_b$ degradation by LDC.

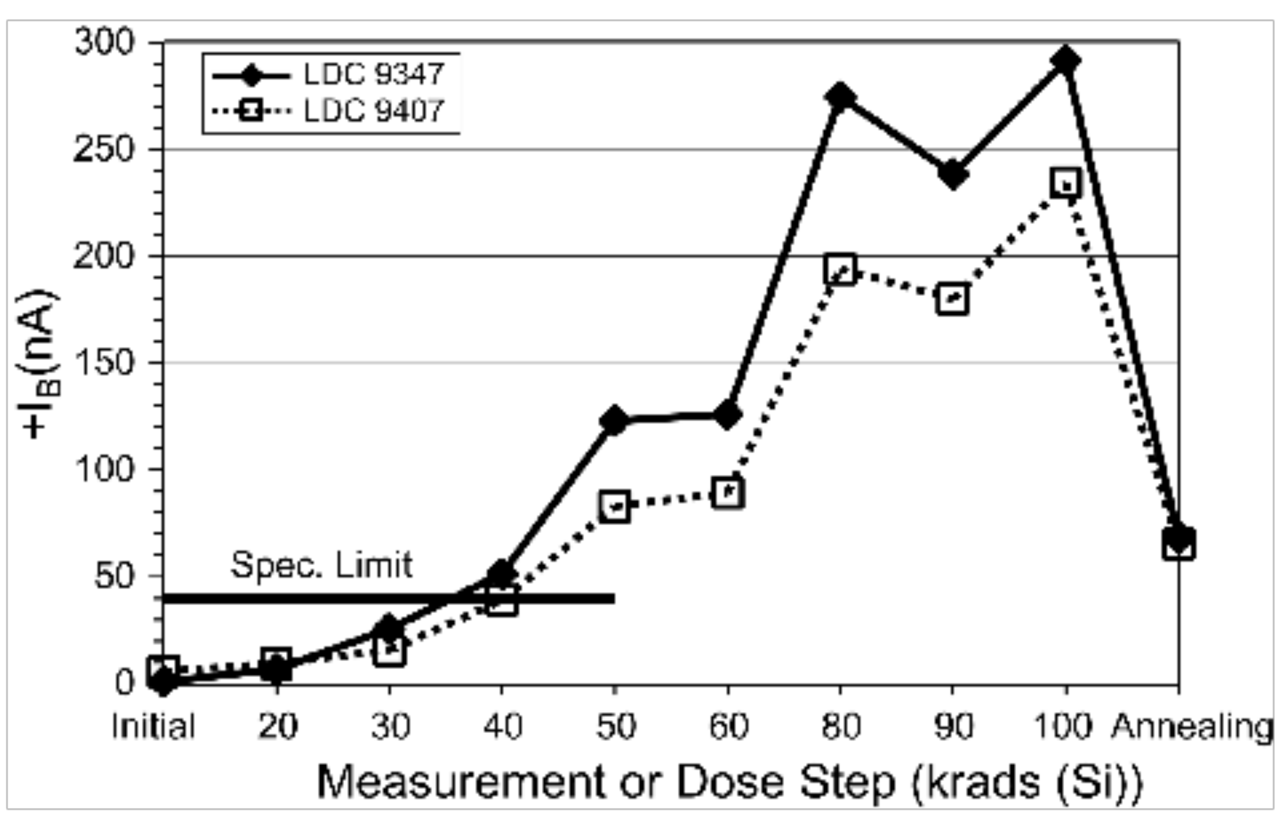

Fig. 2. Analog Devices OP27A $-I_b$ degradation by LDC.

2) *54ACTQ16245*

The 54ACTQ16245 16-bit transceiver from National Semiconductor was tested to 20krads(Si) with an average dose rate of 0.23rads(Si)/s. The eight test devices were statically biased. Some V_{OL} measurements exceeded specification limits after 10krads(Si) only to return to within specification limits at higher dose levels and following annealing. Following the 15krads(Si) exposure, all devices go beyond specifications for all 8 I_{CC} measurements. Two devices had readings in certain I_{CC} measurements that fell below the lower specification limit for those tests while all devices in all other I_{CC} tests exceeded the upper specification limits. After 20krads(Si), all devices had all 8 I_{CC} measurements exceeding specification limits. Following 168 hours of room temperature annealing, the results become more complicated. Five devices exhibited what is interpreted to be a significant secondary effect in the form of long-term charge trap collection. The four I_{CC}-high measurements in these devices went from significantly exceeding the specification limits for I_{CC} to falling significantly below the specification limits for these I_{CC} parameters with three specific exceptions within this subgroup where the measurements remained only slightly higher than specification limits. For these five devices, all of the I_{CC}-low measurements continued to exceed the specification limits for those parameters. All other devices continued to exceed specification limits for all I_{CC} parameters. These results imply that there is a propensity for the devices to collect charge traps over time that cause additional damage. The fact that this is not noted in all of the samples tested indicates that there is an inconsistent electrical margin for the devices within this lot.

3) *Blue LED (470nm)*

Displacement damage testing was performed on a 470nm blue LED die (InGaN), manufactured by AXT Optoelectronics, custom packaged by Micropac. Five devices were exposed to 63MeV protons at UCD-CNL. The devices were unbiased during each irradiation step. The LEDs were tested in a custom wooden jig to eliminate stray light and enable test repeatability.

The LED response was measured by sweeping the LED forward current from 0.1mA to 20mA in log steps and collecting the light output (I_C) with a photo diode that remained constant and unirradiated during all testing. The devices were measured twice after each exposure to check for charge injection annealing that can result from testing the devices. There was typically a 10nA increase in collector current between the first and second test. This does not significantly change the results in any way and implies nominal charge injection annealing.

The LEDs showed no significant degradation up to $3x10^{11}$ p/cm^2 with a photocurrent drop of ~50nA. Slight degradation is seen after $5x10^{11}$ p/cm^2 and $1x10^{12}$ p/cm^2 with a 0.103 to 0.168µA drop in photocurrent. It should be noted that so long as I_F is greater than 1mA, the devices do perform consistently. Fig. 3 shows typical LED response to increasing fluence for these devices.

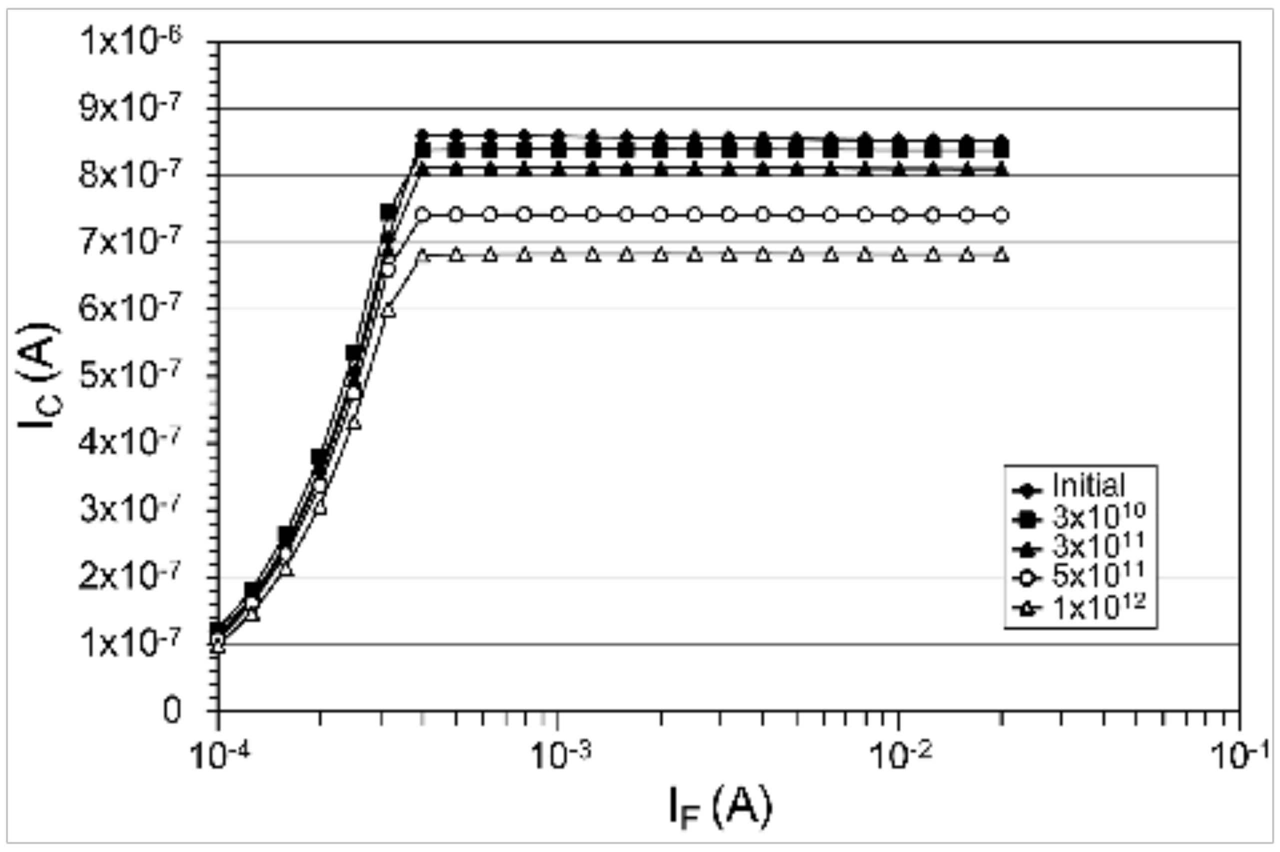

Fig. 3. Micropac (AXT Optoelectronics die) 470nm InGaN blue LED proton displacement damage as a function of total fluence in p/cm^2.

4) LED/PT Encoder Pair

Displacement damage testing was performed on LED/PT encoder pairs, custom packaged by Micropac. A total of four pairs of devices were exposed to 63MeV protons at UCD CNL. The devices were unbiased during each irradiation step. The device pairs were custom packaged in a single unit that had the full area of the LED exposed, a small air gap, a tall but narrow aperture, and the PT behind the aperture. The aperture was designed to mimic the encoder blade that will pass between the devices in this mission's application. This enabled the devices to be qualified together as a system in a mission-specific flight configuration. The importance of this style of testing was demonstrated by Kniffin, et.al., at the 2003 RADECS Conference [4].

The tests performed on the encoder pairs were conducted as follows. The collector current (I_C) of the PT was swept from 1μA to 20mA in log steps and was done by a parametric analyzer while measuring V_{CE}. This was done while the LED forward current (I_F) was held constant from 0 to 20mA in 1mA steps. Figures 4 through 9 show the progression of degradation for a given device pair. Each line of data on the graphs represents each PT I_C sweep with the corresponding LED I_F given in the legend.

No significant degradation was seen up to 5×10^{10} p/cm^2. Degradation was uniform from this point forward, affecting all devices nearly equally. The devices show degradation in both the amount of I_C that can be delivered before shut off and in the increase in V_{CE}. At the mission required test fluence of 3×10^{11} p/cm^2, there is nearly an order of magnitude increase in V_{CE} for any given point where the pair is on. The device pairs also show what was effectively a failure for LED I_F = 1mA at 1×10^{12} p/cm^2 total fluence.

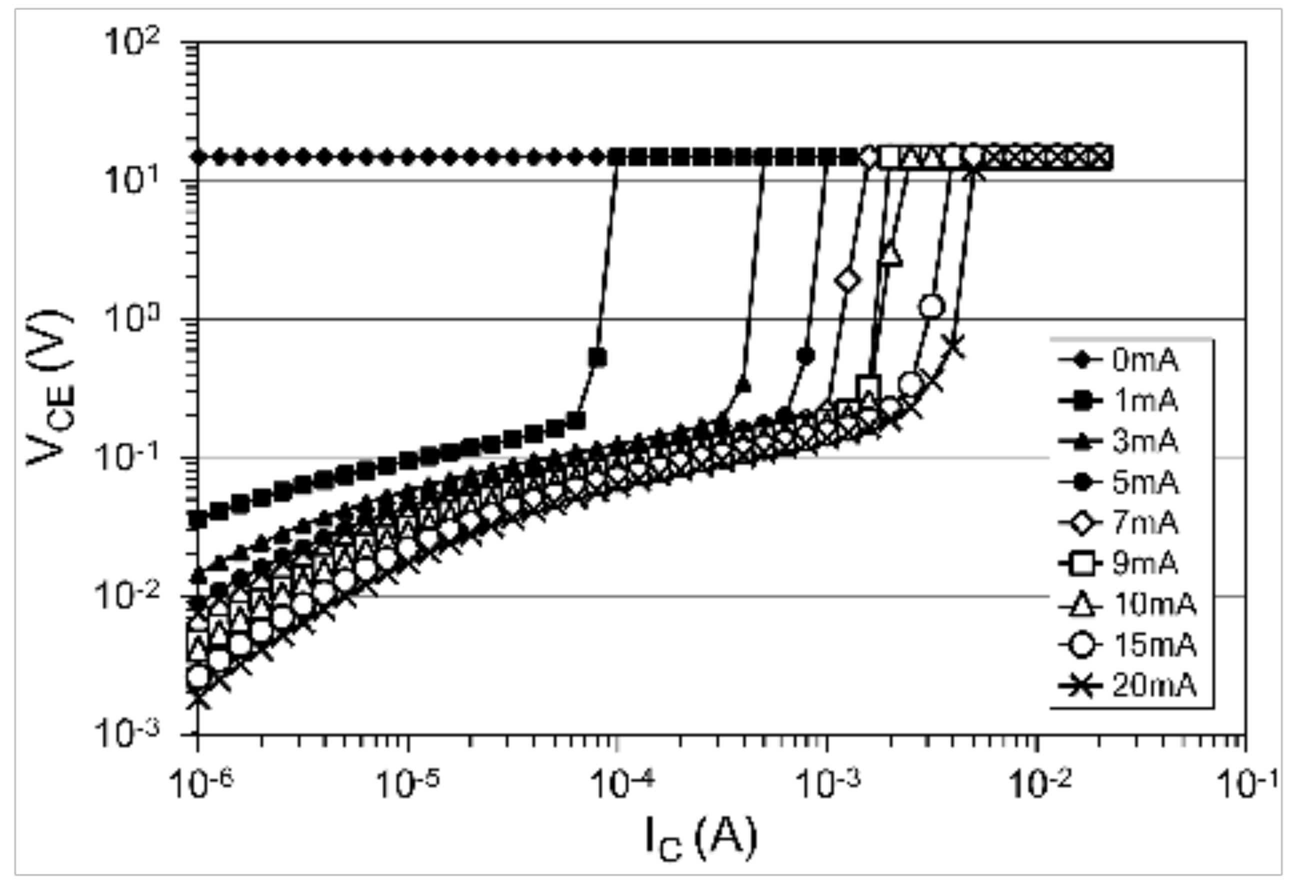

Fig. 4. Micropac custom encoder pair PT V_{CE} measurements as a function of PT I_C at various LED I_F (Pre-Irradiation).

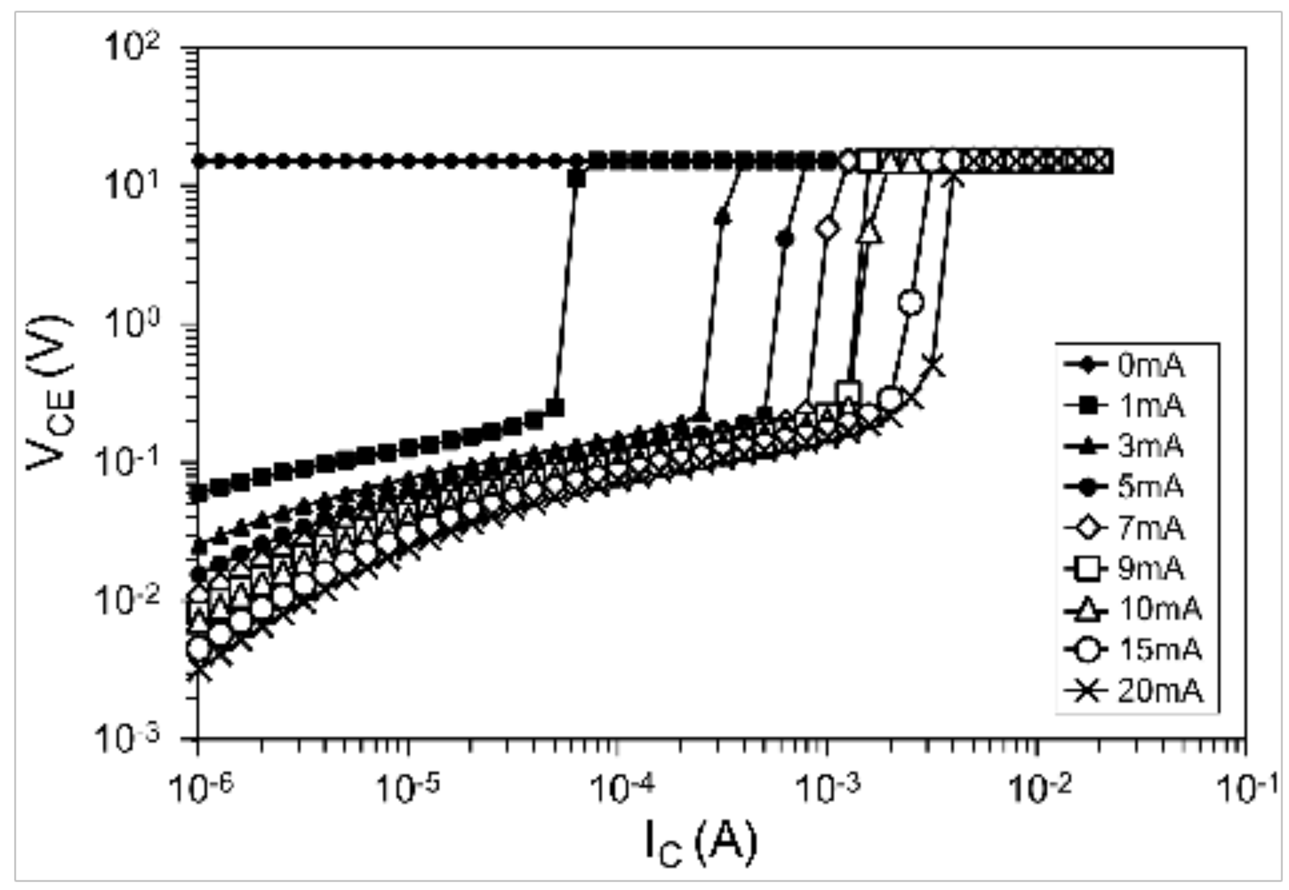

Fig. 5. Micropac custom encoder pair PT V_{CE} measurements as a function of PT I_C at various LED I_F (5×10^{10} p/cm^2).

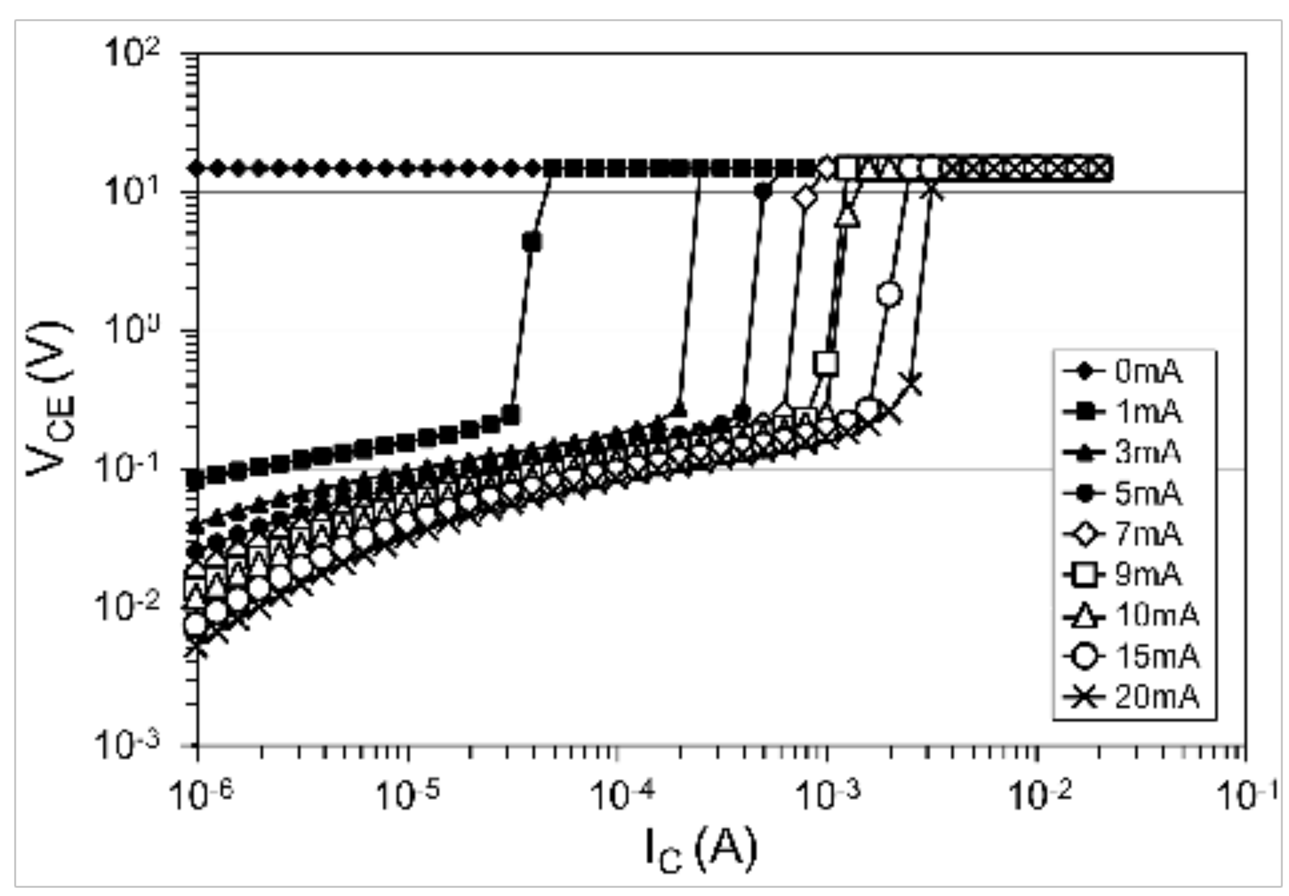

Fig. 6. Micropac custom encoder pair PT V_{CE} measurements as a function of PT I_C at various LED I_F (1×10^{11} p/cm^2).

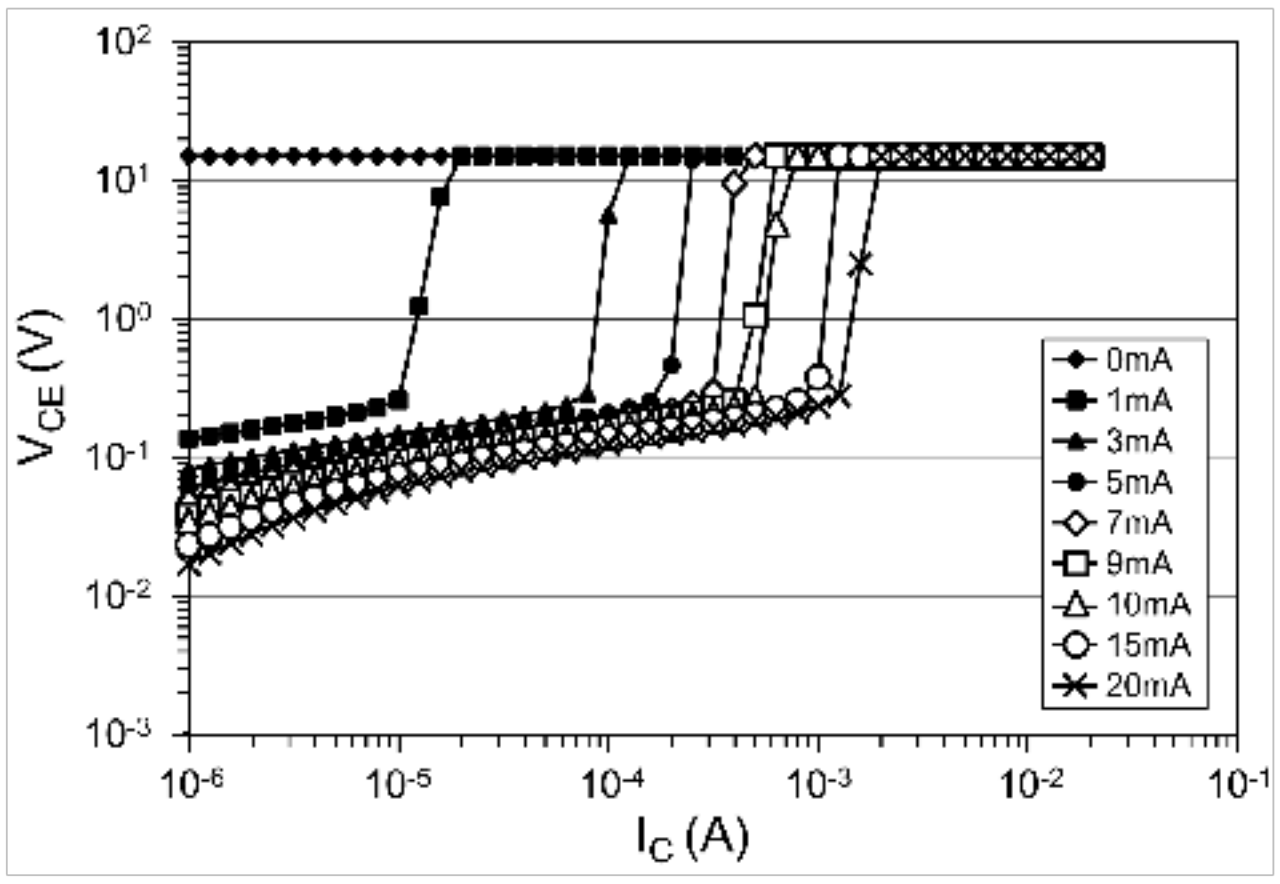

Fig. 7. Micropac custom encoder pair PT V_{CE} measurements as a function of PT I_C at various LED I_F ($3x10^{11}$ p/cm^2).

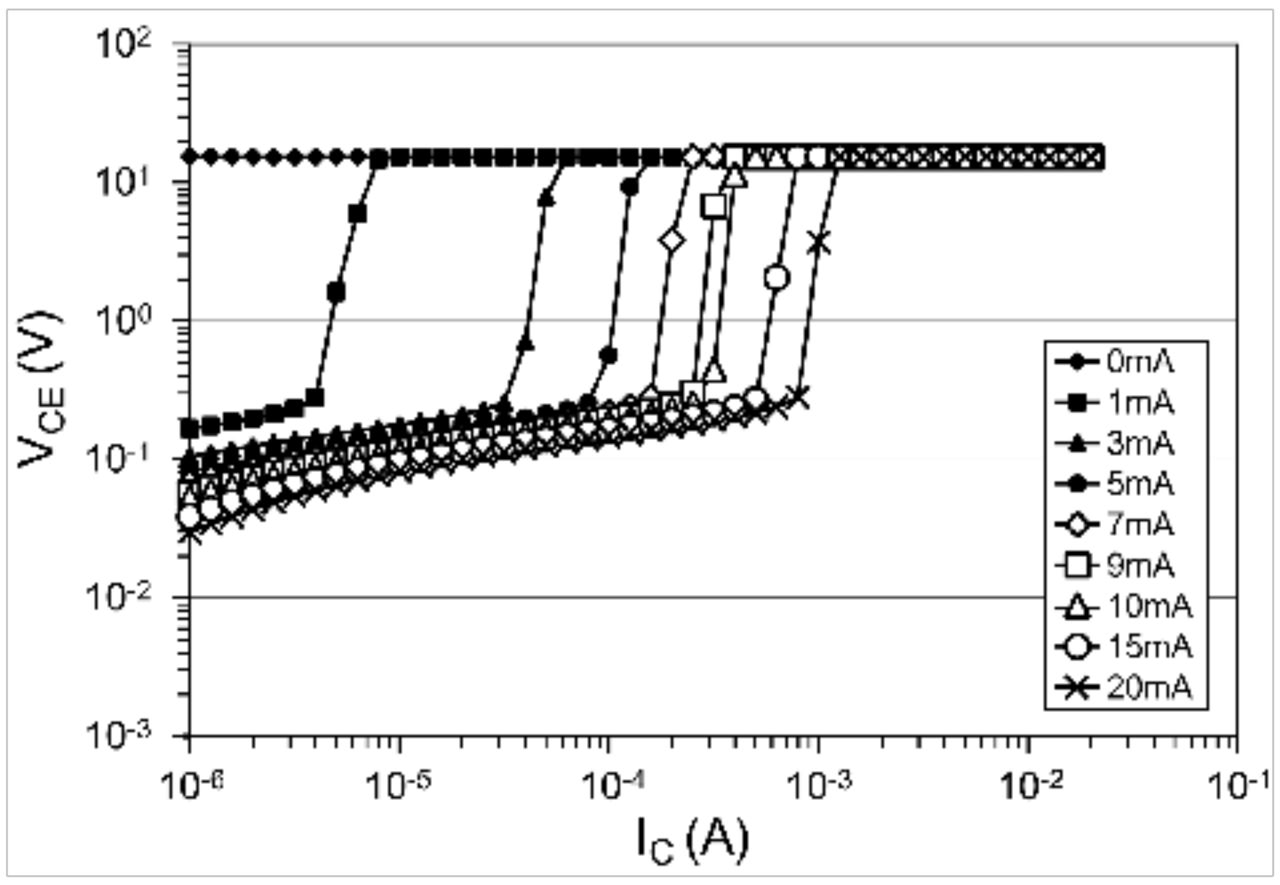

Fig. 8. Micropac custom encoder pair PT V_{CE} measurements as a function of PT I_C at various LED I_F ($5x10^{11}$ p/cm^2).

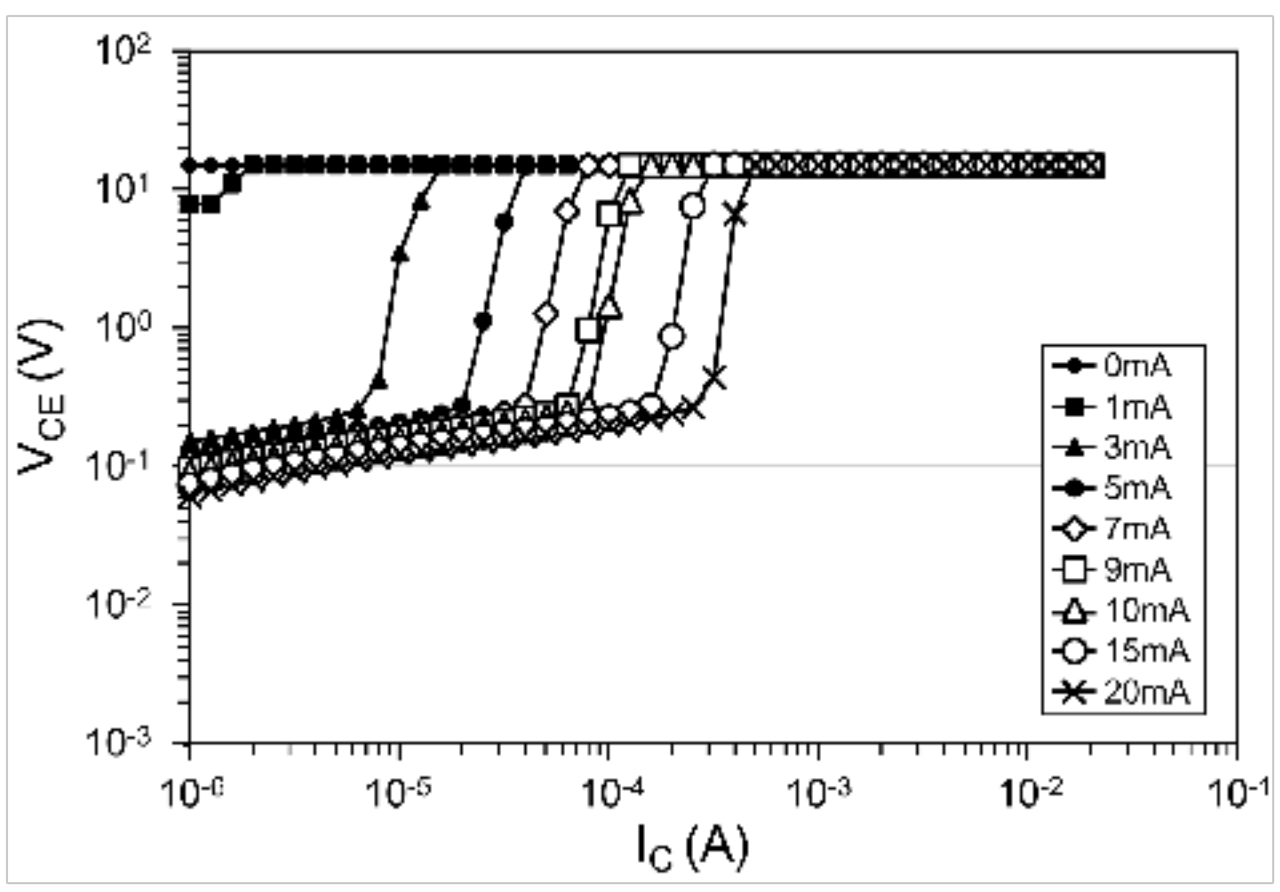

Fig. 9. Micropac custom encoder pair PT V_{CE} measurements as a function of PT I_C at various LED I_F ($1x10^{12}$ p/cm^2).

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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