Characterization of the Effects of 250 MeV Proton-Induced Total Ionizing Dose and Displacement Damage on the 66266 Optocoupler

Scott Messenger, Codie Mishler, James Hack and Paul Dudek

2022 IEEE Radiation Effects Data Workshop (REDW) (in conjunction with 2022 NSREC) | 978-1-6654-8856-3/22/$31.00 ©2022 IEEE | DOI: 10.1109/REDW56037.2022.9921540

***Abstract*— This paper explores the combined effects of total ionizing dose and displacement damage caused by 250 MeV protons on the Micropac 66266 optocoupler. Proton fluences up to 4x10^{12} were used for this radiation test.**

I. Introduction

THE scope of this paper includes total ionizing dose (TID) testing, as well as displacement damage (DD) testing of the Micropac 66266 optocoupler. Device single event effect response to heavy ion bombardment is outside of the scope of this paper.

Both TID and DD testing was performed concurrently using 250 MeV protons which have a range in silicon of >2 cm. NIEL and stopping power data were used to develop the test plan to achieve the desired levels of DD and TID, respectively.

II. Background

A. Device Overview

The datasheet for this device is given in [1]. The light emitting diode (LED) is made of AlGaAs and emits at a wavelength of 850 nm, the integrated circuit is Si, and the die coating is Dow Corning 3-6121, which is a high refractive index, translucent elastomer. Figs. 1 and 2 show the device schematic and pictures of the 6-pin gull wing (GW) package used in the 66266. Note that [2] gives some radiation results for 3 families of Micropac optocouplers. The three families with the TO-5 package are: 1) 66092 (880 nm LED & 40 mil silicon phototransistor), 2) 66168 (660 nm LED & 40 mil silicon phototransistor), and 3) 66227 (850 nm LED & 40 mil silicon phototransistor). The 66266 is in the same family as the 66227 but has the 6-pin GW package and a 25 mil silicon phototransistor.

B. Prior Radiation Testing

A few relevant prior radiation studies were found on the 66266 optocoupler. Northrop Grumman (NG) perfomed two prior testing campaigns using 200 [3] and 250 [4] MeV protons at the Loma Linda University Medical Center (LLUMC) facility. Devices from [1] were drawn from package date code 1119 of device number 66266-105. An

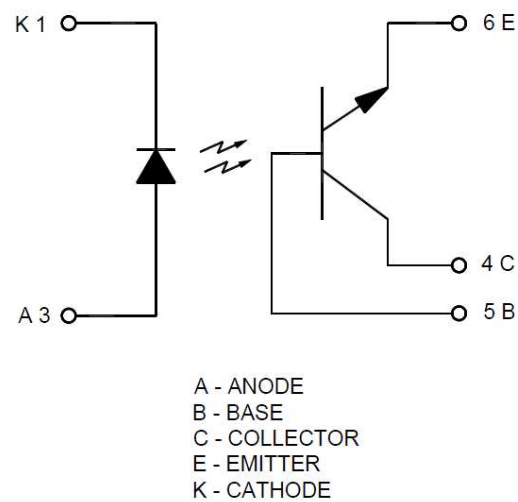

Fig. 1. 66266 schematic diagram.and pin assignments

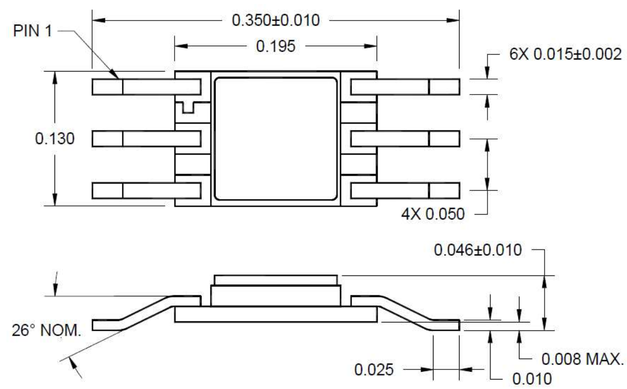

Fig. 2. 66266 package dimensions. (Units are in inches)

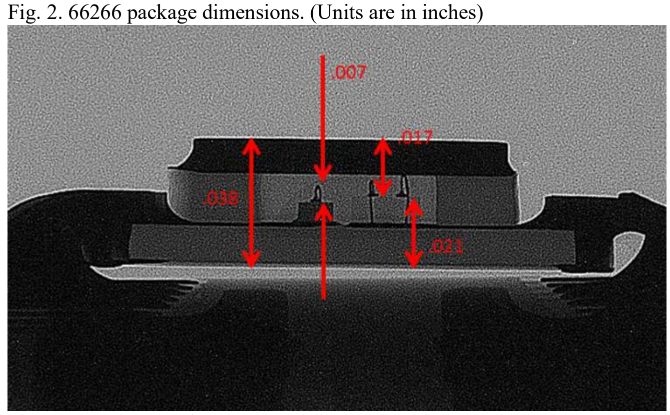

Fig. 3.X-ray image of 66266 device in cross section, overlaid with dimensions of interest (units in inches).

equivalent total ionizing dose (TID) of 20 krad(Si) was given to the devices and all parameters except for the charge transfer ratio (CTR, i.e. output current at collector of phototransistor divided by input current to the LED) were

Manuscript received 9 July 2022.

S. Messenger is with Northrop Grumman Corporation, Linthicum Heights, MD 21090 USA (410-993-3976, scott.messenger@ngc.com)

C. Mishler is with Northrop Grumman Corporation, Linthicum Heights, MD 21090 USA (410-993-3976, michael.mishler@ngc.com)

J. Hack is with Northrop Grumman Corporation, Linthicum Heights, MD 21090 USA (410-649-3009, james.hack@ngc.com)

P. Dudek is with Northrop Grumman Corporation, Linthicum Heights, MD 21090 USA (410-993-9621, james.hack@ngc.com)

within datasheet tolerances. The CTR at low currents was considerably degraded, but at an input current of 10 mA (V_{CE}=13.2V), the CTR was measured to be 2.65. The second round of NGMS testing [4] used parts drawn from package date code 1608 of part number 66266-303HSD. 250 MeV proton fluences of $4.6x10^{11}$ and $1.15x10^{12}$ p^+/cm^2 were used corresponding to ~23 and ~58 krad(Si) of ionizing dose deposition. V_{CE} values of 5, 13 and 33V were applied and CTR values were determined at 3, 8, 11 mA diode current values. A worse case degradation amount of CTR/CTR_o=0.35 was measured for the 3 mA input current. No bias dependence was noted on the results.

Costantino, et al., [5] irradiated 66266 parts with 30 and 60 MeV protons and showed results for the I_f=1 mA, V_{CE}=5V measurement condition. The normalized CTR degradation is shown to be 0.2 following a 3 MeV proton fluence of $2x10^{11}$ p^+/cm^2. No bias dependence was noted. One interesting additional experiment was performed in this work where, using delidded parts, they obtained results for the LED and phototransistor separately through preferential shielding of the proton beam. The overall device response was shown to be driven by damage to the phototransistor. The LED was much more radiation tolerant consistent with some of the work performed by Johnston, et al. [6].

Experimental Details

A. Devices Under Test

The 66266 optocouplers used had the manufacturer's part number as 66266-303HSD.

Sixteen (16) devices were obtained for radiation testing from package date code 1739. These devices were individually serialized by the manufacturer. The serial numbers were divided into two (2) bias groups for irradiation, as indicated in Table I.

The sixteen (16) parts used in this test were divided into three groups and renumbered for simplicity.

1. Two (2) were used as control samples which were unirradiated during all testing.
2. Seven (7) devices were irradiated under electrical bias during proton irradiation in accordance with Table I.
3. Seven (7) devices were irradiated unbiased during proton irradiation in accordance with Table I below.

TABLE I
DEVICE GROUP DEFINITIONS AND IRRADIATION BIAS CONDITIONS

	$V_{IN,diode}$	V_{CC}	Serial Numbers
Biased	9.35V (8 mA/part)	0.5, 1, 2.5, 5	1, 2, 3, 4, 5, 6, 7
Unbiased	N/A	0.5, 1, 2.5, 5	9, 10, 11, 12, 13, 14, 15
Control	N/A	0.5, 1, 2.5, 5	8,16

.

B. Irradiation Details

TID and DD irradiations of the 66266 optocouplers were performed using 250 MeV protons at LLUMC on December 2, 2017 to the fluence (dose) levels given in Table II below. The total 250 MeV proton beam fluences were chosen to be $1x10^{11}$, $2x10^{11}$ $4x10^{11}$, $7x10^{11}$ and $1x10^{12}$ p^+/cm^2 to blanket the TID requirements of 20 and 50 krad(Si). A subset of parts (#2,4,6 in Table I) were taken out to higher fluences of $2x10^{12}$ and $4x10^{12}$ p^+/cm^2 (unbiased). The proton flux was limited to $3.5x10^8$ $p^+/cm^2/s$ (17.7 rad(Si)/s). The TID data in Table II were determined from the stopping power value of 3.165 $MeVcm^2/g$ for 250 MeV protons in silicon as found on the PSTAR website [7]. The associated DD values were determined using the following NIEL values as obtained from the SR-NIEL website [8] for 1 MeV neutrons ($2.457x10^{-3}$ $MeVcm^2/g$) and 250 MeV protons ($1.79x10^{-3}$ $MeVcm^2/g$) in silicon. Irradiating to the TID values in this way results in a slight overirradiation (~17%) of the DD requirements ($2.5x10^{11}$ and $6.25x10^{11}$ n/cm^2).

TABLE II
TOTAL IONIZING DOSE AND DISPLACEMENT DAMAGE VALUES

250 MeV Proton Fluence ($\#/cm^2$)	Equivalent Total Ionizing Dose krad(Si)	1-MeV Equivalent Neutron Fluence ($\#/cm^2$)
$1x10^{11}$	5.07	$7.29x10^{10}$
$2x10^{11}$	10.14	$1.46x10^{11}$
$4x10^{11}$	20.28	$2.92x10^{11}$
$7x10^{11}$	35.5	$5.10x10^{11}$
$1x10^{12}$	50.7	$7.29x10^{11}$
$2x10^{12}$	101.4	$1.46x10^{12}$
$4x10^{12}$	202.8	$2.92x10^{12}$

C. Test Equipment & Measurement Details

The circuit diagram for the biased case (V_{in}) is given in Fig. 4 and a picture of the test board is shown in Figure 5. Device characterization was performed with a National Instruments PXIe 1082 chassis with two PXI-4132 Source Measure Units (SMU) and a PXIe-2524 Switch Matrix. The two SMU's were configured into a two channel Parametric Analyzer using LabVIEW.

The 66266 devices were individually soldered to Capital Advanced Technologies surfboard (part # 9163) and inserted into the 10 channel modified transistor bias/test. The surfboard design allowed for easy changes between measurements and biases by simply moving one pin.

Characterization was performed by applying stepped steady state voltages on the phototransistor (V_{CC}) and sweeping the voltage on the LED through the manufacturers operation region from off to on (7nA-20mA) [1], recording the output currents at the collector of the phototransistor. Four values of V_{CC} were used (0.5, 1, 2.5 and 5V) for analysis and the phototransistor output currents were measured out to 20 mA. This PXIe system with the switching matrix allows for 10 devices to be measured seemlessly on one test board thereby greatly automating the measurements between irradiations. Figures 6 and 7 show some measurement results of the CTR for the biased and unbiased cases, respectively, for V_{CC}=5V where the pre-irradiation data are given along with 99/90 statistics (average, 99/90+ (upper dashed line) and 99/90- (lower dashed line)).

The large variation in the CTR at the peak values are consistent with the results shown in [2] for that family of parts. Figure 8 shows pre-irradiation results for the unbiased case comparing the different V_{CC} values. Note that device #7 was shorted throughout the experiments. Therefore 6 devices were biased and 7 were unbiased during these radiation experiments. The irradiation test was executed with the following sequence of events (location)

1. Baseline measurements (NGC and LLUMC)
2. Irradiation Step 1 (LLUMC)
3. Post-irradiation measurements 1 (LLUMC
4. Repeat 2 and 3 until proposed irradiations complete
5. Unbiased anneal (~l0 weeks at T_{room}) (LLUMC)
6. Post-irradiation measurements (NGC)
7. Biased anneal (1 week @ 100C) (NGC)
8. Post-anneal measurements (NGC)

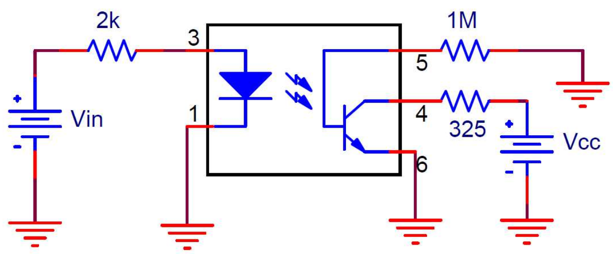

Fig. 4. Schematic diagram of bias circuit. For the unbiased case all pins were grounded.

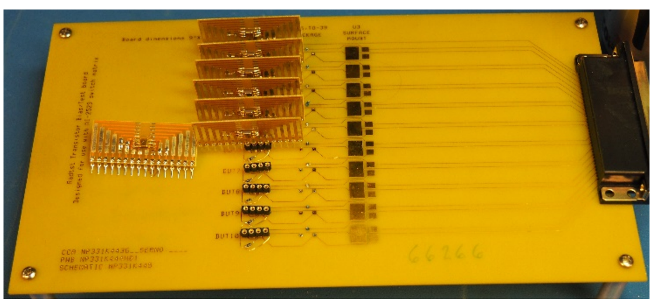

Fig. 5. Image of test board. The surfboards fit into sockets and the board can be manipulated for either measurement or bias conditions.

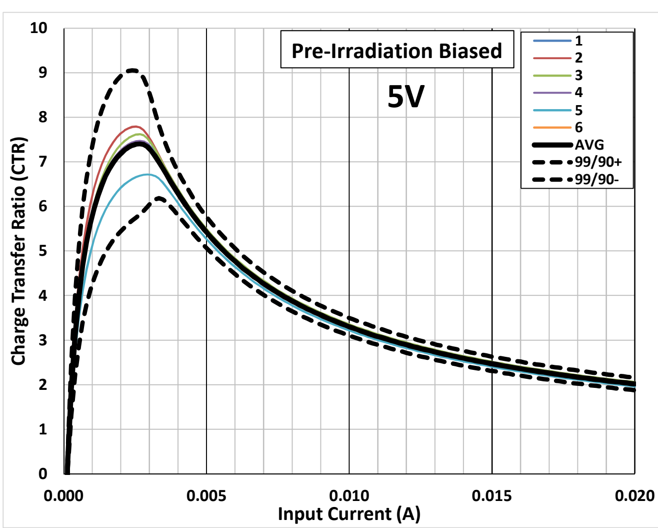

Fig. 6. Pre-irradiation results for biased 66266 devices (V_{CC}=5V).

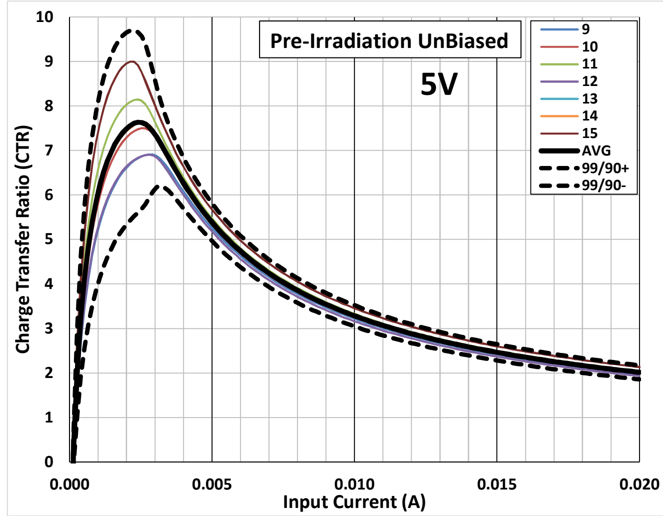

Fig. 7. Pre-irradiation results for unbiased 66266 devices (V_{CC}=5V).

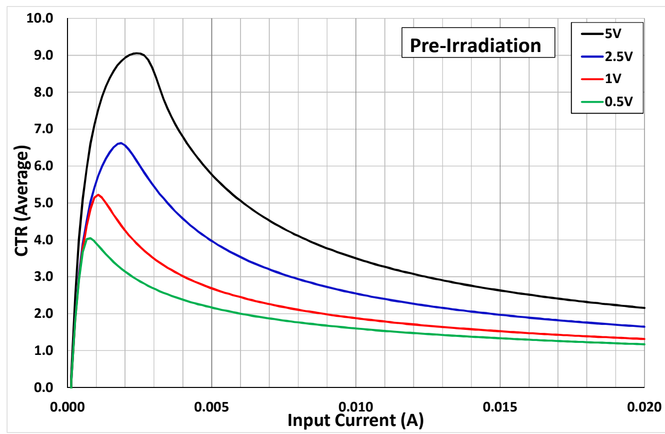

Fig.8. Pre-irradiation results for unbiased 66266 devices as function of V_{CC}.

III. Test Results and Analysis

A. Charge Transfer Ratio (CTR)

Results will be given in detail for the one case of V_{CC}=5V, of which the parts were biased during irradiation with the remainder of the results being shown in the Appendices. The CTR values as a function of input current to the LED (V_{CC}=5V case, biased during irradiation) following 250 MeV proton fluences of $1x10^{11}$, $2x10^{11}$ $4x10^{11}$, $7x10^{11}$ and $1x10^{12}$ p^+/cm^2 are given in Figs. 9a, 9b, 9c, 9d, and 9e, respectively, along with the 99/90 statistics as in Figs. 6 and 7. Figures 10a, 10b, and 10c show these data as a function of fluence for the average, 99/90+ and 99/90- statistics, respectively. The pre-anneal and post-anneal (100^{o}C, 1 week) are also shown in Figs. 10a, 10b and 10c. The remainder of the CTR data determined in this study: V_{CC}=5V (unbiased), V_{CC}=2.5V (unbiased and biased), V_{CC}=1V (unbiased and biased), V_{CC}=0.5V (unbiased and biased) are given in Appendix A. Note that the biased cases show data covering 250 MeV proton fluences accumulated to a total fluence of $1x10^{12}$ p^+/cm^2 while the unbiased cases show further irradiation data to a total of $4x10^{12}$ p^+/cm^2. To present these data in a more convenient form, the ratios of the CTR values relative to the unirradiated cases, i.e. CTR/CTR_0 have also been determined for a few input current values (1 mA, 2 mA, 3 mA, 4 mA, 5 mA, and 10 mA). The results for the V_{CC}=5V case (biased during irradiation) is shown in Figs. 11a and 11b for the average and 99/90- statistics, respectively.

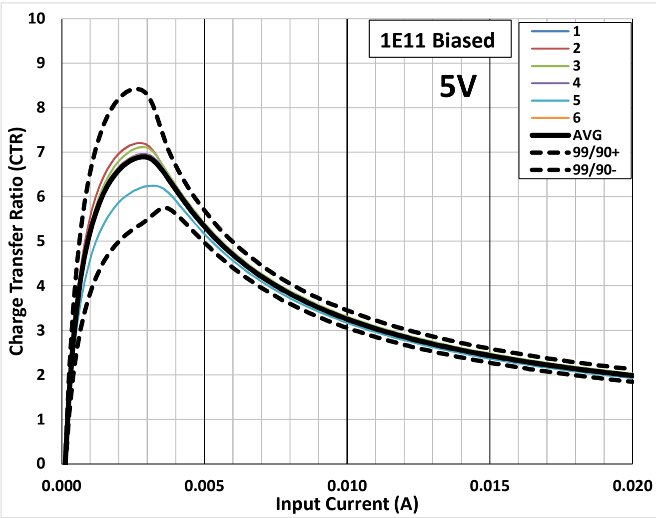

Fig.9a. Radiation results for biased 66266 (V_{CC}=5V) following a 250 MeV proton fluence of $1x10^{11}$ p^{+}/cm^{2}.

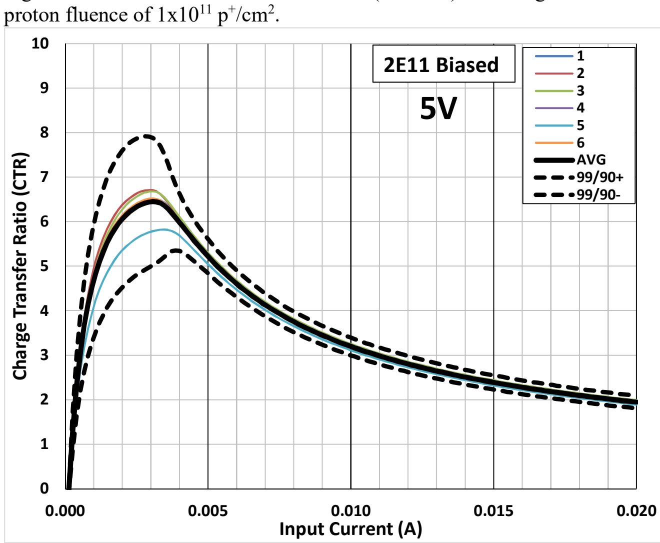

Fig.9b. Radiation results for biased 66266 (V_{CC}=5V) following a 250 MeV proton fluence of $2x10^{11}$ p^{+}/cm^{2}.

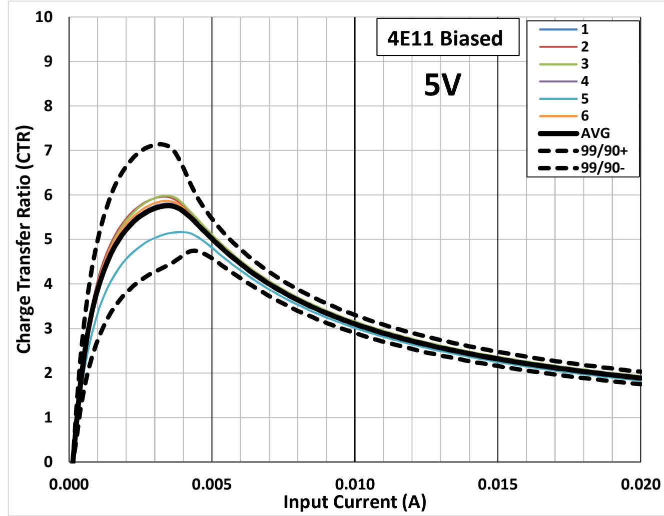

Fig.9c. Radiation results for biased 66266 (V_{CC}=5V) following a 250 MeV proton fluence of $4x10^{11}$ p^{+}/cm^{2}.

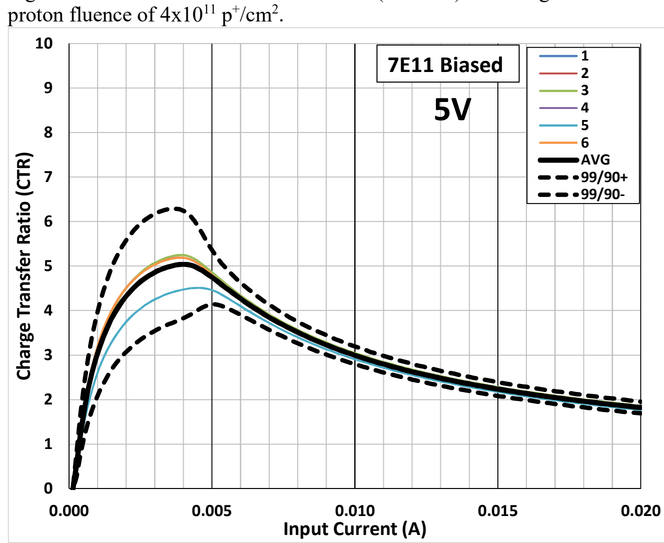

Fig.9d. Radiation results for biased 66266 (V_{CC}=5V) following a 250 MeV proton fluence of $7x10^{11}$ p^{+}/cm^{2}.

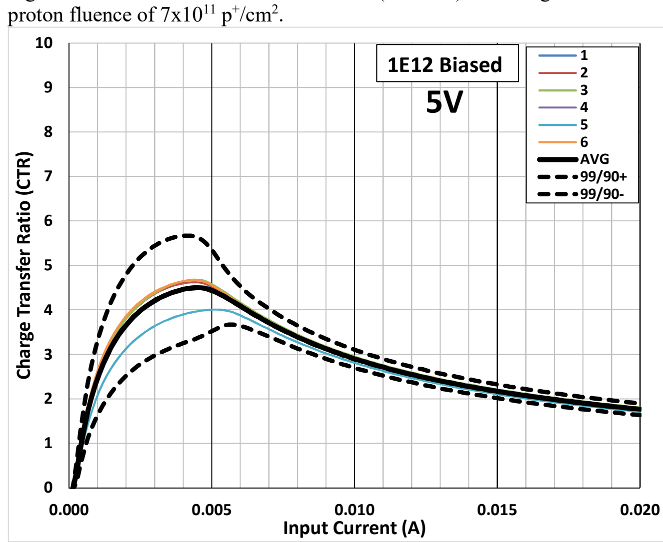

Fig.9e. Radiation results for biased 66266 (V_{CC}=5V) following a 250 MeV proton fluence of $1x10^{21}$ p^{+}/cm^{2}.

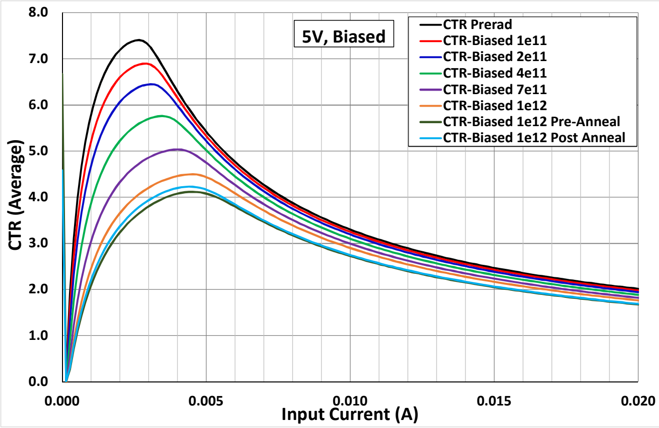

Fig.10a. Radiation results for biased 66266 (V_{CC}=5V) showing the average statistical results for all fluences up to $1\text{x}10^{12}$ p^+/cm^2 and including pre-and post-anneal (100ºC, 1week) conditions.

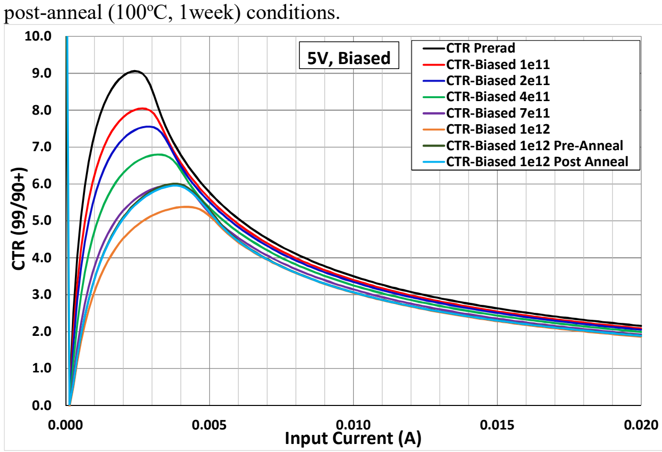

Fig.10b. Radiation results for biased 66266 (V_{CC}=5V) showing the 99/90+ statistical results for all fluences up to $1\text{x}10^{12}$ p^+/cm^2 and including pre-and post-anneal (100ºC, 1week) conditions.

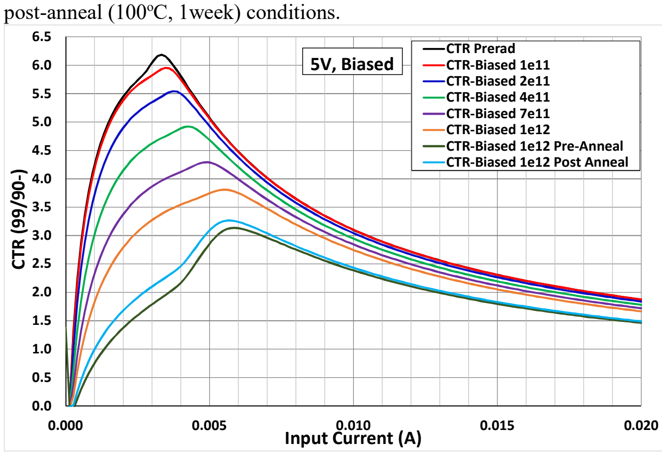

Fig.10c. Radiation results for biased 66266 (V_{CC}=5V) showing the 99/90- statistical results for all fluences up to $1\text{x}10^{12}$ p^+/cm^2 and including pre-and post-anneal (100ºC, 1week) conditions.

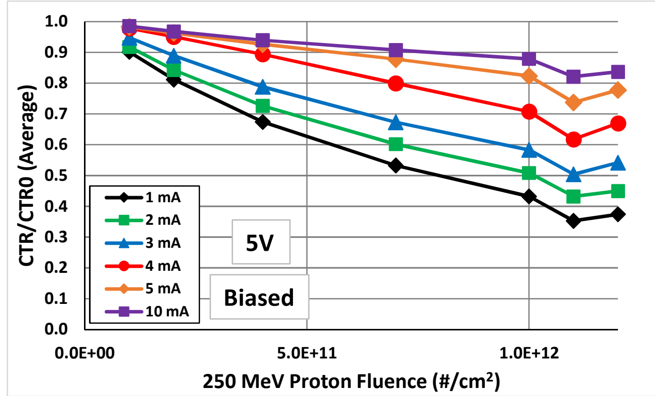

Fig.11a. Radiation results for biased 66266 (V_{CC}=5V) showing the average statistical results for all fluences up to $1\text{x}10^{12}$ p^+/cm^2 and including pre-and post-anneal (100ºC, 1week) conditions. Data for several input currents (1 mA, 2 mA,3 mA, 4 mA, 5 mA and 10 mA) are given.

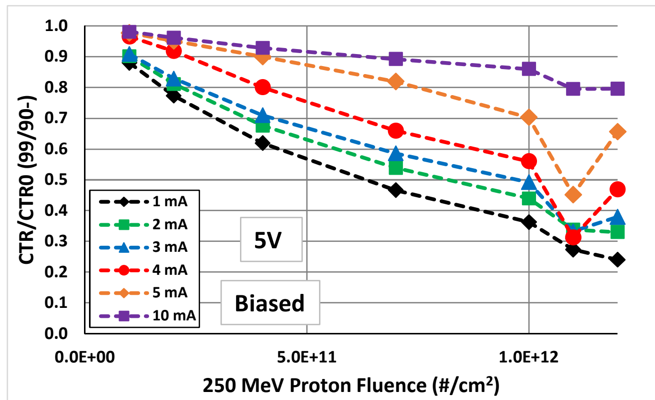

Fig.11b. Radiation results for biased 66266 (V_{CC}=5V) showing the 99/90- statistical results for all fluences up to $1\text{x}10^{12}$ p^+/cm^2 and including pre-and post-anneal (100ºC, 1week) conditions. Data for several input currents (1 mA, 2 mA,3 mA, 4 mA, 5 mA and 10 mA) are given.

The results show measurable degradation at all proton fluences but meet the requirements at the 50 krad(Si) equivalent TID level (250 MeV proton fluence ~10^{12} p^+/cm^2). The worst-case 99/90- CTR values (@ 2 mA input current following anneal) at 50 krad(Si) for V_{CC} values of 5V, 2.5V, 1V, and 0.5V are 3.7, 3.4, 3.0 and 2.1, respectively, representing degradation ratios from pre-irradiation conditions of 0.33, 0.36, 0.55 and 0.58, respectively. There was no effect of bias during the irradiations on these devices. Thermal annealing (100ºC, 1 week) was largely inconsequential in device performance.

IV. Conclusion

Radiation testing of both displacement damage and high dose rate total ionizing dose from 250 MeV protons has shown the 66266 optocoupler to be tolerant to a fluence of 10^{12} p^+/cm^2 corresponding to equivalent TID and DD values of 50.7 krad(Si) and $7.3\text{x}10^{11}$ 1-MeV equivalent neutrons, respectively. No effects of bias during irradiations were found.

V. References

[1] "66266, 6 pin gull wing proton radiation tolerant optocoupler with 850 nm LED," Micropac Industries, Inc. Optoelectronic Products Division, 3/31/16, datasheet.

[2] "Dose Rate Sensitivity & Displacement Damage on Optocoupler TO-5 Package based on Types 66092, 66168 and 66227," Micropac Industries, Inc. Optoelectronic Products Division, September 2012.

[3] J. Horner, "HCPL-625k and 66266 Optocoupler Radiation Test Report," unpublished.

[4] J. Hack and P. Dudek, "Characterization of the Effects of Proton Induced Total Ionizing Dose and Displacement Damage on the Micropac 66266 Optocoupler," unpublished

[5] A. Costantino, S. Hernandez, V. Ferlet-Cavrois, M. Muschutiello, L. Marchand, and A. Mohammadzadeh, "Compendium of Recent Protno and Co60 Radiation Test Data in Radiation-Tolerant Optocouplers and COTS," Proceedings RADEC 2012.

[6] A.H. Johnston, B.G. Rax, L.E. Selva, and C.E. Barnes, "Proton Degradation of Light Emitting Diodes," IEEE Trans. Nucl. Sci. 46, 1781 (1999).

[7] PSTAR - https://physics.nist.gov/PhysRefData/Star/Text/PSTAR.html

[8] SR-NIEL - http://www.sr-niel.org/

VI. Appendix A – Additional Data

A. V_{CC}=5V, Unbiased

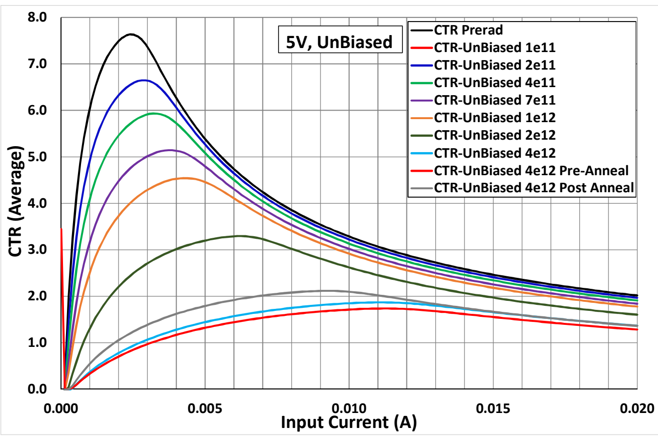

Fig. A1a. Radiation results for unbiased 66266 (V_{CC}=5V) showing the average statistical results for all fluences up to $4x10^{12}$ p^{+}/cm^{2} and including pre-and post-anneal (100ºC, 1week) conditions.

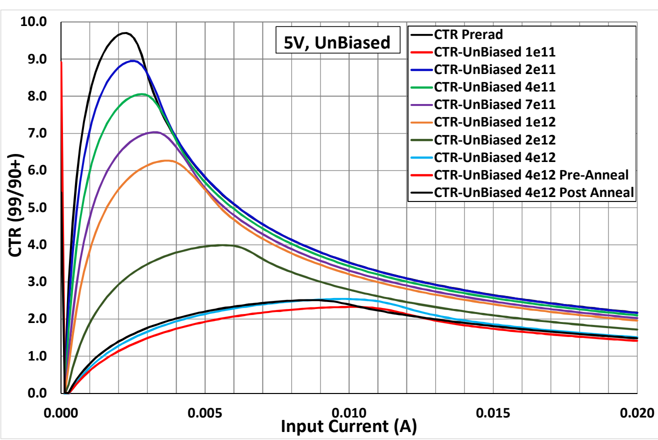

Fig. A1b. Radiation results for unbiased 66266 (V_{CC}=5V) showing the 99/90+ statistical results for all fluences up to $4x10^{12}$ p^{+}/cm^{2} and including pre-and post-anneal (100ºC, 1week) conditions.

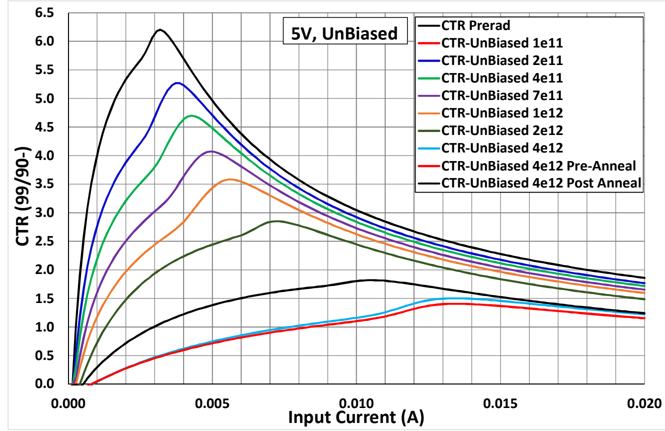

Fig. A1c. Radiation results for unbiased 66266 (V_{CC}=5V) showing the 99/90- statistical results for all fluences up to $4x10^{12}$ p^{+}/cm^{2} and including pre-and post-anneal (100ºC, 1week) conditions.

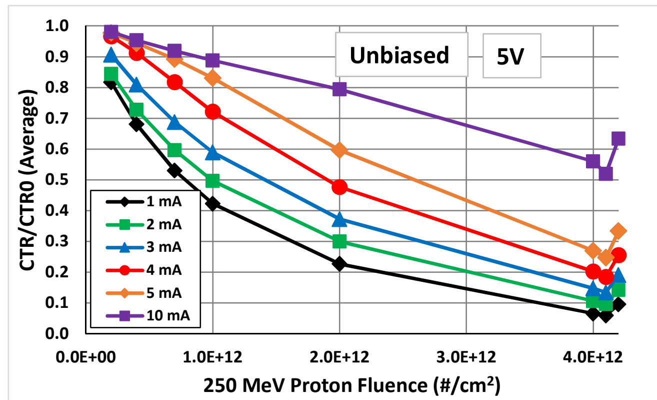

Fig. A1d. Radiation results for unbiased 66266 (V_{CC}=5V) showing the average statistical results for all fluences up to $4x10^{12}$ p^{+}/cm^{2} and including pre-and post-anneal (100ºC, 1week) conditions. Data for several input currents (1 mA, 2 mA,3 mA, 4 mA, 5 mA and 10 mA) are given.

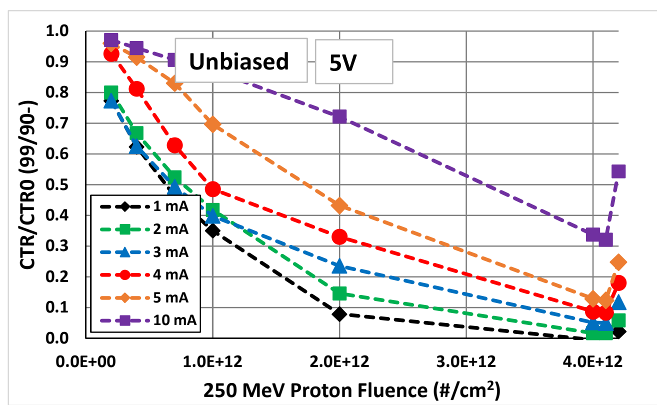

Fig. A1e. Radiation results for unbiased 66266 (V_{CC}=5V) showing the 99/90- statistical results for all fluences up to $4x10^{12}$ p^{+}/cm^{2} and including pre-and post-anneal (100ºC, 1week) conditions. Data for several input currents (1 mA, 2 mA,3 mA, 4 mA, 5 mA and 10 mA) are given.

B. V_{CC}=2.5V, Biased

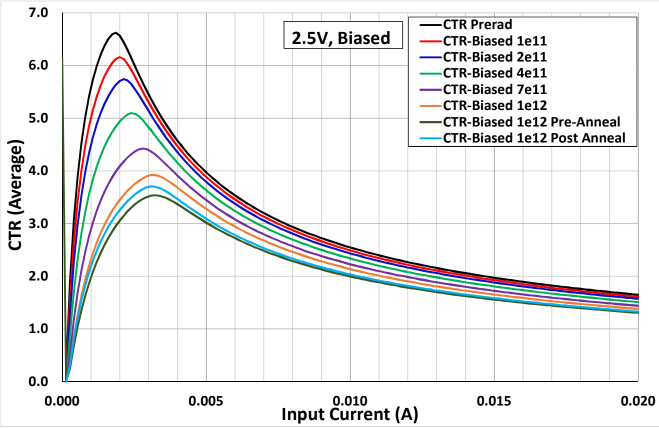

Fig.B1a. Radiation results for biased 66266 (V_{CC}=2.5V) showing the average statistical results for all fluences up to $1\text{x}10^{12}$ p^+/cm^2 and including pre-and post-anneal (100ºC, 1week) conditions.

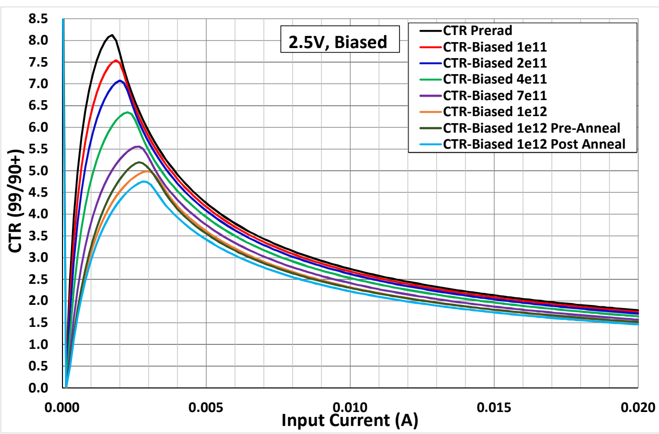

Fig. B1b. Radiation results for biased 66266 (V_{CC}=2.5V) showing the 99/90+ statistical results for all fluences up to $1\text{x}10^{12}$ p^+/cm^2 and including pre-and post-anneal (100ºC, 1week) conditions.

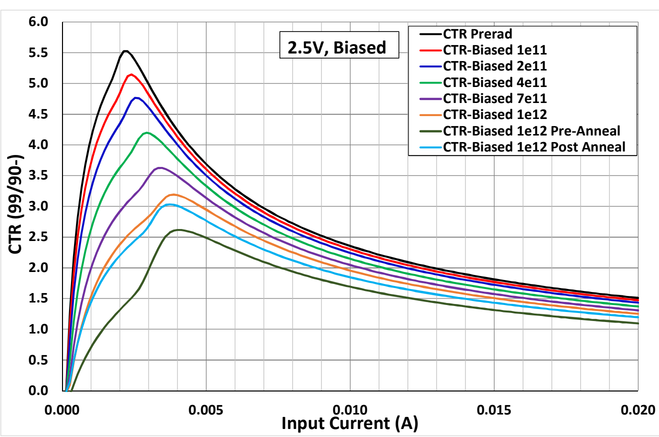

Fig. B1c. Radiation results for biased 66266 (V_{CC}=2.5V) showing the 99/90- statistical results for all fluences up to $1\text{x}10^{12}$ p^+/cm^2 and including pre-and post-anneal (100ºC, 1week) conditions.

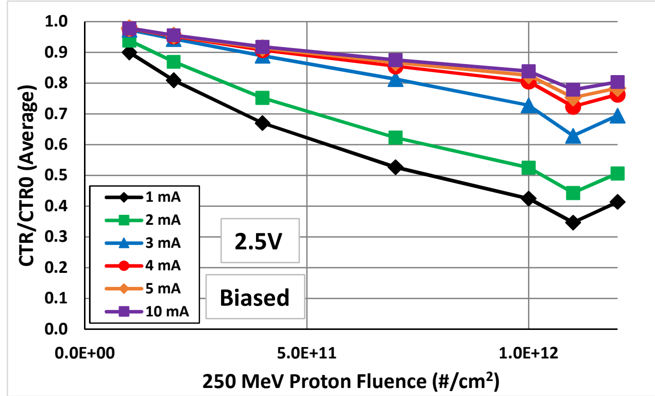

Fig. B1d. Radiation results for biased 66266 (V_{CC}=2.5V) showing the average statistical results for all fluences up to $1\text{x}10^{12}$ p^+/cm^2 and including pre-and post-anneal (100ºC, 1week) conditions. Data for several input currents (1 mA, 2 mA,3 mA, 4 mA, 5 mA and 10 mA) are given.

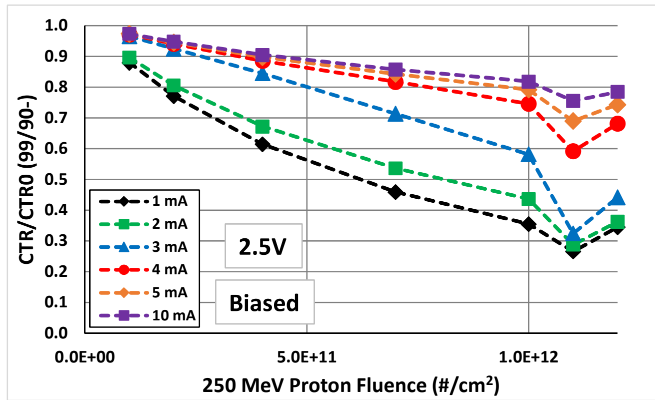

Fig. B1e. Radiation results for biased 66266 (V_{CC}=2.5V) showing the 99/90- statistical results for all fluences up to $1\text{x}10^{12}$ p^+/cm^2 and including pre-and post-anneal (100ºC, 1week) conditions. Data for several input currents (1 mA, 2 mA,3 mA, 4 mA, 5 mA and 10 mA) are given.

C. V_{CC}=2.5V, UnBiased

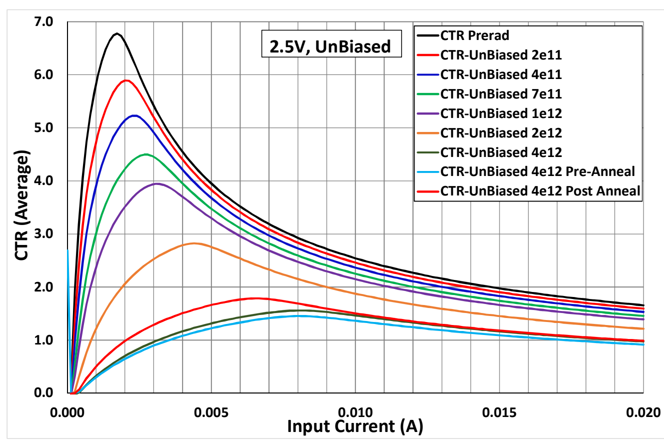

Fig. C1a. Radiation results for unbiased 66266 (V_{CC}=2.5V) showing the average statistical results for all fluences up to $4\text{x}10^{12}$ p^+/cm^2 and including pre-and post-anneal (100ºC, 1week) conditions.

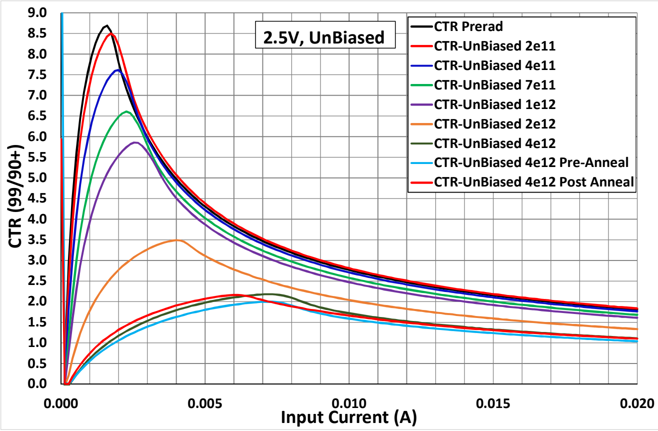

Fig. C1b. Radiation results for unbiased 66266 (V_{CC}=2.5V) showing the 99/90+ statistical results for all fluences up to 4x10^{12} p^{+}/cm^2 and including pre-and post-anneal (100ºC, 1week) conditions.

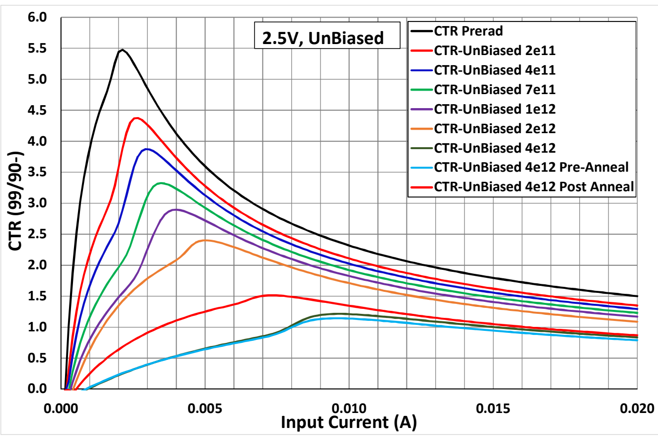

Fig. C1c. Radiation results for unbiased 66266 (V_{CC}=2.5V) showing the 99/90- statistical results for all fluences up to 4x10^{12} p^{+}/cm^2 and including pre-and post-anneal (100ºC, 1week) conditions.

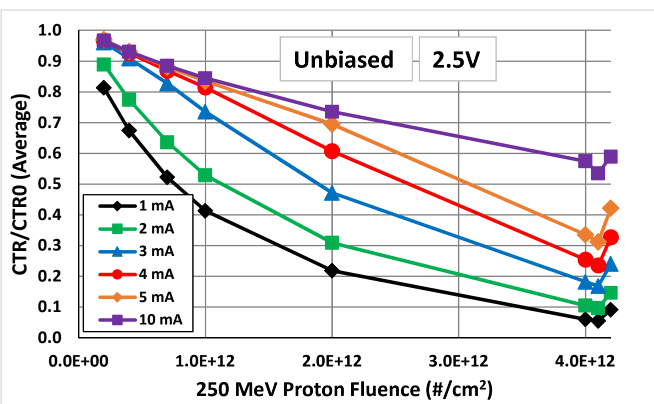

Fig. C1d. Radiation results for unbiased 66266 (V_{CC}=2.5V) showing the average statistical results for all fluences up to 4x10^{12} p^{+}/cm^2 and including pre-and post-anneal (100ºC, 1week) conditions. Data for several input currents (1 mA, 2 mA,3 mA, 4 mA, 5 mA and 10 mA) are given.

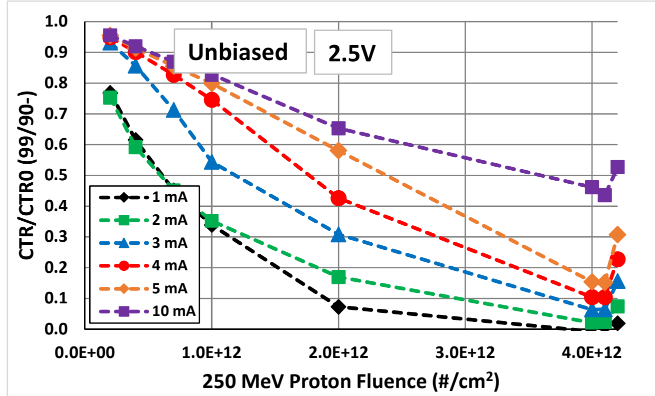

Fig. C1e. Radiation results for unbiased 66266 (V_{CC}=2.5V) showing the 99/90- statistical results for all fluences up to 4x10^{12} p^{+}/cm^2 and including pre-and post-anneal (100ºC, 1week) conditions. Data for several input currents (1 mA, 2 mA,3 mA, 4 mA, 5 mA and 10 mA) are given.

D. V_{CC}=1V, Biased

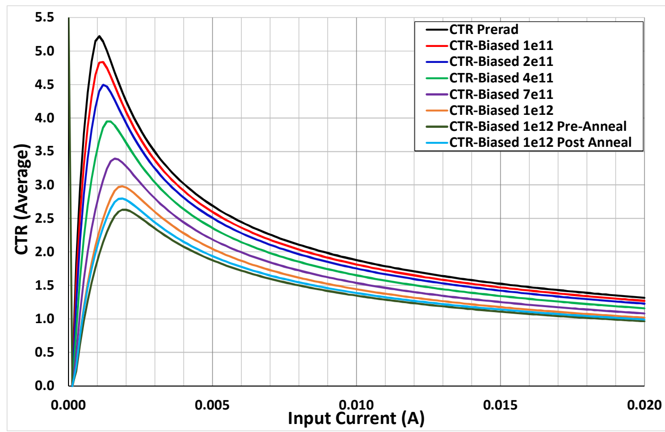

Fig. D1a. Radiation results for biased 66266 (V_{CC}=1V) showing the average statistical results for all fluences up to 1x10^{12} p^{+}/cm^2 and including pre-and post-anneal (100ºC, 1week) conditions.

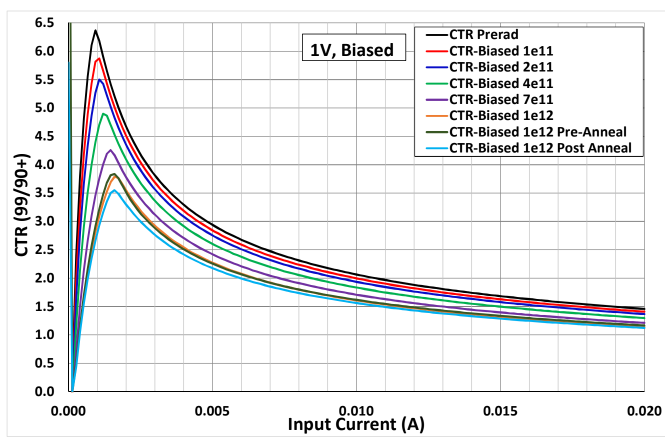

Fig. D1b. Radiation results for biased 66266 (V_{CC}=1V) showing the 99/90+ results for all fluences up to 1x10^{12} p^{+}/cm^2 and including pre-and post-anneal (100ºC, 1week) conditions.

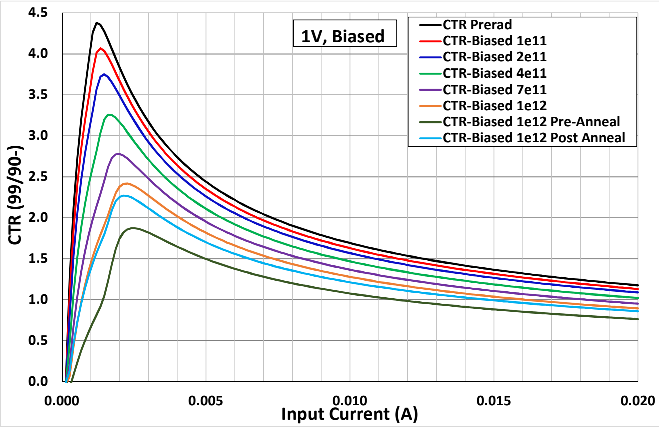

Fig. D1c. Radiation results for biased 66266 (V_{CC}=1V) showing the 99/90- results for all fluences up to $1x10^{12}$ p^{+}/cm^{2} and including pre-and post-anneal (100ºC, 1week) conditions.

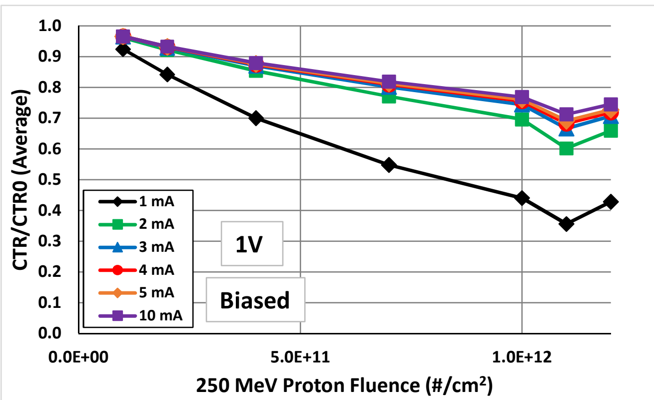

Fig. D1d. Radiation results for biased 66266 (V_{CC}=1V) showing the average statistical results for all fluences up to $1x10^{12}$ p^{+}/cm^{2} and including pre-and post-anneal (100ºC, 1week) conditions. Data for several input currents (1 mA, 2 mA,3 mA, 4 mA, 5 mA and 10 mA) are given.

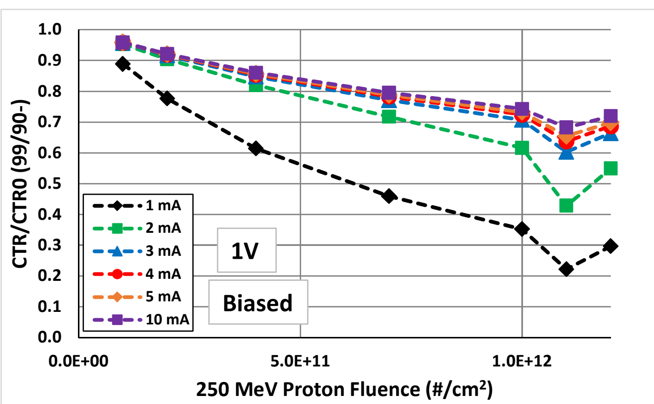

Fig. D1e. Radiation results for biased 66266 (V_{CC}=1V) showing the 99/90- statistical results for all fluences up to $1x10^{12}$ p^{+}/cm^{2} and including pre-and post-anneal (100ºC, 1week) conditions. Data for several input currents (1 mA, 2 mA,3 mA, 4 mA, 5 mA and 10 mA) are given.

E. V_{CC}=1V, UnBiased

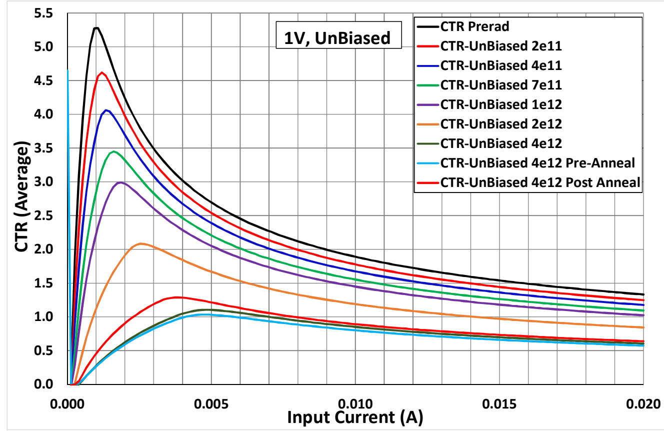

Fig. E1a. Radiation results for unbiased 66266 (V_{CCX}=1V) showing the average statistical results for all fluences up to $4x10^{12}$ p^{+}/cm^{2} and including pre-and post-anneal (100ºC, 1week) conditions.

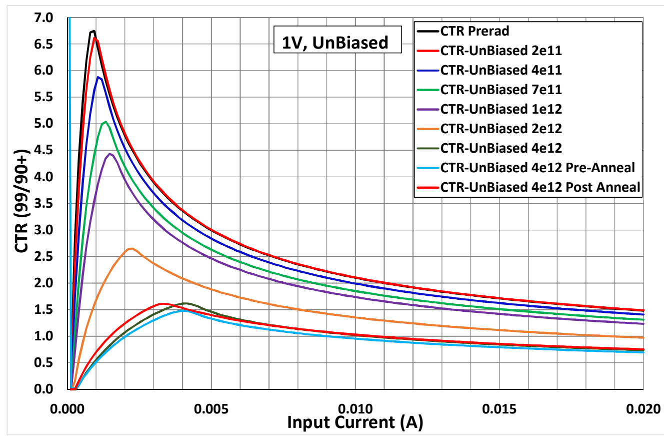

Fig. E1b. Radiation results for unbiased 66266 (V_{CC}=1V) showing the 99/90+ statistical results for all fluences up to $4x10^{12}$ p^{+}/cm^{2} and including pre-and post-anneal (100ºC, 1week) conditions.

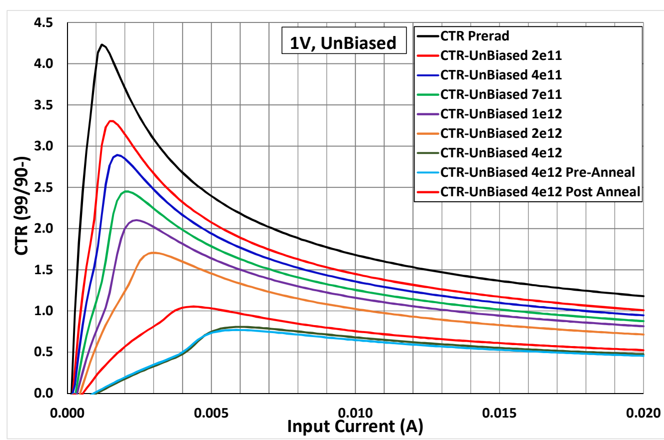

Fig. E1c. Radiation results for unbiased 66266 (V_{CC}=1V) showing the 99/90- statistical results for all fluences up to $4x10^{12}$ p^{+}/cm^{2} and including pre-and post-anneal (100ºC, 1week) conditions.

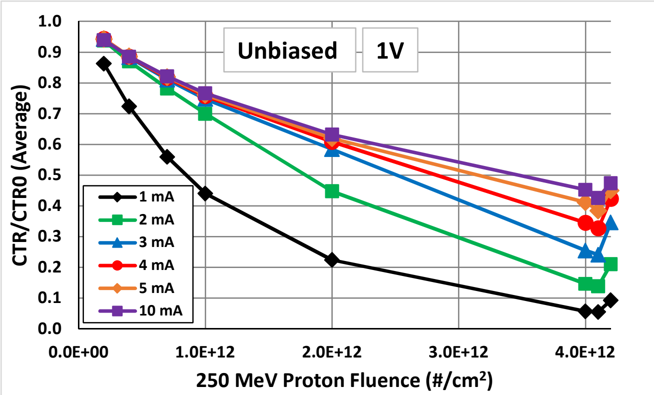

Fig. E1d. Radiation results for unbiased 66266 (V_{CC}=1V) showing the average statistical results for all fluences up to $4x10^{12}$ p^+/cm^2 and including pre-and post-anneal (100ºC, 1week) conditions. Data for several input currents (1 mA, 2 mA,3 mA, 4 mA, 5 mA and 10 mA) are given.

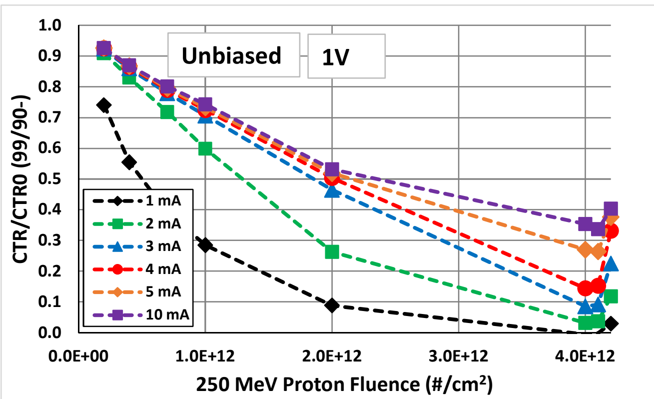

Fig. E1e. Radiation results for unbiased 66266 (V_{CC}=1V) showing the 99/90- statistical results for all fluences up to $4x10^{12}$ p^+/cm^2 and including pre-and post-anneal (100ºC, 1week) conditions. Data for several input currents (1 mA, 2 mA,3 mA, 4 mA, 5 mA and 10 mA) are given.

F. V_{CC}=0.5V, Biased

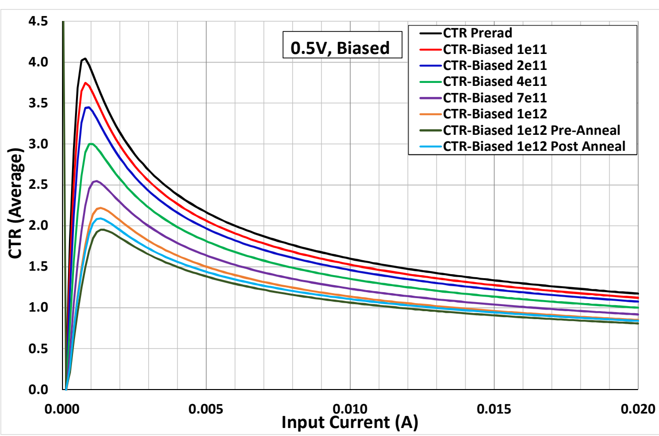

Fig. F1a. Radiation results for biased 66266 (V_{CC}=0.5V) showing the average statistical results for all fluences up to $1x10^{12}$ p^+/cm^2 and including pre-and post-anneal (100ºC, 1week) conditions.

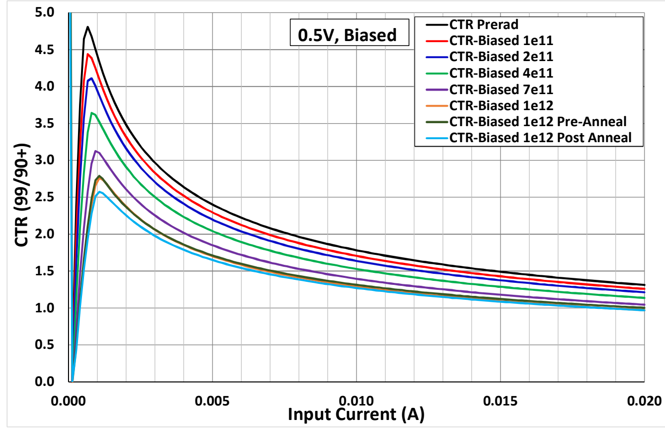

Fig. F1b. Radiation results for biased 66266 (V_{CC}=0.5V) showing the 99/90+ statistical results for all fluences up to $1x10^{12}$ p^+/cm^2 and including pre-and post-anneal (100ºC, 1week) conditions.

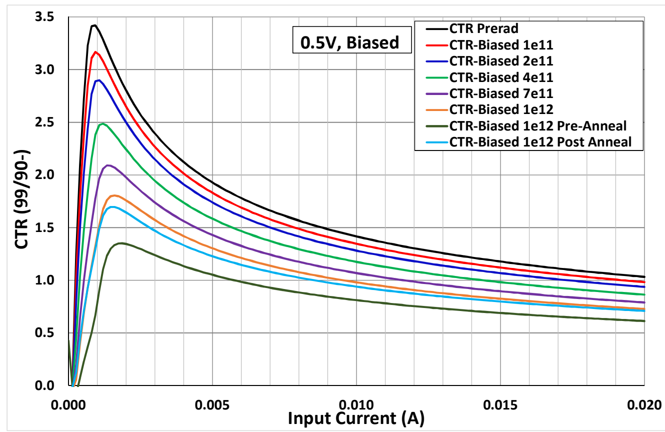

Fig. F1c. Radiation results for biased 66266 (V_{CC}=0.5V) showing the 99/90- statistical results for all fluences up to $1x10^{12}$ p^+/cm^2 and including pre-and post-anneal (100ºC, 1week) conditions.

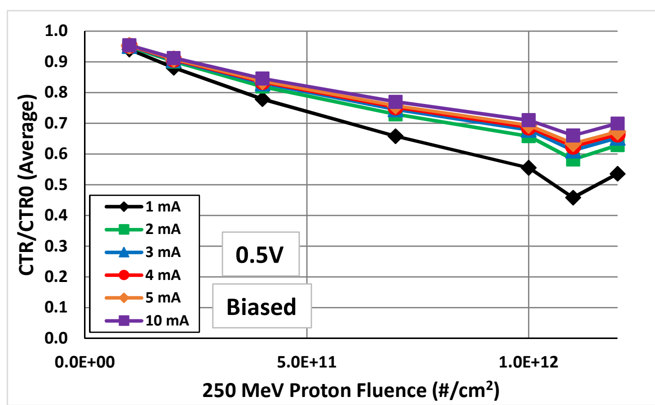

Fig. F1d. Radiation results for biased 66266 (V_{CC}=0.5V) showing the average statistical results for all fluences up to $1x10^{12}$ p^+/cm^2 and including pre-and post-anneal (100ºC, 1week) conditions. Data for several input currents (1 mA, 2 mA,3 mA, 4 mA, 5 mA and 10 mA) are given.

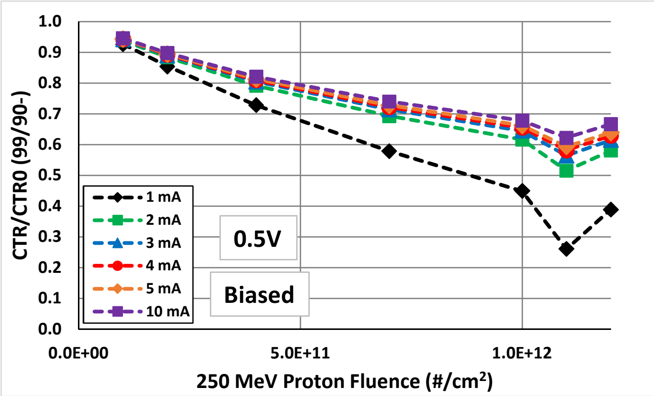

Fig. F1e. Radiation results for biased 66266 (V_{CC}=0.5V) showing the 99/90- statistical results for all fluences up to $1x10^{12}$ p^+/cm^2 and including pre-and post-anneal (100ºC, 1week) conditions. Data for several input currents (1 mA, 2 mA,3 mA, 4 mA, 5 mA and 10 mA) are given.

G. *V_{CC}=0.5V, UnBiased*

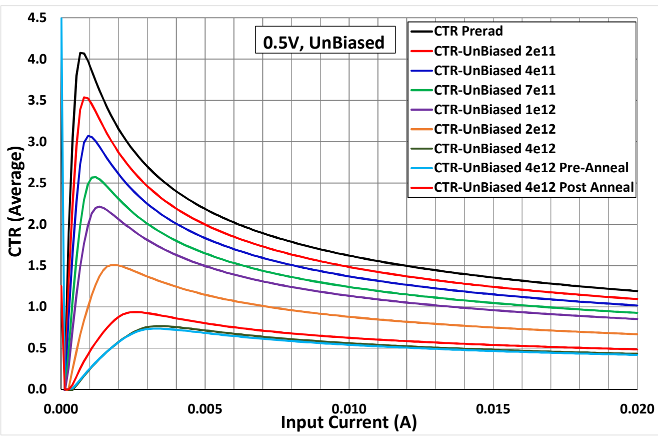

Fig. G1a. Radiation results for unbiased 66266 (V_{CC}=0.5V) showing the average statistical results for all fluences up to $4x10^{12}$ p^+/cm^2 and including pre-and post-anneal (100ºC, 1week) conditions.

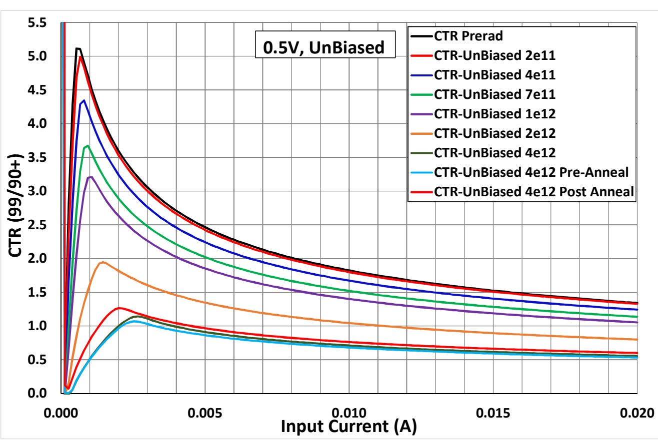

Fig. G1b. Radiation results for unbiased 66266 (V_{CC}=0.5V) showing the 99/90+ statistical results for all fluences up to $4x10^{12}$ p^+/cm^2 and including pre-and post-anneal (100ºC, 1week) conditions.

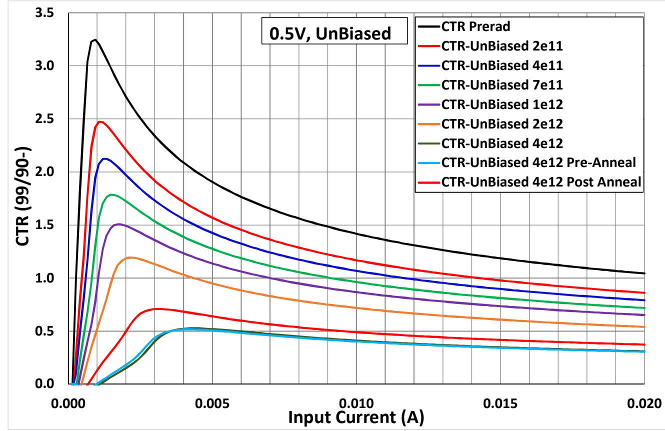

Fig. G1c. Radiation results for unbiased 66266 (V_{CC}=0.5V) showing the 99/90- statistical results for all fluences up to $4x10^{12}$ p^+/cm^2 and including pre-and post-anneal (100ºC, 1week) conditions.

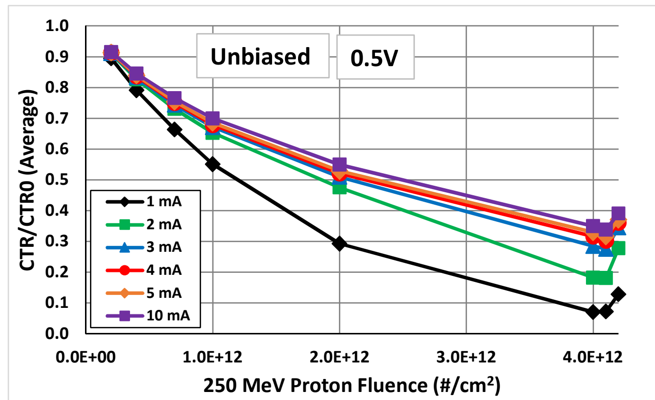

Fig. G1d. Radiation results for unbiased 66266 (V_{CC}=0.5V) showing the average statistical results for all fluences up to $4x10^{12}$ p^+/cm^2 and including pre-and post-anneal (100ºC, 1week) conditions. Data for several input currents (1 mA, 2 mA,3 mA, 4 mA, 5 mA and 10 mA) are given.

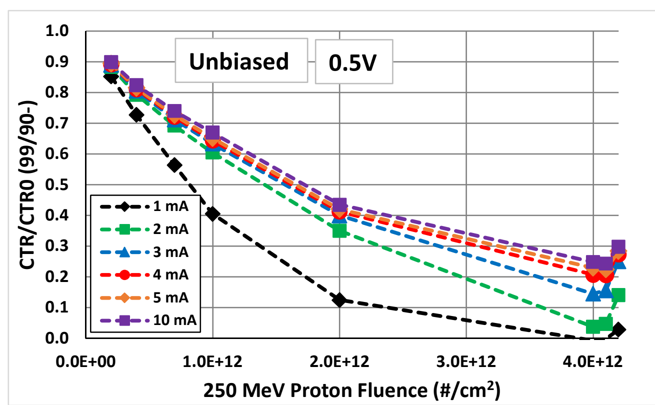

Fig. G1e. Radiation results for unbiased 66266 (V_{CC}=0.5V) showing the 99/90- statistical results for all fluences up to $4x10^{12}$ p^+/cm^2 and including pre-and post-anneal (100ºC, 1week) conditions. Data for several input currents (1 mA, 2 mA,3 mA, 4 mA, 5 mA and 10 mA) are given.