SEE Test Report
Single event effects testing of the Vishay SiB455EDK p-type Power MOSFET

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I. Introduction and Summary of Test Results

This study was undertaken to determine the single event effect susceptibility of the SiB455EDK power MOSFET. This test was conducted at the Texas A&M University Cyclotron Single Event Effects Test Facility (TAMU). Its purpose was to evaluate this device as a candidate for use in NASA flight projects, as well as to examine the heavy-ion response of a p-type trenchFET power device structure.

All failures during these tests were due to single-event gate rupture (SEGR). All tests were conducted in air at either 2°, 45°, or 60° off-normal beam incidence. A summary of the minimum last pass/first fail drain-source voltage (Vds) for a given gate-source voltage bias (Vgs) is provided in Table I below as a function of the ion species, as well as energy, range, and LET at the surface of the device under test (DUT). The total number of devices tested under each beam and bias condition is shown in the final column. These data are plotted in Figure 1.

Table I: Summary of heavy-ion test results. All failures are due to SEGR.

Ion Specie	Surface-Incident Energy (MeV)	Range (um)	Surface-Incident LET (MeV·cm^2/mg)	Angle (deg)	Vgs (V)	Maximum Last Passing Vds (V)	Maximum Vds at Failure (V)	# of Devices Tested
Kr	989	127.5	28.3	2	0	-12	n/a	3
					2	-11	-12	2
					2	n/a	-12	1
					5	-7	-8	3
Ag	1225	112.8	42.9	2	0	-11	-12	2
					5	-7*	-8	3
				45	0	-12	n/a	2
					5	n/a	-9	1
					5	-8	-9	1
				60	0	-12	n/a	1
					5	-9	-12	1

*Elevated Id and Ig during beam exposure, but samples remained within vendor specification. Vds at last clean run was -6 V for all three samples.

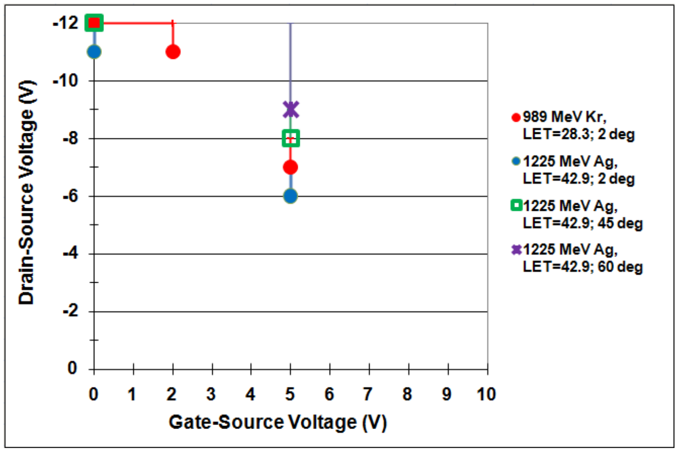

Figure 1. SEE response curve for the SiB455EDK

II. Devices Tested

The sample size for the testing is 29 pieces and one control. The part is manufactured by Vishay Intertechnology as part of their trenchFET Gen III line.

The device is a commercial 9 A, 12 V p-channel trench power MOSFET, part #SiB455EDK. The samples to be tested were provided by Vishay's sample house in July, 2010 in Vishay's new thermally enhanced powerPAK SC-75 surface-mount plastic packaging. Package markings on the samples include the part # code BKW, and lot date code (LDC) 9QZ. Figure 1 shows a cartoon cross-section of the device, revealing the copper leadframe forming the heatsink coupled to the drain contact. The die measures 0.1134 cm x 0.0650 cm, for a total die area of 0.0074 cm^2. Samples were surface-mounted at GSFC onto daughter cards designed to be inserted into wire-wrap sockets on the test board. Samples were then delidded with acid by Timothy Irwin, MEI Technologies. The pieces were visually inspected and electrically characterized by Anthony Phan, MEI Technologies, before and after delidding. Vendor electrical parameter specifications are given in Appendix A.

The gate trench walls are oriented nearly perpendicular to the surface of the die. Figure 2 shows a representative SEM cross-section and labeled cross-section cartoon of a Vishay TrenchFET. In the SEM cross-section, gate trench walls are 2º to 3º off-normal. The vendor has indicated that the device has a closed-cell topology, so that there is no specific trench orientation with respect to the die.

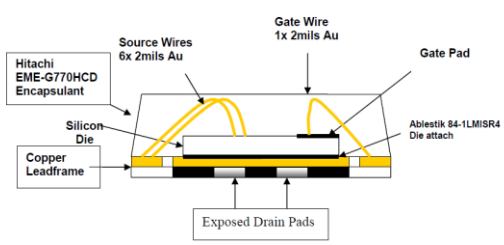

Figure 2. Cartoon cross-section of the device packaging.

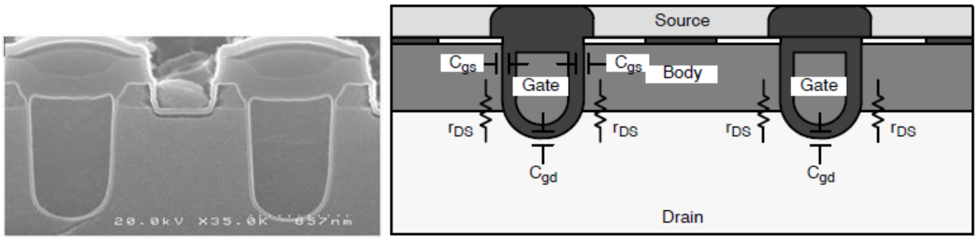

Figure 3. SEM (left) and cartoon (right) cross-section of a representative TrenchFET.
(From: Vishay Siliconix AN605).

III. Test Facility

Facility: Texas A&M University Cyclotron Single Event Effects Test Facility, 15 MeV/amu tune.
Flux: 5×10^3 to 1×10^4 particles/cm^2/s.
Fluence: All tests were run to 1×10^5 p/cm^2 or until destructive events occurred.
Ion species: Kr and Ag. The table below shows the surface-incident beam properties.

Table II. Ion beam properties.

Ion: 15 MeV/u	Surface Energy (MeV)	Surface LET [air gap (cm)] (MeV•cm^2/mg)	Range (μm)	Angle of Incidence (Degrees)
^{84}Kr	989	28.3 [4.08]	127.5	2
^{109}Ag	1225	42.9 [4.08]	112.8	2, 45, 60

IV. Test Setup

The test circuit, as shown in Figure 4, for the power MOSFET contains a Keithley 2400 source meter to provide the gate voltage (set to 0 V, 2 V, or 5 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 second Keithley 2400 source meter provides the appropriate Vds while measuring the drain current. Gate current is limited to 1 mA, and drain current limited to 100 mA, and recorded via GPIB card to a desktop computer at 150 ms intervals.

A probe across the 1 Ω drain sense resistor feeds into a digital oscilloscope that is set to trigger on current transients of a predetermined size, saving them to file. 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. Nine DUTs can be mounted on the test board and individually accessed via a switch box within the control room. The terminals of the devices not under test are then shorted to ground. Testing was conducted in air with the DUT centered within the beam diameter. Ion exposures were conducted at either a 2º, 45º, or 60º angle of incidence to the DUT. The device has a closed-cell topology, so that there is no specific trench orientation with respect to the die.

The test setup is controlled via custom LabView codes written by Hak Kim for this test. One program controls the source measuring units (SMUs), gate current limit, oscilloscope monitoring and transient capture, and gate and drain current sampling and recording. The second LabView code is designed to perform a parametric analysis of each DUT prior to irradiation and following each beam run, recording Igs as a function of Vgs (gate stress test to test the integrity of the gate dielectric), Ids as a function of Vgs at various fixed Vds values for evaluation of total ionizing dose effects, gate threshold voltage (Vth), drain-source breakdown voltage (BVdss), and zero gate voltage drain current (Idss).

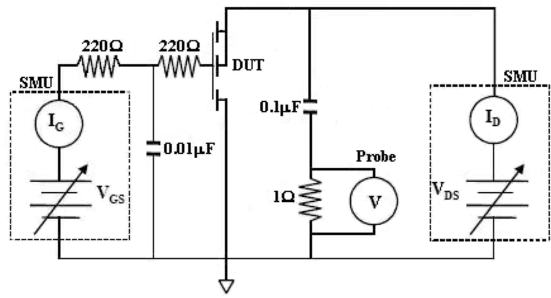

Figure 4. Test setup for the SiB455EDK power MOSFET.

Table III. Test equipment.

Node	Make/model	s/n
Gate	Keithley 2400 source meter	943629 (REAG S/N 1)
Drain	Keithley 2400 source meter Tektronix MSO4104 Probe GW Instek PST-3202 Programmable power supply	(REAG S/N 3) C001418
Other	2 Lenova IBM ThinkCentre desktop computers Power Conditioner Switchbox (custom design)	

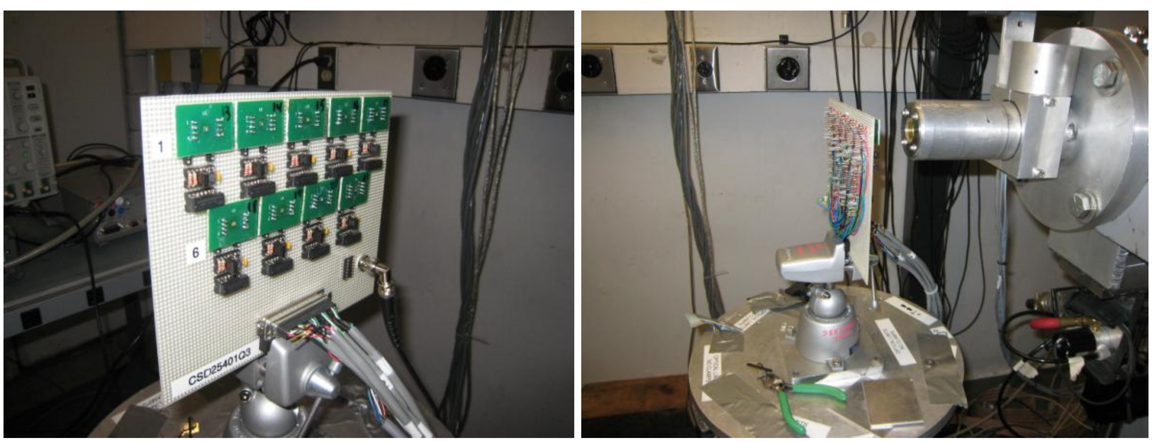

Figure 4. Left: Frontside of board with 9 individually-selectable DUTs mounted. Right: Backside of test board positioned in the beam line.

V. Test Results

Tests were performed at Texas A&M University Cyclotron Single Event Effects Test Facility on August 17-20, 2009. Two monoenergetic ion beams (989 MeV krypton and 1225 MeV silver) were used; all tests were conducted in air with the beam at various angles of incidence to the DUT. Following each run, a post-irradiation gate stress (PIGS) test was performed in which the gate current was measured while the gate voltage was swept from 0V to 8V, then from 0V to -8V, at 0Vds. Each voltage step was held for 500 ms to allow settling prior to the current reading. In addition, Id-Vgs curves were swept at Vds values of -0.01 V and -4.5 V, and Idss measured, to check for ionizing dose effects and device integrity. Table I in Section I summarizes the heavy-ion test results for each bias and beam condition; these results are again plotted below in Fig. 5. Complete results are in Appendix C, with PIGS test results provided in Appendix D. For the runs during which events occurred, strip tape data showing the drain and gate currents sampled just before and during beam exposure are plotted in Appendix E. Pretest electrical characterization results are in Appendix B.

The primary failure mode for this device is SEGR. In Appendix E, most strip tapes demonstrate a symmetric elevation of gate and drain currents, such that Id and Ig are equal in magnitude upon rupture. Several samples (all irradiated with a beam angle of 2°) demonstrated a spike in Id followed by elevated gate and drain currents (Figs. E3, E14, E15, and E17). The primary failure mechanism in these samples is less clear; for these, the drain current remains higher than the elevated gate current following the initial transient. This transient high drain current may indicate a particle strike through the source to the drain. Conversely, the more common failure signature of equal magnitude gate and drain currents may indicate a particle strike through the gate oxide at or near the bottom of the trench. These explanations may be why the device demonstrated reduced sensitivity to failure when the ion beam incidence was at an angle to the device surface. A study on n-type trenchFETs revealed increasing SEGR sensitivity with increasing angle[1]; for these devices, the gate oxide was thicker at the bottom of the trench than along the trench walls, such that ruptures likely occurred in the wall of the trench oxide. SEM studies would be required to confirm the failure pathways in the Vishay samples of this report. Finally, note that in two instances (following runs 44 and 84), samples passed the PIGS test following irradiation, but then failed when the next incremental Vds bias was applied, prior to the ion beam turning on. Both of these samples were irradiated at a beam angle of 2°, and demonstrated equal-magnitude elevations of Ig and Id. Future tests with non-zero Vds during PIGS testing would therefore be appropriate.

"Microdose" failures reported in the n-type trenchFETs[1,2], in which a particle strike down the length of the gate oxide between source and drain permanently turns on the sample, were not seen in this study. In one sample (DUT 7, run 43), the threshold voltage measured immediately following beam exposure was < -1 V, but returned to its pre-run value of -0.54 V upon remeasurement. In this p-type device, charge ionized within the oxide along the trench wall would be expected to cause a shift in threshold voltage to a more negative value, making the sample harder to turn on due to hole trapping. While the initial shift in threshold voltage in DUT 7 followed this expectation, the subsequent recovery suggests the holes were not permanently trapped, or else they were neutralized. Total ionizing dose studies of this device are needed to help characterize the gate oxide charge trapping properties.

[1] Liu, S., *et al.*, "Vulnerable Trench Power MOSFETs under Heavy Ion Irradiation," presented at IEEE Nuclear Space and Radiation Effects Conference, Tuscan, AZ, July 2010.
[2] J. A. Felix, M. R. Shaneyfelt, J. R. Schwank, S. M. Dalton, P. E. Dodd, and J. B. Witcher, "Enhanced degradation in power MOSFET devices due to heavy ion irradiation," *IEEE Transactions on Nuclear Science*, vol. 54, pp. 2181-2189, Dec 2007.

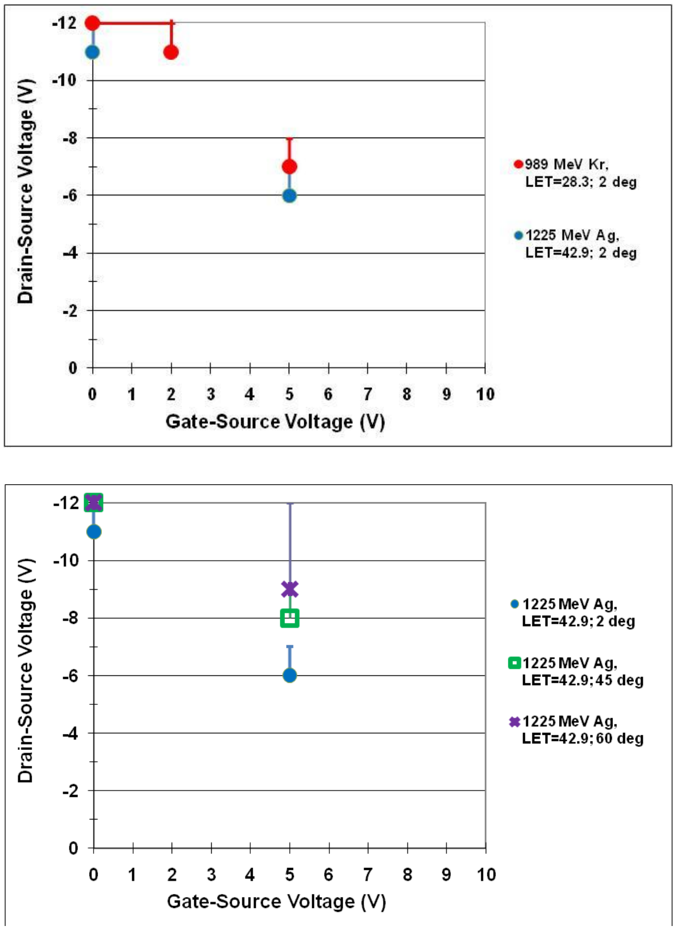

Figure 5. SEE response curves for the SiB455EDK. Top: Kr and Ag curves at 2° beam incidence angle. Bottom: Angular response under Ag irradiation, as a function of applied Vgs.

Appendix A

Table A1. SiB455EDK vendor-specified electrical parameters (partial list).

Parameter	Condition	MIN	MAX	Units
Gate Threshold Voltage (VGSth)	Vds = Vgs, Id = -250 μA	-0.4	-1	V
Zero Gate Voltage Drain Current (Idss)	Vds = -12 V, Vgs = 0 V		-1	μA
Drain-Source Breakdown Voltage (BVdss)	Vgs = 0 V, Id = -250 μA	-12		V
Gate-Source Leakage Current (Igss)	Vgs = +/- 8 V, Vds = 0 V		+/- 10	μA
Static Drain-Source Resistance (Rds_on)	Vgs = -4.5 V, Id = -5.6 A Vgs = -1.5 V, Id = -0.5 A		27 130	mΩ
Forward Voltage (Vsd)	Is = -6.5 A, Vgs = 0V		-1.2	V

Appendix B

Table B1. Pretest electrical characterization.

Part SN	Vth	BVdss	Idss	Igss -	Igss +
	(Volts)	(Volts)	(nA)	(nA)	(nA)
1	(BAD Id-Vgs sweeps)			-616	589
2	-0.54	-12	-23.56	-445	491
3	-0.57	-12	-25.64	-389	563
4	-0.57	-12	-30.06	-538	535
5	-0.55	-12	-18.88	-610	563
6	-0.61	-12	-36.95	-557	846
7	-0.52	-12	-23.09	-549	574
8	-0.6	-12	-113.6	-594	586
9	BAD Id-Vgs sweep				
10	-0.53	-12	-30.32	-472	614
11	-0.56	-12	-20.57	-674	629
12				Igss out of spec	
13	-0.55	-12	-31.43	-542	554
14	-0.54	-12	-34.17	-559	545
15	-0.6	-12	-38.31	-578	754
16	-0.53	-12	-34.26	-386	500
17	-0.52	-12	-29.33	-563	589
18	-0.5	-12	-35.34	-534	544
19	-0.54	-12	-36.81	-803	924
20	-0.58	-12	-44.15	-516	511

Appendix C

Table C1. Raw test data. Beam diameter = 1”; LET, energy, and range are at the die surface, as calculated by TAMU SEUSS (based upon SRIM 1995).

Run Date	Time	Run #	Ion	LET MeV.cm2/mg	Energy MeV/u	Energy MeV	Range µm	Ave. Flux #/cm2/s	Eff.Fluence #/cm2	Dose rad(Si)	Cum. Dose rad(Si)	Angle deg	socket #	S/N	VGS V	VDS V	-Vth V	Idss nA	Pass/Fail	Comments
8/18/10	4:40	24	Ag	42.9	11.3	1225	112.8	8.57E+02	1.00E+05	9.74E+01	9.74E+01	45	3	3	0	-4	0.56	-28.59		
	4:50	25	Ag	42.9	11.3	1225	112.8	1.03E+03	1.00E+05	9.72E+01	1.95E+02	45	3	3	0	-6	0.56	-29.31		
	4:54	26	Ag	42.9	11.3	1225	112.8	1.02E+03	1.00E+05	9.74E+01	2.92E+02	45	3	3	0	-8	0.56	-29.91		
	5:08	27	Ag	42.9	11.3	1225	112.8	9.69E+02	1.00E+05	9.73E+01	3.89E+02	45	3	3	0	-10	0.56	-29.62		
	5:14	28	Ag	42.9	11.3	1225	112.8	9.44E+02	1.00E+05	9.72E+01	4.86E+02	45	3	3	0	-12	0.56	-29.76		no transients
	5:25	29	Ag	42.9	11.3	1225	112.8	1.10E+04	9.97E+05	9.69E+02	9.69E+02	45	2	2	0	-12	0.54	-23.19		
	5:43	30	Ag	42.9	11.3	1225	112.8	1.44E+04	9.29E+05	6.83E+02	1.65E+03	2	2	2	0	-12	0.54	-257.63		sudden increase Ig/Id during run; PIGS in spec
	5:58	31	Ag	42.9	11.3	1225	112.8	1.45E+04	9.93E+05	6.83E+02	1.17E+03	2	3	3	0	-9	0.56	-29.63		
	6:04	32	Ag	42.9	11.3	1225	112.8	1.52E+04	9.94E+05	6.83E+02	1.85E+03	2	3	3	0	-10	0.56	-31.56		glitches on gate during run
	6:08	33	Ag	42.9	11.3	1225	112.8	1.00E+04	1.00E+06	6.88E+02	2.54E+03	2	3	3	0	-11	0.56	-31.11		
	6:13	34	Ag	42.9	11.3	1225	112.8	1.01E+04	2.38E+05	1.64E+02	2.70E+03	2	3	3	0	-12	0.42	n/a	Fail	increase in Ig/Id during run; PIGS out of spec
	6:30	35	Ag	42.9	11.3	1225	112.8	1.01E+04	1.00E+06	6.89E+02	6.89E+02	2	4	4	0	-10	0.57	-30.5		
	6:34	36	Ag	42.9	11.3	1225	112.8	9.90E+03	1.01E+06	6.91E+02	1.38E+03	2	4	4	0	-11	0.57	-32.21		
	6:40	37	Ag	42.9	11.3	1225	112.8	9.61E+03	2.24E+05	1.54E+02	1.53E+03	2	4	4	0	-12	0.57	-282.35		sudden increase Ig/Id during run; PIGS in spec
		38	Ag	42.9	11.3	1225	112.8	9.00E+03	3.67E+04	2.53E+01	2.53E+01	2	5	5	5	-9	0.43	n/a	Fail	Failed on run; PIGS out of spec
	6:59	39	Ag	42.9	11.3	1225	112.8	9.69E+03	1.00E+06	6.88E+02	6.88E+02	2	6	6	5	-5	0.61	-41.18		
	7:04	40	Ag	42.9	11.3	1225	112.8	1.02E+04	9.97E+05	6.86E+02	1.37E+03	2	6	6	5	-6	0.61	-41.78		
	7:10	41	Ag	42.9	11.3	1225	112.8	9.87E+03	7.39E+05	5.09E+02	1.88E+03	2	6	6	5	-7	0.6	-1004.1		sudden increase Ig/Id during run; PIGS in spec
	7:18	42	Ag	42.9	11.3	1225	112.8	1.04E+04	1.00E+06	6.88E+02	6.88E+02	2	7	7	5	-6	0.53	-24.11		
	7:23	43	Ag	42.9	11.3	1225	112.8	1.06E+04	1.01E+06	6.91E+02	1.38E+03	2	7	7	5	-7	(<-1)	-23.1		small breaks on run; redid Vth: -0.54; Idss = -23.28
	7:33	44	Ag	42.9	11.3	1225	112.8	9.40E+03	1.16E+05	8.00E+01	1.46E+03	2	7	7	5	-8	0.53	-212.51		sudden increase Ig/Id during run; PIGS in spec
		45						n/a	n/a	n/a	1.46E+03	2	7	7	5	-9	0.46		Fail	Failed before beam applied. PIGS out of spec
	7:45	46	Ag	42.9	11.3	1225	112.8	9.21E+03	1.00E+06	6.89E+02	6.89E+02	2	8	8	5	-6		-57.78		TAMU run is #45 - didn't notice til too late to reset
	7:49	47	Ag	42.9	11.3	1225	112.8	9.34E+03	9.99E+05	6.87E+02	1.38E+03	2	8	8	5	-7	0.6	-61.16		small increase Ig/Id on run; PIGS in spec
	7:53	48	Ag	42.9	11.3	1225	112.8	9.22E+03	1.38E+05	9.46E+01	1.47E+03	2	8	8	5	-8	0.6	-254.17		more increases in Ig/Id on run; PIGS in spec
	8:25	49	Ag	42.9	11.3	1225	112.8	9.97E+03	2.92E+05	2.84E+02	2.84E+02	45	3	11	5	-9	0.56		Fail	Failed on run; PIGS out of spec
		50	Ag	42.9	11.3	1225	112.8	9.83E+03	1.00E+06	9.75E+02	9.75E+02	45	2	10	5	-7	0.53	-31.38		
	8:37	51	Ag	42.9	11.3	1225	112.8	9.68E+03	1.00E+06	9.72E+02	1.95E+03	45	2	10	5	-8	0.53	-31.08		
	8:41	52	Ag	42.9	11.3	1225	112.8	9.66E+03	1.00E+06	9.75E+02	2.92E+03	45	2	10	5	-9	0.49		Fail	Failed on run; PIGS out of spec

(Table cont’d next page)

Run Date	Time	Run #	Ion	LET MeV.cm2/mg	Energy MeV/u	Energy MeV	Range µm	Ave. Flux #/cm2/s	Eff.Fluence #/cm2	Dose rad(Si)	Cum. Dose rad(Si)	Angle deg	socket #	S/N	VGS V	VDS V	-Vth V	Idss nA	Pass/Fail	Comments
8/19/10	2:19	68	Kr	28.3	11.8	989	127.5	1.05E+04	1.00E+06	4.55E+02	4.55E+02	2	2	14	0	-12	0.56	-40.15		
	2:25	69	Kr	28.3	11.8	989	127.5	1.01E+04	3.87E+05	1.76E+02	6.30E+02	2	2	14	2	-12	0.52		Fail	Failed on run; PIGS out of spec
	2:36	70	Kr	28.3	11.8	989	127.5	5.06E+03	9.99E+05	4.54E+02	4.54E+02	2	3	15	0	-12	0.59	-42.45		
	2:41	71	Kr	28.3	11.8	989	127.5	4.96E+03	1.00E+06	4.54E+02	9.08E+02	2	3	15	2	-10	0.6	-42.25		
	2:47	72	Kr	28.3	11.8	989	127.5	4.98E+03	1.00E+06	4.54E+02	1.36E+03	2	3	15	2	-11	0.6	-42.03		
	2:53	73	Kr	28.3	11.8	989	127.5	4.79E+03	1.03E+05	4.67E+01	1.41E+03	2	3	15	2	-12	0.58		Fail	Failed on run; PIGS out of spec
	3:01	74	Kr	28.3	11.8	989	127.5	4.76E+03	1.00E+06	4.55E+02	4.55E+02	2	4	16	0	-12	0.53	-37.24		
	3:07	75	Kr	28.3	11.8	989	127.5	4.74E+03	1.00E+06	4.55E+02	9.10E+02	2	4	16	1	-12	0.53	-38.44		
	3:15	76	Kr	28.3	11.8	989	127.5	9.73E+02	5.04E+05	2.29E+02	1.14E+03	2	4	16	2	-12	0.53	-36.34		
	3:26	77	Kr	28.3	11.8	989	127.5	9.72E+02	7.28E+04	3.31E+01	1.17E+03	2	4	16	3	-12	0.51		Fail	Failed on run; PIGS out of spec
	3:34	78	Kr	28.3	11.8	989	127.5	1.03E+03	4.30E+05	1.96E+02	1.96E+02	2	5	17	2	-12	0.48		Fail	Failed on run; PIGS out of spec
	3:56	79	Kr	28.3	11.8	989	127.5	5.02E+03	9.98E+05	4.54E+02	4.54E+02	2	6	18	5	-6	0.51	-39.25		
	4:01	80	Kr	28.3	11.8	989	127.5	5.01E+03	1.00E+06	4.55E+02	9.08E+02	2	6	18	5	-7	0.51	-40.32		
	4:06	81	Kr	28.3	11.8	989	127.5	5.00E+03	9.99E+05	4.54E+02	1.36E+03	2	6	18	5	-8	0.51	-38.78		
	4:12	82	Kr	28.3	11.8	989	127.5	4.97E+03	9.56E+04	4.34E+01	1.41E+03	2	6	18	5	-9	0.49		Fail	Failed on run; PIGS out of spec
	4:18	83	Kr	28.3	11.8	989	127.5	4.89E+03	1.00E+06	4.54E+02	4.54E+02	2	7	19	5	-7	0.54	-39.34		
	4:23	84	Kr	28.3	11.8	989	127.5	4.87E+03	1.00E+06	4.54E+02	9.09E+02	2	7	19	5	-8	0.55	-211.02		sudden increase Id/Ig during run; PIGS in spec
	4:29	85						n/a	n/a	n/a	9.09E+02	2	7	19	5	-9	0.53		Fail	Failed before beam applied. PIGS out of spec
	4:36	86	Kr	28.3	11.8	989	127.5	4.75E+03	1.00E+06	4.55E+02	4.55E+02	2	8	20	5	-7	0.59	-48.34		
	4:42	87	Kr	28.3	11.8	989	127.5	4.80E+03	1.00E+06	4.55E+02	9.10E+02	2	8	20	5	-8	0.58	-183.3		sudden increase Id/Ig during run; PIGS in spec
	4:48	88	Kr	28.3	11.8	989	127.5	4.65E+03	5.69E+04	2.59E+01	9.36E+02	2	8	20	5	-9	0.57	-9956	Fail	Failed on run; PIGS out of spec
8/20/10	1:44	120	Ag	42.9	11.3	1225	112.8	1.05E+04	1.00E+06	1.38E+03	1.38E+03	60	1	13	0	-7	0.55	-33.85		
	1:49	121	Ag	42.9	11.3	1225	112.8	1.00E+04	9.98E+05	1.37E+03	2.75E+03	60	1	13	0	-8	0.55	-32.41		glitch on gate/drain during run
	1:55	122	Ag	42.9	11.3	1225	112.8	1.01E+04	9.99E+05	1.37E+03	4.12E+03	60	1	13	0	-9	0.55	-33.52		
	2:01	123	Ag	42.9	11.3	1225	112.8	1.01E+04	1.00E+06	1.38E+03	5.50E+03	60	1	13	0	-10	0.55	-33.16		
	2:07	124	Ag	42.9	11.3	1225	112.8	1.01E+04	1.00E+06	1.38E+03	6.87E+03	60	1	13	0	-11	0.55	-32.74		
	2:12	125	Ag	42.9	11.3	1225	112.8	1.01E+04	1.00E+06	1.38E+03	8.25E+03	60	1	13	0	-12	0.55	-32.97		
	2:17	126	Ag	42.9	11.3	1225	112.8	9.38E+03	9.99E+05	1.37E+03	9.62E+03	60	1	13	5	-5	0.55	-34.05		
	2:24	127	Ag	42.9	11.3	1225	112.8	1.10E+04	9.97E+05	1.37E+03	1.10E+04	60	1	13	5	-6	0.55	-33.27		
	2:36	128	Ag	42.9	11.3	1225	112.8	1.07E+04	1.00E+06	1.37E+03	1.24E+04	60	1	13	5	-7	0.55	-33.15		
	2:42	129	Ag	42.9	11.3	1225	112.8	1.05E+04	1.00E+06	1.38E+03	1.37E+04	60	1	13	5	-8	0.55	-32.68		
	2:47	130	Ag	42.9	11.3	1225	112.8	9.97E+03	1.00E+06	1.38E+03	1.51E+04	60	1	13	5	-9	0.55	-36.41		
	2:53	131	Ag	42.9	11.3	1225	112.8	9.57E+03	1.12E+05	1.54E+02	1.53E+04	60	1	13	5	-12	0.55	n/a	Fail	Failed on run; PIGS out of spec

Appendix D

Table D1. Post-irradiation gate stress (PIGS) test. Table contains PIGS test following the last passing run and first failing run for each DUT.

Run #	pre-29	29	30	pre-24	33	34	36	37	pre-38	38
DUT S/N	2	2	2	3	3	3	4	4	5	5
Date	8/18/2010	8/18/2010	8/18/2010	8/18/2010	8/18/2010	8/18/2010	8/18/2010	8/18/2010	8/18/2010	8/18/2010
Time	6:12	6:17	6:34	5:25	7:00	7:03	7:26	7:30	7:37	7:40
Vgs (V):	Igs (A):									
0	-4.91E-11	8.20E-11	-9.06E-11	-3.85E-11	3.79E-11	-5.88E-11	-6.48E-12	1.73E-11	-2.07E-11	-4.46E-10
1	1.08E-09	1.13E-09	1.25E-09	1.58E-09	2.87E-09	3.99E-09	1.23E-09	1.42E-09	1.18E-09	1.90E-09
2	4.62E-09	4.78E-09	5.20E-09	5.41E-09	6.43E-09	3.31E-08	4.81E-09	5.98E-09	4.85E-09	1.71E-08
3	1.46E-08	1.50E-08	1.65E-08	1.58E-08	1.81E-08	1.69E-07	1.54E-08	1.81E-08	1.55E-08	1.07E-07
4	3.62E-08	3.73E-08	4.17E-08	3.89E-08	4.01E-08	5.71E-07	3.85E-08	4.42E-08	3.94E-08	6.40E-07
5	7.87E-08	8.04E-08	8.93E-08	8.33E-08	8.57E-08	1.39E-06	8.33E-08	9.78E-08	8.53E-08	3.07E-06
6	1.54E-07	1.55E-07	1.73E-07	1.66E-07	1.69E-07	4.13E-06	1.66E-07	1.94E-07	1.70E-07	**1.65E-05**
7	2.80E-07	2.84E-07	3.19E-07	3.12E-07	3.16E-07	**1.86E-05**	3.07E-07	4.22E-07	3.16E-07	5.46E-05
8	4.91E-07	4.95E-07	6.74E-07	5.63E-07	5.69E-07	1.26E-04	5.51E-07	9.00E-07	5.63E-07	1.42E-04
-1	-7.66E-10	-8.13E-10	-8.25E-10	-9.73E-10	-8.84E-10	-2.56E-08	-7.92E-10	-8.84E-10	-7.80E-10	-1.41E-09
-2	-3.49E-09	-3.69E-09	-4.04E-09	-3.83E-09	-3.86E-09	-4.42E-07	-3.75E-09	-4.76E-09	-3.80E-09	-6.02E-09
-3	-1.17E-08	-1.25E-08	-1.42E-08	-1.14E-08	-1.25E-08	-1.82E-06	-1.26E-08	-1.65E-08	-1.29E-08	-2.12E-08
-4	-3.03E-08	-3.24E-08	-3.71E-08	-2.79E-08	-2.99E-08	-5.06E-06	-3.32E-08	-4.38E-08	-3.44E-08	-6.87E-08
-5	-6.69E-08	-7.08E-08	-8.79E-08	-6.00E-08	-6.52E-08	-1.43E-05	-7.61E-08	-1.02E-07	-7.97E-08	-5.21E-07
-6	-1.34E-07	-1.41E-07	-1.90E-07	-1.19E-07	-1.26E-07	-3.50E-05	-1.57E-07	-2.26E-07	-1.66E-07	-4.78E-06
-7	-2.47E-07	-2.59E-07	-3.79E-07	-2.21E-07	-2.31E-07	-7.92E-05	-3.01E-07	-4.97E-07	-3.26E-07	-2.22E-05
-8	-4.45E-07	-4.61E-07	-9.22E-07	-3.89E-07	-4.05E-07	-1.83E-04	-5.62E-07	-8.49E-07	-6.10E-07	-7.35E-05

Run #	40	41	42	43	44	45	47	48	pre-49	49
DUT S/N	6	6	7	7	7	7	8	8	11	11
Date	8/18/2010	8/18/2010	8/18/2010	8/18/2010	8/18/2010	8/18/2010	8/18/2010	8/18/2010	8/18/2010	8/18/2010
Time	7:55	8:01	8:09	8:14	8:23	8:27	8:40	8:43	9:10	9:14
Vgs (V):	Igs (A):									
0	-5.96E-10	-5.57E-10	-5.49E-10	-5.24E-10	-5.04E-10	-4.40E-10	-5.31E-10	-4.87E-10	-7.19E-13	-4.55E-10
1	1.38E-09	1.35E-09	1.21E-09	1.21E-09	1.31E-09	1.12E-09	1.20E-09	1.28E-09	1.26E-09	1.16E-09
2	5.52E-09	6.71E-09	4.95E-09	5.04E-09	5.66E-09	5.25E-09	5.22E-09	5.67E-09	5.17E-09	5.24E-09
3	1.74E-08	2.24E-08	1.57E-08	1.57E-08	1.77E-08	1.73E-08	1.65E-08	1.80E-08	1.61E-08	1.68E-08
4	4.58E-08	5.94E-08	3.98E-08	4.02E-08	4.47E-08	4.84E-08	4.15E-08	4.53E-08	4.11E-08	4.24E-08
5	1.05E-07	1.39E-07	8.63E-08	8.69E-08	9.39E-08	1.70E-07	9.29E-08	9.96E-08	9.07E-08	9.43E-08
6	2.20E-07	3.01E-07	1.71E-07	1.74E-07	1.88E-07	1.10E-06	1.87E-07	2.01E-07	1.83E-07	2.00E-07
7	4.38E-07	6.70E-07	3.21E-07	3.24E-07	3.50E-07	7.56E-06	3.56E-07	4.05E-07	3.46E-07	3.41E-06
8	8.50E-07	1.51E-06	5.79E-07	5.84E-07	7.20E-07	**2.31E-05**	6.73E-07	9.16E-07	6.29E-07	3.35E-05
-1	-1.43E-09	-1.69E-09	-1.32E-09	-1.29E-09	-1.37E-09	-1.25E-09	-1.34E-09	-1.39E-09	-8.47E-10	-1.41E-09
-2	-5.52E-09	-7.73E-09	-5.39E-09	-5.44E-09	-6.45E-09	-5.41E-09	-5.64E-09	-5.82E-09	-3.86E-09	-5.79E-09
-3	-1.64E-08	-2.66E-08	-1.69E-08	-1.71E-08	-2.07E-08	-1.68E-08	-1.77E-08	-1.90E-08	-1.33E-08	-1.79E-08
-4	-4.12E-08	-7.13E-08	-4.25E-08	-4.29E-08	-5.50E-08	-4.35E-08	-4.44E-08	-5.18E-08	-3.65E-08	-4.62E-08
-5	-9.04E-08	-1.69E-07	-9.30E-08	-9.26E-08	-1.21E-07	-1.05E-07	-9.90E-08	-1.16E-07	-8.48E-08	-1.06E-07
-6	-1.82E-07	-3.59E-07	-1.80E-07	-1.83E-07	-2.30E-07	-3.39E-07	-2.08E-07	-2.43E-07	-1.80E-07	-2.45E-07
-7	-3.43E-07	-7.87E-07	-3.31E-07	-3.34E-07	-4.32E-07	-2.60E-06	-3.94E-07	-5.14E-07	-3.55E-07	-9.74E-07
-8	-6.22E-07	-1.69E-06	-5.82E-07	-5.89E-07	-7.76E-07	-1.91E-05	-7.77E-07	-9.34E-07	-6.74E-07	-1.31E-05

Run #	51	52	68	69	72	73	76	77	pre-78	78
DUT S/N	10	10	14	14	15	15	16	16	17	17
Date	8/18/2010	8/18/2010	8/19/2010	8/19/2010	8/19/2010	8/19/2010	8/19/2010	8/19/2010	8/19/2010	8/19/2010
Time	9:28	9:33	3:09	3:14	3:39	3:42	4:12	4:16	4:19	4:30
Vgs (V):										
0	-5.06E-10	-4.97E-10	3.20E-11	-1.85E-10	-2.18E-10	-2.08E-10	-2.29E-10	-3.18E-10	-3.86E-11	-2.46E-10
1	1.24E-09	3.87E-09	1.15E-09	1.19E-09	1.23E-09	1.87E-09	1.19E-09	1.13E-09	1.21E-09	1.64E-09
2	5.30E-09	3.04E-08	5.08E-09	5.54E-09	4.95E-09	9.98E-09	4.72E-09	5.09E-09	5.11E-09	6.45E-09
3	1.66E-08	1.27E-07	1.59E-08	1.78E-08	1.61E-08	3.07E-08	1.47E-08	1.58E-08	1.64E-08	1.96E-08
4	4.22E-08	3.90E-07	4.02E-08	4.51E-08	4.21E-08	7.57E-08	3.56E-08	3.90E-08	4.14E-08	4.99E-08
5	9.15E-08	1.04E-06	8.67E-08	1.09E-07	9.64E-08	1.78E-07	7.73E-08	8.73E-08	9.08E-08	1.31E-07
6	1.81E-07	3.60E-06	1.71E-07	1.31E-06	2.07E-07	4.52E-07	1.53E-07	2.09E-07	1.79E-07	9.75E-07
7	3.37E-07	**1.40E-05**	3.15E-07	**1.46E-05**	4.03E-07	3.93E-06	2.80E-07	1.98E-06	3.31E-07	**1.87E-05**
8	6.10E-07	6.28E-05	5.58E-07	4.65E-05	7.55E-07	**3.79E-05**	4.91E-07	**3.96E-05**	5.89E-07	5.97E-05
-1	-1.35E-09	-1.12E-08	-8.05E-10	-2.99E-09	-1.18E-09	-5.30E-09	-9.80E-10	-2.09E-09	-8.15E-10	-3.10E-09
-2	-5.16E-09	-8.97E-08	-3.85E-09	-1.67E-08	-4.64E-09	-2.86E-08	-4.13E-09	-1.62E-08	-3.77E-09	-1.38E-08
-3	-1.61E-08	-3.91E-07	-1.31E-08	-5.93E-08	-1.46E-08	-1.01E-07	-1.28E-08	-6.22E-08	-1.28E-08	-4.64E-08
-4	-4.09E-08	-1.68E-06	-3.45E-08	-2.81E-07	-3.75E-08	-3.63E-07	-3.20E-08	-2.45E-07	-3.44E-08	-2.66E-07
-5	-8.69E-08	-6.32E-06	-7.82E-08	-1.87E-06	-8.43E-08	-1.54E-06	-6.85E-08	-1.45E-06	-7.87E-08	-2.31E-06
-6	-1.67E-07	-1.95E-05	-1.61E-07	-8.92E-06	-1.71E-07	-6.67E-06	-1.34E-07	-8.18E-06	-1.60E-07	-1.07E-05
-7	-3.02E-07	-4.72E-05	-3.10E-07	-2.65E-05	-3.31E-07	-2.02E-05	-2.42E-07	-2.89E-05	-3.07E-07	-2.94E-05
-8	-5.23E-07	-1.07E-04	-5.70E-07	-5.66E-05	-6.10E-07	-4.40E-05	-4.18E-07	-6.40E-05	-5.63E-07	-6.07E-05

Run #	81	82	83	84	85	86	87	88	130	131
DUT S/N	18	18	19	19	19	20	20	20	13	13
Date	8/19/2010	8/19/2010	8/19/2010	8/19/2010	8/19/2010	8/19/2010	8/19/2010	8/19/2010	8/20/2010	8/20/2010
Time	4:58	5:01	5:10	5:16	5:19	5:28	5:34	5:38	3:38	3:42
Vgs (V):										
0	-5.51E-10	-4.31E-10	-5.52E-10	-5.90E-10	-4.76E-10	-4.84E-10	-5.02E-10	-4.73E-10	-5.89E-10	-5.22E-10
1	1.30E-09	1.39E-09	1.42E-09	1.48E-09	1.92E-09	1.22E-09	1.24E-09	1.38E-09	1.39E-09	5.98E-08
2	5.24E-09	6.08E-09	6.01E-09	6.87E-09	8.93E-09	5.01E-09	5.38E-09	6.01E-09	5.61E-09	9.63E-07
3	1.65E-08	1.89E-08	1.95E-08	2.21E-08	2.73E-08	1.54E-08	1.65E-08	1.81E-08	1.73E-08	3.41E-06
4	4.07E-08	5.00E-08	5.09E-08	5.70E-08	6.92E-08	3.79E-08	4.11E-08	4.52E-08	4.22E-08	8.32E-06
5	8.76E-08	1.18E-07	1.16E-07	1.26E-07	3.30E-07	8.04E-08	8.88E-08	1.04E-07	8.98E-08	**1.63E-05**
6	1.68E-07	3.77E-07	2.42E-07	2.63E-07	4.04E-06	1.57E-07	1.75E-07	3.01E-07	1.71E-07	3.25E-05
7	3.07E-07	3.69E-06	4.81E-07	5.16E-07	**1.94E-05**	2.89E-07	3.25E-07	1.45E-06	3.13E-07	5.94E-05
8	5.40E-07	**3.68E-05**	9.24E-07	1.01E-06	5.12E-05	5.11E-07	6.86E-07	**2.51E-05**	5.44E-07	9.84E-05
-1	-1.43E-09	-1.91E-09	-1.52E-09	-1.59E-09	-4.88E-08	-1.35E-09	-1.34E-09	-1.47E-09	-1.47E-09	-5.13E-07
-2	-5.71E-09	-8.33E-09	-6.16E-09	-6.78E-09	-3.49E-07	-5.40E-09	-5.48E-09	-6.04E-09	-5.71E-09	-4.69E-06
-3	-1.78E-08	-2.50E-08	-1.98E-08	-2.19E-08	-1.52E-06	-1.64E-08	-1.77E-08	-1.84E-08	-1.75E-08	-1.52E-05
-4	-4.39E-08	-6.95E-08	-5.13E-08	-5.62E-08	-5.64E-06	-4.04E-08	-4.56E-08	-4.71E-08	-4.35E-08	-3.28E-05
-5	-9.50E-08	-2.15E-07	-1.15E-07	-1.33E-07	-1.56E-05	-8.74E-08	-1.04E-07	-1.08E-07	-9.47E-08	-5.46E-05
-6	-1.87E-07	-1.37E-06	-2.38E-07	-2.76E-07	-3.46E-05	-1.74E-07	-2.17E-07	-2.36E-07	-1.88E-07	-8.40E-05
-7	-3.41E-07	-8.46E-06	-4.66E-07	-5.47E-07	-6.71E-05	-3.26E-07	-4.49E-07	-5.77E-07	-3.46E-07	-1.21E-04
-8	-6.08E-07	-3.54E-05	-8.82E-07	-1.08E-06	-1.22E-04	-5.81E-07	-8.21E-07	-8.11E-06	-6.17E-07	-1.61E-04

Appendix E
Strip tape data of gate and drain currents during selected beam runs.

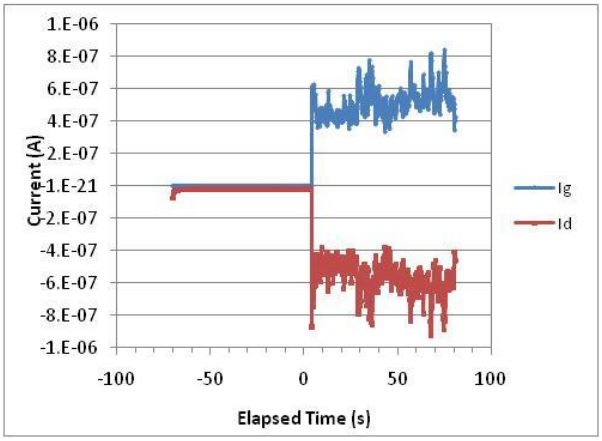

Fig. E1. Run 30, DUT 2, Vds = -12V, Vgs = 0V; 2° angle of incidence; Ag ions.

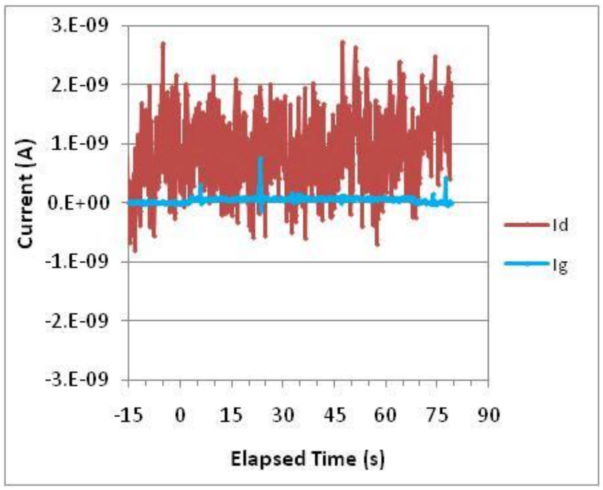

Fig. E2. Run 32, DUT 3, Vds = -10V, Vgs = 0V; 2° angle of incidence; Ag ions: Transient spikes in Ig during and after beam exposure.

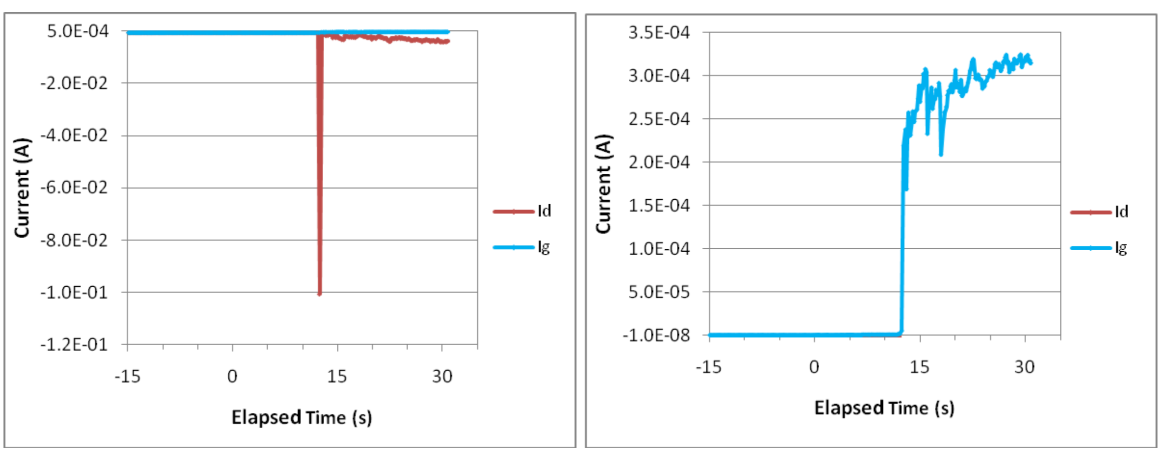

Fig. E3. Run 34, DUT 3, Vds = -12V, Vgs = 0V; 2° angle of incidence; Ag ions.

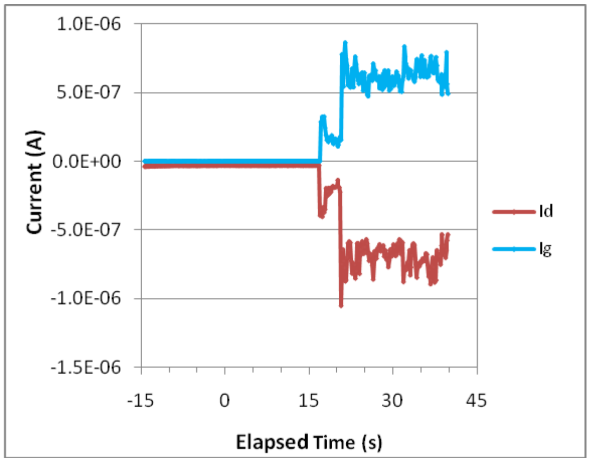

Fig. E4. Run 37, DUT 4, Vds = -12V, Vgs = 0V; 2° angle of incidence; Ag ions.

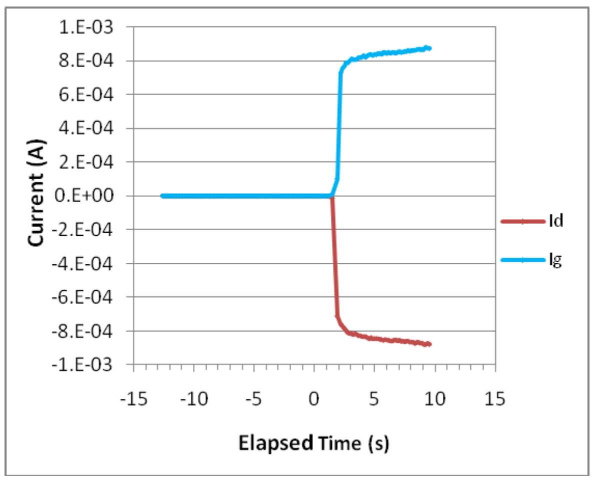

Fig. E5. Run 38, DUT 5, Vds = -9V, Vgs = 5V; 2° angle of incidence; Ag ions.

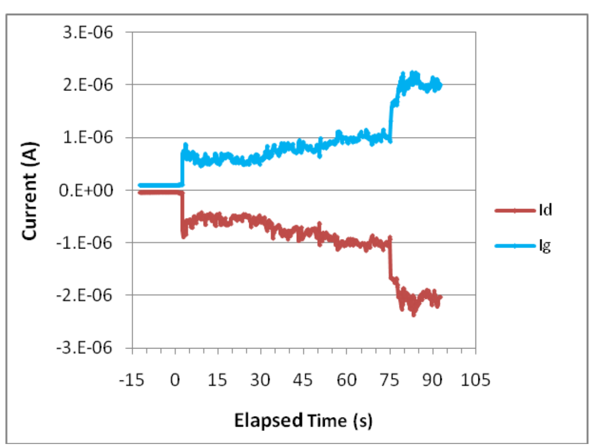

Fig. E6. Run 41, DUT 6, Vds = -7V, Vgs = 5V; 2° angle of incidence; Ag ions.

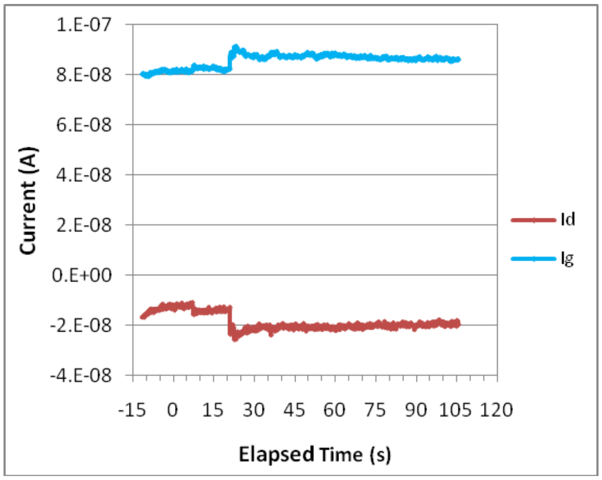

Fig. E7. Run 43, DUT 7, Vds = -7V, Vgs = 5V; 2° angle of incidence; Ag ions.

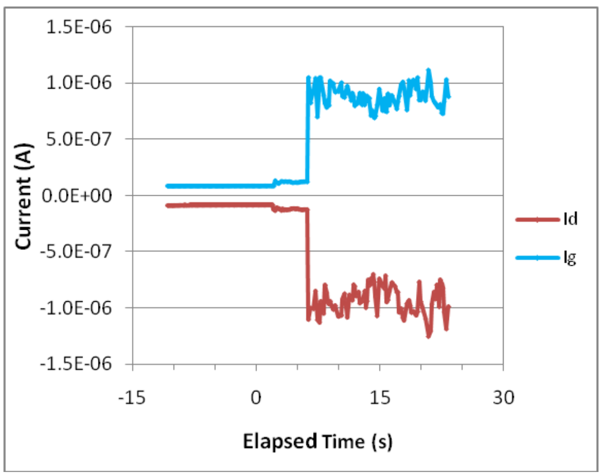

Fig. E8. Run 44, DUT 7, Vds = -8V, Vgs = 5V; 2° angle of incidence; Ag ions.

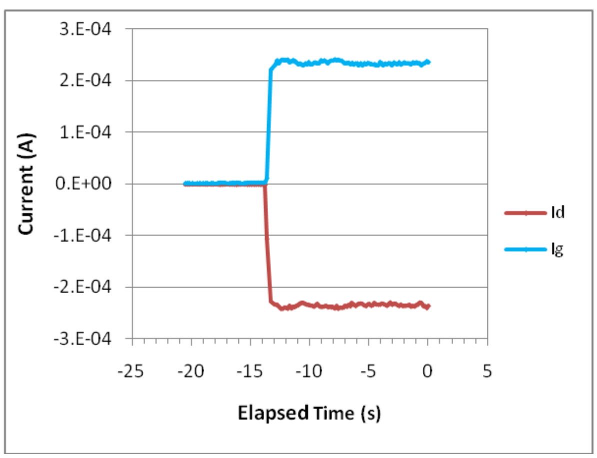

Fig. E9. Run 45, DUT 7, Vds = -9, Vgs = 5V. Beam was never turned on: DUT failed about 7 seconds after bias applied, despite passing PIGS test after run 44.

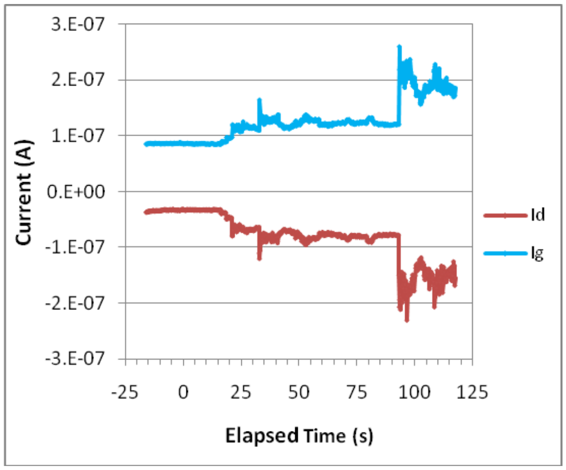

Fig. E10. Run 47, DUT 8, Vds = -7V, Vgs = 5V; 2° angle of incidence; Ag ions.

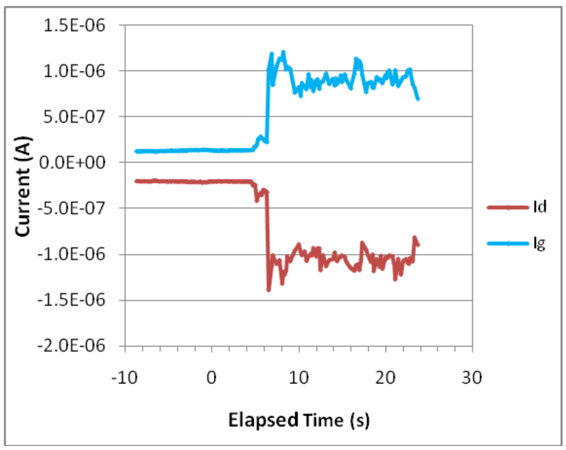

Fig. E11. Run 48, DUT 8, Vds = -8V, Vgs = 5V; 2° angle of incidence; Ag ions.

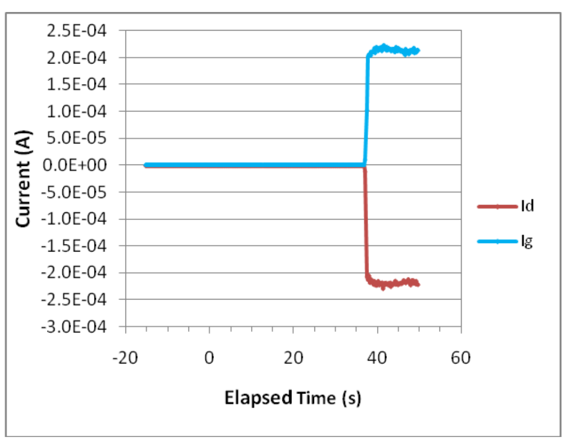

Fig. E12. Run 49, DUT 11, Vds = -9V, Vgs = 5V; 45° angle of incidence; Ag ions.

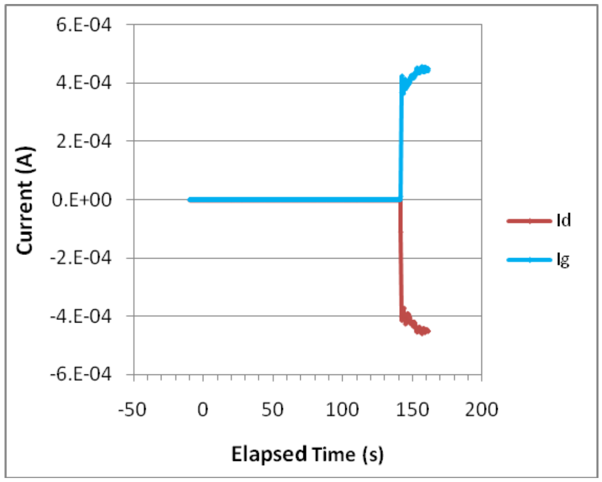

Fig. E13. Run 52, DUT 10, Vds = -9V, Vgs = 5V; 45° angle of incidence; Ag ions.

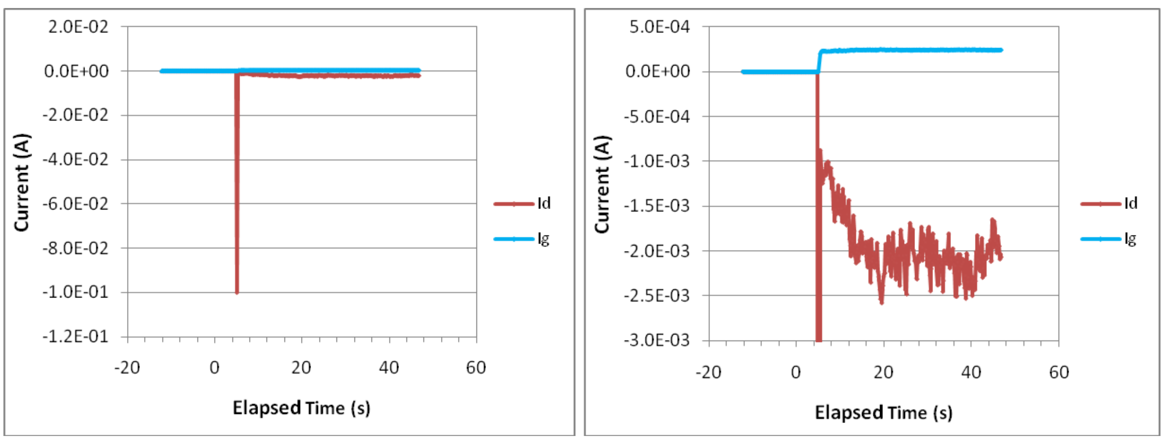

Fig. E14. Run 69, DUT 14, Vds = -12V, Vgs = 2V; 2° angle of incidence; Kr ions.

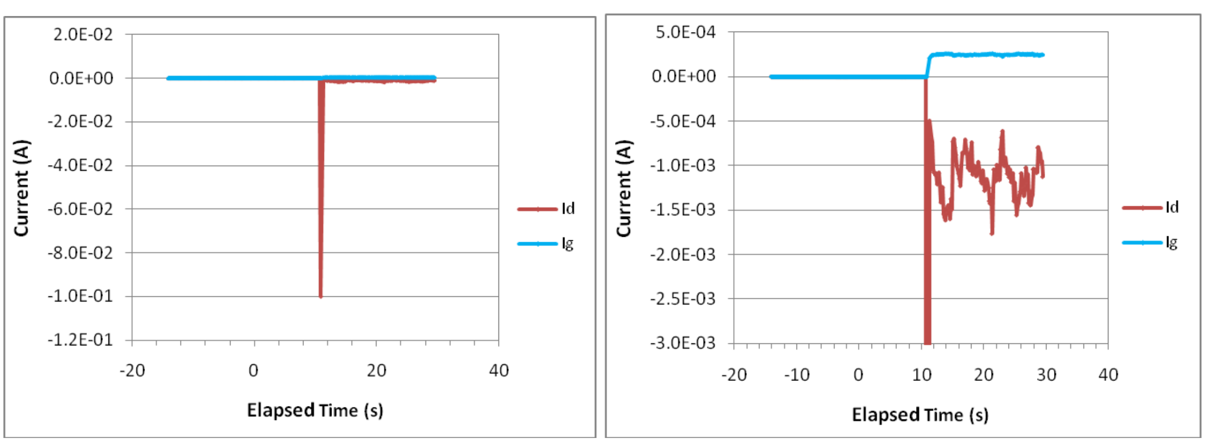

Fig. E15. Run 73, DUT 15, Vds = -12V, Vgs = 2V; 2° angle of incidence; Kr ion

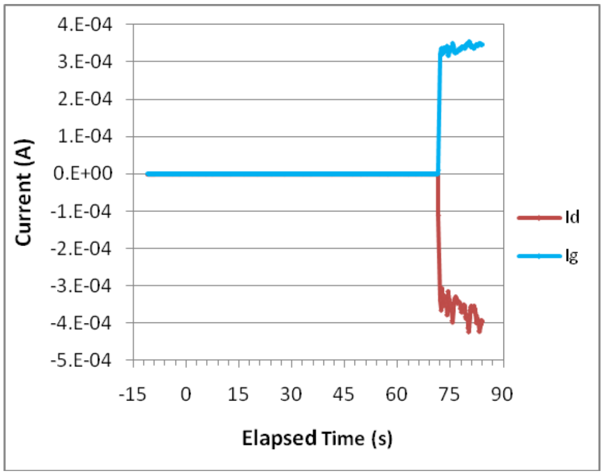

Fig. E16. Run 77, DUT 16, Vds = -12V, Vgs = 3V; 2° angle of incidence; Kr ions.

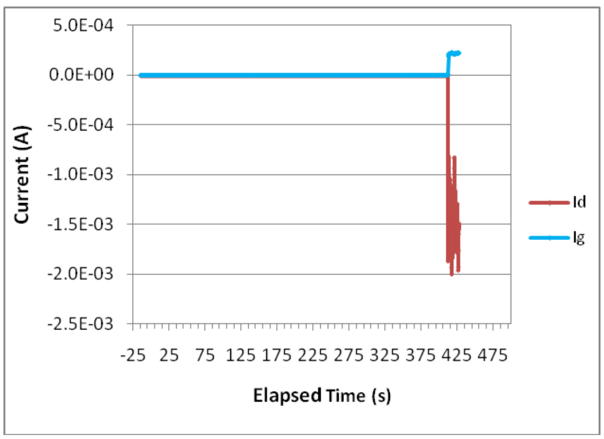

Fig. E17. Run 78, DUT 17, Vds = -12V, Vgs = 2V; 2° angle of incidence; Kr ions.

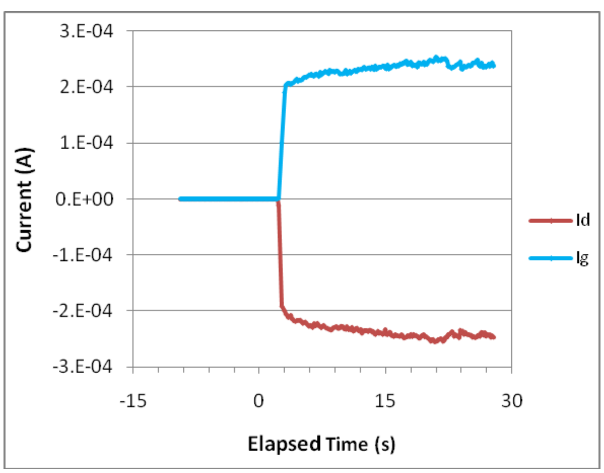

Fig. E18. Run 82, DUT 18, Vds = -9V, Vgs = 5V; 2° angle of incidence; Kr ions.

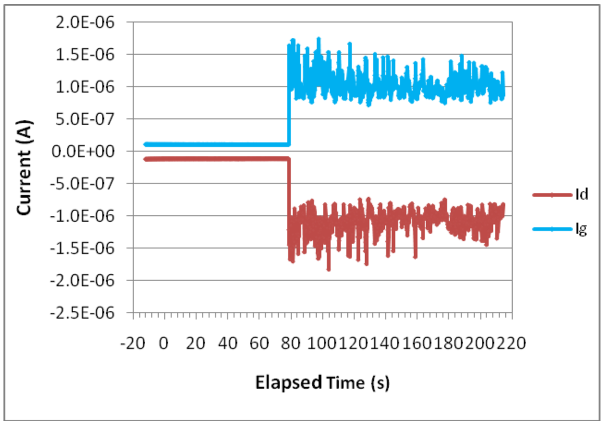

Fig. E19. Run 84, DUT 19, Vds = -8V, Vgs = 5V; 2° angle of incidence; Kr ions.

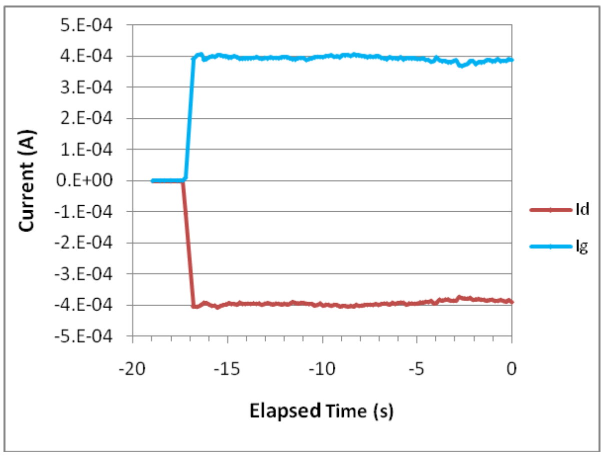

Fig. E20. Run 85, DUT 19, Vds = -9V, Vgs = 5V; Beam was never turned on: DUT failed about 2 seconds after bias applied, despite passing PIGS test after run 84.

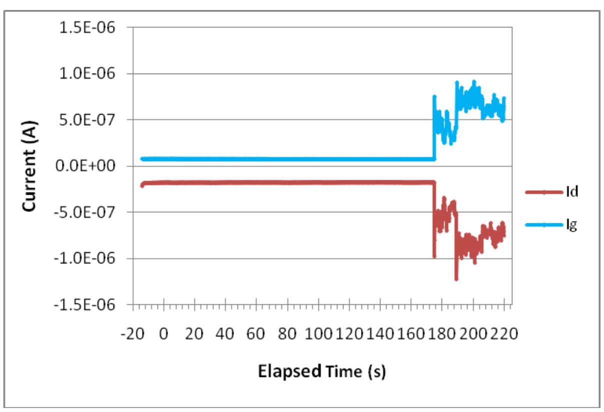

Fig. E21. Run 87, DUT 20, Vds = -8V, Vgs = 5V; 2° angle of incidence; Kr ions.

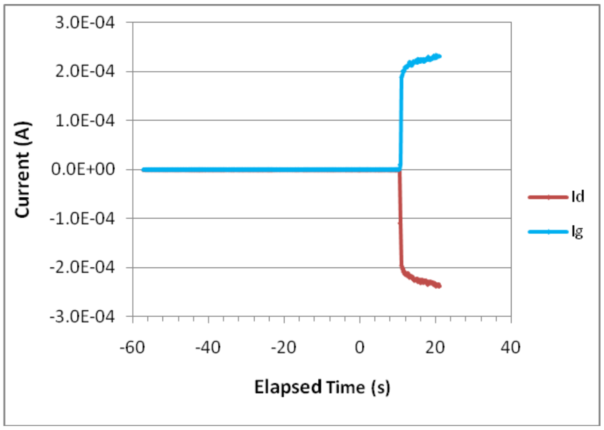

Fig. E22. Run 88, DUT 20, Vds = -9V, Vgs = 5V; 2° angle of incidence; Kr ions.

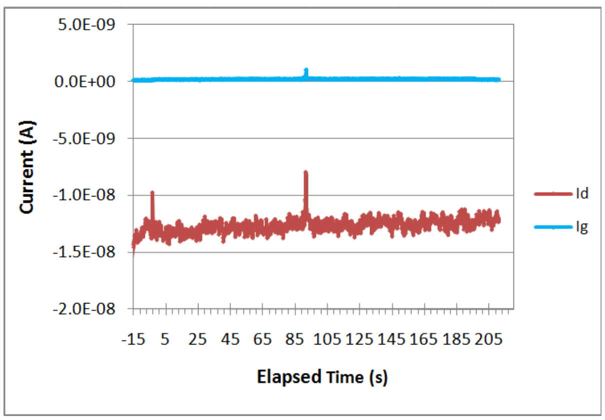

Fig. E23. Run 121, DUT 13, Vds = -8V, Vgs = 0V; 60° angle of incidence; Ag ions.

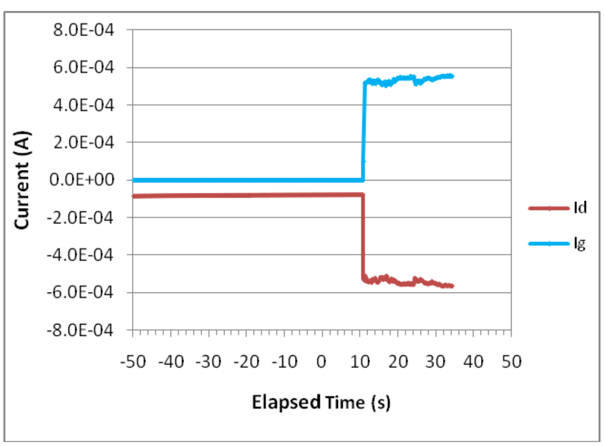

Fig. E24. Run 131, DUT 13, Vds = -12V, Vgs = 5V; 60° angle of incidence; Ag ions.