Single-Event Effect Testing of the Vishay Si7414DN n-Type TrenchFET® Power MOSFET

J.-M. Lauenstein[1], M.C. Casey[1], M.A. Campola[1], A.M. Phan[2], E.P. Wilcox[2], A.D. Topper[2], and R.L. Ladbury[1]

NASA Goddard Space Flight Center
Code 561.4, Radiation Effects and Analysis Group
8800 Greenbelt RD
Greenbelt, MD 20771

Test Dates: Sept. 26, 2016; Oct. 15, 2016; Nov. 8, 2016; Mar. 22, 2017; Apr. 12, 2017
Report Date: 15 April 2017

[1]NASA Goddard Space Flight Center, Greenbelt, MD USA
[2]ASRC Federal Space and Defense, Inc., Greenbelt, MD USA

I. Introduction and Summary of Test Results

This study was being undertaken to determine the single event effect susceptibility of the commercial Vishay 60-V TrenchFET® power MOSFET, part # Si7414DN. Heavy-ion testing was conducted at the Texas A&M University Cyclotron Single Event Effects Test Facility (TAMU) and the Lawrence Berkeley National Laboratory BASE Cyclotron Facility (LBNL). In addition, initial 200-MeV proton testing was conducted at Massachusetts General Hospital (MGH) Francis H. Burr Proton Beam Therapy Center. Testing was performed to evaluate this device for single-event effects from lower-LET, lighter ions relevant to higher risk tolerant space missions.

All catastrophic failures during these tests were due to single-event burnout (SEB). SEB is defined to have occurred as a sudden increase in drain current that resulted in functional failure of the part such that the drain-source pathway became resistive. The part therefore failed the breakdown voltage (BV_{DSS}) test. At lower biases (down to and including 0 V_{DS}), localized dosing of the gate oxide from individual heavy-ion strikes occurred which effectively formed regions in the transistor channel with a substantially lower gate threshold voltage. As a result, at 0 V gate-source bias (V_{GS}), these regions either turned on or permitted substantial subthreshold current to flow, raising the off-state leakage current. This current could be reduced by the application of a negative V_{GS} (hard turn-off). Note that the elevated drain current upon catastrophic failure could not be turned off even with under the maximum -20 V gate-source bias. It is hypothesized that the catastrophic damage is due to a similar dosing mechanism whereby channel inversion upon an ion passing through the gate oxide resulted in a local increase in current flow that combined with the high V_{DS}, led to lattice damage from the sudden increase in power deposition in a very small volume of silicon. This mechanism would explain why the catastrophic event did not result in run-away drain current that is typical of SEB from an impact-ionization mechanism and turn-on of the parasitic BJT formed from the source (emitter), body (base), and drain (collector) junctions. Additional studies (which are beyond the scope of these tests) would be needed to identify the actual failure mechanism, especially in light of the ability to prevent SEB by adding a current-limiting resistor on the drain node which quenches the drain voltage upon a current spike.

Tests were conducted at normal beam incidence in air or in vacuum. Tests were performed under a 0 V gate-source bias, with the drain-source voltage (V_{DS}) incrementally increased before each beam run. A summary of the minimum last pass/first catastrophic fail V_{DS} is provided in Table I below as a function of the ion species, energy, range, and LET at the surface of the device under test (DUT). Incident energy, range, and LET were determined by either the TAMU Seuss software or LBNL software based upon SRIM. Sample size refers to the number of DUTs with the given passing/failing Vds. Figure 1 plots these results. In the plot, square markers indicate the last passing V_{DS} of an individual DUT, and the error bar extends to the V_{DS} at which catastrophic failure occurred. The red x marker indicates a DUT that failed upon the first beam run. This DUT demonstrates that the threshold for catastrophic failure is not reduced by the degradation occurring in prior beam exposures.

Table I: Summary of Heavy-Ion Test Results for Individual Samples

Ion Species	Surface-Incident Energy	Range	Surface-Incident LET	V_{GS}	Maximum Last Passing V_{DS}	Minimum V_{DS} at Failure	Sample Size
	(MeV)	*(μm)*	*(MeV·cm²/mg)*	*(V)*	*(V)*	*(V)*	#
Ne	283	279	2.7	0	42	45	1
Ar	548	202	8.2	0	30	33	1
					42	45	2
	400	130	9.7		---	45	1
Cu	659	108	21	0	---	39	1
					39	42	1
					42	45	1
Kr	886	110	31	0	39	42	1

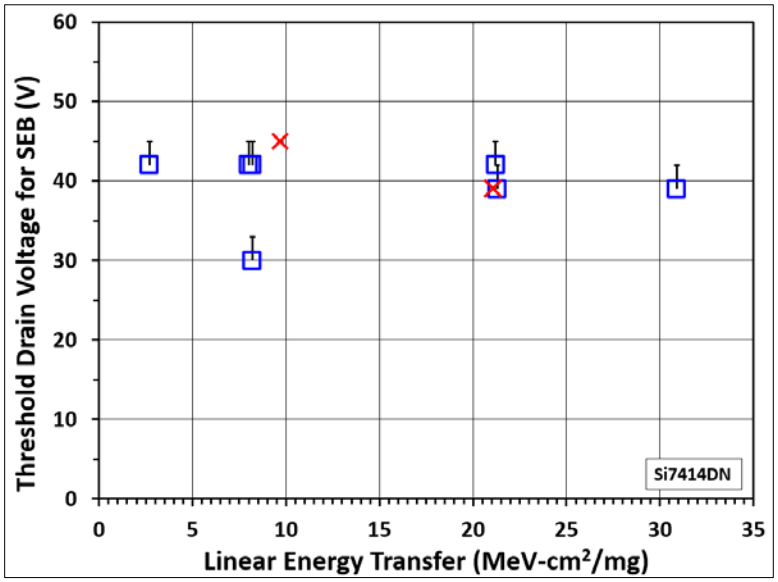

Figure 1. Maximum passing V_{DS} for each DUT as a function of ion LET. Error bars extend to the V_{DS} at which catastrophic failure occurred. The red x symbols mark the bias at which a DUT failed on its first beam exposure, suggesting prior exposures did not affect the V_{DS} necessary for failure.

II. Devices Tested

The sample size for this testing was 16 pieces, with an additional 12 pieces evaluated for heavy-ion induced localized dosing effects when in a grounded configuration. The Si7414DN is manufactured by Vishay Siliconix. It is a commercial-grade n-channel trench-gate vertical power MOSFET that has been optimized for pulse-width modulation. It is rated at 60 V, 8.7 A, with 25 mΩ on-state resistance, and comes in a PowerPAK 1212-8 plastic package.

The pieces were decapsulated either by acid-etch in-house by Ted Wilcox, ASRC, or sent out for decapsulation. Parts were electrically characterized at GSFC by Alyson Topper, ASRC, then retested on-site just prior to beam exposure. Manufacturer electrical specifications are provided in Appendix A. The die area is approximately 2.2 mm x 1.5 mm (0.03 cm^2). Figure 2 shows a picture of a decapsulated sample mounted on a daughter card. The stripline cell topology is oriented as indicated by the arrow in the photo.

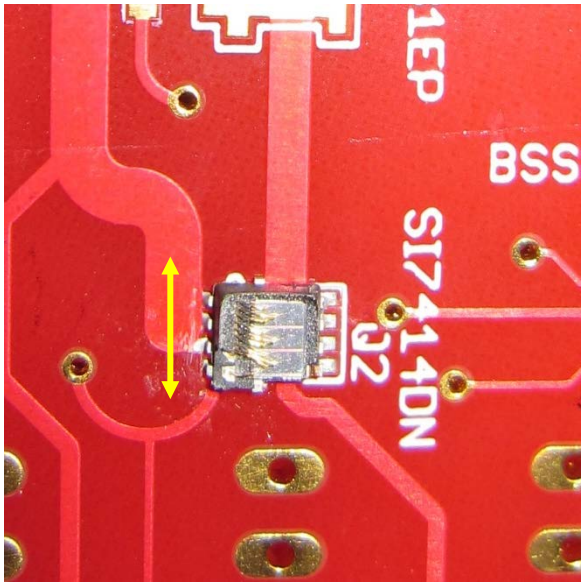

Figure 2. Photograph of decapsulated PowerPAK 1212-8 packaged Si7414DN device under test, mounted on a daughter card for testing. Yellow vertical arrow indicates direction of stripline cell topology.

III. Test Facilities

Facilities:

- Texas A&M University Cyclotron Single Event Effects Test Facility, 15 MeV/amu tune;
- Lawrence Berkeley National Laboratory BASE Cyclotron Facility, 10 MeV/amu tune;
- Massachusetts General Hospital Francis H. Burr Proton Beam Therapy Center, 200 MeV.

Flux:

- 1 x 10^3 cm^{-2}-s^{-1} to 2 x 10^4 cm^{-2}-s^{-1} for heavy-ion tests to establish SEB thresholds; 1 x 10^8 cm^{-2}-s^{-1} for proton runs.
- 500 cm^{-2}-s^{-1} to 1 x 10^5 cm^{-2}-s^{-1} for special unbiased (pins grounded) tests.

Fluence:

All exposures were run to the lesser of the following fluence or until destructive events occurred:

- 3 x 10^5 cm^{-2} to 3 x 10^6 cm^{-2} for heavy-ion tests to establish SEB thresholds; 1 x 10^{10} cm^{-2} for proton runs (with a single DUT taken to a proton fluence of 1 x 10^{11} cm^{-2} at full rated V_{DS}).
- In steps up to a total of 1 x 10^7 cm^{-2} for unbiased tests.

Ion species:

- H, Ne, Ar, Cu, and Kr

Table II below shows the surface-incident beam properties as calculated by the given facility software.

Table II. Ion Beam Properties

Facility	Ion	Air Gap *(cm)*	Surface Energy *(MeV)*	Surface LET *(MeV·cm²/mg)*	Range *(μm)*
MGH	^{1}H	15	200	0.0036	138,600
TAMU	^{20}Ne	1.5	283	2.7	279
TAMU	^{40}Ar	1.5	548	8.2	202
LBNL	^{40}Ar	0	400	9.7	130
LBNL	^{65}Cu	0	659	21	108
LBNL	^{86}Kr	0	886	31	110

IV. Test Setup

Heavy Ion Testing:

The test circuit for the power MOSFET and block diagrams of the setup are shown in Figures 3 and 4. The test circuit contains either a Keithley 2400 or 2635A source meter to provide the gate voltage while measuring the gate current. A filter is placed at the gate node of each device under test (DUT) to dampen noise at the gate. A Keithley 2410 or 2657A source meter provides the appropriate V_{DS} while measuring the drain current; a 500 Ω resistor is optionally switched into series with the Keithley 2410 or 2657A to protect it from sudden high-current transients; it is switched out during device characterization tests. Gate current is limited to 1 mA, and drain current limited to 20 mA (Keithley 2410) or 119 mA (Keithley 2657A), and recorded via GPIB card (2400 series) or Ethernet cable (2600 series) to a desktop computer at approximately 250 ms intervals. If desirable for error mode analysis, a current limiting resistor may be jumpered into series with the drain to protect the DUT from destructive SEB. All equipment is plugged into a power conditioner.

Six DUTs can be mounted on the test board via daughter cards and individually accessed via dry Reed relays controlled by an Agilent DAQ 34907A data acquisition/switch unit and powered by a 5-V power supply. All terminals of the devices not under test are then floating. Testing was conducted in air (TAMU) or in vacuum (LBNL) with the DUT centered within the 1 inch beam diameter. Unless otherwise specified, ion exposures were conducted at 0º tilt angle (where 0º tilt is normal incidence to the DUT). Photographs of the test setup and DUT test board are shown in Figure 5.

The test setup is controlled via a custom LabVIEW program written by Alyson Topper and Hak Kim, ASRC Federal Space and Defense, which forms a user interface for the Lua-based scripts that run the Keithley 2600 series SMUs, or SCPI commands to the Keithley 2400 series SMUs. The program controls the SMUs, providing a live plot of the gate and drain currents during sampling and recording, and performing a parametric analysis of each DUT prior to irradiation and following each beam run. Characterizations include, if selected: gate threshold voltage (V_{th}), I_D as a function of V_{GS} at various fixed V_{DS} values for evaluation of total ionizing dose effects, drain-source breakdown voltage (BV_{DSS}), zero gate voltage drain current (I_{DSS}), and I_G and I_D as a function of V_{GS} at 0 V_{DS} (post-irradiation gate stress (PIGS) test to check the integrity of the gate dielectric).

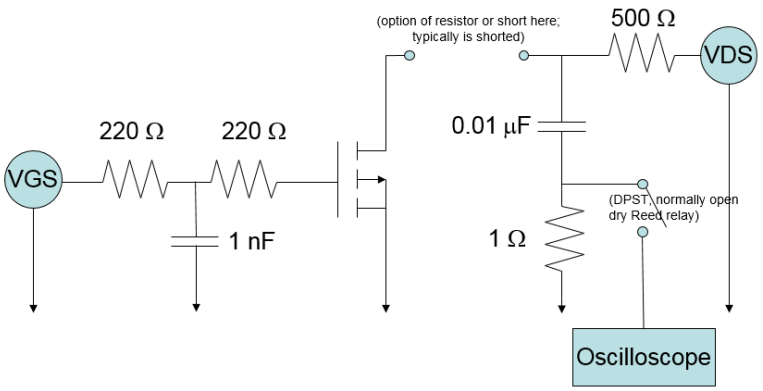

Figure 3. Equivalent test circuit for the Si7414DN power MOSFET.

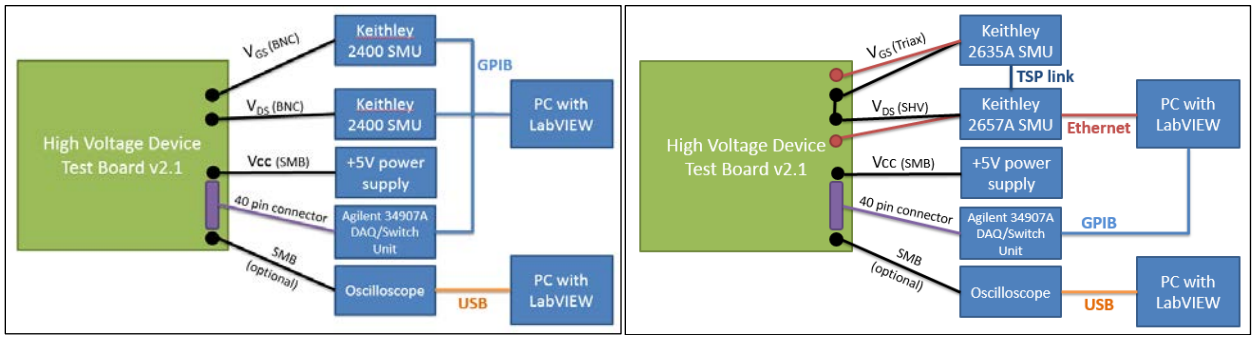

Figure 4. Left: Block diagram of test setup with 2400-series Keithley SMUs; Right: setup with 2600-series Keithley SMUs.

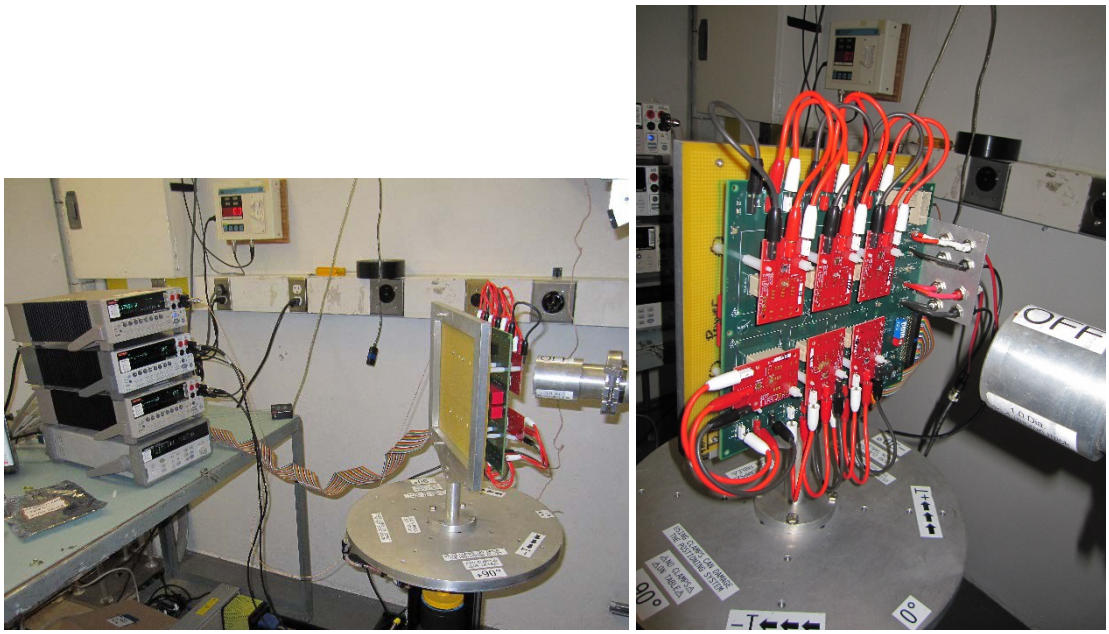

Figure 5. Left: DUT test board and 2400-series equipment in TAMU beam cave; Right: Mother board with 6 daughter cards mounted.

Proton Testing:

Individual DUTs mounted to daughter cards were placed in a vise clamp and positioned at normal incidence, approximately 15 cm from the beam port in air (see Figure 6). Source, drain, and gate voltages were supplied directly by two Keithley 2400 SMUs controlled by the same LabVIEW codes described above. In this preliminary test, no stiffening capacitance was added to the drain node.

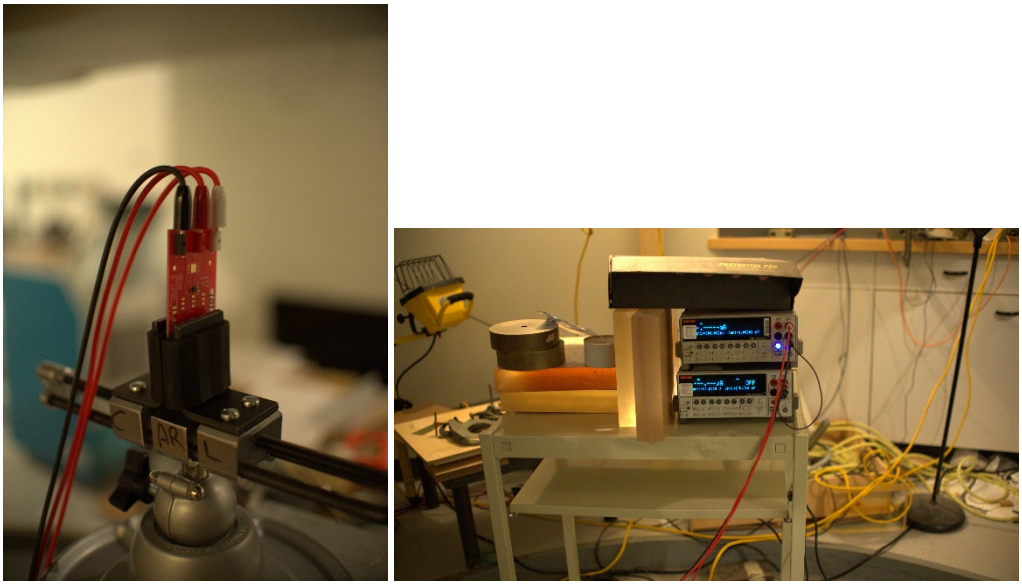

Figure 6. At proton test facility, DUT on daughter PCB aligned in air at normal incidence in proton beam (left photo) receives voltage inputs directly from two Keithley 2400 SMUs (right photo).

V. Test Results

Except when noted, parts were assessed for ion effects at a 0-V gate-source bias. Under irradiation with test ions heavier than protons, the Si7414DN was susceptible to single-event burnout at voltages indicated in Table I and Figure 1, in section I above. SEB is defined to have occurred upon a sudden increase in drain current that resulted in functional failure of the part such that the drain-source pathway became resistive rather than rectifying. The part therefore failed the breakdown voltage (BV_{DSS}) test. At lower biases (down to and including 0 V_{DS}), localized dosing of the gate oxide from individual heavy-ion strikes occurred. As a result of this dosing, at 0 V gate-source bias (V_{GS}), these dosed regions either turned on or permitted substantial subthreshold current to flow, raising the off-state leakage current. This current could be reduced by the application of a negative V_{GS} (hard turn-off). Note that the elevated drain current upon SEB could not be turned off even with under the maximum -20 V gate-source bias.

Preliminary 200-MeV proton tests revealed current spikes at V_{DS} greater than 42 V (see Appendix D, Figures D69-D84), with variability in the actual onset voltage. The frequency of these spikes increased substantially at 60 V_{DS}. Additional tests must be performed using the MIL-STD-750 TM1080-compliant test circuit shown in Figure 3, which includes a drain-node stiffening capacitor, to establish whether these current spikes are SEB events that were quenched due to SMU voltage sagging as the current demand from the SMU suddenly increased by several orders of magnitude.

It is well-established in the literature that trench-gate n-type MOSFETs are susceptible to substantial gate threshold voltage shifts due to ions passing through the gate oxide along the length of the channel. Ionized and subsequently trapped charge changes the flatband voltage at the ion strike location, effectively creating a local region within the overall channel width whose gate threshold voltage is lower than the surrounding channel width. This effect can be seen as a hump in the drain current vs. gate voltage curve because this region of the channel turns on prior to the rest of the transistor channel. The impact of the ions on the flatband voltage is dependent on the amount of charge trapped in the oxide or at the oxide/silicon interface, and thus is a function of the ion strike location, ion LET, and the electric field in the oxide (applied V_{GS} and V_{DS}). Additionally, the impact on the overall transistor performance is also dependent on the number of localized dosed locations (thus the effective total width of the channel having a reduced threshold voltage). Figure 7 shows the shift in measured threshold voltage for 5 samples, each irradiated with a different ion species. In the plot, for protons, neon, and argon, all runs began at the same bias conditions (V_{DS} = 24 V, V_{GS} = 0 V) and then were incremented in 3-V steps. For copper and krypton, the bias condition remained at V_{DS} = 0 V, V_{GS} = 0 V for all runs. As can be seen in Figure 7, heavier ions have a greater impact on threshold voltage for a given dose. Importantly, this dosing occurs even when the part is in the off-state, such that cold spares on orbit will suffer degradation due to flatband voltage shifts that are larger in magnitude than would be predicted by standard total ionizing dose tests using gamma rays or even protons.

A summary of the SEB failure threshold as a function of ion species, energy, and LET is given in the Introduction of this report. Complete results are in the appendices. Appendix B provides the run logs; electrical characterization (pre- and post-irradiation) results are given in Appendix C, and striptape current measurements taken during the individual beam runs are plotted in Appendix D, and commentary on the results given in the Figure legends.

Included in the test campaign was a single sample irradiated with 548 MeV Ar while at -10 V_{GS} and 24 V_{DS}. This DUT (#12, run 39, TAMU September 2016) did not exhibit increases in drain current during irradiation (Figure D40) because the externally applied V_{GS} kept the part in the off state despite flatband voltage shifts. Upon electrical characterization, however, the part showed substantial dosing effects presumably due to the higher charge yield within the oxide. The pre- and post-rad IV curves are shown in Figure 8.

Finally, the SEB failure mechanism was verified in part by the addition of a 10-kΩ resistor in series with the drain node (see Figure 3 – the optional resistor location) of DUT 11 (runs 26-38 of the September 2016 TAMU test campaign). This part was irradiated with 548-MeV argon and exhibited only dosing effects but no SEB, up to the maximum rated 60 V_{DS}. Note that current limiting is not a valid SEB circumvention technique on orbit due to the transient current spikes (upon suppressed SEB events) stressing the part and potentially resulting in premature failure.

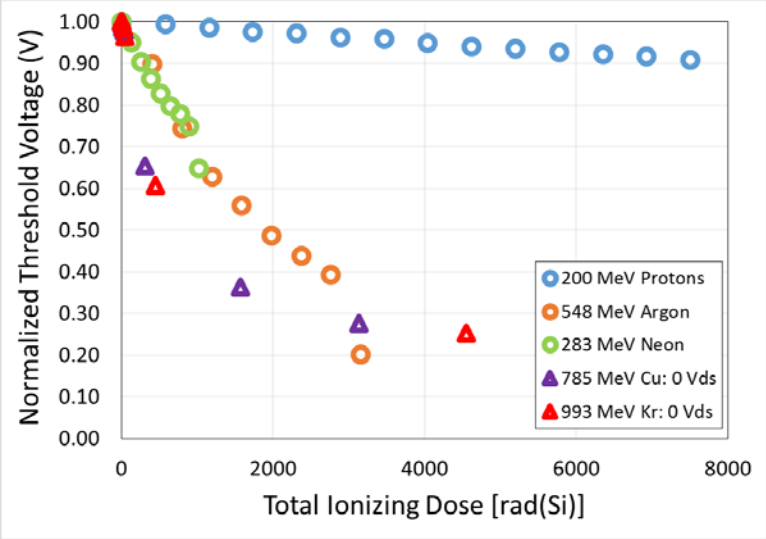

Figure 7. Threshold voltage shift (normalized to pre-rad threshold voltage) as a function of total ionizing dose from different ion species. Vgs = 0 V during irradiation. Each symbol for protons, Ar, and Ne represent 3-V step-wise increases in Vds from an initial value of 24 V; for Cu and Kr, Vds was held at 0 V for all dose steps.

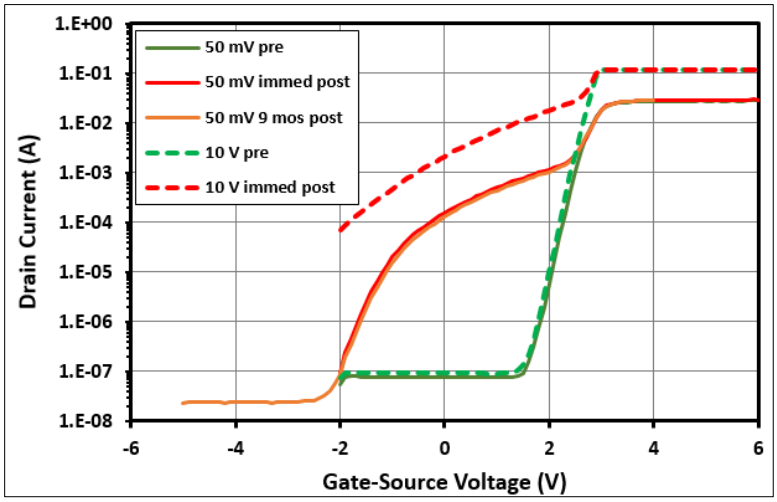

Figure 8. Drain current versus gate bias at V_{DS} = 50 mV (solid lines) and 10 V (dashed lines), prior to irradiation with 548 MeV Ar (green lines) and immediately after irradiation at -10 V_{GS}, 24 V_{DS}. Additional measurement at 50 mV taken 9 months later (light orange line) shows no annealing has occurred. Total fluence during irradiation = $3x10^6$ cm^{-2} (393 rad(Si)).

Appendix A

Table A1. Si7414DN Manufacturer-Specified Electrical Parameters (Partial List)

Parameter	Condition	MIN	MAX	Units
Gate Threshold Voltage ($V_{GS(th)}$)	V_{DS} = V_{GS}, I_D = 250 μA	1	3	V
Zero Gate Voltage Drain Current (I_{DSS})	V_{DS} = 60 V, V_{GS} = 0 V		1	μA
Drain-Source Breakdown Voltage (BV_{DSS})	(rating only: condition not specified)*	60		V
Gate-Source Leakage Current (I_{GSS})	V_{GS} = +/- 20 V, V_{DS} = 0 V		+/-100	nA
Static Drain-Source Resistance ($R_{DS(on)}$)	V_{GS} = 10 V, I_D =8.7 A		0.025	Ω
Forward Voltage (V_{SD})	I_S = 3.2 A, V_{GS} = 0 V		1.2	V

*****Condition used during this test campaign: V_{GS} = 0 V; I_D = 250 μA

Appendix B

Table B1. Raw test data from 26 September 2016 at TAMU. Beam diameter = 1"; LET and energy are after beam airgap of 1.5mm.
NOTE: Ion characteristics in table are from TAMU's SEUSS software based upon SRIM 1998.

Run #	Date	Time	DUT #	SEL #	VDS [V]	VGS [V]	Ion	Energy [MeV/u]	Energy [MeV]	LET [MeV-cm²/mg]	Air Gap [mm]	Flux [cm⁻² s⁻¹]	Eff Fluence [cm⁻²]	Dose [rad(Si)]	Cum. Dose [rad(Si)]	External Drain Resistor [Ohms]	Vth [V]	BVdss [V]	+20 PIGS	-20 PIGS	Pass/ Fail	Comments
1	9/26/2016	12:33:06 AM	7	1	24	0	Ar	13.7	548	8.2	15	3.30E+04	3.01E+06	4.07E+02	4.07E+02	0	1.34	67	5 pA	-175 pA	Pass	Saw several breaks in the drain on the order of 100s of nA. Looks like it tries to recover after each break. Appears to be one very small change in the gate.
2	9/26/2016	12:45:19 AM	7	1	27	0	Ar	13.7	548	8.2	15	3.96E+04	2.99E+06	3.91E+02	7.98E+02	0	1.11	67	10 pA	-175 pA	Pass	Saw several breaks in the drain on the order of a few uA.
3	9/26/2016	12:50:28 AM	7	1	30	0	Ar	13.7	548	8.2	15	3.42E+04	3.02E+06	3.95E+02	1.19E+03	0	0.94	67	5 pA	-175 pA	Pass	Saw several breaks in the drain on the order of a few uA.
4	9/26/2016	12:54:37 AM	7	1	33	0	Ar	13.7	548	8.2	15	2.72E+04	2.99E+06	3.91E+02	1.58E+03	0	0.83	67	10 pA	-150 pA	Pass	Saw several breaks in the drain on the order of a few uA.
5	9/26/2016	12:58:46 AM	7	1	36	0	Ar	13.7	548	8.2	15	3.25E+04	2.99E+06	3.91E+02	1.97E+03	0	0.73	67	10 pA	-150 pA	Pass	Saw several breaks in the drain on the order of a few uA.
6	9/26/2016	1:03:36 AM	7	1	39	0	Ar	13.7	548	8.2	15	1.84E+04	2.99E+06	3.92E+02	2.37E+03	0	0.65	67	10 pA	-150 pA	Pass	Saw several breaks in the drain on the order of a few uA.
7	9/26/2016	1:08:19 AM	7	1	42	0	Ar	13.7	548	8.2	15	1.55E+04	3.00E+06	3.93E+02	2.76E+03	0	0.59	67	10 pA	-145 pA	Pass	Saw several breaks in the drain on the order of a few uA.
8	9/26/2016	1:13:54 AM	7	1	45	0	Ar	13.7	548	8.2	15	1.53E+04	3.01E+06	3.93E+02	3.15E+03	0	0.30	2	1 mA	-1 mA	Fail	Saw one 1 mA break almost immediately after the beam turned on and then there was a 12 mA jump at the end of the run. After the beam was turned off there was a quick ~7 mA spike, and then current jumped back up to 19 mA and remained there until voltage was removed.
9	9/26/2016	1:24:02 AM	8	2	12	0	Ar	13.7	548	8.2	15	3.16E+04	3.00E+06	3.93E+02	3.93E+02	0	1.49	66	250 nA	-1.7 uA	~~Fail~~	Saw several breaks in the drain on the order of 100s of nA. Went back and checked -- **the prerad currents were high to begin with.**
10	9/26/2016	1:31:18 AM	9	3	6	0	Ar	13.7	548	8.2	15	2.66E+04	2.99E+06	3.91E+02	3.91E+02	0	1.81	66	30 pA	-200 pA	Pass	Saw several breaks in the drain on the order of a few nA. Then there was one 500 nA break. And then a 700 nA one.
11	9/26/2016	1:36:44 AM	9	3	9	0	Ar	13.7	548	8.2	15	3.58E+04	2.98E+06	3.90E+02	7.82E+02	0	1.60	66	30 pA	-180 pA	Pass	Saw several small breaks.
12	9/26/2016	1:40:45 AM	9	3	12	0	Ar	13.7	548	8.2	15	3.99E+04	3.00E+06	3.92E+02	1.17E+03	0	1.45	66	25 pA	-175 pA	Pass	Saw several small breaks.
13	9/26/2016	1:45:30 AM	9	3	15	0	Ar	13.7	548	8.2	15	3.87E+04	2.99E+06	3.91E+02	1.56E+03	0	1.33	66	25 pA	-170 pA	Pass	Saw several small breaks.
14	9/26/2016	1:49:51 AM	9	3	18	0	Ar	13.7	548	8.2	15	3.35E+04	2.99E+06	3.90E+02	1.96E+03	0	1.21	66	20 pA	-160 pA	Pass	Saw several small breaks.
15	9/26/2016	1:54:57 AM	9	3	21	0	Ar	13.7	548	8.2	15	2.77E+04	3.01E+06	3.93E+02	2.35E+03	0	1.11		20 pA	-160 pA	Pass	Saw several small breaks.
16	9/26/2016	1:59:16 AM	9	3	24	0	Ar	13.7	548	8.2	15	2.16E+04	3.01E+06	3.93E+02	2.74E+03	0	1.02	66	20 pA	-160 pA	Pass	Saw several small breaks.
17	9/26/2016	2:04:03 AM	9	3	27	0	Ar	13.7	548	8.2	15	2.88E+04	3.00E+06	3.93E+02	3.13E+03	0	0.92	66	20 pA	-150 pA	Pass	Saw several small breaks.
18	9/26/2016	2:08:43 AM	9	3	30	0	Ar	13.7	548	8.2	15	2.43E+04	3.01E+06	3.94E+02	3.53E+03	0	0.86	66	20 pA	-150 pA	Pass	Saw several small breaks.
19	9/26/2016	2:13:20 AM	9	3	33	0	Ar	13.7	548	8.2	15	2.66E+04	3.01E+06	3.94E+02	3.92E+03	0	0.77	66	20 pA	-150 pA	Pass	Saw several small breaks.
20	9/26/2016	2:19:05 AM	9	3	36	0	Ar	13.7	548	8.2	15	3.03E+04	2.99E+06	3.91E+02	4.31E+03	0	0.71	66	20 pA	-145 pA	Pass	Saw several small breaks.
21	9/26/2016	2:23:58 AM	9	3	39	0	Ar	13.7	548	8.2	15	2.91E+04	3.01E+06	3.94E+02	4.71E+03	0	0.65	66	20 pA	-145 pA	Pass	Saw several small breaks.
22	9/26/2016	2:28:37 AM	9	3	42	0	Ar	13.7	548	8.2	15	2.78E+04	2.99E+06	3.91E+02	5.10E+03	0	0.59	62	20 pA	-140 pA	Pass	Saw several small breaks.
23	9/26/2016	2:32:58 AM	9	3	45	0	Ar	13.7	548	8.2	15	2.08E+04	3.00E+06	2.92E+02	5.39E+03	0	0.35	2	15 pA	-140 pA	Fail	Current jumped to 10 mA almost immediately.

Run #	Date	Time	DUT #	SEL #	VDS [V]	VGS [V]	Ion	Energy [MeV/u]	Energy [MeV]	LET [MeV-cm²/mg]	Air Gap [mm]	Flux [cm⁻² s⁻¹]	Eff Fluence [cm⁻²]	Dose [rad(Si)]	Cum. Dose [rad(Si)]	External Drain Resistor [Ohms]	Vth [V]	BVdss [V]	+20 PIGS	-20 PIGS	Pass/ Fail	Comments
24	9/26/2016	2:40:36 AM	**10**	4	**30**	0	Ar	13.7	548	8.2	15	2.11E+04	2.99E+06	3.91E+02	3.91E+02	0	1.29	66	10 pA	-185 pA	Pass	Saw current increases in the 10s of uA
25	9/26/2016	2:45:26 AM	10	4	**33**	0	Ar	13.7	548	8.2	15	2.21E+04	3.01E+06	3.93E+02	7.85E+02	0	0.92	**6**	5 pA	-175 pA	**Fail**	Saw a 1 mA increase shortly after the beam turned on.
26	9/26/2016	2:53:36 AM	**11**	5	**24**	0	Ar	13.7	548	8.2	15	1.70E+04	3.01E+06	3.94E+02	3.94E+02	**10k**	1.47	67	70 pA	-220 pA	Pass	Scope was connected during the beam run but no transietns were recorded. Parameters are all recorded in post file to remove resistor.
27	9/26/2016	3:03:43 AM	11	5	**27**	0	Ar	13.7	548	8.2	15	2.76E+04	2.99E+06	3.92E+02	7.85E+02	**10k**	1.17	67	70 pA	-210 pA	Pass	Forgot to save transients, but scope never triggered anyway. Parameters were recorded in post file.
28	9/26/2016	3:09:39 AM	11	5	**30**	0	Ar	13.7	548	8.2	15	2.52E+04	2.99E+06	3.91E+02	1.18E+03	**10k**	1.03	67	70 pA	-210 pA	Pass	Scope was connected during the beam run but no transietns were recorded. Parameters are all recorded in post file.
29	9/26/2016	3:14:53 AM	11	5	**33**	0	Ar	13.7	548	8.2	15	2.38E+04	3.01E+06	3.94E+02	1.57E+03	**10k**	0.90	67	70 pA	-200 pA	Pass	Scope was connected during the beam run but no transietns were recorded. Parameters are all recorded in post file.
30	9/26/2016	3:19:20 AM	11	5	**36**	0	Ar	13.7	548	8.2	15	1.60E+04	2.99E+06	3.92E+02	1.96E+03	**10k**	0.81	67	70 pA	-200 pA	Pass	Scope was connected during the beam run but no transietns were recorded. Parameters are all recorded in post file.
31	9/26/2016	3:24:50 AM	11	5	**39**	0	Ar	13.7	548	8.2	15	1.54E+04	2.99E+06	3.91E+02	2.35E+03	**10k**	0.73	67	70 pA	-200 pA	Pass	Scope was connected during the beam run but no transietns were recorded. Parameters are all recorded in post file.
32	9/26/2016	3:31:16 AM	11	5	**42**	0	Ar	13.7	548	8.2	15	2.14E+04	2.99E+06	3.91E+02	2.74E+03	**10k**	0.64	67	70 pA	-200 pA	Pass	Scope was connected during the beam run but no transietns were recorded. Parameters are all recorded in post file.
33	9/26/2016	3:36:51 AM	11	5	**45**	0	Ar	13.7	548	8.2	15	2.32E+04	3.00E+06	3.93E+02	3.14E+03	**10k**	0.57	66	70 pA	-200 pA	Pass	Scope was connected during the beam run but no transietns were recorded. Parameters are all recorded in post file.
34	9/26/2016	3:42:03 AM	11	5	**48**	0	Ar	13.7	548	8.2	15	2.29E+04	3.00E+06	3.93E+02	3.53E+03	**10k**	0.50	63	70 pA	-200 pA	Pass	Beam run looks to be more of a constant degradation than jumps.
35	9/26/2016	3:46:52 AM	11	5	**51**	0	Ar	13.7	548	8.2	15	1.99E+04	2.99E+06	3.92E+02	3.92E+03	**10k**	0.45	60	70 pA	-200 pA	Pass	Beam run looks to be more of a constant degradation than jumps.
36	9/26/2016	3:54:00 AM	11	5	**54**	0	Ar	13.7	548	8.2	15	2.07E+04	2.99E+06	3.91E+02	4.31E+03	**10k**	0.42	57	70 pA	-200 pA	Pass	Beam run looks to be more of a constant degradation than jumps.
37	9/26/2016	4:00:28 AM	11	5	**57**	0	Ar	13.7	548	8.2	15	2.11E+04	3.00E+06	3.92E+02	4.70E+03	**10k**	0.38	54	70 pA	-200 pA	Pass	Beam run looks to be more of a constant degradation than jumps.
38	9/26/2016	4:05:47 AM	11	5	**60**	0	Ar	13.7	548	8.2	15	2.38E+04	2.99E+06	3.91E+02	5.10E+03	**10k**	0.34	51	70 pA	-200 pA	Pass	Beam run looks to be more of a constant degradation than jumps.
39	9/26/2016	4:12:39 AM	**12**	6	**24**	**-10**	Ar	13.7	548	8.2	15	2.18E+04	3.00E+06	3.93E+02	3.93E+02	0	0.65	**1**	10 pA	-175 pA	**Fail??**	Saw 1 nA increase in drain current and corresponding 50 pA increase in gate current shortly after the beam turned on. After the beam turned off, both currents returned to their original values. (looked like charge collection.)

Run #	Date	Time	DUT #	SEL #	VDS [V]	VGS [V]	Ion	Energy [MeV/u]	Energy [MeV]	LET [MeV-cm²/mg]	Air Gap [mm]	Flux [cm⁻² s⁻¹]	Eff Fluence [cm⁻²]	Dose [rad(Si)]	Cum. Dose [rad(Si)]	External Drain Resistor [Ohms]	Vth [V]	BVdss [V]	+20 PIGS	-20 PIGS	Pass/ Fail	Comments
60	9/26/2016	6:50:51 AM	17	4	24	0	Ne	14.2	283	2.7	15	1.77E+04	3.00E+06	1.28E+02	127.8	0	2.17	67	2 nA	-2 nA	Pass	Only charge collection originally, but then saw a 20 nA break in the drain and then a 10 nA break towards the end of the run.
61	9/26/2016	6:56:31 AM	17	4	27	0	Ne	14.2	283	2.7	15	1.68E+04	3.01E+06	1.28E+02	255.8	0	2.06	67	2 nA	-2 nA	Pass	Saw a 10 nA increase in drain current. And then several small breaks.
62	9/26/2016	7:02:33 AM	17	4	30	0	Ne	14.2	283	2.7	15	1.35E+04	3.00E+06	1.28E+02	383.4	0	1.97	67	2 nA	-2 nA	Pass	Saw two 600 nA breaks in the drain.
63	9/26/2016	7:08:27 AM	17	4	33	0	Ne	14.2	283	2.7	15	1.57E+04	3.01E+06	1.28E+02	511.4	0	1.89	67	2 nA	-2 nA	Pass	Saw one small DECREASE in drain current.
64	9/26/2016	7:14:04 AM	17	4	36	0	Ne	14.2	283	2.7	15	1.72E+04	3.00E+06	1.28E+02	639.3	0	1.82	67	2 nA	-2 nA	Pass	Saw two small (50 nA) breaks
65	9/26/2016	7:19:24 AM	17	4	39	0	Ne	14.2	283	2.7	15	1.62E+04	2.99E+06	1.27E+02	766.7	0	1.78	67	2 nA	-2 nA	Pass	Saw one 200 nA break.
66	9/26/2016	7:25:12 AM	17	4	42	0	Ne	14.2	283	2.7	15	1.51E+04	3.01E+06	1.28E+02	894.7	0	1.71	67	2 nA	-2 nA	Pass	Saw several small breaks and one 1 uA one.
67	9/26/2016	7:30:45 AM	17	4	45	0	Ne	14.2	283	2.7	15	1.57E+04	2.99E+06	1.28E+02	1022.2	0	1.48	5	1 nA	-1.2 nA	Fail	Saw several small breaks and then 1.3 mA

Table B2. Raw test data from 12 April 2017 at LBNL. LET and energy are at surface of die; testing was in vacuum.

NOTE: Ion characteristics in table are as reported at LBNL. Pre- and post-drain & gate currents, as well as Igss values, are approximations only.

RUN INFO				DUT SETUP		BEAM DIAGNOSTICS: For Si, before parylene coating											IRRADIATION RESULTS										
Time	Run	DUT	Socket	V_{GS} [V]	V_{DS} [V]	Ion	Energy [MeV/u]	Energy [MeV]	Tilt Angle	Roll Angle	LET [MeV-cm²/mg]	Ave Flux [/(cm²-s)]	Eff. Fluence [/cm²]	Dose [rad(Si)]	Cum. Dose [rad(Si)]	Pre Ig	Pre Id	Pass/Fail	Event Notes	Post Ig [A]	Post Id [A]	Delta Ig/ fluence	Delta Id/ fluence	Post Vth [V]	Post BVdss [V]	Post Idss [A]	Post Igss+ [A]	Post Igss- [A]
3:30	89	114	1	0	24	Cu	10	659	0	0	21.2	1.576E+03	3.01E+05	1.02E+02	1.020E+02	-4.00E-13	1.55E-10		250nA, hundreds of nA jumps	-4.50E-13	3.15E-06	-1.66E-19	1.05E-11	1.82	xxx	8.41E-06	-2.20E-11	-4.50E-11
3:35	90	114	1	0	27	Cu	10	659	0	0	21.2	1.560E+03	3.01E+05	1.02E+02	2.040E+02	-5.00E-13	2.49E-06		4uA event many small events	-1.00E-12	9.12E-06	-1.66E-18	2.20E-11	1.34	xxx	2.51E-05	-2.00E-11	-4.20E-11
3:40	91	114	1	0	30	Cu	10	659	0	0	21.2	1.537E+03	3.01E+05	1.02E+02	3.060E+02	-6.00E-13	8.56E-06		nothing notable	-1.00E-12	1.22E-05	-1.33E-18	1.21E-11	1.15	xxx	3.29E-05	-2.00E-11	-4.00E-11
3:45	92	114	1	0	33	Cu	10	659	0	0	21.2	1.541E+03	3.01E+05	1.02E+02	4.080E+02	-6.00E-13	1.22E-05		same as seen on previous Cu run	-6.00E-13	1.62E-05	0.00E+00	1.33E-11	1.02	xxx	4.18E-05	-2.00E-11	-4.00E-11
3:50	93	114	1	0	36	Cu	10	659	0	0	21.2	1.534E+03	3.01E+05	1.02E+02	5.100E+02	-6.50E-13	1.64E-05		no fails	-4.50E-13	2.30E-05	6.64E-19	2.22E-11	0.917	xxx	5.61E-05	-2.00E-11	-4.00E-11
3:56	94	114	1	0	39	Cu	10	659	0	0	21.2	2.782E+03	3.02E+05	1.02E+02	6.123E+02	-4.50E-13	2.39E-05		no fails, soft breakdown though	-5.00E-13	3.51E-05	-1.66E-19	3.70E-11	0.805	69	7.69E-05	-2.00E-11	-4.00E-11
4:01	95	114	1	0	42	Cu	10	659	0	0	21.2	2.751E+03	1.55E+05	5.26E+01	6.649E+02	-6.00E-13	3.52E-05	Fail	failed	-8.00E-13	9.23E-04	-1.29E-18	5.72E-09	0.684	10	xxx	-2.00E-11	-4.00E-11
4:07	96	120	2	0	33	Cu	10	659	0	0	21.2	2.731E+03	5.02E+05	1.70E+02	1.701E+02	-3.00E-13	2.85E-10		no failures, some charge collection, uA level jumps	-6.00E-13	6.97E-06	-5.97E-19	1.39E-11	1.53	xxx	1.73E-05	1.50E-10	-3.00E-10
4:12	97	120	2	0	36	Cu	10	659	0	0	21.2	2.697E+03	5.02E+05	1.70E+02	3.401E+02	-2.00E-13	6.60E-06		no failures, some charge collection, uA level jumps	-4.00E-13	4.43E-06	-3.98E-19	-4.32E-12	1.18	xxx	3.43E-05	1.50E-10	-3.00E-10
4:18	98	120	2	0	39	Cu	10	659	0	0	21.2	2.757E+03	5.02E+05	1.70E+02	5.101E+02	-2.00E-13	1.37E-05		no failures, some charge collection, uA level jumps	-5.00E-13	2.83E-05	-5.98E-19	2.91E-11	0.946	69	3.63E-06	1.50E-10	-3.00E-10
4:23	99	120	2	0	42	Cu	10	659	0	0	21.2	2.765E+03	5.02E+05	1.70E+02	6.802E+02	-2.00E-13	2.78E-05		no failures, some charge collection, uA level jumps	-5.00E-13	3.83E-05	-5.97E-19	2.09E-11	0.825	xxx	8.08E-05	1.50E-10	-3.00E-10
4:28	100	120	2	0	45	Cu	10	659	0	0	21.2	2.733E+03	8.56E+04	2.90E+01	7.092E+02	-2.00E-13	4.04E-05	Fail	failed	-1.00E-12	1.99E-03	-9.34E-18	2.28E-08	0.694	7	xxx	1.50E-10	-3.00E-10
4:33	101	107	3	0	39	Cu	10	659	0	0	21.2	2.685E+03	6.61E+04	2.24E+01	2.238E+01	-5.00E-13	3.40E-10	Fail	300uA jump, stopped run	-5.00E-13	3.13E-04	0.00E+00	4.74E-09	2.15	34	xxx	-2.00E-11	-4.50E-11
13:54	111	117	1	0	24	Kr	10	886	0	0	30.9	3.242E+03	3.03E+05	1.50E+02	1.495E+02	-4.00E-13	1.70E-10		no failures, some charge collection, uA level jumps	-4.00E-13	4.50E-06	0.00E+00	1.49E-11	1.69	xxx	1.22E-05	-2.20E-11	-1.00E-10
13:57	112	117	1	0	27	Kr	10	886	0	0	30.9	3.227E+03	3.03E+05	1.50E+02	2.991E+02	-4.00E-13	3.66E-06		no failures, some charge collection, uA level jumps	-4.00E-13	1.36E-05	0.00E+00	3.28E-11	1.21	72	3.56E-05	-2.00E-11	-1.00E-10
14:02	113	117	1	0	30	Kr	10	886	0	0	30.9	3.210E+03	3.03E+05	1.50E+02	4.486E+02	-5.00E-13	1.21E-05		no failures, some charge collection, uA level jumps	-4.00E-13	2.13E-05	3.30E-19	3.04E-11	1.02	xxx	5.33E-05	-2.00E-11	-1.00E-10
14:06	114	117	1	0	33	Kr	10	886	0	0	30.9	3.199E+03	3.02E+05	1.49E+02	5.977E+02	-4.00E-13	2.06E-05		no failures, some charge collection, uA level jumps	-5.00E-13	3.56E-05	-3.31E-19	4.97E-11	0.864	72	8.33E-05	-2.00E-11	-1.00E-10
14:10	115	117	1	0	36	Kr	10	886	0	0	30.9	3.180E+03	3.02E+05	1.49E+02	7.467E+02	-5.00E-13	3.59E-05		no failures, some charge collection, uA level jumps	-5.00E-13	4.72E-05	0.00E+00	3.74E-11	0.756	72	1.03E-04	-2.00E-11	-1.00E-10
14:14	116	117	1	0	39	Kr	10	886	0	0	30.9	3.131E+03	3.02E+05	1.49E+02	8.958E+02	-6.00E-13	4.79E-05		no failures, some charge collection, uA level jumps	-6.00E-13	6.30E-05	0.00E+00	5.00E-11	0.674	72	1.26E-04	-2.00E-11	-1.00E-10
14:18	117	117	1	0	42	Kr	10	886	0	0	30.9	3.127E+03	1.08E+05	5.33E+01	9.491E+02	-5.00E-13	6.49E-05	Fail	failed, mA	5.00E-12	1.38E-03	5.09E-17	1.22E-08	0.446	7	xxx	-2.00E-11	-1.00E-10

Table B3. Raw test data from 8 November 2016 at LBNL. LET and energy are at surface of die; testing was in vacuum.
NOTE: Ion characteristics in table are as reported at LBNL. Pre- and post-drain & gate currents, as well as Igss values, are approximations only.

RUN INFO				DUT SETUP		BEAM DIAGNOSTICS: For Si, before parylene coating								IRRADIATION RESULTS										
Time	Run	DUT	Socket	V_{GS} [V]	V_{DS} [V]	Ion	Energy [MeV/u]	Energy [MeV]	LET [MeV-cm^2/mg]	Flux [/(cm^2-s)]	Eff. Fluence [/cm^2]	Dose [rad(Si)]	Cum. Dose [rad(Si)]	Pre Ig	Pre Id	Pass/Fail	Event Notes	Post Ig [A]	Post Id [A]	Delta Ig/ fluence	Delta Id/ fluence	Post Vth [V]	Post BVdss [V]	Post Idss [A]	Post Igss+ [A]	Post Igss- [A]
4:58	56	5	3	0	0	Cu	10.0	659	21.2	5.901E+02	1.04E+04	3.52E+00	3.523E+00	-3.0E-13	-2.9E-10		There was some spontaneous recover after the beam was turned (-340 pA) and then jumped again to -247 pA	-3.0E-13	-3.8E-10	0	-9.13462E-15	2.24	73	2.57E-09	-2.70E-11	-5.80E-11
5:10	57	5	3	0	0	Cu	10.0	659	21.2	5.966E+02	1.05E+04	3.56E+00	7.079E+00	-5.0E-13	-3.2E-10			-5.0E-10	-3.2E-10	-4.8E-14	-2.85714E-16	2.23	73	2.63E-09	-2.60E-11	-5.50E-11
5:17	58	5	3	0	0	Cu	10.0	659	21.2	5.640E+02	3.03E+04	1.03E+01	1.734E+01	-4.0E-13	-3.2E-10			-4.0E-13	-5.0E-08	0	-1.64015E-12	2.22	73	1.19E-06	-2.60E-11	-5.00E-11
5:27	59	5	3	0	0	Cu	10.0	659	21.2	5.742E+02	5.04E+04	1.71E+01	3.441E+01	-4.00E-13	-3.60E-08			-4.00E-13	-4.40E-08	0	-1.58699E-13	2.20	73	9.21E-07	-2.60E-11	-4.60E-11
6:47	60	6	4	0	0	Cu	10.0	659	21.2	6.231E+02	1.01E+05	3.40E+01	3.404E+01	1.60E-07	-5.90E-07		The gate, drain, and source are all shorted together on board	1.55E-07	-5.95E-07	-5E-14	-4.97512E-14	2.19	73	1.88E-08	-2.00E-11	-5.50E-11
6:51	61	4	5	0	0	Cu	10.0	659	21.2	6.359E+02	1.01E+05	3.40E+01	3.404E+01				Passive irradiation -- G, D, S shorted together on board with no voltage applied.					2.18	73	1.28E-08	-2.00E-11	-5.00E-11
7:00	62	1	3	0	0	Cu	10.0	659	21.2	6.594E+02	1.04E+04	3.52E+00	3.519E+00	-4.00E-13	-2.00E-11		Replicating DUT 5	-4.00E-13	6.80E-09	0	6.564E-13	2.16	73	2.60E-08	-3.00E-11	-4.80E-11
7:07	63	1	3	0	0	Cu	10.0	659	21.2	6.930E+02	1.04E+04	3.53E+00	7.045E+00	-4.00E-13	-3.50E-09			-2.86E-13	-3.58E-09	1.1E-17	-7.68492E-15	2.16	73	1.86E-08	-3.00E-11	-4.50E-11
7:10	64	1	3	0	0	Cu	10.0	659	21.2	6.920E+02	3.06E+04	1.04E+01	1.740E+01	-4.00E-13	-2.35E-09			-4.00E-13	-2.30E-09	0	1.63506E-15	2.15	73	1.52E-08	-2.50E-11	-1.00E-10
7:15	65	1	3	0	0	Cu	10.0	659	21.2	7.529E+02	5.05E+04	1.71E+01	3.451E+01	-4.00E-13	-2.20E-09		one jump in Id	-4.00E-13	-3.00E-09	0	-1.58416E-14	2.13	73	1.65E-08	-3.00E-11	-1.00E-10
8:06	66	16	6	0	45	Ar	10.0	400	9.7	1.633E+01	3.35E+02	5.22E-02	5.224E-02	-6.50E-13	3.60E-10	Fail	saw a 700 uA event almost immediately after turning the beam on. Now that it's broken, Id is creeping up after beam was turned off.	-2.00E-13	6.80E-04	1.3E-15	2.02864E-06	2.28	23		-3.00E-11	-5.50E-11

Table B4. Raw test data from 15 October 2017 at MGH

Run #	Time	DUT #	VDS [V]	VGS [V]	Energy [MeV]	Collimater Size	Beam Style	MU	Time Counts	Live Time (s)	Flux [cm-2 s-1]	Eff Fluence [cm-2]	Dose [rad(Si)]	Cumulative Dose [rad(Si)]	Vth [V]	Pass/ Fail	Comments
1		102	24	0	200	1 in x 1 in	Scatter	83.017	1.79	107.4	9.28E+07	9.96E+09	5.77E+02	5.77E+02	2.18	Pass	Labview problem. Can't get actual BVdss values on display. Have to go back and extract from data.
2		102	27	0	200	1 in x 1 in	Scatter	83.017	1.72	103.2	9.65E+07	9.96E+09	5.77E+02	1.15E+03	2.16	Pass	
3		102	30	0	200	1 in x 1 in	Scatter	83.02	1.68	100.8	9.88E+07	9.96E+09	5.77E+02	1.73E+03	2.14	Pass	
4	12:11 PM	102	33	0	200	1 in x 1 in	Scatter	83.03	1.71	102.6	9.71E+07	9.96E+09	5.77E+02	2.31E+03	2.13	Pass	
5	12:15 PM	102	36	0	200	1 in x 1 in	Scatter	83.04	1.66	99.6	1.00E+08	9.96E+09	5.77E+02	2.89E+03	2.11	Pass	
6	12:21 PM	102	39	0	200	1 in x 1 in	Scatter	83.02	1.76	105.6	9.43E+07	9.96E+09	5.77E+02	3.46E+03	2.10	Pass	
7	12:26 PM	102	42	0	200	1 in x 1 in	Scatter	83.02	1.8	108	9.22E+07	9.96E+09	5.77E+02	4.04E+03	2.08	Pass	
8	12:31 PM	102	45	0	200	1 in x 1 in	Scatter	83.02	1.81	108.6	9.17E+07	9.96E+09	5.77E+02	4.62E+03	2.06	Pass	
9	12:36 PM	102	48	0	200	1 in x 1 in	Scatter	83.02	1.8	108	9.22E+07	9.96E+09	5.77E+02	5.19E+03	2.05	Pass	Saw two 120 nA spikes during the run
10	12:42 PM	102	51	0	200	1 in x 1 in	Scatter	83.02	1.85	111	8.98E+07	9.96E+09	5.77E+02	5.77E+03	2.03	Pass	
11	12:47 PM	102	54	0	200	1 in x 1 in	Scatter	83.02	1.86	111.6	8.93E+07	9.96E+09	5.77E+02	6.35E+03	2.02	Pass	Saw a 90 nA, a 120 nA, and a 140 nA spike during the run
12	12:53 PM	102	57	0	200	1 in x 1 in	Scatter	83.03	1.85	111	8.98E+07	9.96E+09	5.77E+02	6.92E+03	2.01	Pass	Saw two 140 nA spikes during the run
13	12:58 PM	102	60	0	200	1 in x 1 in	Scatter	83.01	1.81	108.6	9.17E+07	9.96E+09	5.77E+02	7.50E+03	1.99	Pass	Saw a 160 nA, 160 nA, 70 nA, 160 nA, 30 nA, 160 nA, 160 nA, 160 nA, 160 nA, 160 nA, and 40 nA spikes during the run
14	1:11 PM	103	60	0	200	1 in x 1 in	Scatter	83.02	1.83	109.8	9.07E+07	9.96E+09	5.77E+02	5.77E+02	2.29	Pass	Saw a ton of ~160 nA spikes during the run
15	1:16 PM	103	60	0	200	1 in x 1 in	Scatter	83.02	18.07	1084.2	9.19E+06	9.96E+09	5.77E+02	1.15E+03	2.13	Pass	Lots of ~160 nA spikes and smaller, two ~320 nA, one ~350 nA during the run
16	1:38 PM	103	60	-10	200	1 in x 1 in	Scatter	83.01	1.86	111.6	8.93E+07	9.96E+09	5.77E+02	1.73E+03	2.06	Pass	Current started very high & continued to decrease throughout run to ~ 550 uA by end
17	1:51 PM	104	45	0	200	1 in x 1 in	Scatter	83.02	1.89	113.4	8.79E+07	9.96E+09	5.77E+02	5.77E+02	2.25	Pass	One 120 nA, 20 nA during the run
18	1:56 PM	104	48	0	200	1 in x 1 in	Scatter	83.01	1.89	113.4	8.78E+07	9.96E+09	5.77E+02	1.15E+03	2.24	Pass	One 120 nA spike during the run
19	2:01 PM	104	51	0	200	1 in x 1 in	Scatter	83.02	1.88	112.8	8.83E+07	9.96E+09	5.77E+02	1.73E+03	2.22	Pass	One 140 nA spike during the run
20	2:06 PM	104	54	0	200	1 in x 1 in	Scatter	83.02	1.86	111.6	8.93E+07	9.96E+09	5.77E+02	2.31E+03	2.20	Pass	One 140 nA, 60 nA, and 80 nA spike during the run
21	2:11 PM	104	57	0	200	1 in x 1 in	Scatter	83.01	1.84	110.4	9.02E+07	9.96E+09	5.77E+02	2.88E+03	2.19	Pass	One 85 nA spike during the run
22	2:16 PM	104	60	0	200	1 in x 1 in	Scatter	83.01	1.79	107.4	9.27E+07	9.96E+09	5.77E+02	3.46E+03	2.17	Pass	Several 160 nA, one 30 nA spikes during the
23	2:20 PM	104	60	-10	200	1 in x 1 in	Scatter	83.01	1.67	100.2	9.94E+07	9.96E+09	5.77E+02	4.04E+03	2.10	Pass	Current was again very high, so there's no way we'll see any spikes on the order of 100s of nAs. ID started at ~5 mA, but has dropped to ~650 uA by the end of the run.
24	2:31 PM	105	45	0	200	1 in x 1 in	Scatter	83.01	1.8	108	9.22E+07	9.96E+09	5.77E+02	5.77E+02	2.26	Pass	
25	2:37 PM	105	48	0	200	1 in x 1 in	Scatter	83.01	1.82	109.2	9.12E+07	9.96E+09	5.77E+02	1.15E+03	2.24	Pass	
26	2:42 PM	105	51	0	200	1 in x 1 in	Scatter	83.01	1.82	109.2	9.12E+07	9.96E+09	5.77E+02	1.73E+03	2.23	Pass	
27	2:47 PM	105	54	0	200	1 in x 1 in	Scatter	83.01	1.81	108.6	9.17E+07	9.96E+09	5.77E+02	2.31E+03	2.21	Pass	Saw three 140 nA spikes during the run
28	2:52 PM	105	57	0	200	1 in x 1 in	Scatter	83.02	1.8	108	9.22E+07	9.96E+09	5.77E+02	2.88E+03	2.19	Pass	saw one 140 nA, one 10 nA spikes during the run
29	2:56 PM	105	60	0	200	1 in x 1 in	Scatter	83.01	1.78	106.8	9.33E+07	9.96E+09	5.77E+02	3.46E+03	2.18	Pass	Saw 120 nA, several 160 nA durign the run

Appendix C

Table C1. Pre- and Post-Irradiation Electrical Characterization Test Results for 9/26/2017 TAMU Tests
Note: Shaded columns flag new DUT. Out-of-spec values are in orange or red text.

Run #:	pre	1	2	3	4	5	6	7	8	pre	9
DUT S/N:	7	7	7	7	7	7	7	7	7	8	8
Run Vds (V):	--	24	27	30	33	36	39	42	45	--	12
Ion species:	--	Ar	Ar	Ar	Ar	Ar	Ar	Ar	Ar	--	Ar
Vgs (V)	Igs (A)										
0	-2.4E-13	-7.9E-13	5.4E-13	1.0E-12	9.2E-13	1.1E-13	1.0E-12	8.8E-13	1.5E-09	4.2E-09	2.9E-10
2	1.9E-13	5.2E-13	1.3E-12	-8.4E-12	-9.7E-12	-9.8E-12	-8.9E-12	-9.6E-12	7.8E-05	3.4E-07	3.3E-07
4	8.5E-12	5.5E-12	6.4E-12	5.9E-12	6.2E-12	5.3E-12	6.1E-12	6.0E-12	2.9E-04	1.1E-06	5.7E-07
6	-3.1E-11	-2.9E-11	-2.7E-11	-2.8E-11	-2.8E-11	-2.9E-11	-2.8E-11	-2.7E-11	6.3E-04	2.3E-06	1.2E-06
8	-2.6E-11	-2.2E-11	-2.1E-11	-2.2E-11	-2.1E-11	-2.2E-11	-2.2E-11	-2.1E-11	> 0.001	3.8E-06	8.2E-07
10	-2.2E-11	-1.6E-11	-1.5E-11	-1.6E-11	-1.6E-11	-1.7E-11	-1.7E-11	-1.6E-11	> 0.001	4.7E-06	1.2E-06
12	-1.8E-11	-1.0E-11	-9.5E-12	-1.1E-11	-1.1E-11	-1.1E-11	-1.1E-11	-1.1E-11	> 0.001	2.1E-06	1.1E-06
14	-1.5E-11	-5.3E-12	-3.5E-12	-5.0E-12	-6.1E-12	-6.4E-12	-5.8E-12	-6.9E-12	> 0.001	4.3E-07	1.0E-06
16	-1.0E-11	-6.6E-13	1.1E-12	-7.9E-13	-1.8E-12	-8.9E-13	-1.2E-12	-1.8E-12	> 0.001	4.2E-07	2.8E-07
18	-6.7E-12	4.5E-12	5.4E-12	3.3E-12	3.4E-12	2.9E-12	3.9E-12	2.5E-12	> 0.001	1.3E-07	2.4E-07
20	-3.3E-12	9.1E-12	9.1E-12	7.0E-12	7.8E-12	7.3E-12	8.3E-12	6.6E-12	> 0.001	1.8E-07	2.3E-07
0	-6.1E-11	-8.9E-11	-8.9E-11	-8.7E-11	-8.7E-11	-8.7E-11	-8.6E-11	-8.6E-11	1.1E-09	-2.1E-08	-1.4E-08
-2	-8.1E-11	-3.2E-11	-3.3E-11	-3.1E-11	-3.1E-11	-3.2E-11	-3.0E-11	-3.1E-11	-4.7E-05	-1.2E-07	-7.5E-08
-4	-9.0E-11	-9.2E-11	-9.2E-11	-9.1E-11	-9.1E-11	-9.2E-11	-9.2E-11	-9.1E-11	-4.3E-04	-3.1E-07	-1.7E-07
-6	-9.2E-11	-9.6E-11	-9.6E-11	-9.6E-11	-9.3E-11	-9.4E-11	-9.4E-11	-9.6E-11	< -0.001	-7.3E-07	-3.2E-07
-8	-9.4E-11	-3.8E-11	-3.8E-11	-9.9E-11	-9.9E-11	-9.8E-11	-9.9E-11	-9.9E-11	< -0.001	-1.0E-06	-6.3E-07
-10	-9.6E-11	-1.0E-10	-1.0E-10	-4.1E-11	-4.1E-11	-4.1E-11	-4.0E-11	-4.0E-11	< -0.001	-8.7E-07	-7.5E-07
-12	-9.9E-11	-1.1E-10	-1.1E-10	-1.0E-10	-1.0E-10	-1.0E-10	-1.0E-10	-1.0E-10	< -0.001	-8.2E-07	-8.6E-07
-14	-4.0E-11	-4.7E-11	-4.7E-11	-4.5E-11	-4.5E-11	-4.5E-11	-4.4E-11	-4.4E-11	< -0.001	-8.4E-07	-1.2E-06
-16	-3.9E-11	-4.8E-11	-4.8E-11	-4.8E-11	-4.6E-11	-4.7E-11	-4.6E-11	-4.5E-11	< -0.001	-7.8E-07	-1.8E-06
-18	-4.9E-11	-1.1E-10	-1.1E-10	-1.1E-10	-1.1E-10	-1.1E-10	-1.1E-10	-1.1E-10	< -0.001	-8.9E-07	-1.7E-06
-20	-2.0E-10	-1.8E-10	-1.7E-10	-1.6E-10	-1.5E-10	-1.5E-10	-1.5E-10	-1.4E-10	< -0.001	-9.8E-07	-1.8E-06
BVdss (V):	67	67	67	67	67	67	67	67	1.995	67	66
Idss (uA):	0.1177	8.96	21.58	41.52	55.23	83.71	105	140.3	n/a	0.1331	7.472
Vth (V):	2.20	1.34	1.11	0.94	0.83	0.73	0.65	0.59	0.30	2.33	1.49

Run #:	pre	10	11	12	13	14	15	16	17	18	19	20	21	22	23
DUT S/N:	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9
Run Vds (V):	--	6	9	12	15	18	21	24	27	30	33	36	39	42	45
Ion species:	--	Ar	Ar	Ar	Ar	Ar	Ar	Ar	Ar	Ar	Ar	Ar	Ar	Ar	Ar
Vgs (V)	Igs (A)														
0	-1.6E-13	1.7E-13	1.0E-12	1.7E-12	4.6E-13	3.0E-13	1.4E-12	2.3E-12	1.0E-12	2.1E-12	2.0E-12	1.8E-12	2.2E-12	1.5E-12	1.1E-12
2	3.6E-12	4.3E-12	8.2E-12	4.1E-12	2.9E-12	3.1E-12	3.4E-12	4.6E-12	-6.5E-12	-5.9E-12	-6.0E-12	-6.0E-12	5.0E-12	3.9E-12	-7.3E-12
4	1.4E-11	1.6E-11	1.1E-11	1.1E-11	1.0E-11	9.7E-12	1.0E-11	1.1E-11	1.0E-11	1.1E-11	1.1E-11	1.0E-11	-8.4E-13	-1.4E-12	-2.9E-12
6	-2.3E-11	-2.0E-11	-2.0E-11	-2.0E-11	-2.1E-11	-2.2E-11	-2.1E-11	-2.1E-11	-2.2E-11	-2.1E-11	-2.1E-11	-2.1E-11	-2.1E-11	-2.0E-11	-2.3E-11
8	-1.6E-11	-1.1E-11	-1.2E-11	-1.2E-11	-1.3E-11	-1.4E-11	-1.4E-11	-1.4E-11	-1.5E-11	-1.4E-11	-1.4E-11	-1.4E-11	-1.4E-11	-1.3E-11	-1.6E-11
10	-9.4E-12	-3.1E-12	-4.4E-12	-5.7E-12	-5.7E-12	-7.8E-12	-8.0E-12	-6.6E-12	-8.4E-12	-7.8E-12	-8.2E-12	-7.8E-12	-8.2E-12	-7.6E-12	-1.0E-11
12	-3.6E-12	5.0E-12	2.4E-12	-1.5E-13	-3.8E-14	-1.6E-12	-1.7E-12	-9.0E-13	-1.4E-12	-2.5E-12	-3.0E-12	-2.6E-12	-2.0E-12	-2.4E-12	-5.0E-12
14	1.8E-12	1.2E-11	9.2E-12	6.1E-12	5.6E-12	5.2E-12	3.9E-12	4.6E-12	3.4E-12	2.7E-12	2.1E-12	3.2E-12	3.4E-12	2.6E-12	-1.9E-13
16	6.5E-12	1.8E-11	1.5E-11	1.2E-11	1.1E-11	1.1E-11	9.4E-12	1.0E-11	8.6E-12	8.2E-12	7.8E-12	8.2E-12	8.4E-12	8.3E-12	4.3E-12
18	1.2E-11	2.4E-11	2.2E-11	1.8E-11	1.7E-11	1.6E-11	1.5E-11	1.5E-11	1.3E-11	1.3E-11	1.3E-11	1.3E-11	1.4E-11	1.4E-11	9.4E-12
20	1.6E-11	3.1E-11	2.8E-11	2.4E-11	2.3E-11	2.1E-11	2.1E-11	2.1E-11	1.9E-11	1.8E-11	1.7E-11	1.8E-11	1.9E-11	1.9E-11	1.4E-11
0	-8.5E-11	-3.8E-11	-3.8E-11	-7.7E-11	-3.7E-11	-3.8E-11	-3.7E-11	-3.6E-11	-3.6E-11	-3.6E-11	-3.6E-11	-3.6E-11	-3.6E-11	-3.6E-11	-3.7E-11
-2	-9.8E-11	-2.2E-11	-2.1E-11	-3.2E-11	-2.1E-11	-2.0E-11	-1.9E-11	-1.9E-11	-2.0E-11	-1.9E-11	-1.9E-11	-1.9E-11	-1.9E-11	-1.9E-11	-2.3E-11
-4	-3.8E-11	-9.0E-11	-8.8E-11	-9.3E-11	-8.8E-11	-8.8E-11	-8.6E-11	-8.6E-11	-8.6E-11	-8.4E-11	-8.5E-11	-8.8E-11	-8.7E-11	-8.6E-11	-8.8E-11
-6	-1.0E-10	-9.6E-11	-9.7E-11	-9.9E-11	-9.6E-11	-9.6E-11	-9.4E-11	-9.3E-11	-9.1E-11	-9.2E-11	-9.3E-11	-9.3E-11	-9.3E-11	-9.4E-11	-9.3E-11
-8	-1.1E-10	-4.2E-11	-4.0E-11	-4.1E-11	-3.8E-11	-3.8E-11	-3.7E-11	-3.6E-11	-1.0E-10	-9.8E-11	-1.0E-10	-1.0E-10	-9.7E-11	-9.9E-11	-9.8E-11
-10	-1.1E-10	-4.4E-11	-4.2E-11	-1.0E-10	-4.0E-11	-4.0E-11	-3.8E-11	-3.7E-11	-4.1E-11	-4.1E-11	-4.1E-11	-4.0E-11	-4.0E-11	-4.0E-11	-4.0E-11
-12	-1.2E-10	-5.0E-11	-4.7E-11	-1.1E-10	-4.4E-11	-4.3E-11	-4.2E-11	-4.1E-11	-4.2E-11	-4.1E-11	-4.1E-11	-4.0E-11	-4.0E-11	-4.0E-11	-4.0E-11
-14	-1.2E-10	-1.2E-10	-1.1E-10	-1.1E-10	-1.1E-10	-1.1E-10	-1.1E-10	-1.1E-10	-4.6E-11	-4.5E-11	-4.6E-11	-4.5E-11	-4.5E-11	-4.4E-11	-4.3E-11
-16	-1.1E-10	-1.2E-10	-1.2E-10	-1.2E-10	-1.2E-10	-1.2E-10	-1.2E-10	-1.2E-10	-1.1E-10	-1.1E-10	-1.1E-10	-1.1E-10	-1.1E-10	-1.1E-10	-1.1E-10
-18	-1.3E-10	-1.3E-10	-1.3E-10	-1.3E-10	-1.3E-10	-1.2E-10	-1.2E-10	-1.2E-10	-1.2E-10	-1.2E-10	-1.2E-10	-1.2E-10	-1.2E-10	-1.2E-10	-1.2E-10
-20	-2.2E-10	-2.0E-10	-1.8E-10	-1.8E-10	-1.7E-10	-1.6E-10	-1.6E-10	-1.6E-10	-1.5E-10	-1.5E-10	-1.5E-10	-1.5E-10	-1.4E-10	-1.4E-10	-1.4E-10
BVdss (V):	66	66	66	66	66	66	--	66	66	66	66	66	66	62	1.995
Idss (uA):	0.1522	1.42	1.586	2.561	3.778	5.573	--	20.41	37.94	47.66	74.00	86.46	19.82	224.8	n/a
Vth (V):	2.25	1.82	1.60	1.45	1.34	1.21	1.12	1.02	0.92	0.86	0.77	0.71	0.65	0.59	0.35

Run #:	pre	24	25	pre	26	27	28	29	30	31	32	33	34	35	36	37	38
DUT S/N:	**10**	10	10	**11**	11	11	11	11	11	11	11	11	11	11	11	11	11
Run Vds (V):	--	30	33	--	24, 10 kΩ	27, 10 kΩ	30, 10 kΩ	33, 10 kΩ	36, 10 kΩ	39, 10 kΩ	42, 10 kΩ	45, 10 kΩ	48, 10 kΩ	51, 10 kΩ	54, 10 kΩ	57, 10 kΩ	60, 10 kΩ
Ion species:	--	Ar	Ar	--	Ar	Ar	Ar	Ar	Ar	Ar	Ar	Ar	Ar	Ar	Ar	Ar	Ar
Vgs (V)																	
0	2.9E-13	4.2E-13	-3.2E-13	-1.6E-12	9.5E-13	1.6E-12	2.1E-12	2.0E-12	2.9E-12	2.3E-12	2.2E-12	8.4E-13	1.4E-12	1.5E-12	5.4E-13	2.1E-12	2.2E-12
2	-7.1E-12	1.7E-12	-9.2E-12	1.1E-10	3.0E-12	1.2E-11	3.0E-12	3.4E-12	2.8E-12	3.0E-12	3.2E-12	2.4E-12	2.0E-12	1.2E-11	8.7E-13	2.6E-12	2.3E-12
4	1.7E-11	7.2E-12	6.5E-12	2.5E-10	2.8E-11	2.4E-11	2.5E-11	2.5E-11	2.5E-11	2.5E-11	2.4E-11	2.4E-11	2.4E-11	1.3E-11	1.3E-11	1.3E-11	1.4E-11
6	-2.1E-11	-2.6E-11	-2.7E-11	3.8E-10	1.7E-13	-4.8E-13	2.4E-13	-1.1E-13	6.1E-13	3.7E-13	6.5E-13	-1.3E-12	1.4E-13	1.5E-13	-3.8E-13	-2.1E-13	5.3E-13
8	-1.4E-11	-1.9E-11	-2.0E-11	5.5E-10	1.3E-11	1.2E-11	1.3E-11	1.2E-11	1.3E-11	1.3E-11	1.3E-11	1.1E-11	1.2E-11	1.2E-11	1.1E-11	1.1E-11	1.2E-11
10	-7.8E-12	-1.3E-11	-1.4E-11	7.2E-10	2.4E-11	2.4E-11	2.4E-11	2.4E-11	2.3E-11	2.4E-11	2.3E-11	2.2E-11	2.2E-11	2.3E-11	2.1E-11	2.1E-11	2.2E-11
12	-6.9E-13	-7.4E-12	-8.6E-12	8.9E-10	3.3E-11	3.5E-11	3.4E-11	3.4E-11	3.3E-11	3.3E-11	3.3E-11	3.2E-11	3.2E-11	3.2E-11	3.1E-11	3.1E-11	3.1E-11
14	7.1E-12	-2.3E-12	-4.5E-12	1.0E-09	4.5E-11	4.4E-11	4.3E-11	4.4E-11	4.3E-11	4.2E-11	4.2E-11	4.1E-11	4.2E-11	4.3E-11	4.0E-11	4.0E-11	3.9E-11
16	1.1E-11	3.5E-12	-3.3E-13	1.2E-09	5.4E-11	5.4E-11	5.2E-11	5.3E-11	5.2E-11	5.2E-11	5.3E-11	5.1E-11	5.1E-11	5.1E-11	5.0E-11	4.8E-11	4.8E-11
18	1.7E-11	7.0E-12	4.4E-12	1.4E-09	6.4E-11	6.3E-11	6.2E-11	6.2E-11	6.1E-11	6.1E-11	6.2E-11	6.0E-11	6.0E-11	5.9E-11	5.9E-11	5.6E-11	5.7E-11
20	2.3E-11	1.0E-11	8.5E-12	1.5E-09	7.3E-11	7.2E-11	7.1E-11	7.2E-11	7.0E-11	7.0E-11	7.1E-11	7.0E-11	6.9E-11	6.8E-11	6.8E-11	6.5E-11	6.5E-11
0	-6.7E-11	-9.5E-11	-9.3E-11	-2.2E-10	-6.1E-11	-6.1E-11	-6.1E-11	-6.1E-11	-6.1E-11	-6.1E-11	-6.1E-11	-6.1E-11	-6.1E-11	-6.1E-11	-6.1E-11	-6.1E-11	-6.0E-11
-2	-8.8E-11	-3.2E-11	-9.7E-11	-4.1E-10	-3.2E-11	-3.2E-11	-3.1E-11	-3.1E-11	-3.1E-11	-3.1E-11	-3.1E-11	-3.1E-11	-3.1E-11	-3.1E-11	-3.0E-11	-3.0E-11	-3.0E-11
-4	-1.0E-10	-9.3E-11	-9.9E-11	-5.3E-10	-4.1E-11	-4.0E-11	-4.0E-11	-3.9E-11	-3.9E-11	-3.9E-11	-4.0E-11	-4.0E-11	-3.9E-11	-3.9E-11	-3.9E-11	-3.8E-11	-3.8E-11
-6	-4.0E-11	-9.7E-11	-9.9E-11	-6.5E-10	-1.2E-10	-1.2E-10	-1.1E-10	-1.1E-10	-1.1E-10	-1.1E-10	-1.2E-10	-1.1E-10	-1.1E-10	-1.1E-10	-1.1E-10	-1.1E-10	-1.1E-10
-8	-1.0E-10	-3.8E-11	-3.8E-11	-7.6E-10	-1.3E-10	-1.3E-10	-1.3E-10	-1.3E-10	-1.3E-10	-1.3E-10	-1.3E-10	-1.3E-10	-1.3E-10	-1.3E-10	-1.2E-10	-1.3E-10	-1.2E-10
-10	-1.1E-10	-1.0E-10	-1.0E-10	-8.6E-10	-1.3E-10	-1.2E-10	-1.2E-10	-1.3E-10	-1.2E-10	-1.2E-10	-1.3E-10	-1.2E-10	-1.2E-10	-1.2E-10	-1.2E-10	-1.2E-10	-1.3E-10
-12	-1.1E-10	-1.1E-10	-1.1E-10	-9.5E-10	-1.5E-10	-1.5E-10	-1.5E-10	-1.4E-10	-1.5E-10	-1.5E-10	-1.5E-10	-1.5E-10	-1.5E-10	-1.5E-10	-1.4E-10	-1.4E-10	-1.4E-10
-14	-1.2E-10	-4.7E-11	-1.1E-10	-9.2E-10	-1.6E-10	-1.6E-10	-1.6E-10	-1.5E-10	-1.5E-10	-1.5E-10	-1.6E-10	-1.5E-10	-1.5E-10	-1.5E-10	-1.5E-10	-1.5E-10	-1.4E-10
-16	-1.1E-10	-4.8E-11	-1.2E-10	-1.1E-09	-1.7E-10	-1.7E-10	-1.7E-10	-1.6E-10	-1.6E-10	-1.6E-10	-1.6E-10	-1.6E-10	-1.6E-10	-1.6E-10	-1.6E-10	-1.6E-10	-1.6E-10
-18	-1.4E-10	-1.2E-10	-1.1E-10	-1.2E-09	-1.8E-10	-1.7E-10	-1.7E-10	-1.7E-10	-1.7E-10	-1.7E-10	-1.7E-10	-1.7E-10	-1.7E-10	-1.7E-10	-1.7E-10	-1.7E-10	-1.7E-10
-20	-2.4E-10	-1.9E-10	-1.8E-10	-1.4E-09	-2.2E-10	-2.1E-10	-2.1E-10	-2.0E-10	-2.0E-10	-2.0E-10	-2.0E-10	-2.0E-10	-2.0E-10	-2.0E-10	-2.0E-10	-1.9E-10	-1.9E-10
BVdss (V):	66	66	**5.995**	67	67	67	67	67	67	67	67	66	63	**59.99**	**57**	**54**	**51**
Idss (uA):	0.1629	19.82	n/a	0.1591	10.31	21.09	30.37	49.82	66.81	99.11	131.8	175.5	220.8	262.9	n/a	n/a	n/a
Vth (V):	2.29	1.30	0.92	2.26	1.47	1.17	1.03	0.90	0.81	0.73	0.64	0.57	0.50	0.45	0.42	0.38	0.34

Run #:	pre	39	pre	60	61	62	63	64	65	66	67
DUT S/N:	**12**	12	**17**	17	17	17	17	17	17	17	17
Run Vds (V):	--	**24 (-10Vgs)**	--	24	27	30	33	36	39	42	45
Ion species:	--	Ar	--	**Ne**	Ne	Ne	Ne	Ne	Ne	Ne	Ne
Vgs (V)											
0	9.6E-14	3.0E-12	-1.1E-12	-2.1E-12	-2.0E-12	-7.2E-13	-2.4E-13	-2.5E-13	-6.5E-13	4.6E-13	-5.7E-13
2	-6.1E-12	-2.9E-11	9.2E-11	1.8E-10	1.9E-10	1.9E-10	1.9E-10	1.9E-10	1.9E-10	1.9E-10	8.4E-11
4	1.7E-11	9.3E-12	1.9E-10	3.7E-10	3.8E-10	3.7E-10	3.8E-10	3.8E-10	3.8E-10	3.7E-10	2.0E-10
6	-2.2E-11	-2.4E-11	2.4E-10	5.2E-10	5.2E-10	5.1E-10	5.2E-10	5.2E-10	5.2E-10	5.1E-10	2.5E-10
8	-1.4E-11	-1.8E-11	3.3E-10	7.1E-10	7.1E-10	7.0E-10	7.1E-10	7.1E-10	7.1E-10	7.0E-10	3.5E-10
10	-7.3E-12	-1.2E-11	4.3E-10	8.9E-10	9.0E-10	8.9E-10	9.0E-10	9.0E-10	9.0E-10	8.9E-10	4.5E-10
12	-1.4E-12	-6.8E-12	5.3E-10	1.1E-09	1.2E-09	1.1E-09	1.2E-09	1.2E-09	1.2E-09	1.1E-09	5.6E-10
14	3.9E-12	-1.6E-12	6.2E-10	1.3E-09	1.3E-09	1.3E-09	1.3E-09	1.3E-09	1.3E-09	1.3E-09	6.6E-10
16	1.0E-11	2.4E-12	7.1E-10	1.5E-09	1.5E-09	1.5E-09	1.5E-09	1.5E-09	1.5E-09	1.5E-09	7.7E-10
18	1.5E-11	5.6E-12	8.1E-10	1.7E-09	1.7E-09	1.7E-09	1.7E-09	1.7E-09	1.7E-09	1.7E-09	8.7E-10
20	1.9E-11	9.2E-12	9.1E-10	1.9E-09	1.9E-09	1.9E-09	1.9E-09	1.9E-09	1.9E-09	1.9E-09	9.8E-10
0	-8.4E-11	-9.3E-11	-1.1E-10	-4.4E-11	-4.2E-11	-4.1E-11	-4.1E-11	-4.0E-11	-4.1E-11	-3.9E-11	-1.3E-10
-2	-9.9E-11	-6.3E-11	-2.0E-10	-2.2E-10	-2.2E-10	-2.1E-10	-2.1E-10	-2.1E-10	-2.1E-10	-2.1E-10	-2.1E-10
-4	-3.8E-11	-2.8E-11	-3.0E-10	-4.7E-10	-4.7E-10	-4.6E-10	-4.6E-10	-4.6E-10	-4.6E-10	-4.6E-10	-3.1E-10
-6	-3.6E-11	-8.8E-11	-3.8E-10	-6.6E-10	-6.6E-10	-6.5E-10	-6.6E-10	-6.5E-10	-6.5E-10	-6.5E-10	-4.0E-10
-8	-1.0E-10	-9.5E-11	-4.7E-10	-8.3E-10	-8.5E-10	-8.3E-10	-8.5E-10	-8.5E-10	-8.3E-10	-8.4E-10	-5.1E-10
-10	-4.4E-11	-9.8E-11	-5.7E-10	-9.8E-10	-9.8E-10	-9.7E-10	-9.8E-10	-9.8E-10	-9.8E-10	-9.7E-10	-6.1E-10
-12	-4.3E-11	-3.9E-11	-6.6E-10	-1.2E-09	-1.2E-09	-1.2E-09	-1.2E-09	-1.2E-09	-1.2E-09	-1.2E-09	-7.1E-10
-14	-4.8E-11	-3.8E-11	-7.5E-10	-1.4E-09	-1.4E-09	-1.4E-09	-1.4E-09	-1.4E-09	-1.4E-09	-1.4E-09	-8.2E-10
-16	-1.1E-10	-4.0E-11	-8.3E-10	-1.6E-09	-1.6E-09	-1.6E-09	-1.6E-09	-1.6E-09	-1.6E-09	-1.6E-09	-9.3E-10
-18	-1.3E-10	-1.1E-10	-9.4E-10	-1.8E-09	-1.8E-09	-1.7E-09	-1.8E-09	-1.8E-09	-1.8E-09	-1.7E-09	-9.9E-10
-20	-2.3E-10	-1.8E-10	-9.9E-10	-2.0E-09	-2.0E-09	-1.9E-09	-2.0E-09	-2.0E-09	-2.0E-09	-1.9E-09	-1.1E-09
BVdss (V):	67	**0.9954**	68	66.99	67	67	67	67	67	67	**4.997**
Idss (uA):	0.1394	n/a	0.1081	0.0182	0.0365	0.463	0.379	0.429	0.551	5.696	n/a
Vth (V):	2.30	0.07	2.25	2.17	2.06	1.97	1.89	1.83	1.78	1.71	1.48

Table C2. Pre- and Post-Irradiation Electrical Characterization Test Results for 4/12/2017 LBNL Tests
Note: Shaded columns flag new DUT. Out-of-spec values are in orange or red text

Run #:	pre 89	89	90	91	92	93	94	95	pre 96	96	97	98	99	100
DUT S/N:	114	114	114	114	114	114	114	114	120	120	120	120	120	120
Run Vds (V):	n/a	24	27	30	33	36	39	42	n/a	33	36	39	42	45
Vgs (V)	Igs (A)	Cu	Cu	Cu	Cu	Cu	Cu	Cu	n/a	Cu	Cu	Cu	Cu	Cu
0	-3.24E-13	3.82E-13	-4.23E-14	-8.03E-14	2.62E-13	-9.03E-14	4.06E-13	-2.79E-14	-5.55E-13	-9.99E-13	-1.28E-12	-8.66E-13	-9.01E-13	-4.96E-13
4	4.31E-12	4.18E-12	3.67E-12	3.84E-12	3.90E-12	3.97E-12	4.03E-12	4.00E-12	1.95E-11	3.19E-11	3.34E-11	3.43E-11	3.47E-11	3.17E-11
8	-3.51E-11	-3.60E-11	-3.44E-11	-3.37E-11	-3.34E-11	-3.38E-11	-3.37E-11	-3.26E-11	6.77E-11	7.46E-11	7.61E-11	7.48E-11	7.63E-11	7.76E-11
12	-3.00E-11	-2.97E-11	-2.94E-11	-2.89E-11	-2.86E-11	-2.88E-11	-2.92E-11	-2.86E-11	5.90E-11	5.96E-11	6.04E-11	6.03E-11	6.09E-11	6.06E-11
16	-2.69E-11	-2.67E-11	-2.63E-11	-2.58E-11	-2.67E-11	-2.43E-11	-2.58E-11	-2.58E-11	1.21E-10	1.21E-10	1.22E-10	1.22E-10	1.22E-10	1.21E-10
20	-2.39E-11	-2.40E-11	-2.27E-11	-2.21E-11	-2.30E-11	-2.19E-11	-2.24E-11	-2.29E-11	1.50E-10	1.50E-10	1.53E-10	1.53E-10	1.54E-10	1.52E-10
0	-9.96E-12	-4.61E-11	-2.85E-11	-4.61E-11	-4.64E-11	-4.65E-11	-4.63E-11	-4.64E-11	-2.81E-11	-1.48E-10	-1.50E-10	-1.50E-10	-1.50E-10	-1.51E-10
-4	-7.27E-11	-1.21E-11	-1.15E-11	-1.25E-11	-1.23E-11	-1.22E-11	-1.26E-11	-7.71E-11	-4.37E-11	-3.26E-11	-3.28E-11	-3.33E-11	-3.35E-11	-1.94E-10
-8	-7.68E-11	-7.49E-11	-7.71E-11	-7.98E-11	-7.64E-11	-7.92E-11	-7.85E-11	-8.07E-11	-1.93E-10	-5.28E-11	-5.27E-11	-5.31E-11	-5.30E-11	-2.09E-10
-12	-8.14E-11	-8.12E-11	-8.24E-11	-8.17E-11	-8.06E-11	-8.12E-11	-8.07E-11	-8.35E-11	-2.18E-10	-2.11E-10	-2.12E-10	-2.14E-10	-2.11E-10	-2.25E-10
-16	-8.25E-11	-8.38E-11	-8.45E-11	-8.54E-11	-8.46E-11	-8.44E-11	-8.37E-11	-8.58E-11	-2.38E-10	-2.38E-10	-2.35E-10	-2.37E-10	-2.38E-10	-2.44E-10
-20	-5.35E-11	-4.70E-11	-4.37E-11	-4.12E-11	-4.01E-11	-3.92E-11	-3.80E-11	-3.76E-11	-3.10E-10	-3.03E-10	-2.97E-10	-2.97E-10	-2.92E-10	-2.92E-10
BVdss (V):	69	--	--	--	--	--	69	10	69	--	--	69	--	7
Idss (µA):	0.001393	8.415	25.12	32.94	41.82	56.08	76.85	--	0.001413	17.31	34.31	62.92	80.76	--
Vth (V):	2.22	1.82	1.34	1.15	1.02	0.917	0.805	0.684	2.39	1.53	1.18	0.946	0.825	0.694

Run #:	pre 101	101	pre 111	111	112	113	114	115	116	117
DUT S/N:	107	107	117	117	117	117	117	117	117	117
Run Vds (V):	n/a	39	n/a	24	27	30	33	36	39	42
Vgs (V)	Igs (A)	Cu	n/a	Kr	Kr	Kr	Kr	Kr	Kr	Kr
0	-2.14E-13	-5.37E-13	-2.03E-13	-8.51E-13	-1.09E-12	-1.13E-12	-1.03E-12	-1.13E-12	-8.20E-13	-5.45E-13
4	5.34E-12	5.41E-12	3.97E-12	4.27E-12	3.71E-12	3.79E-12	3.93E-12	4.56E-12	4.68E-12	2.83E-12
8	-3.22E-11	-3.20E-11	-3.60E-11	-3.24E-11	-3.28E-11	-3.20E-11	-3.16E-11	-3.21E-11	-3.09E-11	-3.14E-11
12	-2.73E-11	-2.64E-11	-3.09E-11	-2.78E-11	-2.70E-11	-2.85E-11	-2.64E-11	-2.69E-11	-2.60E-11	-2.67E-11
16	-2.31E-11	-2.17E-11	-2.74E-11	-2.46E-11	-2.32E-11	-2.35E-11	-2.20E-11	-2.19E-11	-2.16E-11	-2.14E-11
20	-1.93E-11	-1.83E-11	-2.48E-11	-2.25E-11	-2.10E-11	-2.04E-11	-1.90E-11	-1.89E-11	-1.82E-11	-1.84E-11
0	-1.10E-11	-4.73E-11	-9.40E-12	-5.29E-11	-5.36E-11	-5.40E-11	-5.52E-11	-5.48E-11	-5.53E-11	-5.51E-11
-4	-7.43E-11	-7.92E-11	-7.35E-11	-1.27E-11	-1.32E-11	-1.35E-11	-1.40E-11	-1.43E-11	-1.48E-11	-4.71E-11
-8	-8.17E-11	-8.23E-11	-7.55E-11	-7.75E-11	-7.80E-11	-7.72E-11	-7.88E-11	-7.78E-11	-7.86E-11	-8.08E-11
-12	-8.36E-11	-8.64E-11	-7.87E-11	-7.94E-11	-8.32E-11	-8.20E-11	-8.15E-11	-8.22E-11	-8.27E-11	-8.45E-11
-16	-8.75E-11	-9.09E-11	-8.24E-11	-8.31E-11	-8.36E-11	-8.62E-11	-8.58E-11	-8.74E-11	-8.67E-11	-9.09E-11
-20	-4.75E-11	-4.58E-11	-3.40E-11	-9.97E-11	-9.85E-11	-9.89E-11	-9.74E-11	-9.90E-11	-9.99E-11	-9.85E-11
BVdss (V):	> 60	34	72	--	72	--	72	72	72	7
Idss (µA):	0.001487	--	0.001625	12.24	35.55	53.27	83.27	102.6	126.4	--
Vth (V):	2.24	2.15	2.31	1.69	1.21	1.02	0.864	0.756	0.674	0.446

Table C3. Pre- and Post-Irradiation Electrical Characterization Test Results for 10/15/2016 MGH Tests
Note: Shaded columns flag new DUT. Out-of-spec values are in orange or red text

Run #:	pre 1	1	2	3	4	5	6	7	8	9	10	11	12	13
DUT S/N:	102	102	102	102	102	102	102	102	102	102	102	102	102	102
Run Vds (V):	0	24	27	30	33	36	39	42	45	48	51	54	57	60
comments:														
Vgs (V)	Ids (A)													
0	-7.40E-12	9.26E-12	1.22E-11	8.35E-12	1.43E-11	8.17E-12	8.31E-12	5.50E-12	7.06E-12	3.18E-12	1.39E-11	6.66E-12	2.60E-12	4.43E-12
2	-5.87E-12	1.13E-11	1.59E-11	1.08E-11	1.44E-11	1.12E-11	9.54E-12	8.63E-12	8.59E-12	4.58E-12	1.45E-11	5.17E-12	3.08E-12	5.57E-12
4	-3.39E-12	1.39E-11	1.41E-11	1.29E-11	1.40E-11	1.21E-11	9.19E-12	1.05E-11	1.07E-11	8.13E-12	7.66E-12	7.26E-12	8.98E-12	5.29E-12
6	4.39E-13	1.61E-11	1.44E-11	1.44E-11	9.92E-12	1.71E-11	2.02E-11	9.56E-12	1.16E-11	8.65E-12	2.63E-12	1.44E-11	1.22E-11	8.93E-12
8	-7.71E-13	1.73E-11	1.58E-11	1.53E-11	1.76E-11	1.97E-11	1.91E-11	1.25E-11	1.68E-11	1.25E-11	1.20E-11	1.62E-11	1.51E-11	1.62E-11
10	6.50E-12	2.11E-11	1.99E-11	1.96E-11	2.66E-11	2.50E-11	1.59E-11	1.57E-11	2.08E-11	1.57E-11	2.57E-11	2.41E-11	1.77E-11	1.81E-11
12	1.10E-11	2.55E-11	2.50E-11	2.25E-11	2.64E-11	2.56E-11	2.19E-11	1.89E-11	2.15E-11	1.84E-11	2.48E-11	2.10E-11	1.84E-11	1.93E-11
14	1.39E-11	2.85E-11	3.07E-11	2.52E-11	2.83E-11	2.99E-11	3.28E-11	2.29E-11	2.61E-11	2.23E-11	1.82E-11	1.66E-11	2.30E-11	2.19E-11
16	1.84E-11	2.87E-11	3.71E-11	3.05E-11	3.71E-11	3.55E-11	3.06E-11	2.88E-11	3.91E-11	2.81E-11	2.50E-11	2.59E-11	2.68E-11	2.65E-11
18	1.04E-11	3.36E-11	3.57E-11	3.36E-11	4.02E-11	3.58E-11	3.40E-11	3.54E-11	3.71E-11	3.06E-11	3.30E-11	2.76E-11	3.14E-11	3.27E-11
20	1.57E-11	3.66E-11	3.22E-11	4.04E-11	3.95E-11	3.99E-11	4.45E-11	3.77E-11	4.07E-11	3.53E-11	4.14E-11	3.72E-11	3.73E-11	3.53E-11
-2	-6.43E-11	-5.50E-11	-5.45E-11	-5.75E-11	-6.34E-11	-6.60E-11	-6.60E-11	-6.83E-11	-6.79E-11	-6.97E-11	-7.09E-11	-7.71E-11	-7.58E-11	-7.95E-11
-4	-3.37E-11	-3.75E-11	-2.90E-11	-2.77E-11	-3.02E-11	-2.69E-11	-2.27E-11	-2.28E-11	-2.43E-11	-2.52E-11	-2.32E-11	-2.98E-11	-2.58E-11	-3.26E-11
-6	-3.27E-11	-1.74E-11	-1.33E-11	-2.15E-11	-1.76E-11	-1.76E-11	-1.46E-11	-1.93E-11	-2.37E-11	-2.24E-11	-1.97E-11	-2.21E-11	-2.36E-11	-2.64E-11
-8	-3.08E-11	-1.72E-11	-1.89E-11	-1.75E-11	-1.62E-11	-2.37E-11	-1.96E-11	-2.16E-11	-2.50E-11	-2.51E-11	-2.86E-11	-1.77E-11	-2.64E-11	-2.62E-11
-10	-3.26E-11	-1.83E-11	-2.65E-11	-1.76E-11	-2.14E-11	-2.63E-11	-2.58E-11	-2.59E-11	-2.75E-11	-3.03E-11	-2.23E-11	-2.83E-11	-3.10E-11	-3.28E-11
-12	-2.91E-11	-2.13E-11	-1.91E-11	-2.27E-11	-2.83E-11	-2.83E-11	-2.79E-11	-2.92E-11	-2.76E-11	-3.19E-11	-2.86E-11	-2.76E-11	-3.44E-11	-3.33E-11
-14	-2.80E-11	-2.50E-11	-2.73E-11	-2.47E-11	-2.84E-11	-2.85E-11	-2.76E-11	-3.34E-11	-3.36E-11	-3.51E-11	-2.80E-11	-3.67E-11	-3.92E-11	-3.58E-11
-16	-3.19E-11	-2.73E-11	-3.22E-11	-2.75E-11	-3.61E-11	-3.19E-11	-3.36E-11	-3.41E-11	-3.62E-11	-3.77E-11	-4.15E-11	-4.00E-11	-4.50E-11	-4.41E-11
-18	-4.33E-11	-3.14E-11	-3.09E-11	-3.38E-11	-3.85E-11	-3.12E-11	-4.39E-11	-4.13E-11	-4.41E-11	-4.89E-11	-3.66E-11	-4.99E-11	-4.88E-11	-5.53E-11
-20	-8.87E-11	-6.53E-11	-5.62E-11	-5.83E-11	-5.62E-11	-5.73E-11	-6.23E-11	-5.68E-11	-6.09E-11	-5.82E-11	-6.00E-11	-6.30E-11	-6.33E-11	-6.43E-11
BVdss (V):														
Idss (uA):	0.000866	0.000922	0.000927	0.001017	0.001158	0.001123	0.001113	0.001229	0.001249	0.001299	0.001355	0.00146	0.001576	0.001581
Vth (V):	2.19	2.18	2.16	2.14	2.13	2.11	2.1	2.08	2.06	2.05	2.03	2.02	2.01	1.99

Run #:	pre 14	14	15	16	pre 17	17	18	19	20	21	22	23
DUT S/N:	103	103	103	103	104	104	104	104	104	104	104	104
Run Vds (V):	0	60	60	60	0	45	48	51	54	57	60	60
comments:				Vgs = -10V								Vgs = -10V
Vgs (V)												
0	1.58E-12	-5.20E-12	-5.27E-12	6.57E-13	-4.41E-11	-3.82E-12	1.19E-11	1.58E-12	4.42E-12	8.85E-12	8.44E-12	1.59E-11
2	-8.20E-12	-4.61E-12	-2.63E-12	5.05E-12	-4.08E-11	-1.38E-12	1.32E-11	4.28E-12	7.92E-12	9.04E-12	1.06E-11	1.79E-11
4	2.38E-12	-1.26E-12	4.51E-12	9.89E-12	-3.70E-11	-7.75E-13	1.29E-11	8.91E-12	1.06E-11	1.25E-11	2.03E-11	1.96E-11
6	-2.24E-12	2.15E-12	1.73E-11	1.94E-11	-4.34E-11	6.93E-12	9.11E-12	1.65E-11	1.70E-11	1.67E-11	2.04E-11	1.49E-11
8	-1.00E-11	8.36E-12	1.42E-11	2.11E-11	-4.21E-11	7.33E-12	1.84E-11	2.37E-11	2.53E-11	2.47E-11	1.97E-11	2.06E-11
10	-7.09E-13	1.14E-11	1.39E-11	2.23E-11	-3.57E-11	1.60E-11	1.84E-11	2.47E-11	2.57E-11	2.76E-11	2.69E-11	3.36E-11
12	5.85E-12	1.56E-11	2.19E-11	2.77E-11	-2.74E-11	1.70E-11	1.54E-11	2.42E-11	2.43E-11	3.17E-11	3.95E-11	3.64E-11
14	-6.18E-13	1.66E-11	3.36E-11	3.68E-11	-3.09E-11	1.69E-11	2.38E-11	3.05E-11	3.12E-11	3.76E-11	4.13E-11	3.50E-11
16	2.21E-12	1.15E-11	4.09E-11	3.72E-11	-2.63E-11	2.35E-11	2.51E-11	3.90E-11	4.34E-11	3.97E-11	3.67E-11	4.13E-11
18	1.41E-11	2.00E-11	5.01E-11	3.84E-11	-2.11E-11	2.44E-11	3.57E-11	3.70E-11	4.46E-11	4.28E-11	4.73E-11	5.42E-11
20	1.08E-11	2.85E-11	4.50E-11	4.20E-11	-2.45E-11	3.01E-11	3.99E-11	4.48E-11	4.14E-11	4.64E-11	5.02E-11	5.55E-11
-2	-7.30E-11	-7.00E-11	-7.41E-11	-6.43E-11	-1.06E-10	-7.25E-11	-7.02E-11	-6.79E-11	-7.33E-11	-7.13E-11	-7.07E-11	-7.59E-11
-4	-2.98E-11	-3.60E-11	-2.61E-11	-2.09E-11	-5.80E-11	-2.92E-11	-2.97E-11	-3.02E-11	-2.40E-11	-2.70E-11	-2.96E-11	-3.10E-11
-6	-2.78E-11	-2.27E-11	-1.81E-11	-1.76E-11	-5.88E-11	-2.84E-11	-2.55E-11	-2.77E-11	-2.65E-11	-2.76E-11	-3.07E-11	-2.86E-11
-8	-3.43E-11	-3.02E-11	-2.51E-11	-2.23E-11	-6.21E-11	-2.93E-11	-2.40E-11	-2.28E-11	-3.45E-11	-3.13E-11	-3.03E-11	-2.83E-11
-10	-3.36E-11	-3.71E-11	-2.48E-11	-3.04E-11	-5.51E-11	-3.27E-11	-3.04E-11	-3.07E-11	-3.60E-11	-3.44E-11	-3.39E-11	-3.26E-11
-12	-2.75E-11	-2.73E-11	-3.75E-11	-3.21E-11	-6.47E-11	-3.12E-11	-4.18E-11	-3.10E-11	-3.10E-11	-3.56E-11	-3.95E-11	-3.93E-11
-14	-3.04E-11	-4.13E-11	-3.29E-11	-3.17E-11	-6.17E-11	-3.56E-11	-3.77E-11	-3.74E-11	-3.79E-11	-4.21E-11	-4.40E-11	-4.38E-11
-16	-3.80E-11	-3.93E-11	-4.10E-11	-3.78E-11	-6.77E-11	-3.82E-11	-4.43E-11	-4.42E-11	-5.18E-11	-4.79E-11	-4.81E-11	-4.69E-11
-18	-4.03E-11	-4.43E-11	-4.83E-11	-4.39E-11	-7.69E-11	-4.46E-11	-4.89E-11	-4.16E-11	-4.89E-11	-4.99E-11	-5.28E-11	-5.35E-11
-20	-7.10E-11	-6.16E-11	-6.55E-11	-6.46E-11	-1.21E-10	-8.04E-11	-7.54E-11	-7.28E-11	-8.01E-11	-7.25E-11	-7.41E-11	-7.35E-11
BVdss (V):												
Idss (uA):	0.000761	0.000776	0.0014	0.2834	0.000655	0.000831	0.000756	0.000927	0.000897	0.000992	0.001048	5.451
Vth (V):	2.30	2.29	2.13	2.06	2.27	2.25	2.24	2.22	2.20	2.19	2.17	2.10

Run #:	pre 24	24	25	26	27	28	29
DUT S/N:	105	105	105	105	105	105	105
Run Vds (V):	0	45	48	51	54	57	60
comments:							
Vgs (V)							
0	-2.40E-11	1.08E-12	2.65E-12	7.57E-12	1.11E-11	1.44E-11	1.39E-11
2	-1.86E-11	7.01E-12	1.13E-11	1.36E-11	2.20E-11	2.28E-11	2.64E-11
4	-6.68E-12	1.73E-11	1.37E-11	2.63E-11	3.10E-11	2.92E-11	3.81E-11
6	-5.31E-12	2.46E-11	2.79E-11	4.46E-11	3.57E-11	4.14E-11	4.39E-11
8	-5.02E-12	2.87E-11	4.49E-11	4.76E-11	4.77E-11	5.97E-11	5.59E-11
10	5.56E-13	3.34E-11	4.85E-11	5.78E-11	6.09E-11	6.14E-11	6.47E-11
12	1.38E-11	4.47E-11	4.56E-11	6.22E-11	6.61E-11	7.39E-11	7.50E-11
14	1.58E-11	4.89E-11	6.37E-11	7.65E-11	7.15E-11	7.84E-11	8.74E-11
16	2.08E-11	6.29E-11	7.43E-11	7.71E-11	8.34E-11	8.65E-11	9.81E-11
18	1.79E-11	6.34E-11	7.75E-11	9.03E-11	9.44E-11	9.09E-11	1.09E-10
20	2.41E-11	6.87E-11	7.41E-11	9.37E-11	9.85E-11	1.08E-10	1.20E-10
-2	-9.89E-11	-8.51E-11	-9.04E-11	-1.01E-10	-8.79E-11	-7.88E-11	-8.66E-11
-4	-5.27E-11	-3.84E-11	-4.36E-11	-5.34E-11	-4.29E-11	-4.08E-11	-4.09E-11
-6	-5.99E-11	-4.10E-11	-4.41E-11	-4.70E-11	-4.18E-11	-3.61E-11	-4.21E-11
-8	-6.30E-11	-4.27E-11	-4.86E-11	-4.21E-11	-5.08E-11	-4.67E-11	-4.95E-11
-10	-6.59E-11	-4.80E-11	-5.29E-11	-4.74E-11	-5.33E-11	-4.90E-11	-5.82E-11
-12	-6.93E-11	-5.53E-11	-6.79E-11	-6.43E-11	-5.99E-11	-6.23E-11	-6.79E-11
-14	-6.37E-11	-6.04E-11	-6.48E-11	-6.00E-11	-6.57E-11	-6.88E-11	-7.58E-11
-16	-6.76E-11	-6.70E-11	-6.23E-11	-7.47E-11	-7.77E-11	-8.17E-11	-8.61E-11
-18	-8.40E-11	-7.32E-11	-7.53E-11	-7.82E-11	-9.67E-11	-9.94E-11	-9.67E-11
-20	-1.03E-10	-9.27E-11	-1.02E-10	-1.03E-10	-1.08E-10	-1.11E-10	-1.09E-10
BVdss (V):							
Idss (uA):	0.000952	0.001048	0.001199	0.001224	0.001304	0.001536	0.001632
Vth (V):	2.27	2.26	2.24	2.23	2.21	2.19	2.18

Appendix D

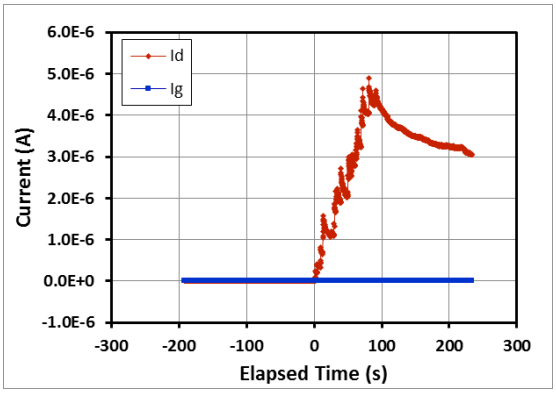

Figure D1. Strip tape data from DUT 7, run 1: 548 MeV Ar. Run bias conditions: 0 Vgs, 24 Vds. Beam shuttered after about 97 seconds.

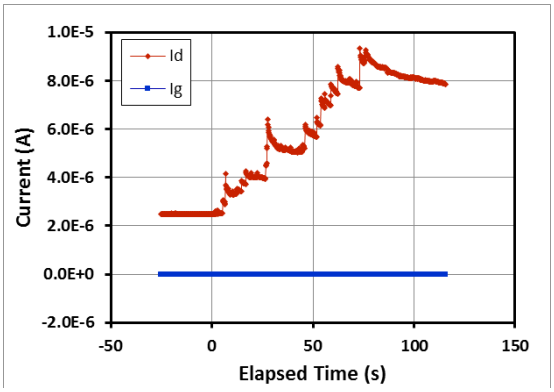

Figure D2. Strip tape data from DUT 7, run 2: 548 MeV Ar. Run bias conditions: 0 Vgs, 27 Vds. Beam shuttered after about 75 seconds.

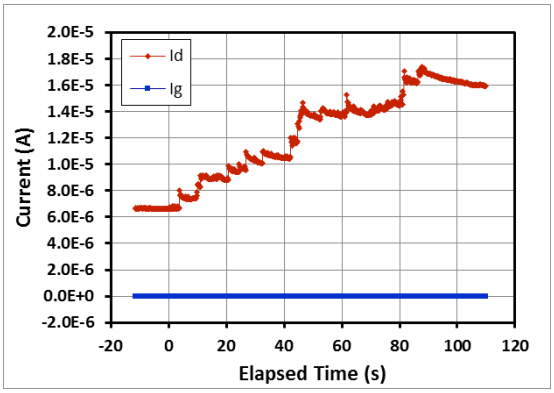

Figure D3. Strip tape data from DUT 7, run 3: 548 MeV Ar. Run bias conditions: 0 Vgs, 30 Vds. Beam shuttered after about 90 seconds.

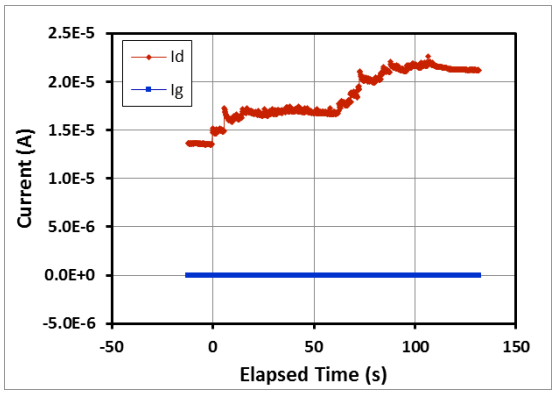

Figure D4. Strip tape data from DUT 7, run 4: 548 MeV Ar. Run bias conditions: 0 Vgs, 33 Vds. Beam shuttered after about 110 seconds.

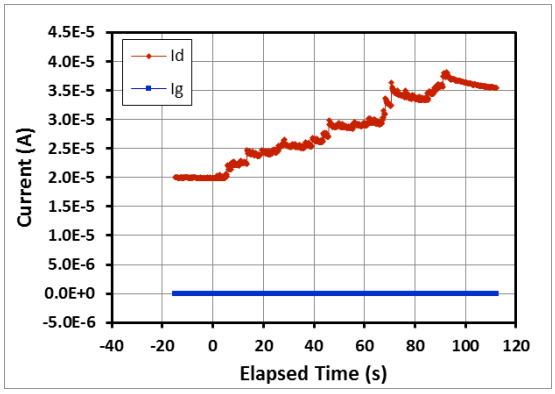

Figure D5. Strip tape data from DUT 7, run 5: 548 MeV Ar. Run bias conditions: 0 Vgs, 36 Vds. Beam shuttered after about 96 seconds.

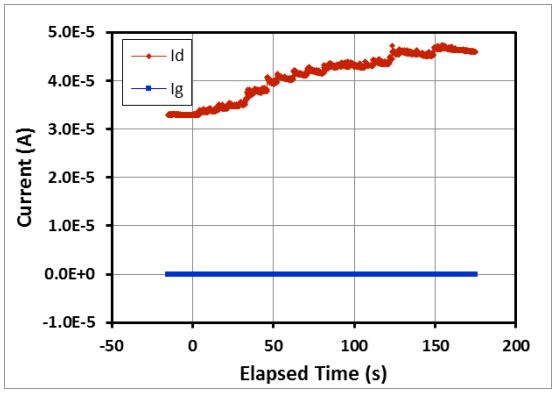

Figure D9. Strip tape data from DUT 7, run 6: 548 MeV Ar. Run bias conditions: 0 Vgs, 39 Vds. Beam shuttered after about 165 seconds.

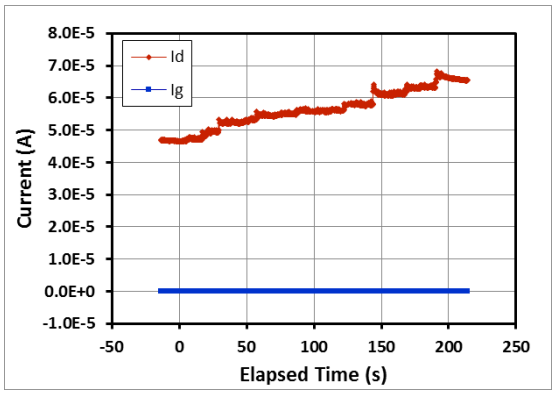

Figure D10. Strip tape data from DUT 7, run 7: 548 MeV Ar. Run bias conditions: 0 Vgs, 42 Vds. Beam shuttered after about 200 seconds.

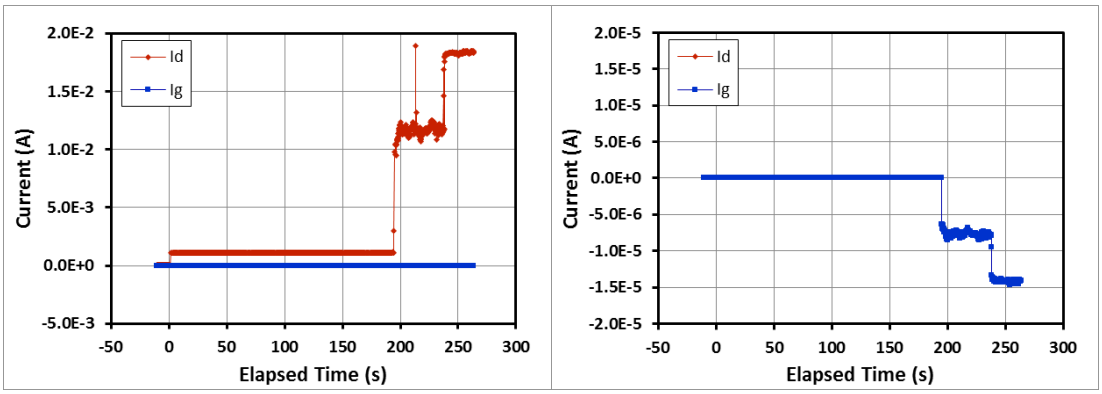

Figure D11. Strip tape data from DUT 7, run 8: 548 MeV Ar. Run bias conditions: 0 Vgs, 45 Vds. Beam shuttered after about 202 seconds. Right panel is the same plot but scaled to reveal gate current changes.

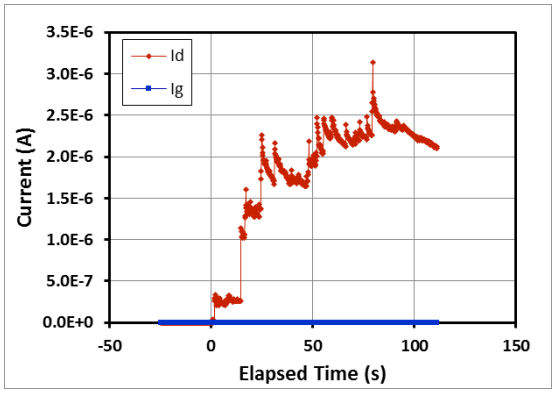

Figure D12. Strip tape data from DUT 8, run 9: 548 MeV Ar. Run bias conditions: 0 Vgs, 12 Vds. Beam shuttered after about 102 seconds. The gate leakage current on this DUT prior to exposure to Ar was out of spec; testing of this device was therefore discontinued.

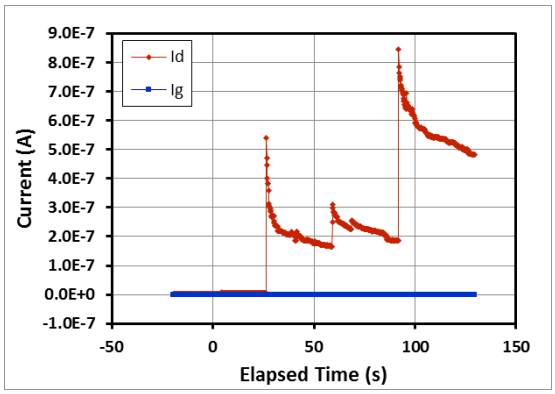

Figure D13. Strip tape data from DUT 9, run 10: 548 MeV Ar. Run bias conditions: 0 Vgs, 6 Vds. Beam shuttered after about 115 seconds.

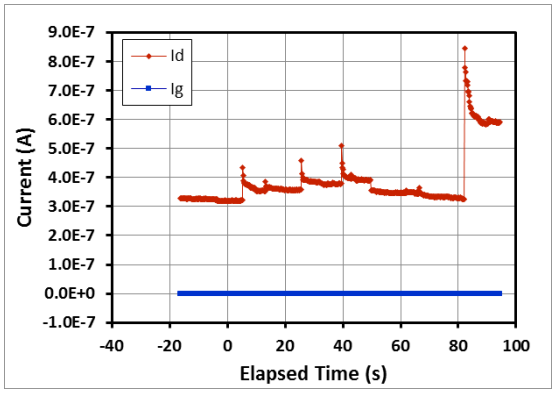

Figure D14. Strip tape data from DUT 9, run 11: 548 MeV Ar. Run bias conditions: 0 Vgs, 9 Vds. Beam shuttered after about 88 seconds.

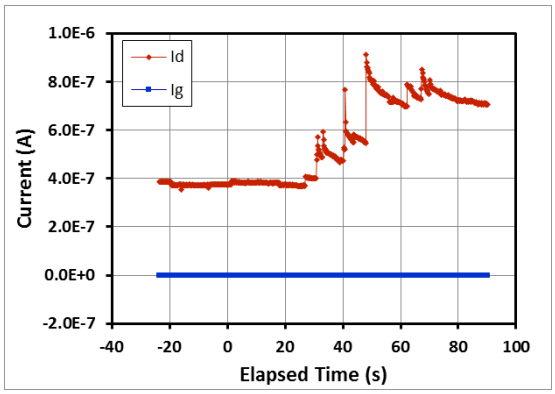

Figure D15. Strip tape data from DUT 9, run 12: 548 MeV Ar. Run bias conditions: 0 Vgs, 12 Vds. Beam shuttered after about 79 seconds.

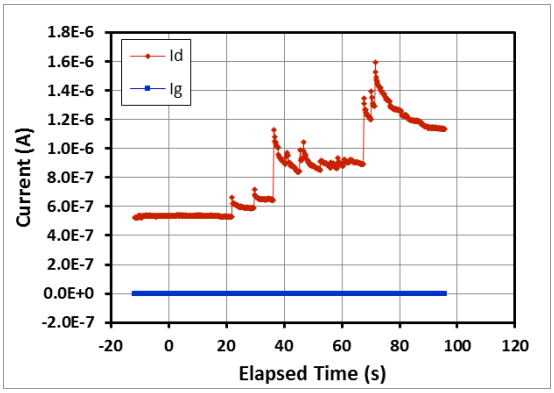

Figure D16. Strip tape data from DUT 9, run 13: 548 MeV Ar. Run bias conditions: 0 Vgs, 15 Vds. Beam shuttered after about 80 seconds.

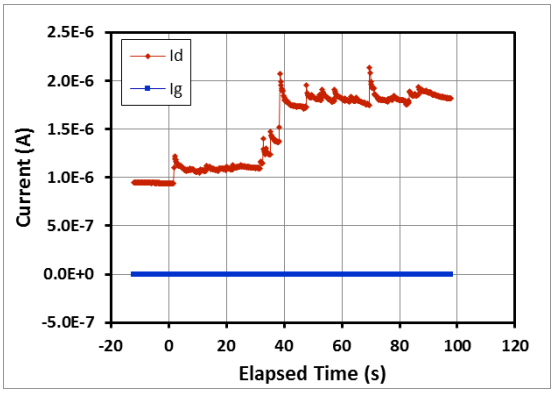

Figure D17. Strip tape data from DUT 9, run 14: 548 MeV Ar. Run bias conditions: 0 Vgs, 18 Vds. Beam shuttered after about 95 seconds.

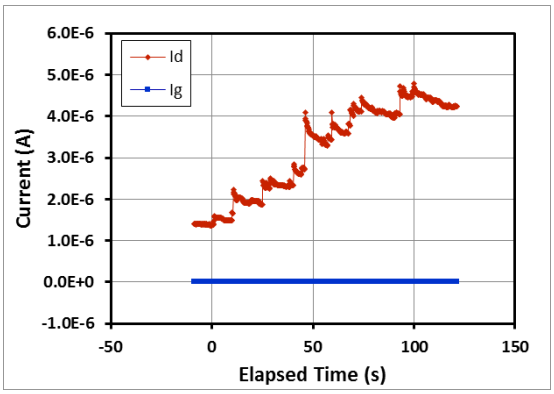

Figure D18. Strip tape data from DUT 9, run 15: 548 MeV Ar. Run bias conditions: 0 Vgs, 21 Vds. Beam shuttered after about 107 seconds.

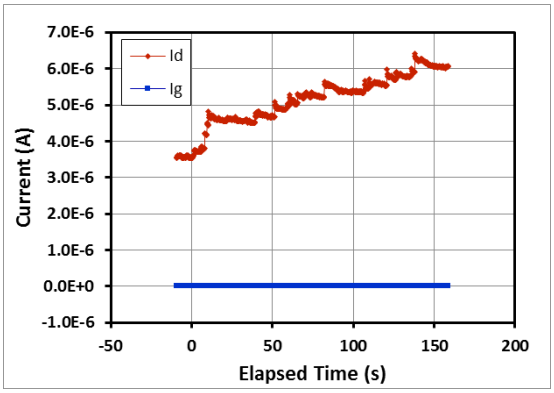

Figure D19. Strip tape data from DUT 9, run 16: 548 MeV Ar. Run bias conditions: 0 Vgs, 24 Vds. Beam shuttered after about 146 seconds.

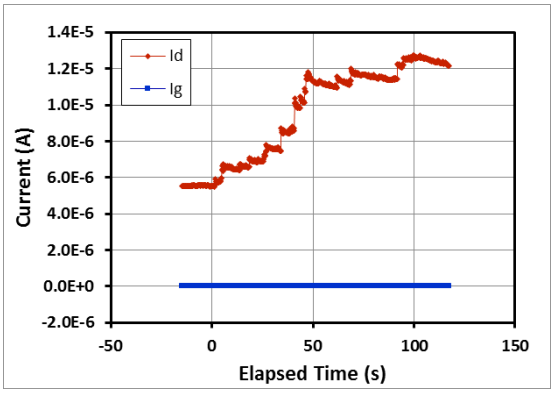

Figure D20. Strip tape data from DUT 9, run 17: 548 MeV Ar. Run bias conditions: 0 Vgs, 27 Vds. Beam shuttered after about 107 seconds.

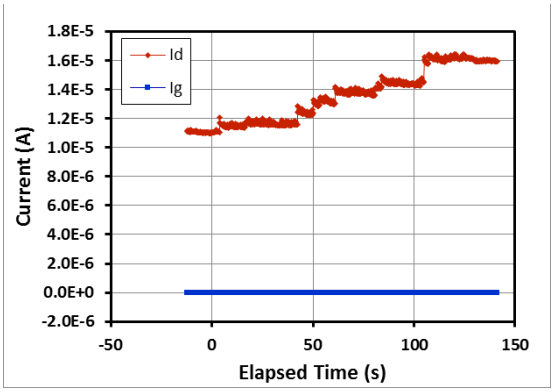

Figure D21. Strip tape data from DUT 9, run 18: 548 MeV Ar. Run bias conditions: 0 Vgs, 30 Vds. Beam shuttered after about 128 seconds.

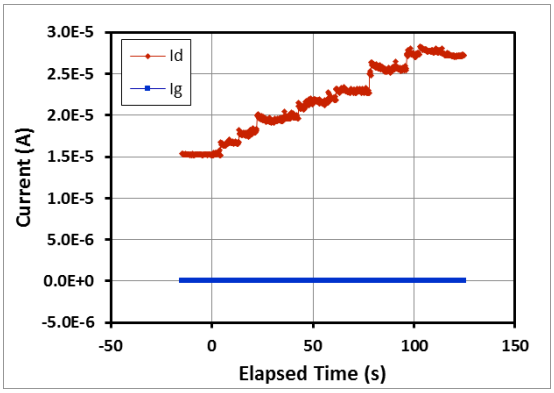

Figure D22. Strip tape data from DUT 9, run 19: 548 MeV Ar. Run bias conditions: 0 Vgs, 33 Vds. Beam shuttered after about 117 seconds.

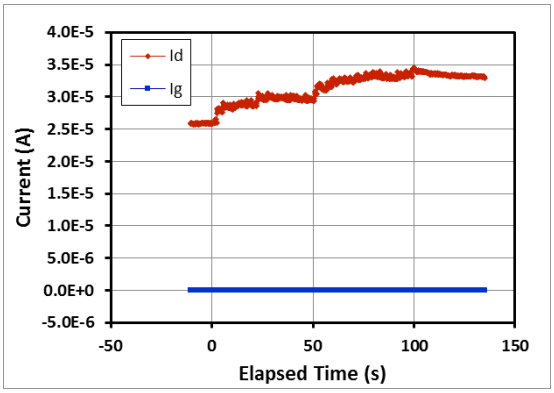

Figure D23. Strip tape data from DUT 9, run 20: 548 MeV Ar. Run bias conditions: 0 Vgs, 36 Vds. Beam shuttered after about 132 seconds.

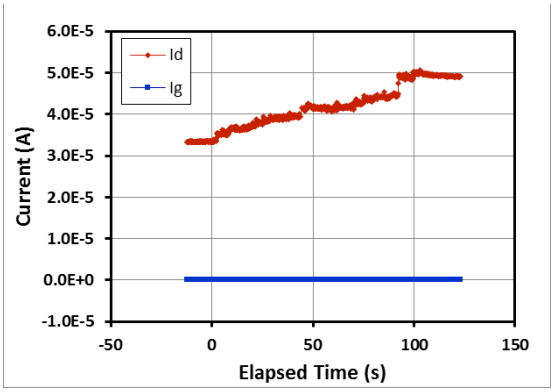

Figure D24. Strip tape data from DUT 9, run 21: 548 MeV Ar. Run bias conditions: 0 Vgs, 39 Vds. Beam shuttered after about 107 seconds.

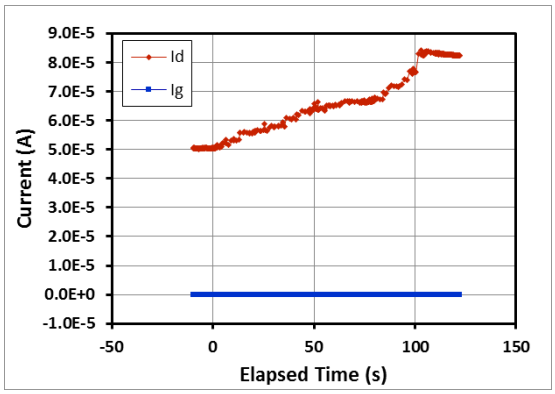

Figure D25. Strip tape data from DUT 9, run 22: 548 MeV Ar. Run bias conditions: 0 Vgs, 42 Vds. Beam shuttered after about 113 seconds.

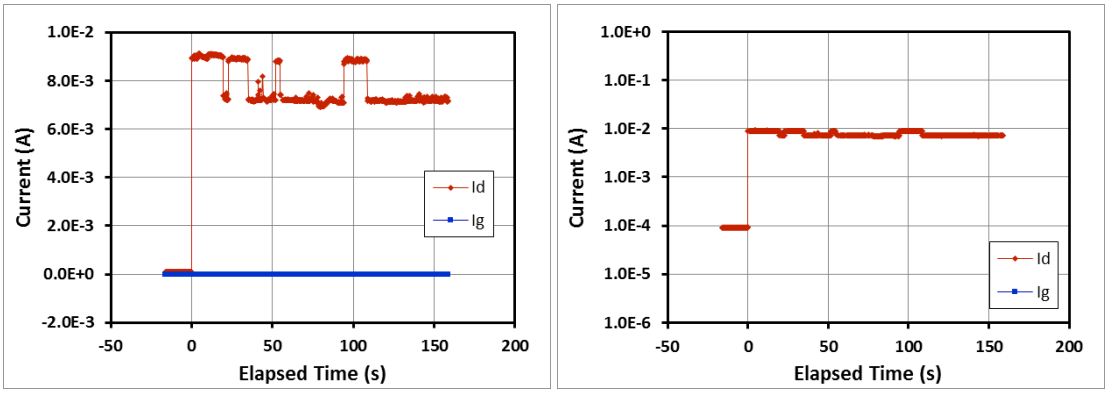

Figure D26. Strip tape data from DUT 9, run 23: 548 MeV Ar. Run bias conditions: 0 Vgs, 45 Vds. Beam shuttered after about 147 seconds. SEB occurs immediately upon beam exposure. Right panel shows same plot but with log scale. Gate current did not change. Instability of drain current is characteristic of trench MOSFET response to heavy-ion exposure and may reflect charge trapping/detrapping in the gate oxide/interface, effectively modifying the local gate threshold voltage at the ion strike location. Additional analyses would be required to understand this phenomenon and are out of scope of this report.

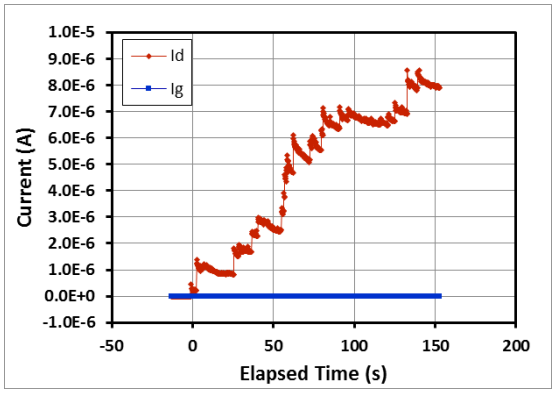

Figure D27. Strip tape data from DUT 10, run 24: 548 MeV Ar. Run bias conditions: 0 Vgs, 30 Vds. Beam shuttered after about 140 seconds.

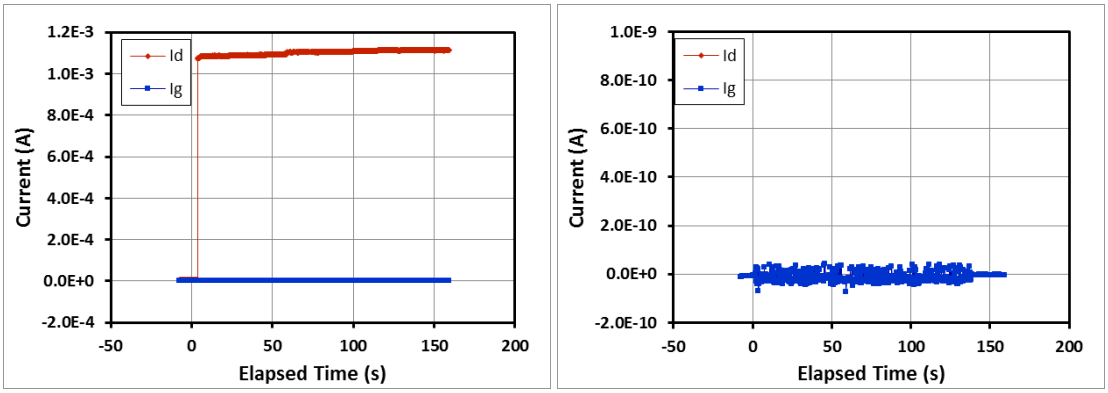

Figure D28. Strip tape data from DUT 10, run 25: 548 MeV Ar. Run bias conditions: 0 Vgs, 33 Vds. Beam shuttered after about 140 seconds. SEB occurred shortly after beam turned on. Gate current remained unchanged, as shown in right panel.

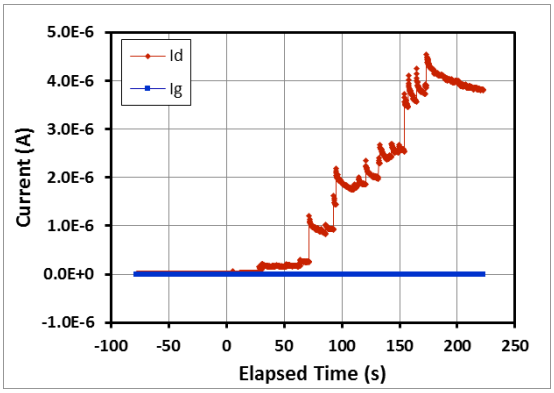

Figure D29. Strip tape data from DUT 11, run 26: 548 MeV Ar. Testing in SEB-protective mode with 10 kΩ external resistor on drain node. Run bias conditions: 0 Vgs, 24 Vds. Beam shuttered after about 196 seconds.

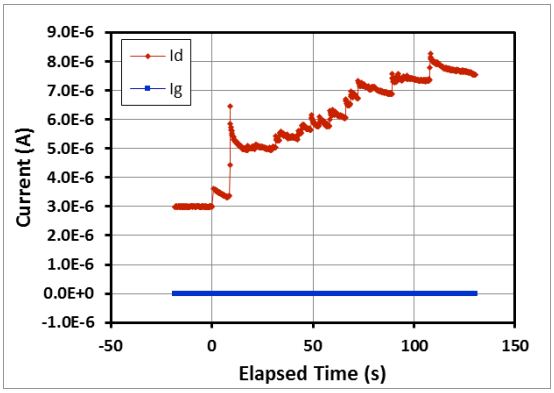

Figure D30. Strip tape data from DUT 11, run 27: 548 MeV Ar. Testing in SEB-protective mode with 10 kΩ external resistor on drain node. Run bias conditions: 0 Vgs, 27 Vds. Beam shuttered after about 112 seconds.

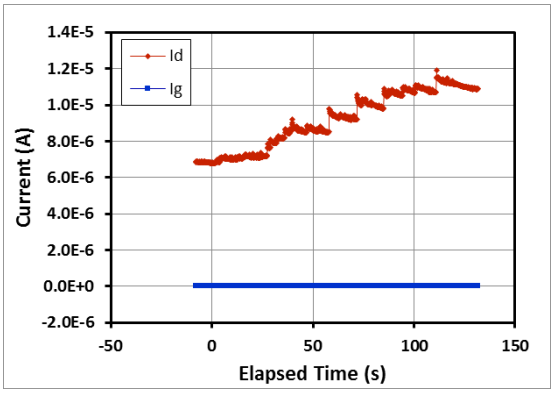

Figure D31. Strip tape data from DUT 11, run 28: 548 MeV Ar. Testing in SEB-protective mode with 10 kΩ external resistor on drain node. Run bias conditions: 0 Vgs, 30 Vds. Beam shuttered after about 124 seconds.

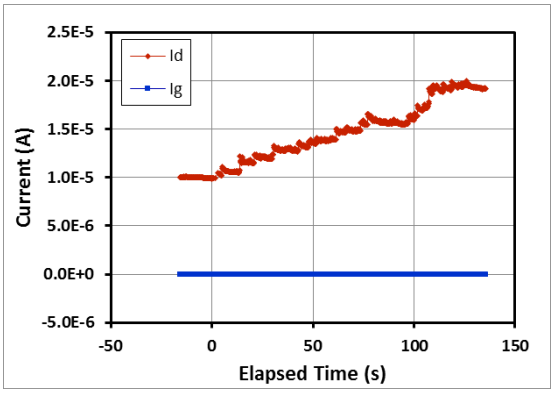

Figure D32. Strip tape data from DUT 11, run 29: 548 MeV Ar. Testing in SEB-protective mode with 10 kΩ external resistor on drain node. Run bias conditions: 0 Vgs, 33 Vds. Beam shuttered after about 129 seconds.

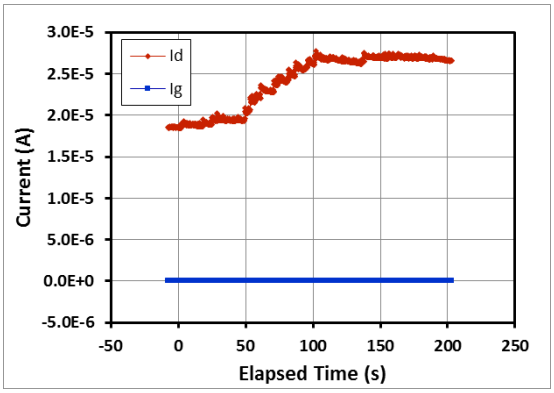

Figure D33. Strip tape data from DUT 11, run 30: 548 MeV Ar. Testing in SEB-protective mode with 10 kΩ external resistor on drain node. Run bias conditions: 0 Vgs, 36 Vds. Beam shuttered after about 193 seconds.

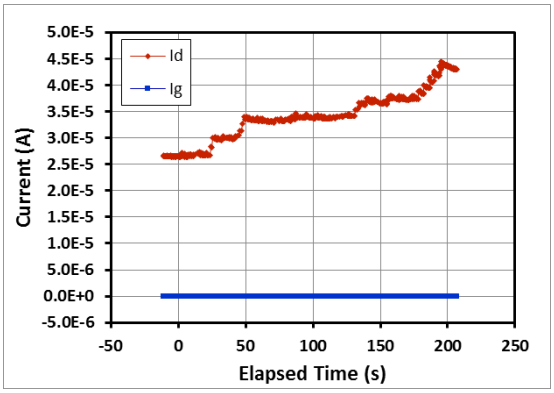

Figure D34. Strip tape data from DUT 11, run 31: 548 MeV Ar. Testing in SEB-protective mode with 10 kΩ external resistor on drain node. Run bias conditions: 0 Vgs, 39 Vds. Beam shuttered after about 198 seconds.

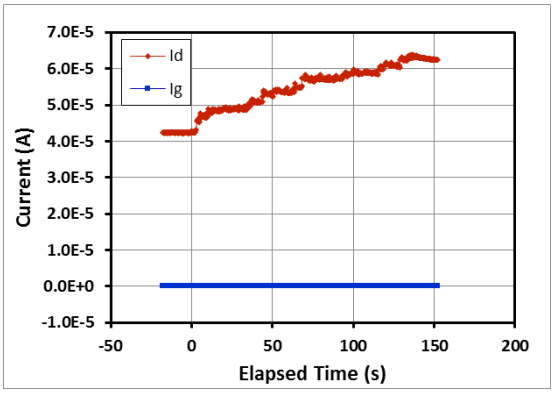

Figure D35. Strip tape data from DUT 11, run 32: 548 MeV Ar. Testing in SEB-protective mode with 10 kΩ external resistor on drain node. Run bias conditions: 0 Vgs, 42 Vds. Beam shuttered after about 143 seconds.

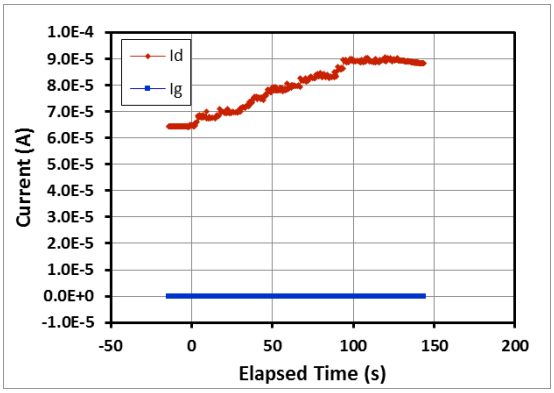

Figure D36. Strip tape data from DUT 11, run 33: 548 MeV Ar. Testing in SEB-protective mode with 10 kΩ external resistor on drain node. Run bias conditions: 0 Vgs, 45 Vds. Beam shuttered after about 138 seconds.

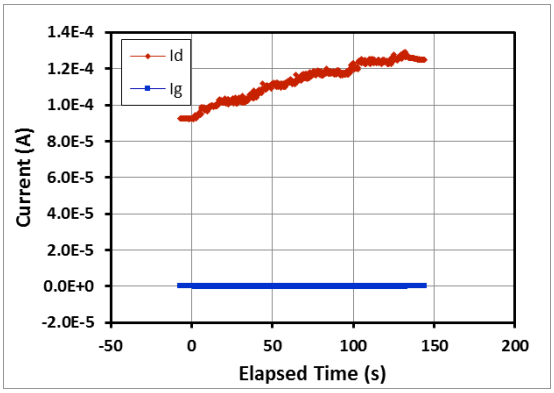

Figure D37. Strip tape data from DUT 11, run 34: 548 MeV Ar. Testing in SEB-protective mode with 10 kΩ external resistor on drain node. Run bias conditions: 0 Vgs, 48 Vds. Beam shuttered after about 135 seconds.

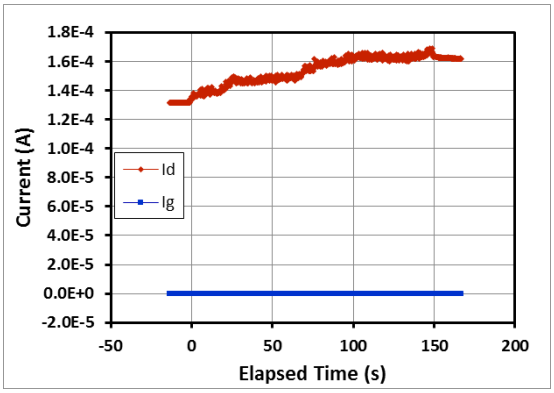

Figure D38. Strip tape data from DUT 11, run 35: 548 MeV Ar. Testing in SEB-protective mode with 10 kΩ external resistor on drain node. Run bias conditions: 0 Vgs, 51 Vds. Beam shuttered after about 159 seconds.

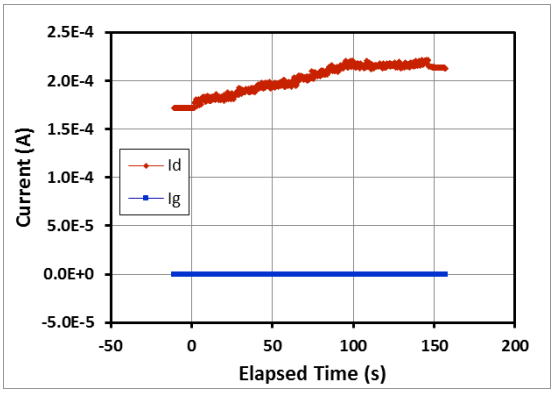

Figure D39. Strip tape data from DUT 11, run 36: 548 MeV Ar. Testing in SEB-protective mode with 10 kΩ external resistor on drain node. Run bias conditions: 0 Vgs, 54 Vds. Beam shuttered after about 150 seconds.

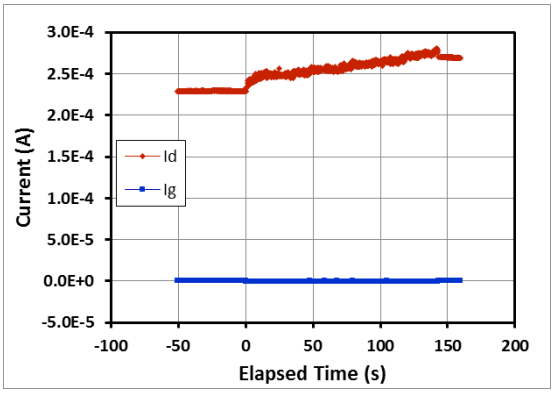

Figure D40. Strip tape data from DUT 11, run 37: 548 MeV Ar. Testing in SEB-protective mode with 10 kΩ external resistor on drain node. Run bias conditions: 0 Vgs, 57 Vds. Beam shuttered after about 149 seconds.

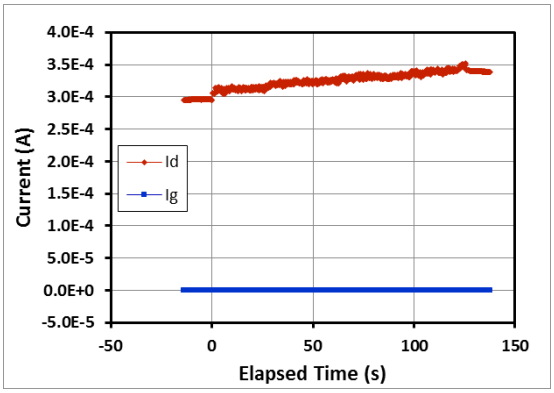

Figure D41. Strip tape data from DUT 11, run 38: 548 MeV Ar. Testing in SEB-protective mode with 10 kΩ external resistor on drain node. Run bias conditions: 0 Vgs, 60 Vds. Beam shuttered after about 131 seconds.

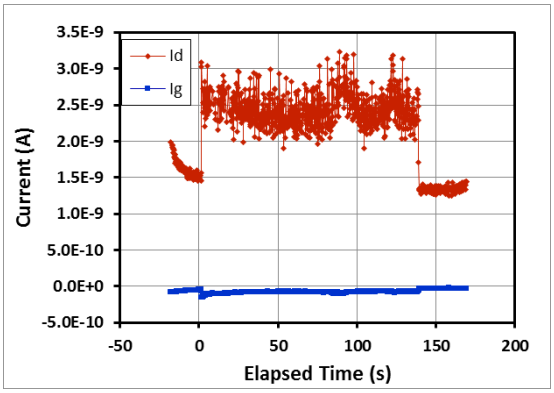

Figure D42. Strip tape data from DUT 12, run 39: 548 MeV Ar. Run bias conditions: -10 Vgs, 24 Vds. Beam shuttered after about 139 seconds. Note that the negative gate bias precluded ion-induced increases in drain current because despite decreases in localized gate threshold voltage at the location of ion strikes through the gate oxide, the channel did not become conducting: the -10 V applied Vgs is sufficiently below the threshold voltage.

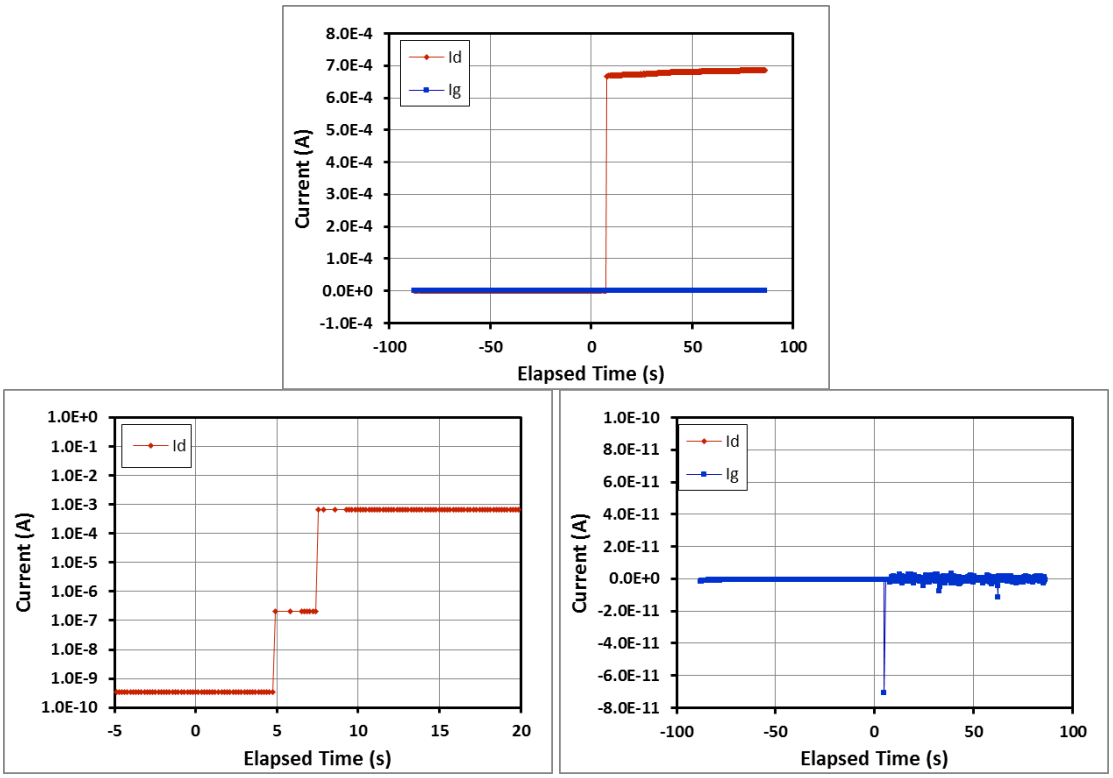

Figure D43. Strip tape data from DUT 16, run 66 (LBNL 11/8/2016): 400 MeV Ar. Run bias conditions: 0 Vgs, 45 Vds. Beam shuttered after about 21 seconds. SEB occurred after about 7 seconds. Lower left panel shows top plot on log scale; lower right panel shows small gate current transient upon initial jump in drain current at about 5 seconds. This test suggests prior dosing does not impact threshold drain voltage required for SEB.

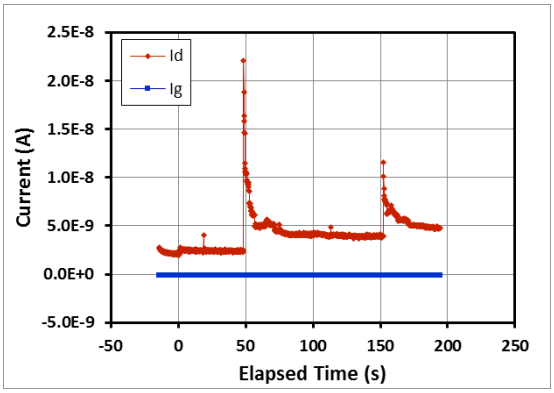

Figure D44. Strip tape data from DUT 17, run 60: 283 MeV Ne. Run bias conditions: 0 Vgs, 24 Vds. Beam shuttered after about 175 seconds. The much lower LET of Ne results in smaller localized dosing effects upon an ion strike down the gate oxide. The fewer events suggests a smaller cross section of susceptibility.

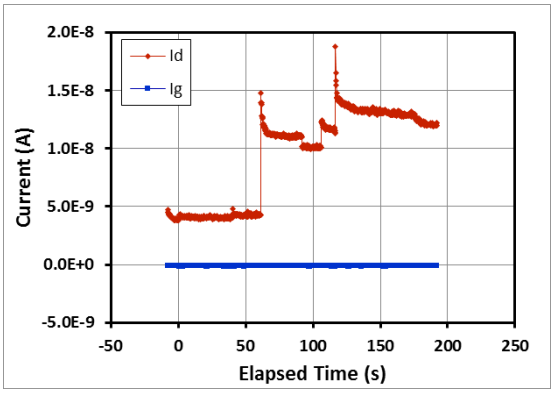

Figure D45. Strip tape data from DUT 17, run 61: 283 MeV Ne. Run bias conditions: 0 Vgs, 27 Vds. Beam shuttered after about 185 seconds.

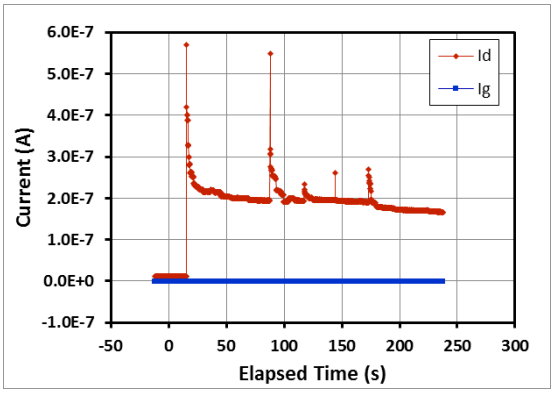

Figure D46. Strip tape data from DUT 17, run 62: 283 MeV Ne. Run bias conditions: 0 Vgs, 30 Vds. Beam shuttered after about 227 seconds.

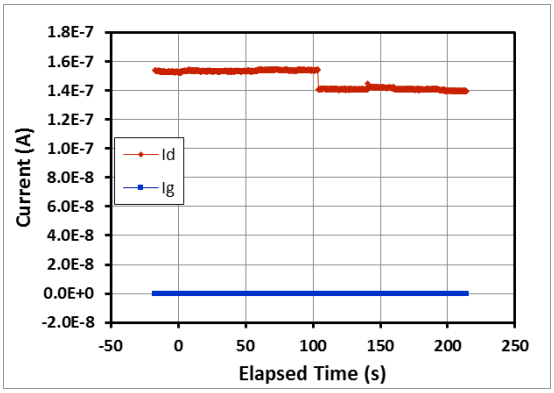

Figure D47. Strip tape data from DUT 17, run 63: 283 MeV Ne. Run bias conditions: 0 Vgs, 33 Vds. Beam shuttered after about 202 seconds. Slight recovery after 100 seconds could be charge detrapping (see Figure D23).

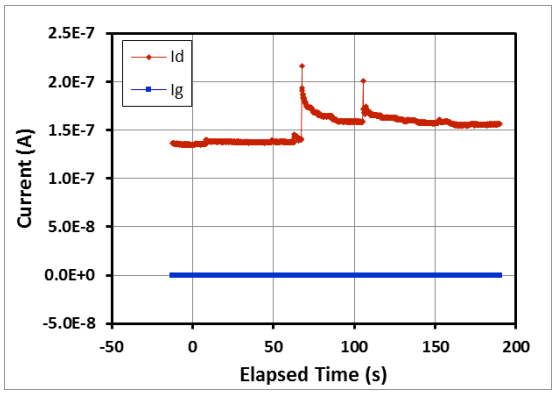

Figure D48. Strip tape data from DUT 17, run 64: 283 MeV Ne. Run bias conditions: 0 Vgs, 36 Vds. Beam shuttered after about 183 seconds.

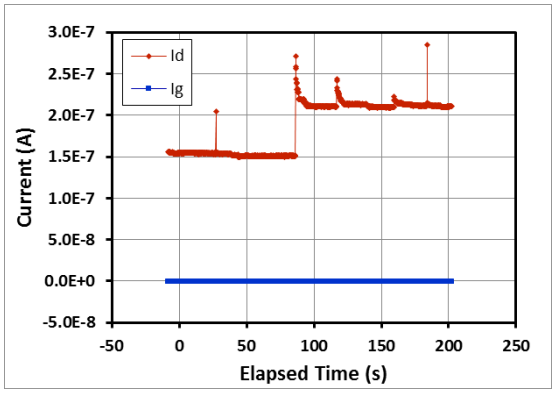

Figure D49. Strip tape data from DUT 17, run 65: 283 MeV Ne. Run bias conditions: 0 Vgs, 39 Vds. Beam shuttered after about 192 seconds.

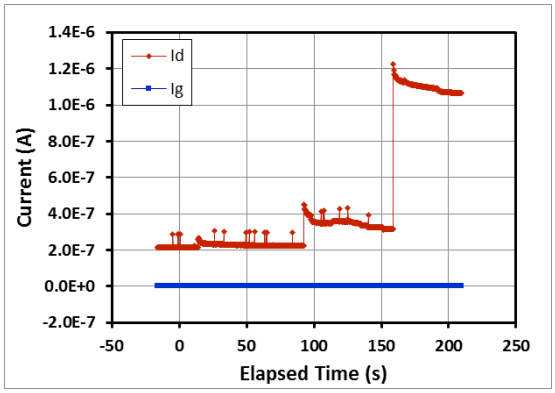

Figure D50. Strip tape data from DUT 17, run 66: 283 MeV Ne. Run bias conditions: 0 Vgs, 42 Vds. Beam shuttered after about 205 seconds.

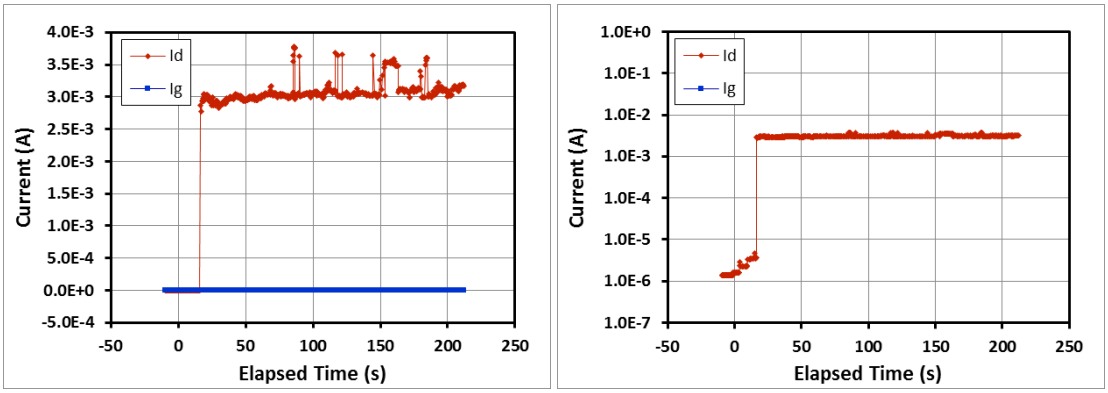

Figure D51. Strip tape data from DUT 17, run 67: 283 MeV Ne. Run bias conditions: 0 Vgs, 45 Vds. Beam shuttered after about 202 seconds. SEB occurs about 17 seconds into the beam run. Gate current does not change. Left panel is replotted on the right in log scale.

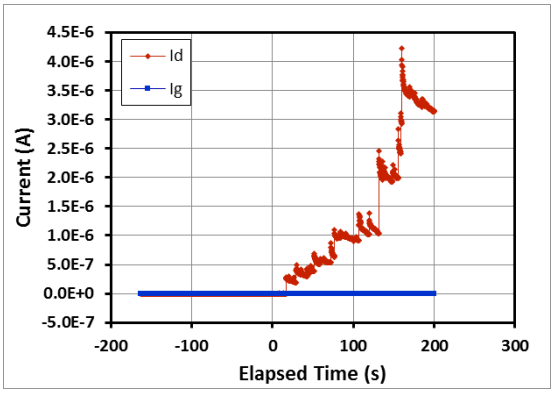

Figure D52. Strip tape data from DUT 114, run 89: 659 MeV Cu. Run bias conditions: 0 Vgs, 24 Vds. Beam shuttered after about 190 seconds.

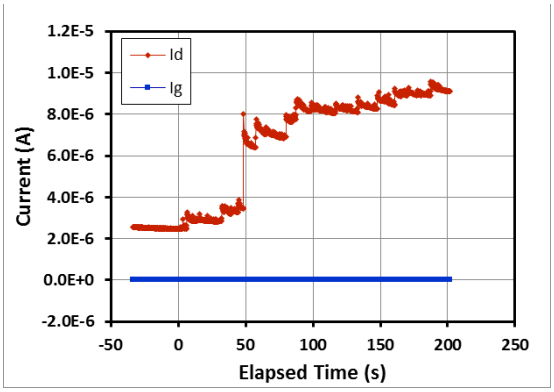

Figure D53. Strip tape data from DUT 114, run 90: 659 MeV Cu. Run bias conditions: 0 Vgs, 27 Vds. Beam shuttered after about 193 seconds.

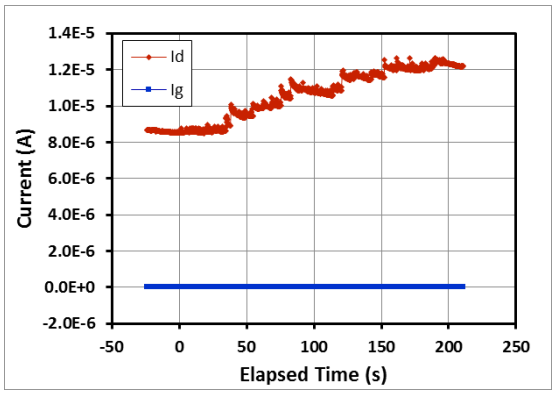

Figure D54. Strip tape data from DUT 114, run 91: 659 MeV Cu. Run bias conditions: 0 Vgs, 30 Vds. Beam shuttered after about 195 seconds.

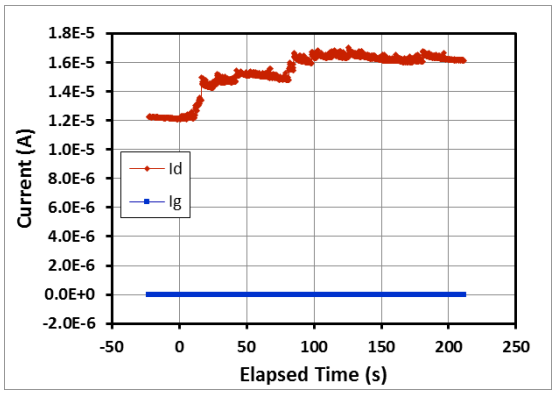

Figure D55. Strip tape data from DUT 114, run 92: 659 MeV Cu. Run bias conditions: 0 Vgs, 33 Vds. Beam shuttered after about 195 seconds.

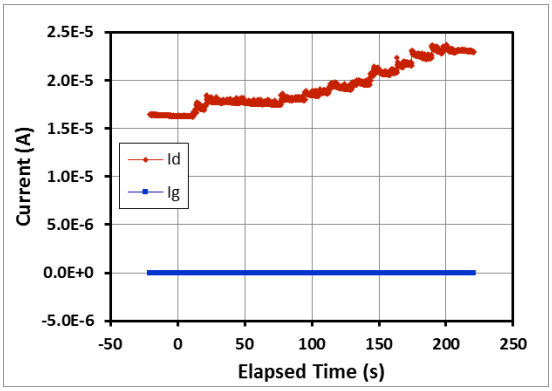

Figure D56. Strip tape data from DUT 114, run 93: 659 MeV Cu. Run bias conditions: 0 Vgs, 36 Vds. Beam shuttered after about 205 seconds.

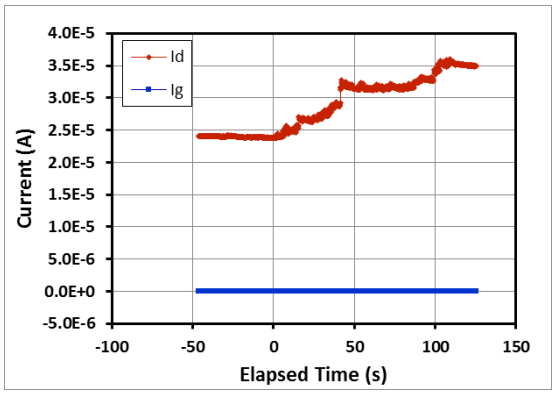

Figure D57. Strip tape data from DUT 114, run 94: 659 MeV Cu. Run bias conditions: 0 Vgs, 39 Vds. Beam shuttered after about 112 seconds.

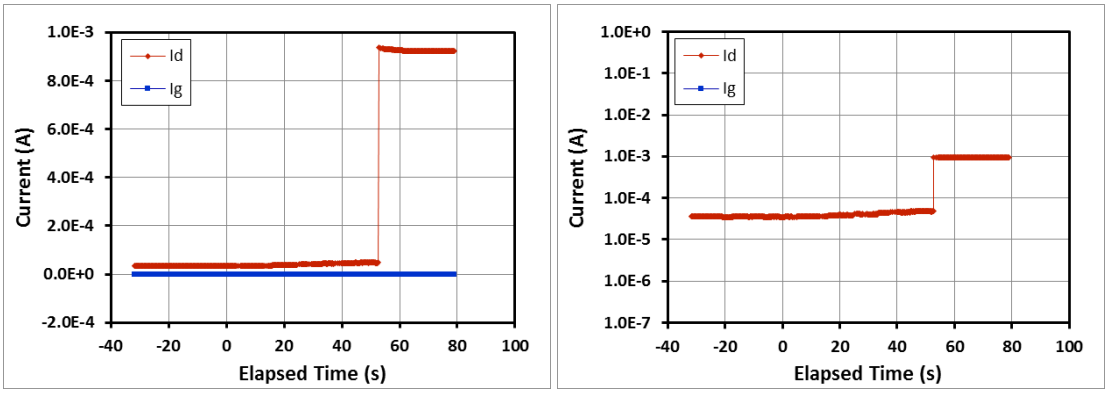

Figure D58. Strip tape data from DUT 114, run 95: 659 MeV Cu. Run bias conditions: 0 Vgs, 42 Vds. SEB occurs after about 52 seconds. Beam shuttered after about 56 seconds. Right panel shows the same plot with log scale. Gate current did not change during run.

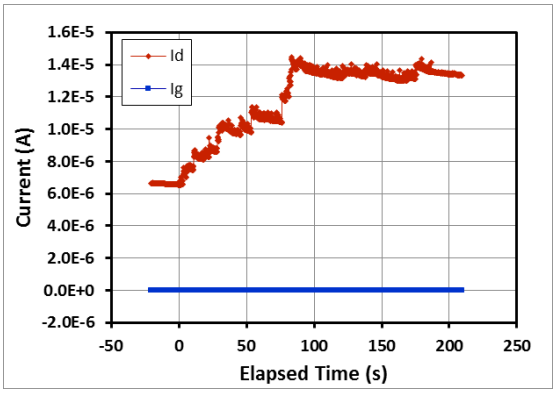

Figure D59. Strip tape data from DUT 120, run 97: 659 MeV Cu. Run bias conditions: 0 Vgs, 36 Vds. Beam shuttered after about 185 seconds.

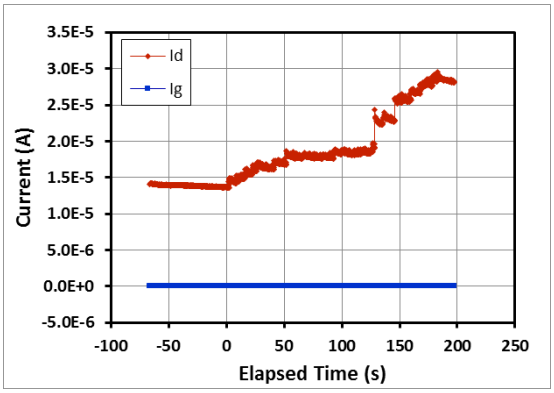

Figure D60. Strip tape data from DUT 120, run 98: 659 MeV Cu. Run bias conditions: 0 Vgs, 39 Vds. Beam shuttered after about 183 seconds.

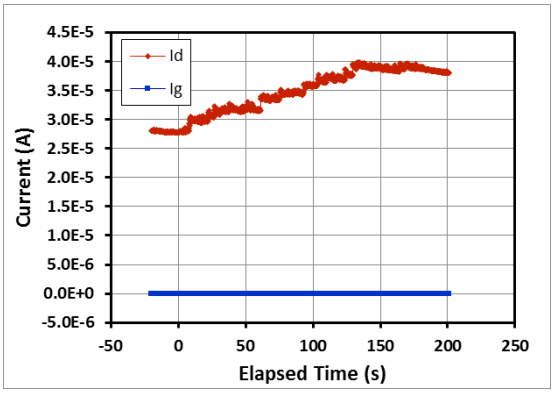

Figure D61. Strip tape data from DUT 120, run 99: 659 MeV Cu. Run bias conditions: 0 Vgs, 42 Vds. Beam shuttered after about 182 seconds.

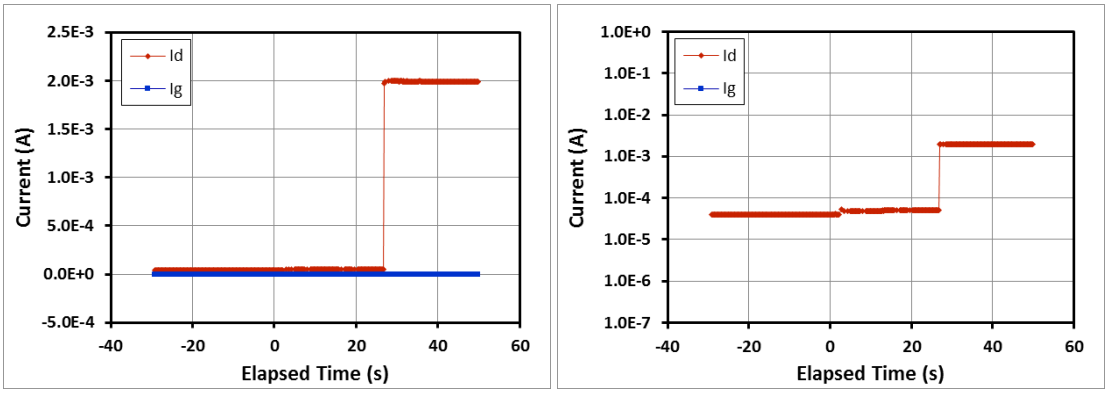

Figure D62. Strip tape data from DUT 120, run 100: 659 MeV Cu. Run bias conditions: 0 Vgs, 45 Vds. SEB occurred at about 27 seconds. Beam shuttered after about 32 seconds. Right panel shows the same plot with log scale. Gate current did not change during run.

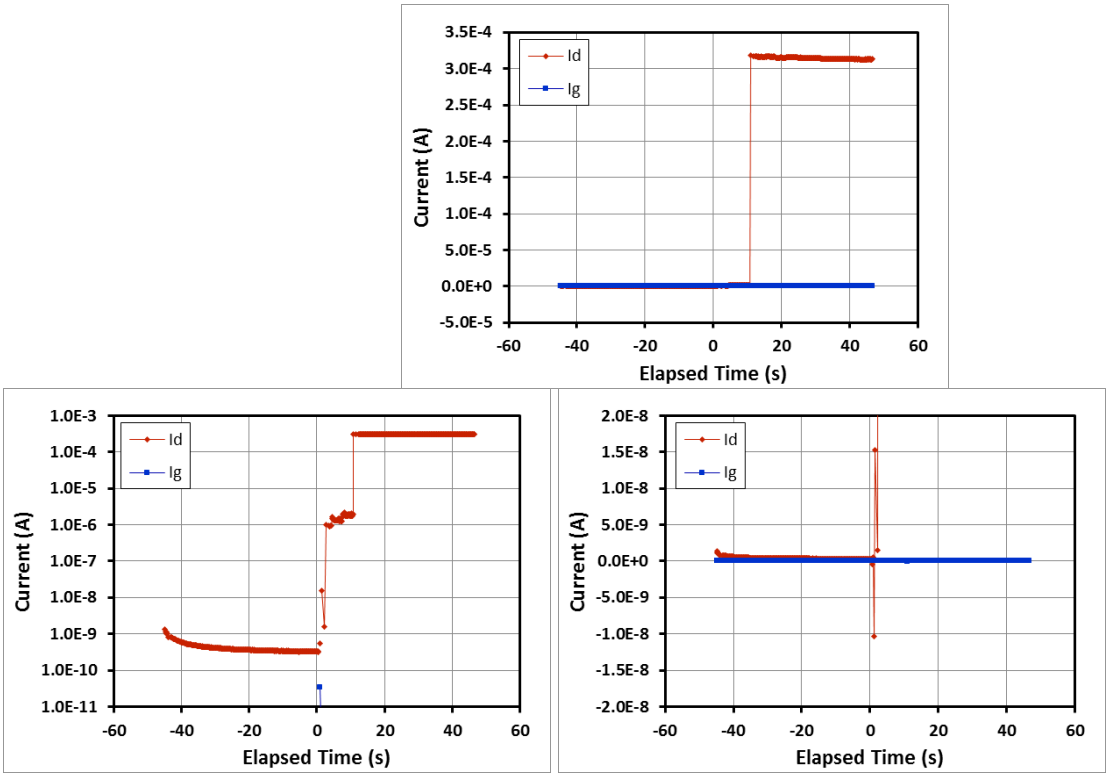

Figure D63. Strip tape data from DUT 107, run 101: 659 MeV Cu. Run bias conditions: 0 Vgs, 39 Vds. SEB occurred at about 10 seconds. Beam shuttered after about 25 seconds. Lower left panel shows the top plot with log scale. Lower right panel is a linear plot showing ringing upon initial beam exposure. Gate current did not change during run. This DUT failed on its first beam exposure and thus may have been
SEB-susceptible to Cu below 39 Vds.

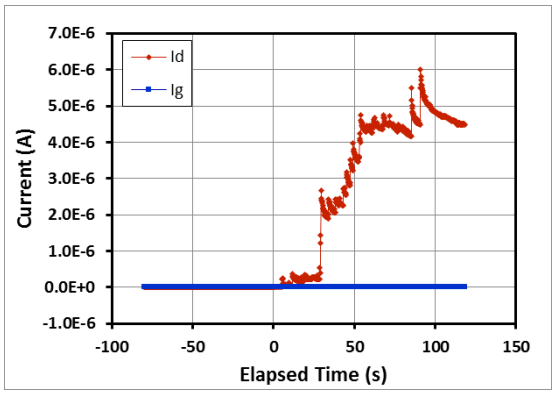

Figure D64. Strip tape data from DUT 117, run 111: 886 MeV Kr. Run bias conditions: 0 Vgs, 24 Vds. Beam shuttered after about 93 seconds.

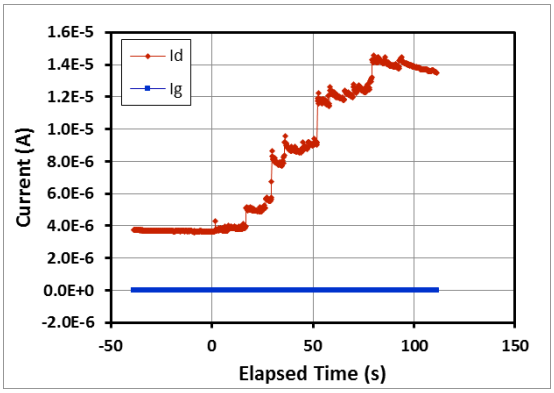

Figure D65. Strip tape data from DUT 117, run 112: 886 MeV Kr. Run bias conditions: 0 Vgs, 27 Vds. Beam shuttered after about 93 seconds.

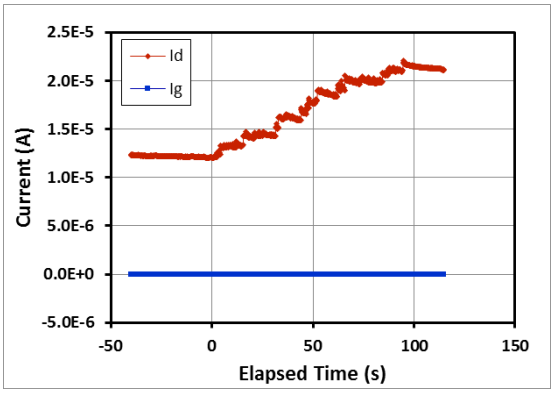

Figure D66. Strip tape data from DUT 117, run 113: 886 MeV Kr. Run bias conditions: 0 Vgs, 30 Vds. Beam shuttered after about 94 seconds.

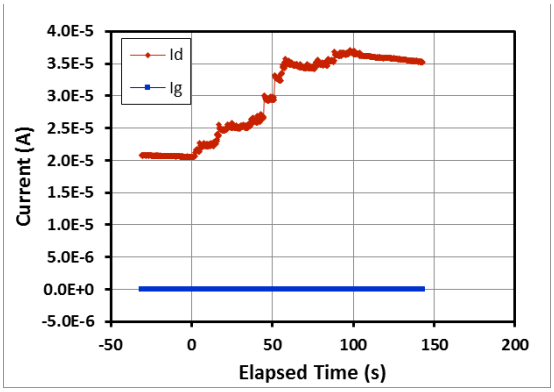

Figure D67. Strip tape data from DUT 117, run 114: 886 MeV Kr. Run bias conditions: 0 Vgs, 33 Vds. Beam shuttered after about 103 seconds.

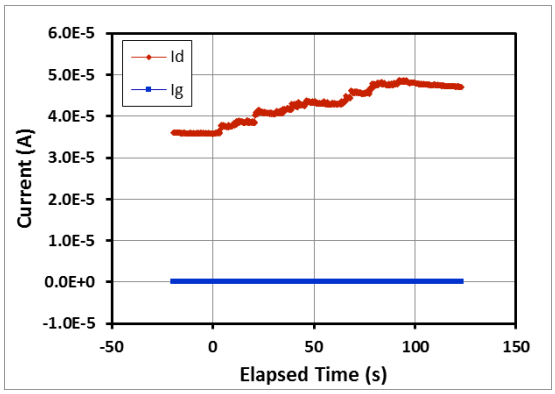

Figure D68. Strip tape data from DUT 117, run 115: 886 MeV Kr. Run bias conditions: 0 Vgs, 36 Vds. Beam shuttered after about 95 seconds.

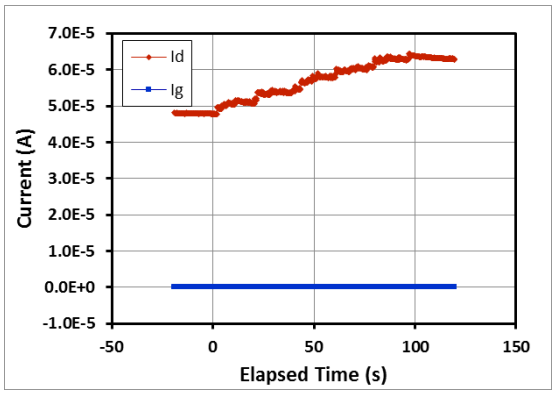

Figure D69. Strip tape data from DUT 117, run 116: 886 MeV Kr. Run bias conditions: 0 Vgs, 39 Vds. Beam shuttered after about 97 seconds.

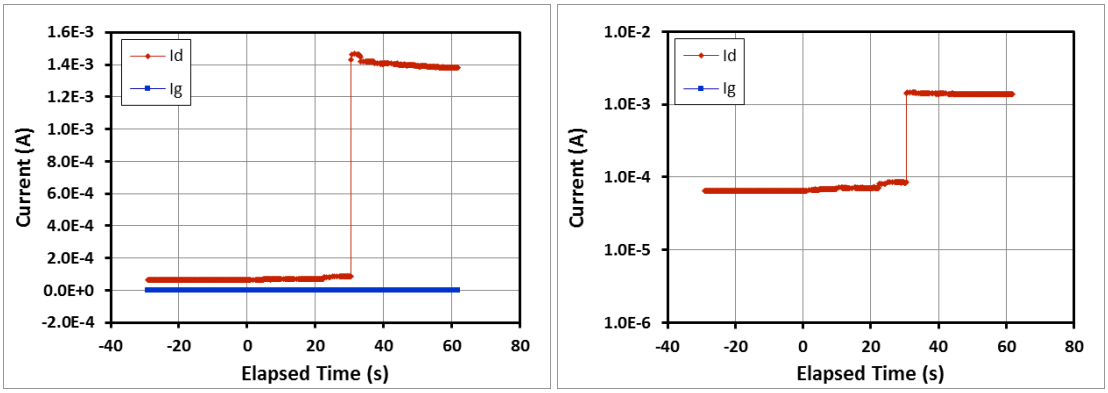

Figure D70. Strip tape data from DUT 117, run 117: 886 MeV Kr. Run bias conditions: 0 Vgs, 42 Vds. SEB occurred at about 30 seconds. Beam shuttered after about 34 seconds. Right panel shows the same plot with log scale. Gate current did not change during run.

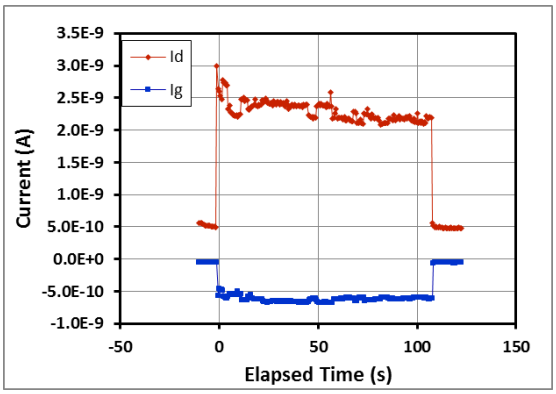

Figure D71. Strip tape data from DUT 102, run 8: 200 MeV protons. Run bias conditions: 0 Vgs, 45 Vds. Beam shuttered after about 110 seconds. Irradiation at lower Vds yielded similar striptapes and are thus not shown.

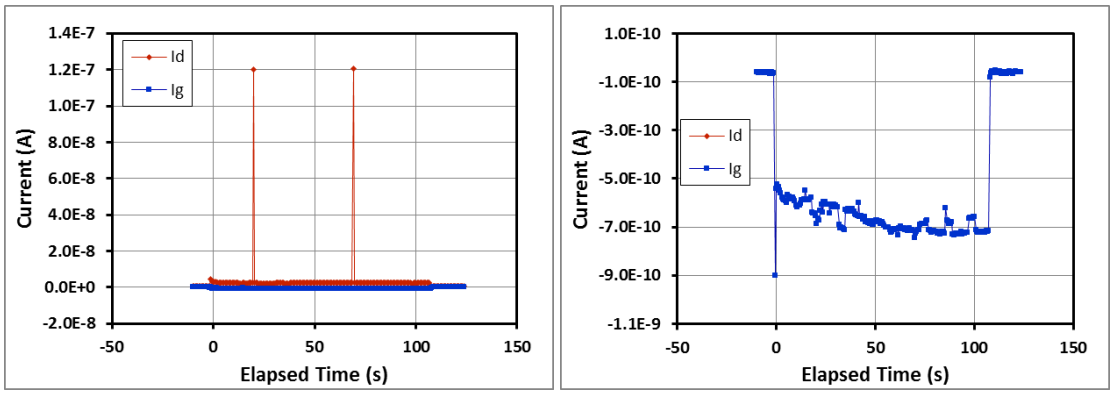

Figure D72. Strip tape data from DUT 102, run 9: 200 MeV protons. Run bias conditions: 0 Vgs, 48 Vds. Beam shuttered after about 110 seconds. Left panel shows two current spikes which may be quenched SEB events. Right panel is replot of left panel on smaller scale to reveal no change in gate current.

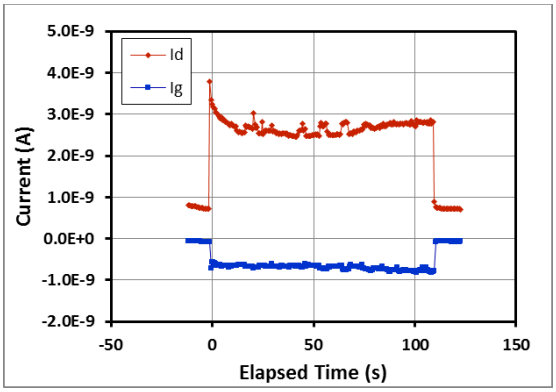

Figure D73. Strip tape data from DUT 102, run 10: 200 MeV protons. Run bias conditions: 0 Vgs, 51 Vds. Beam shuttered after about 111 seconds.

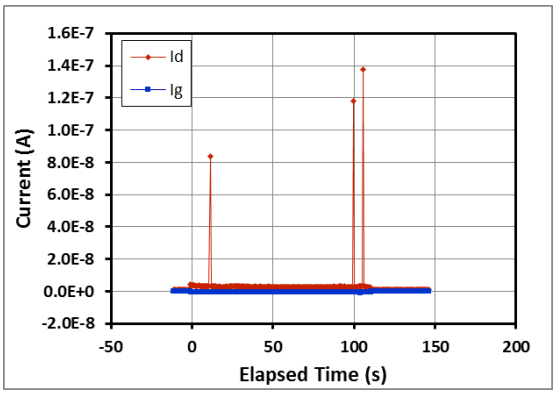

Figure D74. Strip tape data from DUT 102, run 11: 200 MeV protons. Run bias conditions: 0 Vgs, 54 Vds. Beam shuttered after about 113 seconds. Three current spikes may be quenched SEB events. No transients in gate current.

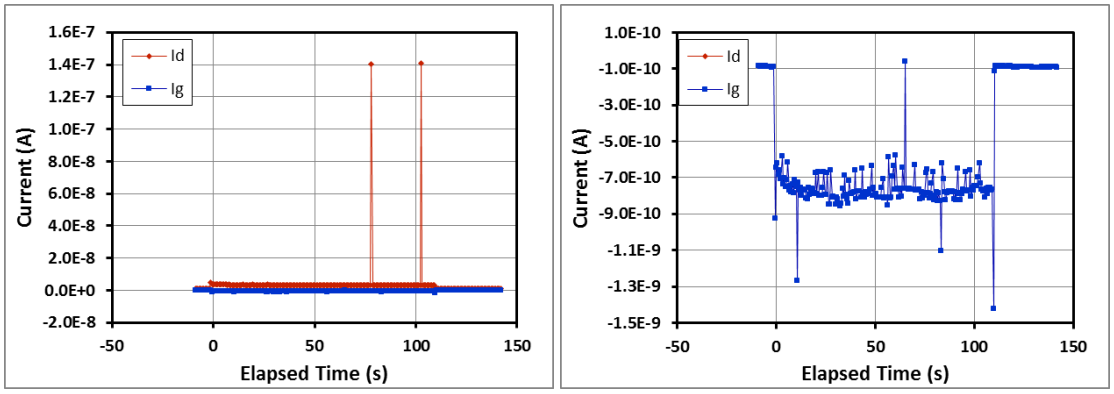

Figure D75. Strip tape data from DUT 102, run 12: 200 MeV protons. Run bias conditions: 0 Vgs, 57 Vds. Beam shuttered after about 110 seconds. Two drain current spikes may be quenched SEB events. Right panel repeats left plot but on smaller scale to show gate current transients that are not correlated with the drain current transients.

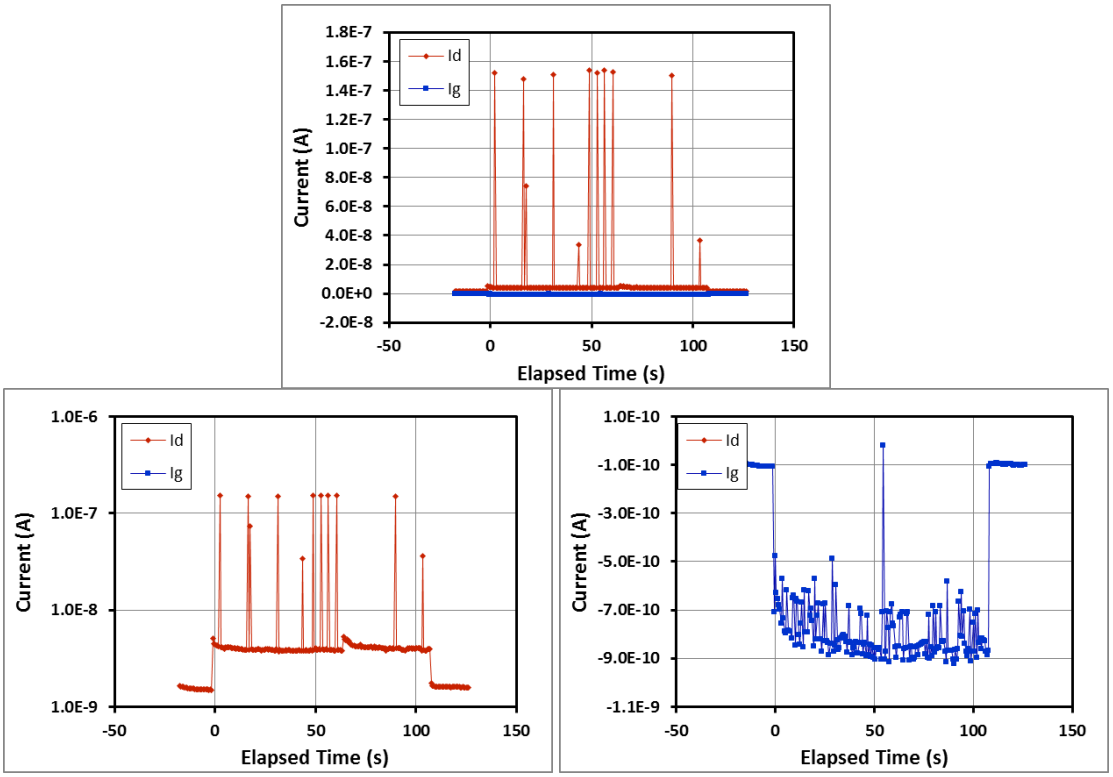

Figure D76. Strip tape data from DUT 102, run 13: 200 MeV protons. Run bias conditions: 0 Vgs, 60 Vds. Beam shuttered after about 110 seconds. Current spikes may be quenched SEB events. Lower panels are replots of top panel, on different y-axis scales.

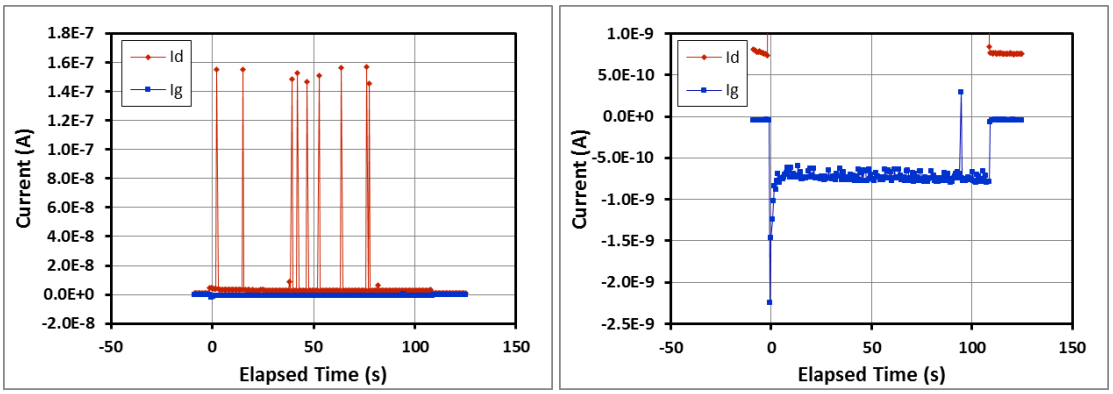

Figure D77. Strip tape data from DUT 103, run 14: 200 MeV protons. Run bias conditions: 0 Vgs, 60 Vds. Beam shuttered after about 110 seconds. Nine current spikes may be quenched SEB events. Gate current shown on smaller scale in right panel.

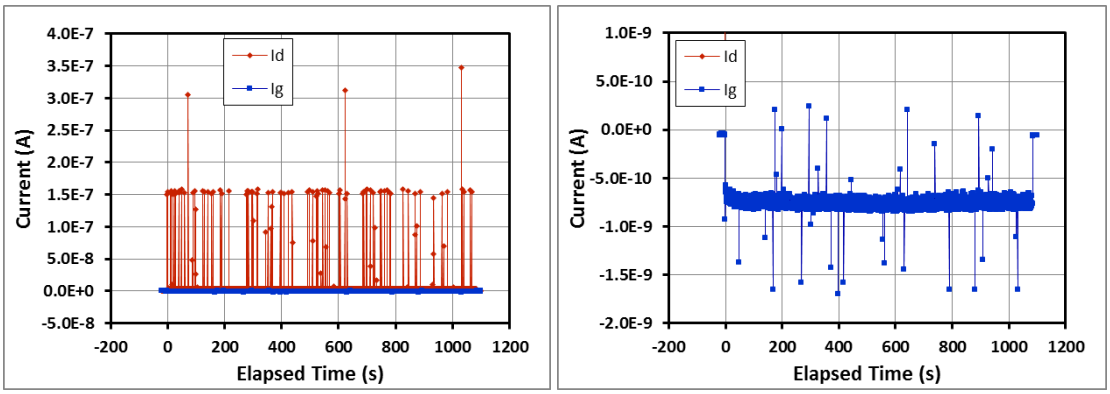

Figure D78. Strip tape data from DUT 103, run 15: 200 MeV protons. Run bias conditions: 0 Vgs, 60 Vds. Beam shuttered after about 1086 seconds. 95 current spikes may be quenched SEB events. Gate current shown on smaller scale in right panel.

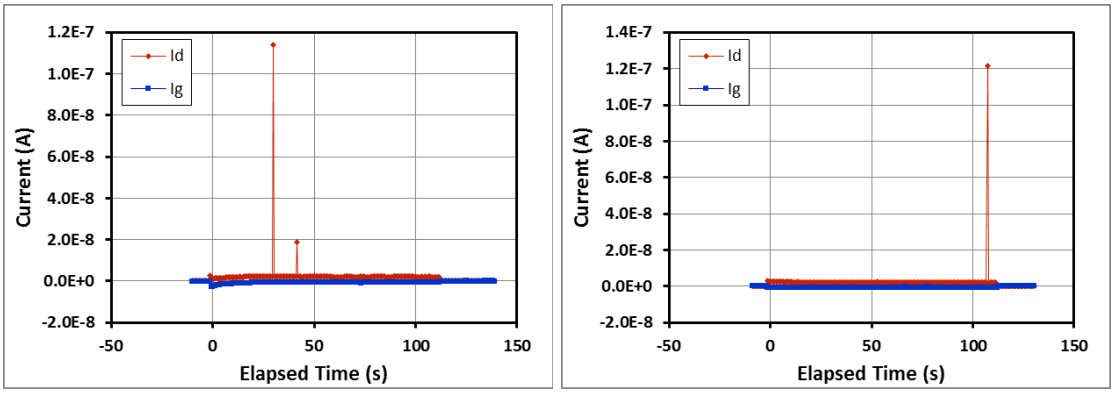

Figure D79. Strip tape data from DUT 104, runs 17 and 18: 200 MeV protons. Run bias conditions: 0 Vgs, 45 Vds (left) and 48 Vds (right).

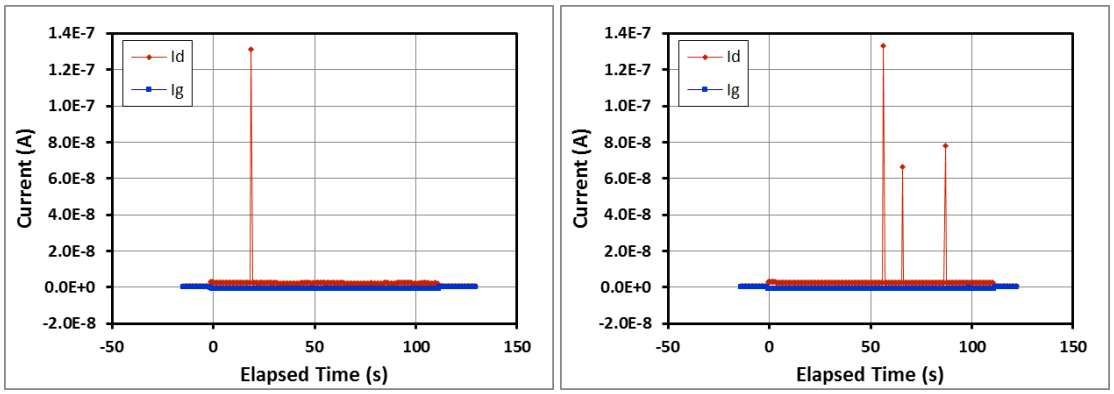

Figure D80. Strip tape data from DUT 104, runs 19 and 20: 200 MeV protons. Run bias conditions: 0 Vgs, 51 Vds (left) and 54 Vds (right).

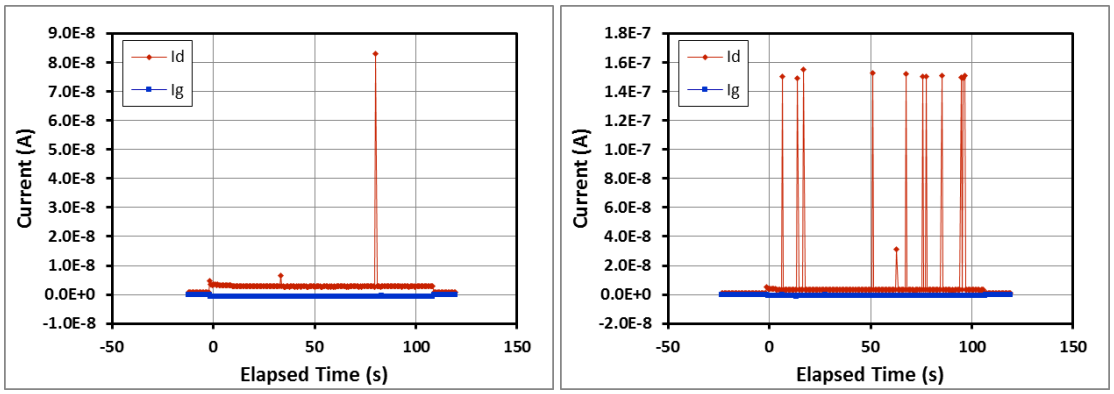

Figure D81. Strip tape data from DUT 104, runs 21 and 22: 200 MeV protons. Run bias conditions: 0 Vgs, 57 Vds (left) and 60 Vds (right).

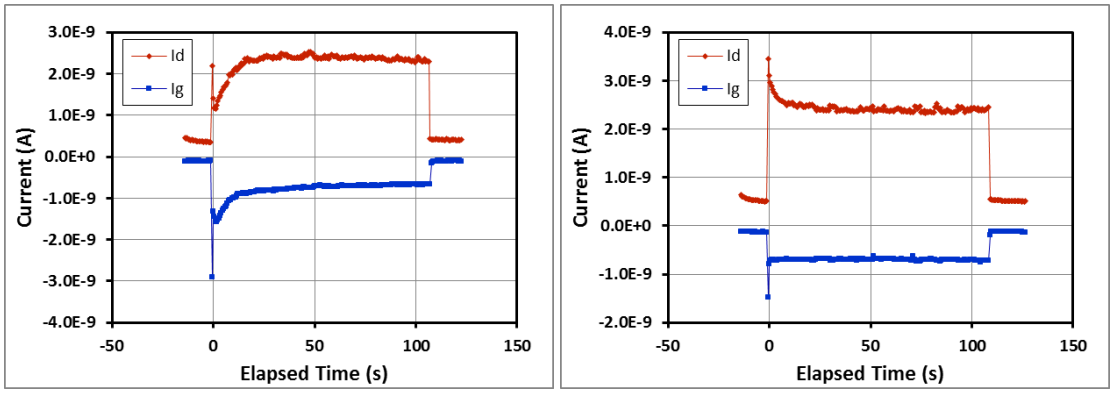

Figure D82. Strip tape data from DUT 105, runs 24 and 25: 200 MeV protons. Run bias conditions: 0 Vgs, 45 Vds (left) and 48 Vds (right).

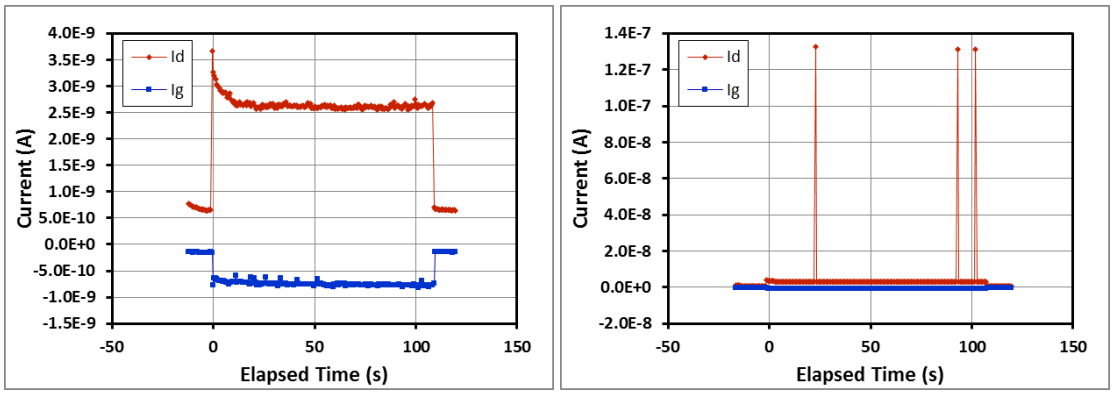

Figure D83. Strip tape data from DUT 105, runs 26 and 27: 200 MeV protons. Run bias conditions: 0 Vgs, 51 Vds (left) and 54 Vds (right).

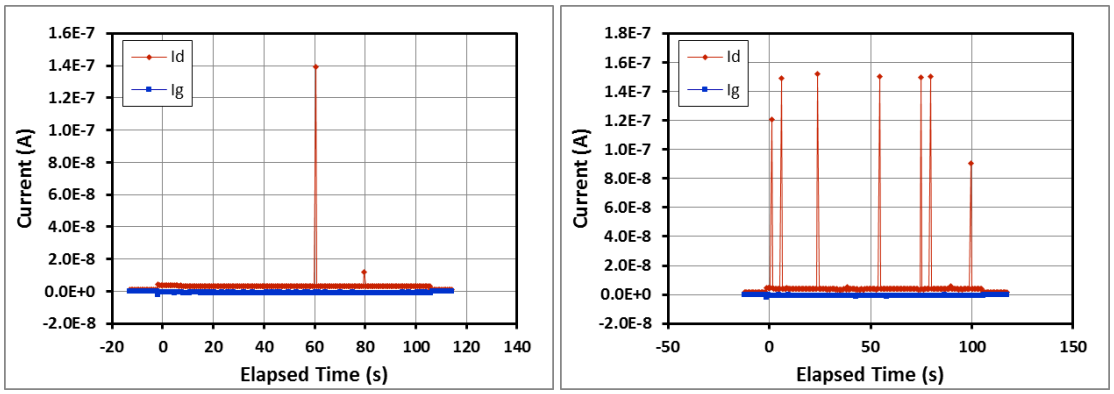

Figure D84. Strip tape data from DUT 105, runs 28 and 29: 200 MeV protons. Run bias conditions: 0 Vgs, 57 Vds (left) and 60 Vds (right).