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I. Introduction and Summary of Test Results

This study was undertaken to determine the single-event effect susceptibility of the radiation-hardened MRH25N12U3 (JANSR2N7593) power MOSFET recently developed by Microchip Technology, Inc. Heavy-ion testing was conducted at the Lawrence Berkeley National Laboratory (LBNL) Berkeley Accelerator Space Effects (BASE) Facility and Brookhaven National Laboratory (BNL) NASA Space Radiation Laboratory (NSRL). Its purpose was to independently evaluate this device as a candidate for use in NASA flight projects.

Samples passed at the full 250-V rated drain-source voltage (V_{DS}) under irradiation with 10 MeV/u silver (linear energy transfer (LET) = 48 MeV·cm^2/mg) with gate biases to -20 V. Under irradiation with 10 MeV/u gold (LET = 86 MeV·cm^2/mg), samples passed at full rated V_{DS} at a gate bias (V_{GS}) of 0 V. Time constraints prevented evaluation at other gate biases. Tests were conducted at normal beam incidence (worst-case angle) in vacuum. Data are plotted in Figure 1 as the last passing V_{DS}. Details are provided in the Results section below. LBNL does not provide beam degraders suitable for heavy-ion penetration range adjustment; all tests were conducted with 10 MeV/u beams that may not be the worst-case test energy for a given species. Finally, it should be noted that it is assumed for an individual sample that operation at bias conditions below those yielding no failure during testing will also result in no failure. For example, samples passing at -20 V_{GS} and the full 250 V_{DS} are assumed to pass at 0, -5, -10, and -15 V_{GS} at 250 V_{DS}. Ion range and LET for LBNL beams were determined using SRIM version 2013, from the ion energy provided by LBNL whereas ion range and LET for NSRL beams were determined using the NSRL stack-up tool (https://www.bnl.gov/nsrl/stackup/) in conjunction with ion energy provided by NSRL.

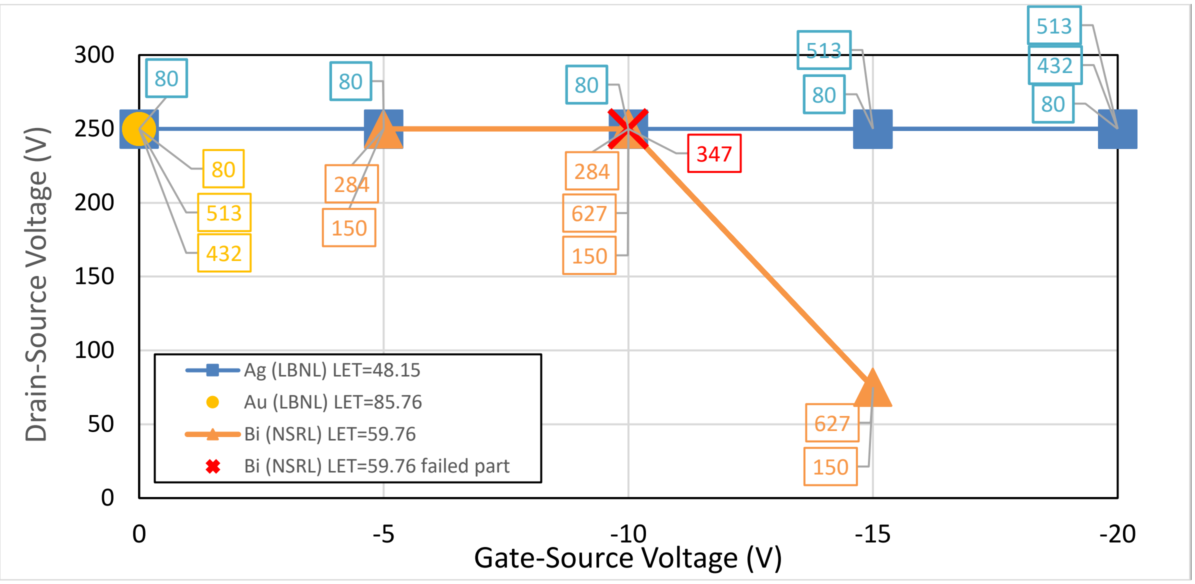


Figure 1. Maximum passing V_{DS} bias as a function of V_{GS} bias during irradiation. DUT serial numbers are indicated by the data points. Red 'x' indicates a single failed part (DUT 347) at V_{GS} = -10V and V_{DS} = 250V.

II. Devices Tested

The sample size for this testing was 3 pieces at the LBNL facility and 4 pieces at the NSRL facility. The part is manufactured by Microchip Technology, Inc. The part is a radiation hardened 12.4 A, 250 V, 0.210 Ω discrete n-channel silicon power MOSFET, part # MRH25N12U3 (JANSR2N7593). Engineering samples were provided by Microchip in May 2021 in SMD 0.5 packages. Samples have a lot date code of C2052. The pieces were mechanically delidded, visually inspected, and electrically characterized at GSFC prior to shipping to test facilities. At the test facilities, a subset of electrical characterizations was performed in the irradiation position prior to radiation exposure.

III. Test Facilities

Facility: Lawrence Berkeley National Laboratory Berkeley Accelerator Space Effects (BASE) Facility, 10 MeV/amu tune.
Flux: 5 x 10^3 ions/cm^2/s to 1.4 x 10^4 ions/cm^2/s.
Fluence: All tests were run to 1 x 10^6 ions/cm^2.
Ion species: Ag and Au. Table 1below shows the LBNL-provided beam energy and surface-incident beam properties as calculated by SRIM, v. 2013 software.

Table III-1. LBNL Ion Beam Properties (in Vacuum)

Ion:	Surface Energy *(MeV)*	Surface LET *(MeV·cm^2/mg)*	Range *(μm)*	Angle of Incidence *(Degrees)*
^{107}Ag	1039	48	90	0
^{197}Au	1956	86	106	0

Facility: BNL NASA Space Radiation Laboratory (NSRL)
Flux: 1 x 10^3 ions/cm^2/s to 2 x 10^3 ions/cm^2/s.
Fluence: All tests were run to 1 x 10^6 ions/cm^2 or first sign of failure
Ion species: Bi. Table 2 below shows the NSRL-provided beam energy and surface-incident beam properties as calculated by the NSRL stack-up tool.

Table III-2. NSRL Ion Beam Properties (in Air)

Ion:	Initial Energy *(MeV/u)*	Polyethylene Degrader Thickness *(mm)*	Surface Energy *(MeV/u)*	Surface LET *(MeV·cm^2/mg)*	Range *(μm)*	Angle of Incidence *(Degrees)*
Bi	147	5	36.8	59.76	770	0

IV. Test Setup

The test circuit and block diagram, as shown in Figures 2 and 3, for the power MOSFET contains a Keithley 2635A source meter to provide the gate voltage (set to 0 V, -5 V, -10 V, -15 V, or -20 V during irradiation) 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 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 2657A to protect it from sudden high-current transients; it is switched out during device characterization tests. A Keithley 2657A-PM-200 diode-based protection unit prevents damage to the 2635A in the event of DUT failure shorting the supplies together. Gate current is limited to 1 mA, drain current limited to 100 mA, and both are recorded via ethernet to a desktop computer at approximately 175 ms intervals. 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. All terminals of the devices not under test are then floating. Testing was conducted in vacuum with the DUT centered within the beam diameter. Ion exposures were conducted at 0º tilt angle (normal incidence to the DUT).

The test setup is controlled via a custom LabVIEW program written by Alyson Topper and Hak Kim, Science Systems and Applications, Inc. The program controls the source measuring units (SMUs), gate current limit, and gate and drain current sampling and recording. It is designed to send LUA scripts to the Keithleys to perform a parametric analysis of each DUT prior to irradiation and following each beam run, recording if selected: gate threshold voltage (Vth), 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} (post-irradiation gate stress (PIGS) test to test the integrity of the gate dielectric).

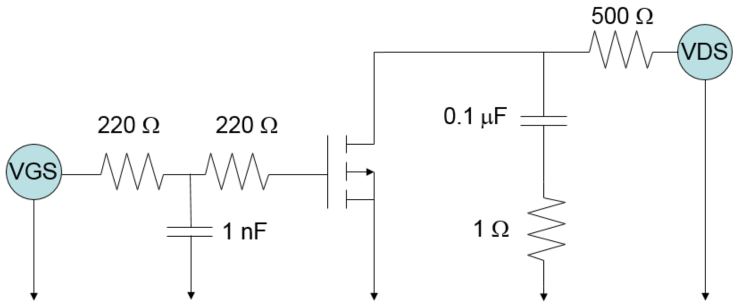


Figure 1. Equivalent test circuit for the JANSR2N7593U3 power MOSFET.

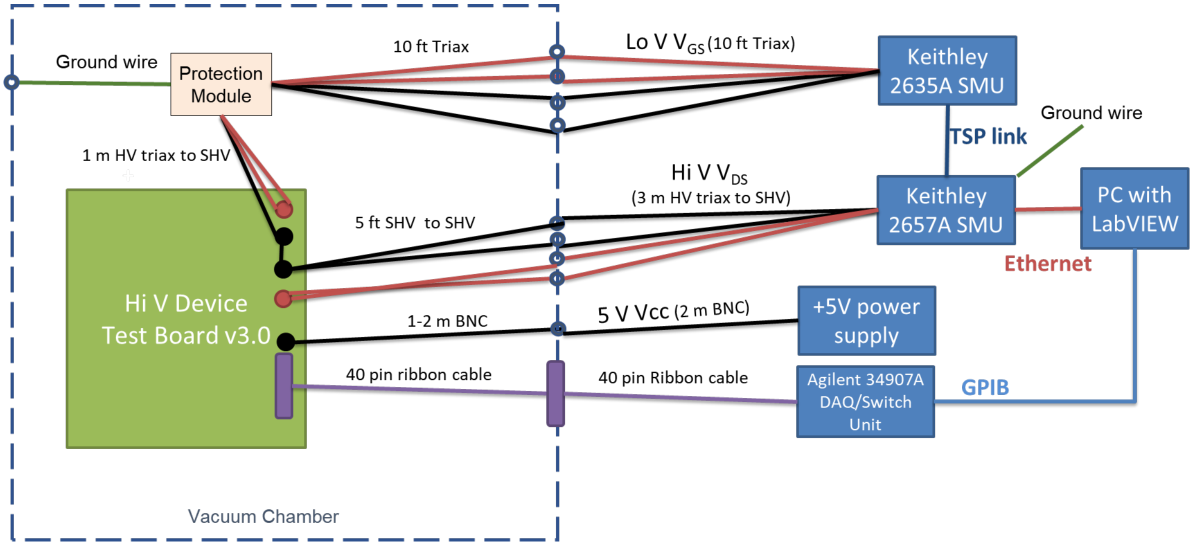


Figure 2. Block diagram of test setup. The dotted line represents the vacuum chamber used at the LBNL facility. The NSRL irradiations occurred in air.

V. Test Results

Prior to the initial beam run and following each run, the zero gate voltage drain current (I_{DSS}) was measured to test the integrity of the drain-source connection, and a gate stress test was performed in which the gate and drain currents were measured while at a fixed 0 V_{DS}, the gate voltage was swept from 0 V to 20 V, then from 0 V to -20 V, in 2 V increments. The +/- 20-V levels were held for 1 s to stress the gate per MIL-STD_750-1 TM1080.1 Condition B. Note that the gate stress test, per TM1080.1, is not performed when the gate is biased ≥ 50% of rated voltage. Failure was defined as the gate current exceeding the manufacturer gate-source leakage current (I_{GSS}) specification of 100 nA during the beam run or during the post-irradiation gate stress (PIGS) test, and/or a sudden, sustained increase in the drain current during the beam run indicative of single event burnout (SEB).

LBNL

The three devices tested under the 10-MeV/u Ag ion beam passed at the full rated 250 V_{DS} with the gate biased to -20 V, then passed again under the 10-MeV/u Au ion beam at 0 V_{GS} at 250 V_{DS}. Time limitations prevented additional testing with Au at negative V_{GS}. Table 3 summarizes the heavy-ion test results for each sample; Figure 1 in Section I plots the bias conditions at which no failures occurred for any DUT. Device electrical specifications are provided in Appendix A, as well as pretest electrical characterizations performed at GSFC and on-site. The run log is given in Appendix B, PIGS and I_{DSS} test results in Appendix C, and example striptape current measurements in Appendix D. Appendix E contains ion beam uniformity and other beam log information.

Table 3. Summary of Heavy-Ion Test Results for Individual Samples (LBNL)

Ion Species	Surface-Incident Energy (MeV)	Range (μm)	Surface-Incident LET(Si) (MeV·cm²/mg)	Beam Angle of Incidence (degrees)	V_{GS} (V)	Maximum Last Passing V_{DS} (V)	Minimum V_{DS} at Failure (V)
Ag	1039	90	48	0	0	250	n/a
					-5	250	n/a
					-10	250	n/a
					-15	250	n/a
					-20	250	n/a
					-20	250	n/a
					-20	250	n/a
Au	1956	106	86	0	0	250	n/a
					0	250	n/a
					0	250	n/a

NSRL

Four devices were tested under the 147-MeV/u Bi ion beam with 5 mm of polyethylene degrader in place resulting in a surface ion energy of 36.8 MeV/u. Time limitations prevented additional testing with higher LET ions. Table 4 summarizes the heavy-ion test results for each sample; Figure 1 in Section I plots the maximum V_{DS} bias conditions at which no failures occurred for a given V_{GS} for the DUTs, with the exception of the part identified as failing at -10 V_{GS} and 250 V_{DS} after passing at -5 V_{GS} and 250 V_{DS}. Device electrical specifications are provided in Appendix A, as well as pretest electrical characterizations performed at GSFC and on-site. The run log is given in Appendix B, PIGS and I_{DSS} test results in Appendix C, and example striptape current measurements in Appendix D. Appendix E contains ion beam uniformity and other beam log information.

Table 4. Summary of Heavy-Ion Test Results for Individual Samples (NSRL)

Ion Species	**Surface-Incident Energy (MeV/u)**	**Range (μm)**	**Surface-Incident LET(Si) (MeV·cm²/mg)**	**Beam Angle of Incidence (degrees)**	**V_{GS} (V)**	**Maximum Last Passing V_{DS} (V)**	**Minimum V_{DS} at Failure (V)**
Bi	36.8	770	59.7	0	-5	250	n/a
					-5	250	n/a
					-10	250	n/a
					-10	250	n/a
					-10	250	n/a
					-10	n/a	250
					-15	75	100
					-15	75	100

Appendix A

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

Parameter	Condition	MIN	MAX	Units
Gate Threshold Voltage (V_{GSth})	$V_{DS} = V_{GS}$, $I_D = 1$ mA	2	4	V
Zero Gate Voltage Drain Current (I_{DSS})	$V_{DS} = 200$ V, $V_{GS} = 0$ V		10	μA
Drain-Source Breakdown Voltage (BV_{DSS})	$V_{GS} = 0$ V, $I_D = 1$ mA	250		V
Gate-Source Leakage Current (I_{GSS})	$V_{GS} = +/- 20$ V, $V_{DS} = 0$ V		+/-100	nA
Static Drain-Source Resistance (R_{DS_on})	$V_{GS} = 12$ V, $I_D = 7.5$ A		0.21	Ω
Forward Voltage (V_{SD})	$I_S = 12.4$ A, $V_{GS} = 0$V		1.2	V

Table A2. Pretest Electrical Characterization - Pre-ship at GSFC
(DUTs mounted in test board; measurements may reflect capacitor leakage currents)

Part SN	$V_{GS(th)}$ (V)	BV_{DSS} (V)	I_{DSS} (nA)	I_{GSS}+ (nA)	I_{GSS}- (nA)
80	3.25	287	910	0.266	-0.381
150	3.31	288	1051	0.235	-0.350
284	3.38	286	1184	0.268	-0.355
347	3.34	285	810	0.258	-0.338
437	3.44	289	979	0.274	-0.371
513	3.27	274	1209	0.263	-0.348
627	3.28	289	1275	0.228	-0.307
729	3.37	283	1064	0.261	-0.335
893	3.37	289	1299	0.233	-0.316
926	3.20	288	1235	0.269	-0.328

Table A3. Pretest Electrical Characterization - At LBNL in Vacuum Chamber
(DUTs mounted in test board; measurements may reflect capacitor leakage currents)

Part SN	Socket Number	$V_{GS(th)}$ (V)	BV_{DSS} (V)	I_{DSS} (nA)	I_{GSS}+ (nA)	I_{GSS}- (nA)
80	1	3.23	> 250	725	0.248	-0.349
513	2	3.29	> 250	3.78	0.226	-0.304
432	3	3.45	> 250	4.40	0.249	-0.337

Table A4. Pretest Electrical Characterization - At NSRL
(DUTs mounted in test board; measurements may reflect capacitor leakage currents)

Part SN	Socket Number	$V_{GS(th)}$ (V)	BV_{DSS} (V)	I_{DSS} (nA)	I_{GSS}+ (nA)	I_{GSS}- (nA)
284	1	3.45	> 250	334	0.233	-0.412
627	1	3.4	> 250	319	0.227	-0.306
347	1	3.35	> 250	328	0.262	-0.345
150	1	3.4	> 250	327	0.233	-0.375

Appendix B

Table B1. Raw test data from 8 June 2021
(Tests in vacuum; ion characteristics per LBNL using SRIM code)

RUN INFO				DUT SETUP		BEAM DIAGNOSTICS: For Si										IRRADIATION RESULTS	
Start Time	Run	DUT	Socket	V_{GS} [V]	V_{DS} [V]	Ion	Energy [MeV/u]	Energy [MeV]	Angle	LET [MeV-cm^2/mg]	Flux [/(cm^2-s)]	Fluence [/cm^2]	Cum Fluence [/cm^2]	Dose [rad(Si)]	Cum. Dose (rad(Si))	SEE Observed on Run	Event Notes
12:32:24	36	80	1	0	225	Ag	10	1039	0	48.15	5.88E+03	1.00E+06	1.00E+06	774	7.737E+02		only Q collection
12:37:22	37	80	1	0	250	Ag	10	1039	0	48.15	5.10E+03	1.00E+06	2.01E+06	773	1.547E+03	PASS	
12:42:45	38	80	1	-5	250	Ag	10	1039	0	48.15	4.99E+03	1.00E+06	3.01E+06	773	2.319E+03	PASS	
12:46:30	39	80	1	-10	250	Ag	10	1039	0	48.15	8.73E+03	1.01E+06	4.01E+06	775	3.095E+03	PASS	
12:50:22	40	80	1	-15	225	Ag	10	1039	0	48.15	8.76E+03	1.00E+06	5.02E+06	774	3.869E+03		
12:54:00	41	80	1	-15	250	Ag	10	1039	0	48.15	9.17E+03	1.00E+06	6.02E+06	774	4.643E+03	PASS	-15 Vg, 250 Vds
12:58:16	42	80	1	-20	25	Ag	10	1039	0	48.15	8.76E+03	1.00E+06	7.02E+06	774	5.417E+03		
1:01:33	43	80	1	-20	40	Ag	10	1039	0	48.15	8.51E+03	1.00E+06	8.03E+06	774	6.191E+03		
1:04:24	44	80	1	-20	50	Ag	10	1039	0	48.15	8.43E+03	1.00E+06	9.03E+06	774	6.965E+03		
1:07:59	45	80	1	-20	60	Ag	10	1039	0	48.15	8.30E+03	1.00E+06	1.00E+07	774	7.738E+03		
1:10:59	46	80	1	-20	70	Ag	10	1039	0	48.15	8.16E+03	1.00E+06	1.10E+07	774	8.513E+03		
1:13:50	47	80	1	-20	80	Ag	10	1039	0	48.15	8.72E+03	1.00E+06	1.20E+07	774	9.286E+03		
1:16:10	48	80	1	-20	100	Ag	10	1039	0	48.15	1.10E+04	1.01E+06	1.30E+07	776	1.006E+04		
1:19:19	49	80	1	-20	125	Ag	10	1039	0	48.15	8.68E+03	1.01E+06	1.41E+07	775	1.084E+04		
1:22:23	50	80	1	-20	150	Ag	10	1039	0	48.15	9.06E+03	1.00E+06	1.51E+07	774	1.161E+04		
1:25:37	51	513	2	-15	250	Ag	10	1039	0	48.15	8.97E+03	1.00E+06	1.00E+06	774	7.737E+02		
1:28:51	52	513	2	-20	150	Ag	10	1039	0	48.15	8.81E+03	1.01E+06	2.01E+06	775	1.549E+03		
1:31:34	53	513	2	-20	200	Ag	10	1039	0	48.15	9.12E+03	1.01E+06	3.01E+06	775	2.324E+03		
1:34:22	54	513	2	-20	250	Ag	10	1039	0	48.15	8.79E+03	1.00E+06	4.02E+06	774	3.098E+03	PASS	
1:37:32	55	432	3	-20	250	Ag	10	1039	0	48.15	8.66E+03	1.00E+06	1.00E+06	774	7.744E+02	PASS	
1:41:03	56	80	1	-20	250	Ag	10	1039	0	48.15	8.78E+03	1.00E+06	1.61E+07	774	1.239E+04	PASS	N=3 at -20 Vgs, 250 Vds
1:50:49	57	80	1	0	150	Au	10	1956	0	85.76	1.23E+04	2.13E+05	2.13E+05	292	1.268E+04		data sheet shows pass at 250 so abort
1:54:09	58	80	1	0	250	Au	10	1956	0	85.76	1.34E+04	1.01E+06	1.22E+06	1385	1.406E+04	PASS	
1:56:40	59	513	2	0	250	Au	10	1956	0	85.76	1.34E+04	1.01E+06	1.01E+06	1383	4.481E+03	PASS	
1:59:59	60	432	3	0	250	Au	10	1956	0	85.76	1.34E+04	1.01E+06	1.01E+06	1383	2.158E+03	PASS	N=3 at 0 VGS, 250 VDS

Table B2. Raw test data from 22 March 2022
(Tests in air; ion characteristics per NSRL stack up tool using 5 mm degrader)

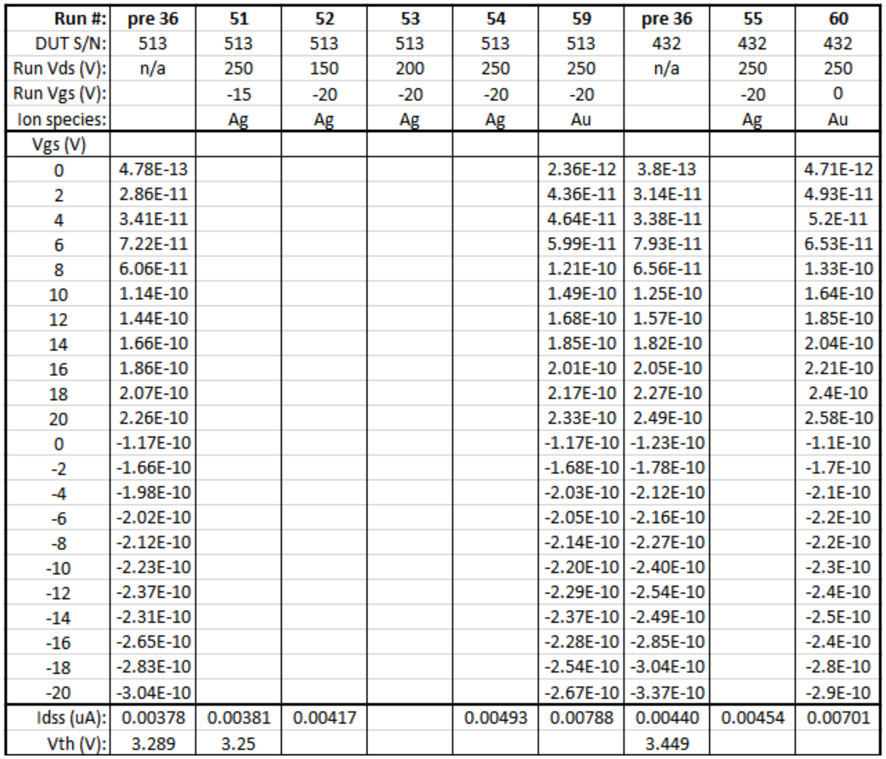
Start Time	Run	DUT	Socket	V_{GS} [V]	V_{DS} [V]	Ion	Energy [MeV/u]	Energy [MeV]	Angle	LET [MeV-cm^2/mg]	Flux [/(cm^2-spill)]	Flux [/(cm^2-min)]	Flux [/(cm^2-s)]	Fluence [/cm^2]	Cum Fluence [/cm^2]	Dose [rad(Si)]	Cum. Dose (rad(Si))	Pre ID	Pre IG	SEE Observed on Run	Event Notes
6:48 PM	1	**284**	**1**	**-5**	**250**	Bi	147		0	59.76	7.50E+03		0	1.00E+06	1.00E+06	956	9.562E+02	8.400E-08	1.500E-12		Magnet didn't engage originally, so no bear
7:03 PM	2	**284**	**1**	-10	**200**	Bi	147		0	59.76	7.50E+03	1.05E+05	1750.5014	1.00E+06	2.00E+06	956	1.912E+03	7.500E-08	2.400E-11		
7:14 PM	3	**284**	1	-10	**225**	Bi	147		0	59.76	7.50E+03	106184.91	1769.7486	1.00E+06	3.00E+06	956	2.869E+03	7.500E-08	1.000E-11		
7:26 PM	4	**284**	1	-10	**250**	Bi	147		0	59.76	7.50E+03	107476.02	1791.2671	1.00E+06	4.00E+06	956	3.825E+03	8.800E-08	2.500E-10		
7:37 PM	5	**284**	1	-15	**125**	Bi	147		0	59.76	7.50E+03	71361.518	1189.3586	1.45E+05	4.14E+06	139	3.963E+03	6.300E-08	7.000E-12		**Gate current increase to -3uA during the beam run**
7:56 PM	6	**627**	1	-10	**250**	Bi	147		0	59.76	7.50E+03	109054.17	1817.5695	1.00E+06	1.00E+06	956	9.562E+02	8.100E-08	4.000E-12		
8:08 PM	7	**627**	1	-15	**50**	Bi	147		0	59.76	7.50E+03	107998.59	1799.9766	1.00E+06	2.00E+06	956	1.912E+03	6.000E-08	1.000E-11		
8:20 PM	8	**627**	1	-15	**75**	Bi	147		0	59.76	7.50E+03	106901.08	1781.6846	1.00E+06	3.00E+06	956	2.869E+03	6.100E-08	1.000E-11		
8:31 PM	9	**627**	1	-15	**100**	Bi	147		0	59.76	7.50E+03	102672.79	1711.2132	7.19E+05	3.72E+06	687	3.556E+03	6.200E-08	6.000E-12		**Gate current increase to -1mA during the beam run**
8:51 PM	10	**347**	1	-10	**250**	Bi	147		0	59.76	7.50E+03	100861.19	1681.0198	7.55E+05	7.55E+05	722	7.224E+02	8.000E-08	7.000E+12		**Gate current increase to -4uA during the beam run**
9:07 PM	11	**150**	1	-5	**250**	Bi	147		0	59.76	7.50E+03	104698.4	1744.9734	1.00E+06	1.00E+06	956	9.562E+02	8.400E-08	3.000E-12		
9:20 PM	12	**150**	1	-10	**225**	Bi	147		0	59.76	7.50E+03	106134.62	1768.9103	1.00E+06	2.00E+06	956	1.912E+03	7.500E-08	1.000E-11		
9:32 PM	13	**150**	1	-10	**250**	Bi	147		0	59.76	7.50E+03	107903.36	1798.3893	1.00E+06	3.00E+06	956	2.869E+03	8.700E-08	1.000E-11		
9:44 PM	14	**150**	1	-15	**50**	Bi	147		0	59.76	7.50E+03	107398.3	1789.9717	1.00E+06	4.00E+06	956	3.825E+03	6.100E-08	9.000E-12		
9:55 PM	15	**150**	1	-15	**75**	Bi	147		0	59.76	7.50E+03	104699.3	1744.9883	1.00E+06	5.00E+06	956	4.781E+03	6.300E-08	8.000E-12		
10:07 PM	16	**150**	1	-15	**100**	Bi	147		0	59.76	7.50E+03	105949.44	1765.824	1.00E+06	6.00E+06	956	5.737E+03	6.500E-08	1.100E-11		Maybe broke the gate a little in the PIGS test?
10:19 PM	17	**150**	1	-15	**125**	Bi	147		0	59.76	7.50E+03	105931.6	1765.5267	1.00E+06	7.00E+06	956	6.693E+03	6.800E-08	8.000E-11		**around 4.5e5 gate current went into nA range.**

Appendix C

Table C1. Selected Pre- and Post-Irradiation Gate Stress Test Results
(per MIL-STD_750-1 TM1080.1, PIGS not necessary to perform after runs with gate biased ≥ 50% of rated voltage)

Run #:	**pre 36**	**36**	**37**	**38**	**39**	**40**	**41**	**42**	**43**	**44**	**45**	**46**	**47**	**48**	**49**	**50**	**56**	**57**	**58**
DUT S/N:	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80
Run Vds (V):	n/a	225	250	250	250	225	250	25	40	50	60	70	80	100	125	150	250	150	250
Run Vgs (V):	n/a	0	0	-5	-10	-15	-15	-20	-20	-20	-20	-20	-20	-20	-20	-20	-20	0	0
Ion species:	n/a	Ag	Ag	Ag	Ag	Ag	Ag	Ag	Ag	Ag	Ag	Ag	Ag	Ag	Ag	Ag	Ag	Au	Au
Vgs (V)	Ig (A)																		
0	-1.23E-13	3.88E-12	3.47E-12	6.29E-12	7.26E-12	1.19E-11	1.06E-11												
2	2.96E-11	4.38E-11	4.94E-11	6.04E-11	6.35E-11	7.17E-11	7.09E-11												
4	3.75E-11	4.62E-11	4.9E-11	5.42E-11	5.62E-11	6.11E-11	6.11E-11												
6	7.04E-11	9.98E-11	6.06E-11	6.52E-11	6.67E-11	7.19E-11	7.13E-11												
8	6.57E-11	7.34E-11	1.21E-10	1.26E-10	1.29E-10	1.34E-10	1.34E-10												
10	1.28E-10	1.38E-10	1.46E-10	1.5E-10	1.53E-10	1.59E-10	1.59E-10												
12	1.58E-10	1.62E-10	1.64E-10	1.69E-10	1.7E-10	1.75E-10	1.76E-10												
14	1.83E-10	1.81E-10	1.81E-10	1.85E-10	1.87E-10	1.9E-10	1.91E-10												
16	2.05E-10	1.99E-10	1.97E-10	1.98E-10	2E-10	2.04E-10	2.03E-10												
18	2.26E-10	2.17E-10	2.12E-10	2.14E-10	2.14E-10	2.18E-10	2.16E-10												
20	2.48E-10	2.40E-10	2.35E-10	2.37E-10	2.35E-10	2.38E-10	2.37E-10												
0	-3.38E-10	-1.21E-10	-1.22E-10	-2.54E-10	-2.54E-10	-2.53E-10	-2.54E-10												
-2	-2.15E-10	-1.73E-10	-1.74E-10	-2.06E-10	-6.07E-11	-2.06E-10	-2.07E-10												
-4	-2.24E-10	-2.06E-10	-2.07E-10	-6.01E-11	-6.87E-11	-2.22E-10	-2.24E-10												
-6	-2.23E-10	-2.11E-10	-2.13E-10	-7.12E-11	-1.85E-10	-2.22E-10	-2.22E-10												
-8	-2.31E-10	-2.21E-10	-2.20E-10	-1.92E-10	-2.05E-10	-6.30E-11	-6.40E-11												
-10	-2.43E-10	-2.33E-10	-2.31E-10	-2.15E-10	-2.17E-10	-7.88E-11	-7.90E-11												
-12	-2.57E-10	-2.43E-10	-2.42E-10	-2.10E-10	-2.09E-10	-1.88E-10	-1.89E-10												
-14	-2.72E-10	-2.53E-10	-2.53E-10	-2.37E-10	-2.38E-10	-2.26E-10	-2.25E-10												
-16	-2.87E-10	-2.46E-10	-2.44E-10	-2.53E-10	-2.50E-10	-2.35E-10	-2.35E-10												
-18	-2.85E-10	-2.77E-10	-2.76E-10	-2.72E-10	-2.67E-10	-2.52E-10	-2.50E-10												
-20	-3.49E-10	-3.28E-10	-3.24E-10	-3.16E-10	-3.10E-10	-2.95E-10	-2.93E-10												
Idss (uA):	0.72460	0.00333	0.00405	0.00425	0.00489	0.00560	0.00600	0.00806	0.00868	0.00930	0.00976	0.00995	0.01076	0.01133	0.67410	0.01204	0.01147		0.01676
Vth (V):	3.23																		

Table C1 continued: Selected Pre- and Post-Irradiation Gate Stress Test Results
(per MIL-STD_750-1 TM1080.1, PIGS not necessary to perform after runs with gate biased ≥ 50% of rated voltage)



Run #:	**pre 36**	**51**	**52**	**53**	**54**	**59**	**pre 36**	**55**	**60**
DUT S/N:	513	513	513	513	513	513	432	432	432
Run Vds (V):	n/a	250	150	200	250	250	n/a	250	250
Run Vgs (V):		-15	-20	-20	-20	-20		-20	0
Ion species:		Ag	Ag	Ag	Ag	Au		Ag	Au
Vgs (V)									
0	4.78E-13					2.36E-12	3.8E-13		4.71E-12
2	2.86E-11					4.36E-11	3.14E-11		4.93E-11
4	3.41E-11					4.64E-11	3.38E-11		5.2E-11
6	7.22E-11					5.99E-11	7.93E-11		6.53E-11
8	6.06E-11					1.21E-10	6.56E-11		1.33E-10
10	1.14E-10					1.49E-10	1.25E-10		1.64E-10
12	1.44E-10					1.68E-10	1.57E-10		1.85E-10
14	1.66E-10					1.85E-10	1.82E-10		2.04E-10
16	1.86E-10					2.01E-10	2.05E-10		2.21E-10
18	2.07E-10					2.17E-10	2.27E-10		2.4E-10
20	2.26E-10					2.33E-10	2.49E-10		2.58E-10
0	-1.17E-10					-1.17E-10	-1.23E-10		-1.1E-10
-2	-1.66E-10					-1.68E-10	-1.78E-10		-1.7E-10
-4	-1.98E-10					-2.03E-10	-2.12E-10		-2.1E-10
-6	-2.02E-10					-2.05E-10	-2.16E-10		-2.2E-10
-8	-2.12E-10					-2.14E-10	-2.27E-10		-2.2E-10
-10	-2.23E-10					-2.20E-10	-2.40E-10		-2.3E-10
-12	-2.37E-10					-2.29E-10	-2.54E-10		-2.4E-10
-14	-2.31E-10					-2.37E-10	-2.49E-10		-2.5E-10
-16	-2.65E-10					-2.28E-10	-2.85E-10		-2.4E-10
-18	-2.83E-10					-2.54E-10	-3.04E-10		-2.8E-10
-20	-3.04E-10					-2.67E-10	-3.37E-10		-2.9E-10
Idss (uA):	0.00378	0.00381	0.00417		0.00493	0.00788	0.00440	0.00454	0.00701
Vth (V):	3.289	3.25					3.449		

Table C1 continued: Selected Pre- and Post-Irradiation Gate Stress Test Results
(per MIL-STD_750-1 TM1080.1, PIGS not necessary to perform after runs with gate biased ≥ 50% of rated voltage)

Run#:	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
DUT S/N:	248	248	248	284	284	627	627	627	627	347	150	150	150	150	150	150	150
Run Vds (V):	250	200	225	250	125	250	50	75	100	250	250	225	250	50	75	100	125
Run Vgs (V):	-5	-10	-10	-10	-15	-10	-15	-15	-15	-10	-5	-10	-10	-15	-15	-15	-15
Ion species:	Bi	Bi	Bi	Bi	Bi	Bi	Bi	Bi	Bi	Bi	Bi	Bi	Bi	Bi	Bi	Bi	Bi
Vgs (V)	Ig (A)																
0	3.59E-11	4.70E-11	5.10E-11	5.08E-11		4.66E-11	5.00E-11	5.22E-11			4.51E-11	4.89E-11	4.59E-11	5.26E-11	4.98E-11	5.42E-11	5.38E-11
2	7.56E-11	8.87E-11	9.83E-11	9.88E-11		8.63E-11	9.85E-11	6.20E-11			8.75E-11	9.58E-11	9.14E-11	6.24E-11	6.00E-11	6.47E-11	6.48E-11
4	6.20E-11	7.06E-11	7.46E-11	7.53E-11		6.72E-11	7.54E-11	5.07E-11			7.05E-11	7.46E-11	7.15E-11	5.13E-11	4.94E-11	5.36E-11	6.57E-11
6	6.54E-11	7.27E-11	7.64E-11	7.67E-11		7.00E-11	7.68E-11	7.26E-11			7.29E-11	7.65E-11	7.30E-11	7.29E-11	7.20E-11	7.54E-11	1.31E-10
8	1.24E-10	1.33E-10	1.38E-10	1.39E-10		1.29E-10	1.39E-10	1.37E-10			1.35E-10	1.38E-10	1.36E-10	1.39E-10	1.36E-10	1.43E-10	4.37E-10
10	1.53E-10	1.60E-10	1.62E-10	1.62E-10		1.58E-10	1.64E-10	1.62E-10			1.59E-10	1.62E-10	1.60E-10	1.64E-10	1.62E-10	1.71E-10	7.64E-10
12	1.74E-10	1.76E-10	1.79E-10	1.78E-10		1.76E-10	1.80E-10	1.80E-10			1.76E-10	1.78E-10	1.74E-10	1.80E-10	1.79E-10	1.96E-10	1.71E-09
14	1.89E-10	1.90E-10	1.92E-10	1.93E-10		1.90E-10	1.92E-10	1.93E-10			1.89E-10	1.91E-10	1.88E-10	1.93E-10	1.93E-10	2.32E-10	3.55E-09
16	2.03E-10	2.03E-10	2.06E-10	2.04E-10		2.01E-10	2.05E-10	2.05E-10			2.02E-10	2.03E-10	2.00E-10	2.06E-10	2.04E-10	2.85E-10	7.70E-09
18	2.18E-10	2.16E-10	2.17E-10	2.15E-10		2.14E-10	2.16E-10	2.16E-10			2.12E-10	2.12E-10	2.11E-10	2.16E-10	2.14E-10	3.96E-10	9.88E-09
20	2.34E-10	2.33E-10	2.33E-10	2.32E-10		2.27E-10	2.30E-10	2.30E-10			2.25E-10	2.26E-10	2.22E-10	2.28E-10	2.27E-10	6.34E-10	3.62E-08
0	-3.34E-10	-3.35E-10	-3.35E-10	-3.35E-10		-3.36E-10	-3.36E-10	-3.37E-10			-3.38E-10	-3.37E-10	-3.39E-10	-3.37E-10	-3.39E-10	-3.38E-10	-1.16E-10
-2	-2.32E-10	-2.34E-10	-2.34E-10	-2.34E-10		-2.35E-10	-2.35E-10	-2.38E-10			-2.37E-10	-2.34E-10	-2.37E-10	-2.36E-10	-2.38E-10	-2.37E-10	-1.98E-10
-4	-2.28E-10	-2.30E-10	-2.28E-10	-2.30E-10		-2.31E-10	-2.33E-10	-2.35E-10			-2.33E-10	-2.33E-10	-2.34E-10	-2.33E-10	-2.36E-10	-2.33E-10	-2.30E-10
-6	-2.21E-10	-2.29E-10	-2.28E-10	-2.29E-10		-2.30E-10	-2.30E-10	-2.31E-10			-2.27E-10	-2.30E-10	-2.32E-10	-2.32E-10	-2.33E-10	-2.33E-10	-3.16E-10
-8	-2.26E-10	-2.32E-10	-2.31E-10	-2.32E-10		-2.33E-10	-2.35E-10	-2.37E-10			-2.30E-10	-2.32E-10	-2.35E-10	-2.34E-10	-2.37E-10	-2.39E-10	-6.54E-10
-10	-2.37E-10	-2.36E-10	-2.32E-10	-2.34E-10		-2.33E-10	-2.38E-10	-2.40E-10			-2.37E-10	-2.35E-10	-2.37E-10	-2.37E-10	-2.41E-10	-2.47E-10	-8.55E-10
-12	-2.48E-10	-2.42E-10	-2.38E-10	-2.36E-10		-2.38E-10	-2.44E-10	-2.46E-10			-2.43E-10	-2.36E-10	-2.37E-10	-2.42E-10	-2.45E-10	-2.63E-10	-1.99E-09
-14	-2.57E-10	-2.54E-10	-2.48E-10	-2.45E-10		-2.47E-10	-2.50E-10	-2.31E-10			-2.51E-10	-2.45E-10	-2.47E-10	-2.28E-10	-2.29E-10	-2.69E-10	-4.58E-09
-16	-2.74E-10	-2.66E-10	-2.61E-10	-2.59E-10		-2.60E-10	-2.49E-10	-2.42E-10			-2.58E-10	-2.53E-10	-2.54E-10	-2.39E-10	-2.40E-10	-3.23E-10	-9.13E-09
-18	-2.72E-10	-2.60E-10	-2.53E-10	-2.51E-10		-2.51E-10	-2.40E-10	-2.55E-10			-2.46E-10	-2.43E-10	-2.44E-10	-2.51E-10	-2.50E-10	-4.16E-10	-1.66E-08
-20	-3.42E-10	-3.27E-10	-3.17E-10	-3.12E-10		-3.02E-10	-2.90E-10	-2.89E-10			-3.07E-10	-3.03E-10	-3.02E-10	-2.97E-10	-2.97E-10	-6.39E-10	-2.84E-08
Idss (uA)	0.0715	0.0718	0.0718	0.0722		0.0697	0.0711	0.0714			0.0724	0.0725	0.0724	0.0745	0.0748	0.0751	0.0808

Appendix D

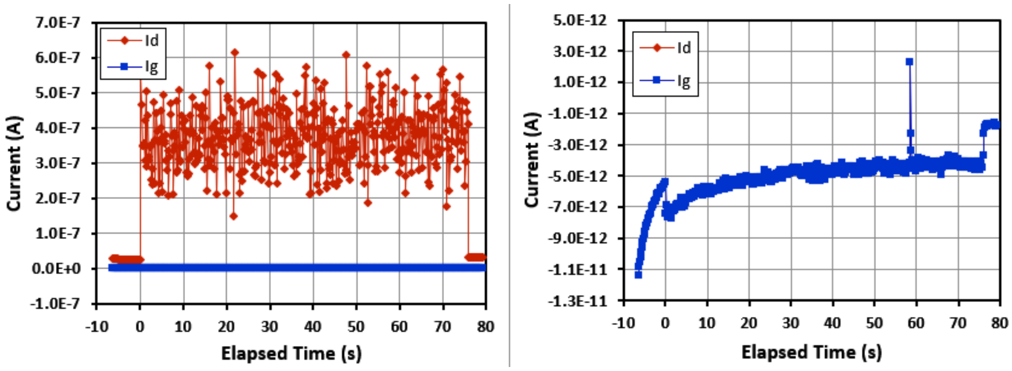


Figure D1. Strip tape data from DUT 80, run 58: 1956 MeV Au. Run bias conditions: 0 V_{GS}, 250 V_{DS}. Beam shuttered after about 76 seconds. Left: charge collection can be seen in drain current trace. Right: board capacitive current present pre-beam (time < 0 s) and into the beam run. As with drain current, gate current reflects charge collection as evidenced by current reduction after beam off. A momentary non-damaging pA-level current spike occurs at about 59 s into the beam run.

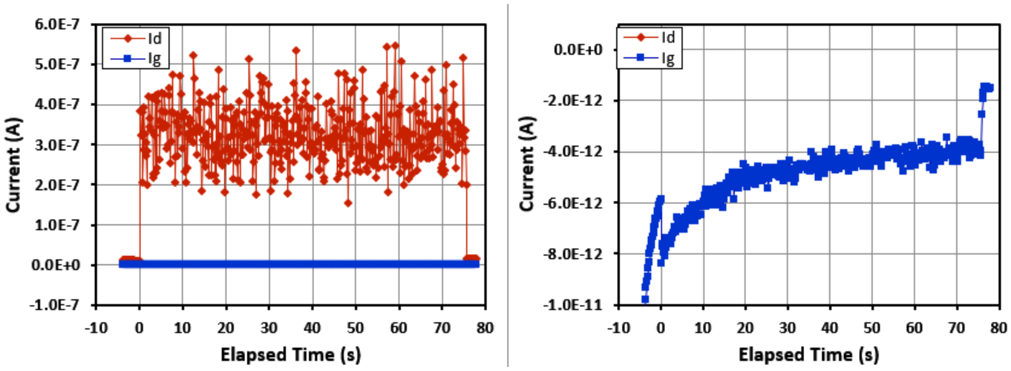


Figure D2. Strip tape data from DUT 513, run 59: 1956 MeV Au. Run bias conditions: 0 V_{GS}, 250 V_{DS}. Beam shuttered after about 75 seconds. Left: charge collection can be seen in drain current trace. Right: board capacitive current present pre-beam (time < 0 s) and into the beam run. As with drain current, gate current reflects charge collection as evidenced by current reduction after beam off.

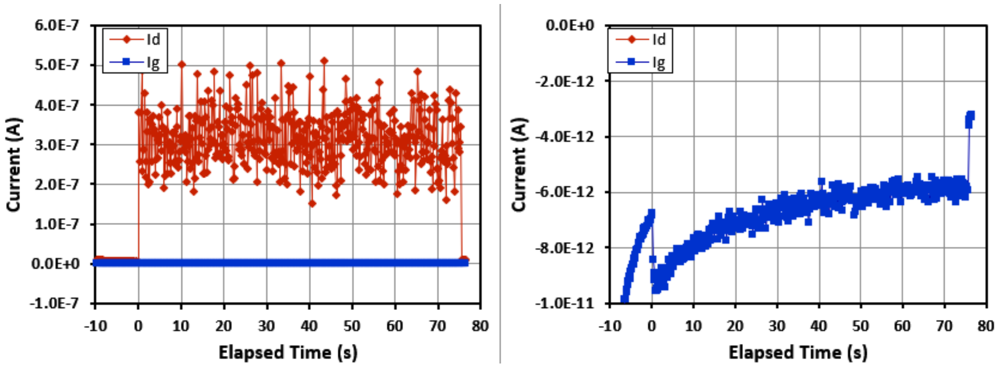


Figure D3. Strip tape data from DUT 432, run 60: 1956 MeV Au. Run bias conditions: 0 V_{GS}, 250 V_{DS}. Beam shuttered after about 76 seconds. Left: charge collection can be seen in drain current trace. Right: board capacitive current present pre-beam (time < 0 s) and into the beam run. As with drain current, gate current reflects charge collection as evidenced by current reduction after beam off.

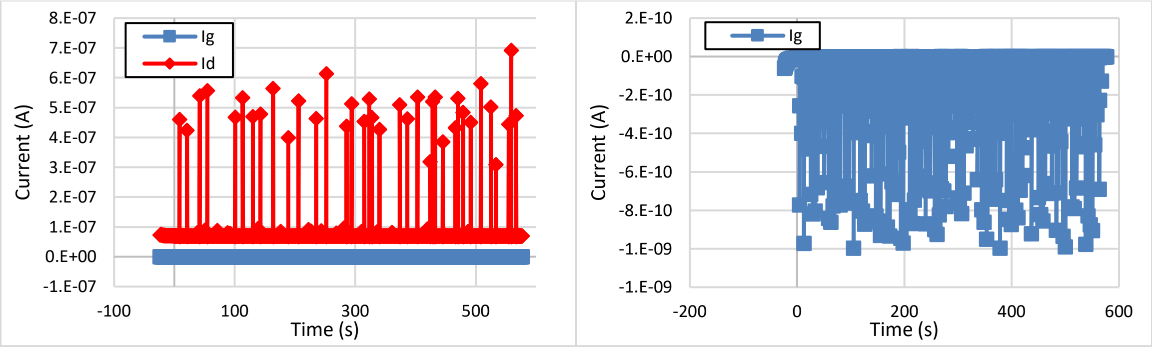


Figure D4. Strip tape data from DUT 248, run 2: Bi. Run bias conditions: -10 V_{GS}, 200 V_{DS}. Beam shuttered after about 600 seconds. Left: charge collection can be seen in drain current trace. Right: The pulsed structure of the NSRL synchrotron beam can be seen to generate large gate current spikes when compared to the LBNL data. Charge dissipates to pA level shortly after beam pulse but the noise generated by the pulse structure is too large to discern baseline gate current.

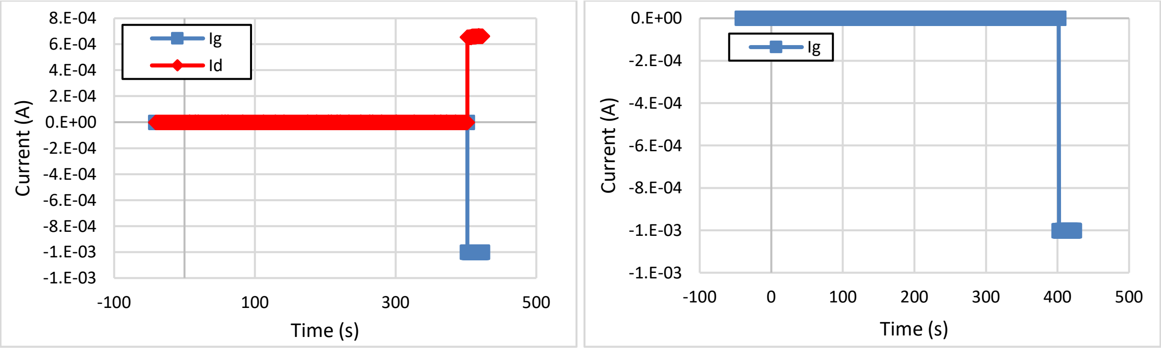


Figure D5. Strip tape data from DUT 627, run 9: Bi. Run bias conditions: -15 V_{GS}, 100 V_{DS}. Beam shuttered after about 422 seconds. Left: Part failure can be seen by large sudden increase in both drain and gate current.

Appendix E

Table E1. LBNL Beam Log

Run#	Date	Time		Total Fluence	Total Eff Fluence	Average Flux	Maximum Flux	Run Time (sec)	DUT	Beam		Ion	LET	Eff LET	Base Angle
36	6/9/2021	12:32:24	AM	1.00E+06	1.00E+06	5.88E+03	6.20E+03	170.56	M001	10	MeV	Ag	48.15	48.15	0
37	6/9/2021	12:37:22	AM	1.00E+06	1.00E+06	5.10E+03	5.88E+03	196.61	M001	10	MeV	Ag	48.15	48.15	0
38	6/9/2021	12:42:45	AM	1.00E+06	1.00E+06	4.99E+03	5.58E+03	200.57	M001	10	MeV	Ag	48.15	48.15	0
39	6/9/2021	12:46:30	AM	1.00E+06	1.00E+06	8.73E+03	1.14E+04	115.15	M001	10	MeV	Ag	48.15	48.15	0
40	6/9/2021	12:50:22	AM	1.00E+06	1.00E+06	8.75E+03	1.17E+04	114.68	M001	10	MeV	Ag	48.15	48.15	0
41	6/9/2021	12:54:00	AM	1.00E+06	1.00E+06	9.17E+03	1.18E+04	109.39	M001	10	MeV	Ag	48.15	48.15	0
42	6/9/2021	12:58:16	AM	1.00E+06	1.00E+06	8.76E+03	1.13E+04	114.51	M001	10	MeV	Ag	48.15	48.15	0
43	6/9/2021	1:01:33	AM	1.00E+06	1.00E+06	8.51E+03	8.93E+03	117.97	M001	10	MeV	Ag	48.15	48.15	0
44	6/9/2021	1:04:24	AM	1.00E+06	1.00E+06	8.43E+03	8.81E+03	119.02	M001	10	MeV	Ag	48.15	48.15	0
45	6/9/2021	1:07:59	AM	1.00E+06	1.00E+06	8.30E+03	8.90E+03	120.87	M001	10	MeV	Ag	48.15	48.15	0
46	6/9/2021	1:10:59	AM	1.00E+06	1.00E+06	8.16E+03	8.83E+03	123.07	M001	10	MeV	Ag	48.15	48.15	0
47	6/9/2021	1:13:50	AM	1.00E+06	1.00E+06	8.72E+03	1.15E+04	114.97	M001	10	MeV	Ag	48.15	48.15	0
48	6/9/2021	1:16:10	AM	1.01E+06	1.01E+06	1.10E+04	1.19E+04	91.83	M001	10	MeV	Ag	48.15	48.15	0
49	6/9/2021	1:19:19	AM	1.00E+06	1.00E+06	8.68E+03	1.09E+04	115.8	M001	10	MeV	Ag	48.15	48.15	0
50	6/9/2021	1:22:23	AM	1.00E+06	1.00E+06	9.06E+03	1.13E+04	110.7	M001	10	MeV	Ag	48.15	48.15	0
51	6/9/2021	1:25:37	AM	1.00E+06	1.00E+06	8.97E+03	9.41E+03	111.84	M002	10	MeV	Ag	48.15	48.15	0
52	6/9/2021	1:28:51	AM	1.01E+06	1.01E+06	8.81E+03	9.68E+03	114.14	M002	10	MeV	Ag	48.15	48.15	0
53	6/9/2021	1:31:34	AM	1.00E+06	1.00E+06	9.12E+03	1.01E+04	110.21	M002	10	MeV	Ag	48.15	48.15	0
54	6/9/2021	1:34:22	AM	1.00E+06	1.00E+06	8.79E+03	1.01E+04	114.11	M002	10	MeV	Ag	48.15	48.15	0
55	6/9/2021	1:37:32	AM	1.00E+06	1.00E+06	8.66E+03	9.35E+03	115.96	M003	10	MeV	Ag	48.15	48.15	0
56	6/9/2021	1:41:03	AM	1.00E+06	1.00E+06	8.78E+03	9.55E+03	114.21	M001	10	MeV	Ag	48.15	48.15	0
57	6/9/2021	1:50:49	AM	2.13E+05	2.13E+05	1.23E+04	1.31E+04	17.25	M001	10	MeV	Au	85.76	85.76	0
58	6/9/2021	1:54:09	AM	1.01E+06	1.01E+06	1.33E+04	1.40E+04	75.52	M001	10	MeV	Au	85.76	85.76	0
59	6/9/2021	1:56:40	AM	1.01E+06	1.01E+06	1.34E+04	1.41E+04	75.43	M002	10	MeV	Au	85.76	85.76	0
60	6/9/2021	1:59:59	AM	1.01E+06	1.01E+06	1.34E+04	1.41E+04	75.03	M003	10	MeV	Au	85.76	85.76	0