RTAXS Single Event Effects Test Report

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SUMMARY

Prototype RTAXS devices were beam-tested at BNL and TAMU for single event effects (SEE), which include single event upset (SEU), single event functional interrupt (SEFI), single event latch-up (SEL) and single event dielectric rupture (SEDR). The key results are list below:

- The SEU-hardened TMR flip-flop (R-cell) meets the hardening target. The SEU rate per flip-flop at geostationary orbit for 100 mil aluminum shielding and solar-minimum environment is below 1.96×10^{-11} upsets/bit•day.
- There is no occurrence of SEFI in any test run.
- There is no occurrence of SEL in any test run. The maximum effective LET used at BNL is 104 MeV•cm^2/mg, and the maximum effective LET used at TAMU is 84 MeV•cm^2/mg.
- There is no occurrence of SEDR in any test run. The maximum LET used at BNL is 60 MeV•cm^2/mg, and the maximum LET used at TAMU is 54 MeV•cm^2/mg.

I. TEST OBJECTIVE

This report combines the results of three heavy-ion-beam tests. The primary objective of these tests is to quantitatively characterize the SEE (single event effects) of the RTAXS product family. The SEE includes SEU (single event upset), SEFI (single event functional interrupt), SEL (single event latch-up) and SEDR (single event dielectric rupture). Particularly, the SEU cross-sections of the storage devices have to be obtained by the beam test. There are two storage devices in RTAXS product: the embedded RAM is reported in another separate report; the testing and analysis of the SEU-hardened TMR flip-flop in the logic module are described in this report.

II. DEVICE UNDER TEST

The devices under test (DUT) are separated into three groups by three separate heavy-ion-beam tests: Group A is made of samples from the first prototype (revision A) device, and this group is tested at BNL; Group B is made of samples from the revised prototype (revision B) device, also tested at BNL; Group C is also made of samples from the revision B prototype, and this group is tested at TAMU. For SEE point of view, revision A and revision B prototypes are practically the same, and they are treated as the same in this report. Table I lists the DUT parameters for each testing group.

Table I. DUT Parameters

	Group A	Group B	Group C
Device	RTAX2000S	RTAX2000S	RTAX1000S
Package	CQFP352	CQFP352	CQFP352
Foundry	UMC	UMC	UMC
Technology	0.15 µm CMOS	0.15 µm CMOS	0.15 µm CMOS
Die Size	18.3 mm×16.9 mm	18.3 mm×16.9 mm	14.4 mm×13.3 mm
Die Lot Number	Rev A prototype	Rev B prototype	Rev B prototype
Date Code	NA	NA	NA
Quantity Tested	2	4	3
Serial Number	307, 315	#1, #2, #3, #4	35475, 35546, 35551
IO Configuration	3.3V PCI	3.3V PCI	3.3V PCI
Design	TMRAXS	TMRAXS	TMRAXS

III. TEST METHODS

This test generally follows the guidelines of two SEE testing standards: ASTM standard F1192M-95, "Standard Guide for the Measurement of Single Event Phenomena (SEP) Induced by Heavy Ion Irradiation on Semiconductor Devices," and JEDEC standard JESD57, "Test Procedures for the Measurement of Single-Event Effects in Semiconductor Devices from Heavy Ion Irradiation."

Specifically, the SEU cross-section is obtained by measuring the in-flux upsets in two shift registers; the SEFI is monitored by the functionality of the shift registers; the SEL and SEDR are tested by measuring the in-flux power supply currents.

A. Irradiation

Group-A and Group-B testing use the Tandem Van de Graaff beam source at Brookhaven National Laboratory; Group-C testing uses the Cyclotron beam source at Texas A&M University. The irradiation details for each run are listed in Table II, III, and IV.

B. Test Logic Design

The test logic design, called TMRAXS, composes of two shift registers, SH1 and SH2; each shift register has 100 stages (flip-flops), and each stage is made of one R-cell. Thus the upsets in these registers can be directly translated into the upsets in R-cells, and the SEU cross-section of the R-cell for a specific LET can be calculated.

C. Experimental Setup and Procedure

Figure 1 shows the block diagram of the testing system. A PC (personal computer) commands the communication between an IO-counter card, which is plugged in a PCI slot on the motherboard, and a DUT board. The IO initiates the operation by starting the generator in the control chip to generate the clock and signal patterns. The signals passing the DUT and a control path are checked in the comparator; the generated errors are fed back into a counter on the IO-counter card. A heavy-ion beam of 1" diameter irradiates only the DUT chip on the DUT board. The communication between the IO-counter and DUT board is through RS422 interfaces.

The data generator generates "1", "0", or checkerboard patterns. The checkerboard pattern is used for detecting SEU because it toggles every flip-flop at the clock edge and it also can detect the "clock" upset. An HP6629 power supply unit is used to monitor the in-flux current for SEL and SEDR detection. This power supply communicates with the PC through a GPIB interface so that the in-flux power supply current is recorded throughout the testing. For the worst case scenario, the power supply voltage is 10% under nominal for SEU testing and 10% over nominal for SEL and SEDR testing.

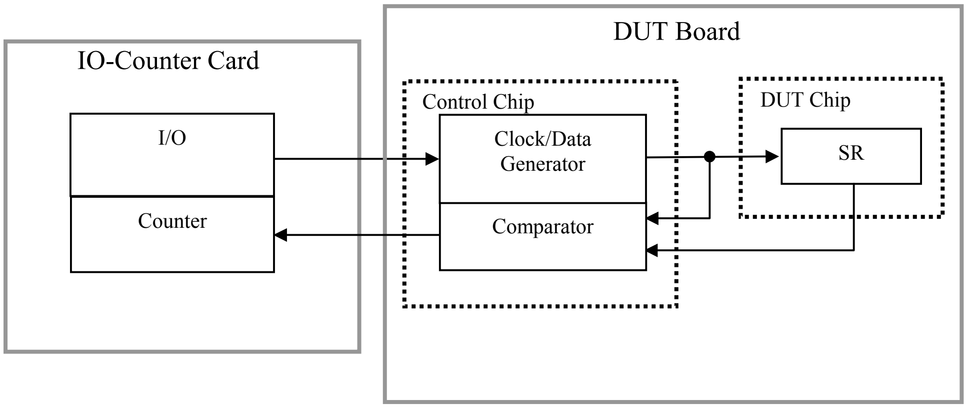

Figure 1 Block diagram showing the measurement of upset-errors

IV. RESULTS AND DISCUSSIONS

A. Test Data

Tables II, III and IV list the Group-A, Group-B and Group-C test data respectively. Key results are:

1. Upsets for each run to the fluence of 10^7 Ions/cm^2 are low, even for high LETs.
2. The upsets at 0° roll and 90° roll is approximately the same. As shown in Figure 2, the TMR flip-flop has three sub-flip-flops stacked vertically. Rolling 90° and tilting will enhance the possibility of the TMR flip-flop upset by ion striking two sub-flip-flops the same time. The distance between the sub-flip-flops is designed to avoid this upset mechanism, which is consistent with the testing result.

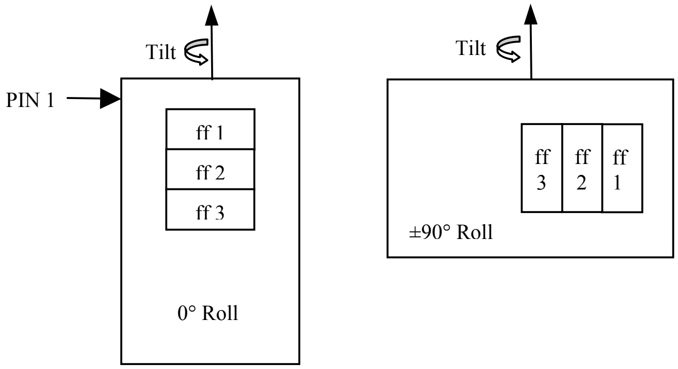

Figure 2 Simplified drawings showing the relative position of the sub-flip-flops in the TMR flip-flop with respect to the roll and tilt angles.

3. Several runs in Group C show the multiple upsets symptom, indicating the possibility of clock upset; particularly run 12 in Group C shows a burst of 28 errors in SH2. However, this error-burst case could not be reproduced by repeating test runs. Since these suspected multiple-upsets are occurred at a very high LET of 62.8 MeV•cm^2/mg, the impact to the upset rate in the standard GEO environment is negligible.
4. There is no occurrence of SEFI in any run.
5. There is no occurrence of SEL in any run.
6. There is no occurrence of SEDR in any run.

Table II. Group-A Test Data

BNL Run	DUT	Bias (V) V_{CCI}/V_{CCA}	Ion	LET (MeV•cm^2/mg)	Tilt	Flux (Ions/cm^2/s)	Fluence (Ions/cm^2)	Upsets		Comments
								SR1	SR2	
298	307	3.3/1.5	Br-81	37.45	0	2.37E+04	1.00E+07	0	1	CB, 2MHz
299	307	3.3/1.5	Br-81	52.96	45	2.44E+04	1.00E+07	1	1	CB, 2MHz
300	307	3.3/1.5	Br-81	52.96	-45	2.67E+04	1.00E+07	1	0	CB, 2MHz
301	307	3.3/1.5	I-127	59.73	0	1.78E+04	8.86E+06	1	0	CB, 2MHz
302	307	3.3/1.5	I-127	68.98	30	1.59E+04	1.00E+07	0	0	CB, 2MHz
303	307	3.3/1.5	I-127	84.48	45	1.11E+04	1.00E+07	0	1	CB, 2MHz
304	307	3.3/1.5	I-127	104.1	55	8.99E+03	1.00E+07	0	1	CB, 2MHz
305	307	3.3/1.5	I-127	68.98	-30	1.28E+04	1.00E+07	0	0	CB, 2MHz
306	307	3.3/1.5	I-127	84.48	-45	3.17E+04	1.00E+07	0	1	CB, 2MHz
307	307	3.3/1.5	I-127	92.93	-50	2.68E+04	1.00E+07	0	0	CB, 2MHz
308	315	3.3/1.5	I-127	59.73	0	4.38E+04	1.00E+07	0	1	CB, 2MHz
309	315	3.3/1.5	I-127	68.98	30	3.70E+04	1.00E+07	0	0	CB, 2MHz
310	315	3.3/1.5	I-127	84.48	45	2.53E+04	1.00E+07	2	0	CB, 2MHz
311	315	3.3/1.5	I-127	104.1	55	2.25E+04	1.00E+07	0	0	CB, 2MHz
312	315	3.3/1.5	I-127	68.98	-30	3.25E+04	1.00E+07	2	0	CB, 2MHz
313	315	3.3/1.5	I-127	84.48	-45	2.28E+04	1.00E+07	0	0	CB, 2MHz
314	315	3.3/1.5	Ni-58	26.58	0	4.14E+04	1.00E+07	1	0	CB, 2MHz
315	315	3.3/1.5	Ni-58	30.69	30	4.76E+04	1.00E+07	0	0	CB, 2MHz
316	315	3.3/1.5	Ni-58	37.59	45	3.66E+04	1.00E+07	0	0	CB, 2MHz
317	315	3.3/1.5	Ni-58	30.7	-30	5.05E+04	1.00E+07	0	1	CB, 2MHz
318	315	3.3/1.5	Ni-58	37.59	-45	4.34E+04	1.00E+07	0	0	CB, 2MHz
319	307	3.3/1.5	Ni-58	26.58	0	3.56E+04	1.00E+07	0	0	CB, 2MHz
320	307	3.3/1.5	Ni-58	30.69	30	4.00E+04	1.00E+07	0	0	CB, 2MHz
321	307	3.3/1.5	Ni-58	37.59	45	3.40E+04	1.00E+07	1	0	CB, 2MHz
322	307	3.3/1.5	Ni-58	30.69	-30	4.29E+04	1.00E+07	1	1	CB, 2MHz
323	307	3.3/1.5	Ni-58	37.59	-45	3.49E+04	1.00E+07	0	0	CB, 2MHz

Table III. Group-B Test Data

BNL Run	DUT	Bias (V) V_{CCI}/V_{CCA}	Ion	LET (MeV•cm^2/mg)	Tilt (Deg)	Roll (Deg)	Flux (Ions/cm^2/s)	Fluence (Ions/cm^2)	Upsets		Comments
									SH1	SH2	
100	#1	3.3/1.5	Br-81	37.46	0	0	1.97E+05	1.01E+07	0	0	CB, 2MHz
101	#1	3.3/1.5	Br-81	37.46	0	0	1.12E+05	1.00E+07	0	1	CB, 2MHz
102	#1	3.0/1.4	Br-81	37.46	0	0	1.19E+05	1.00E+07	0	0	CB, 2MHz
103	#1	3.0/1.4	Br-81	52.98	45	0	8.41E+04	1.00E+07	1	0	CB, 2MHz
104	#1	3.0/1.4	Br-81	52.97	45	0	8.11E+04	1.00E+07	1	0	CB, 2MHz
105	#2	3.0/1.4	Br-81	37.46	0	0	6.28E+04	1.00E+07	1	0	CB, 2MHz
106	#2	3.0/1.4	Br-81	52.98	45	0	3.18E+04	1.00E+07	0	0	CB, 2MHz
107	#2	3.0/1.4	Br-81	52.98	-45	0	2.49E+04	1.00E+07	1	0	CB, 2MHz
108	#2	3.0/1.4	Br-81	37.46	0	-89.1	2.71E+04	1.00E+07	0	0	CB, 2MHz
109	#2	3.0/1.4	Br-81	52.98	45	-89.1	2.43E+04	1.00E+07	1	0	CB, 2MHz
110	#2	3.0/1.4	Br-81	52.98	-45	-89.1	1.81E+04	6.52E+05	NA	NA	Aborted
111	#2	3.0/1.4	Br-81	52.98	-45	-89.1	2.31E+04	1.00E+07	0	0	CB, 2MHz
112	#2	3.0/1.4	Br-81	43.25	-30	-89.1	9.71E+04	1.01E+07	0	0	CB, 2MHz
113	#2	3.0/1.4	Br-81	43.25	-30	-89.1	9.59E+04	1.00E+07	0	1	CB, 2MHz
114	#2	3.0/1.4	Br-81	43.25	30	-89.1	9.54E+04	1.00E+07	0	0	CB, 2MHz
115	#3	3.0/1.4	Br-81	37.46	0	0	1.10E+05	1.01E+07	1	1	CB, 2MHz
116	#3	3.0/1.4	Br-81	37.46	0	0	1.13E+05	1.00E+07	0	0	CB, 2MHz
117	#3	3.0/1.4	Br-81	43.25	30	0	9.64E+04	1.00E+07	1	1	CB, 2MHz
118	#3	3.0/1.4	Br-81	43.25	30	0	9.60E+04	1.00E+07	2	1	CB, 2MHz
119	#3	3.0/1.4	Br-81	43.25	30	0	4.32E+04	9.98E+06	2	1	CB, 2MHz
120	#3	3.0/1.4	Br-81	43.25	-30	0	4.01E+04	1.00E+07	0	1	CB, 2MHz
121	#3	3.0/1.4	Br-81	52.98	45	0	2.90E+04	1.00E+07	0	0	CB, 2MHz
122	#3	3.0/1.4	Br-81	52.98	45	0	2.85E+04	1.00E+07	1	0	CB, 2MHz
123	#3	3.0/1.4	Br-81	52.98	-45	0	3.10E+04	1.00E+07	1	0	CB, 2MHz
124	#3	3.0/1.4	Br-81	43.25	30	-89	3.95E+04	9.95E+06	1	0	CB, 2MHz
125	#3	3.0/1.4	Br-81	43.25	-30	-89	4.11E+04	1.00E+07	2	0	CB, 2MHz
126	#3	3.0/1.4	Br-81	52.98	-45	-89	3.22E+04	1.00E+07	0	0	CB, 2MHz
127	#3	3.0/1.4	Br-81	52.98	45	-89	3.19E+04	1.00E+07	0	0	CB, 2MHz
128	#3	3.0/1.4	Br-81	52.98	45	-89	3.01E+04	1.00E+07	0	1	One, 2MHz
129	#4	3.0/1.4	Br-81	37.46	0	0	6.27E+04	1.00E+07	1	0	CB, 2MHz
130	#4	3.0/1.4	Br-81	43.25	30	0	8.65E+04	1.00E+07	0	0	CB, 2MHz
131	#4	3.0/1.4	Br-81	52.98	45	0	7.06E+04	1.00E+07	3	0	CB, 2MHz
132	#4	3.0/1.4	Br-81	43.25	-30	0	8.38E+04	1.00E+07	0	0	CB, 2MHz
133	#4	3.0/1.4	Br-81	52.97	-45	0	6.82E+04	1.00E+07	1	1	CB, 2MHz
134	#4	3.0/1.4	I-127	59.72	0	0	5.58E+04	9.54E+06	2	1	CB, 2MHz
135	#4	3.0/1.4	I-127	68.96	30	0	4.57E+04	1.00E+07	1	0	CB, 2MHz
136	#4	3.0/1.4	I-127	84.46	45	0	3.49E+04	1.00E+07	0	3	CB, 2MHz
137	#4	3.0/1.4	I-127	68.96	-30	0	3.89E+04	1.00E+07	1	0	CB, 2MHz
138	#4	3.0/1.4	I-127	84.45	-45	0	2.97E+04	1.00E+07	1	0	CB, 2MHz
139	#4	3.6/1.65	I-127	84.45	-45	0	2.79E+04	1.00E+07	0	0	No SEL, No SEDR
140	#4	3.6/1.65	I-127	84.46	45	0	7.08E+04	1.00E+07	0	0	No SEL, No SEDR
141	#4	3.6/1.65	I-127	104.1	55	0	4.80E+04	1.00E+07	0	0	No SEL, No SEDR
142	#4	3.6/1.65	I-127	104.1	-55	0	4.75E+04	1.00E+07	0	0	No SEL, No SEDR
143	#4	3.6/1.65	I-127	59.72	0	0	7.74E+04	1.00E+07	1	0	No SEL, No SEDR
144	#3	3.0/1.4	I-127	59.72	0	0	6.91E+04	9.98E+06	2	1	CB, 2MHz
145	#3	3.0/1.4	I-127	68.96	30	0	5.39E+04	1.00E+07	0	0	CB, 2MHz
146	#3	3.0/1.4	I-127	84.46	45	0	4.12E+04	1.00E+07	0	0	CB, 2MHz
147	#3	3.6/1.65	I-127	104.1	55	0	3.30E+04	1.00E+07	0	0	No SEL, No SEDR
148	#3	3.6/1.65	I-127	104.1	-55	0	3.08E+04	1.00E+07	0	0	No SEL, No SEDR
149	#3	3.6/1.65	I-127	104.1	-55	0	2.81E+04	9.95E+06	0	0	No SEL, No SEDR
150	#3	3.6/1.65	I-127	59.72	0	0	4.66E+04	1.00E+07	2	0	No SEL, No SEDR
151	#2	3.0/1.4	I-127	59.72	0	0	9.33E+04	1.01E+07	2	0	CB, 2MHz
152	#2	3.0/1.4	I-127	68.96	30	0	7.55E+04	1.00E+07	1	0	CB, 2MHz
153	#2	3.0/1.4	I-127	84.46	45	0	5.81E+04	1.00E+07	0	0	CB, 2MHz
154	#2	3.6/1.65	I-127	104.1	55	0	4.07E+04	1.00E+07	0	0	No SEL, No SEDR
155	#2	3.6/1.65	I-127	104.1	-55	0	3.62E+04	1.00E+07	0	0	No SEL, No SEDR

156	#2	3.6/1.65	I-127	59.72	0	0	5.37E+04	1.00E+07	0	0	No SEL, No SEDR
157	#1	3.0/1.4	I-127	59.72	0	0	1.19E+05	9.95E+06	0	0	CB, 2MHz
158	#1	3.0/1.4	I-127	68.96	30	0	1.01E+05	1.00E+07	0	0	CB, 2MHz
159	#1	3.0/1.4	I-127	84.45	45	0	1.01E+05	1.00E+07	0	0	CB, 2MHz
160	#1	3.6/1.65	I-127	104.1	55	0	2.48E+04	1.01E+07	0	0	No SEL, No SEDR
161	#1	3.6/1.65	I-127	104.1	-55	0	4.25E+04	9.89E+06	0	0	No SEL, No SEDR
162	#1	3.6/1.65	I-127	59.72	0	0	4.63E+04	1.00E+07	2	0	No SEL, No SEDR
163	#1	3.0/1.4	Cl-35	11.73	0	0	1.45E+05	1.01E+07	0	0	CB, 2MHz
164	#1	3.0/1.4	Cl-35	13.54	30	0	1.26E+05	1.00E+07	0	0	CB, 2MHz
165	#1	3.0/1.4	Cl-35	16.59	45	0	1.02E+05	1.00E+07	0	0	CB, 2MHz
166	#1	3.0/1.4	Cl-35	13.54	-30	0	1.26E+05	1.00E+07	0	0	CB, 2MHz
167	#1	3.0/1.4	Cl-35	16.59	-45	0	1.02E+05	1.00E+07	0	0	CB, 2MHz
168	#1	3.0/1.4	Cl-35	13.54	30	-89	1.25E+05	1.00E+07	0	0	CB, 2MHz
169	#1	3.0/1.4	Cl-35	16.59	45	-89	1.01E+05	1.00E+07	0	0	CB, 2MHz
170	#2	3.0/1.4	Cl-35	11.73	0	0	1.43E+05	1.00E+07	0	0	CB, 2MHz
171	#2	3.0/1.4	Cl-35	13.54	30	0	1.24E+05	1.00E+07	0	0	CB, 2MHz
172	#2	3.0/1.4	Cl-35	16.59	45	0	1.01E+05	1.00E+07	1	0	CB, 2MHz
173	#2	3.0/1.4	Cl-35	16.59	-45	0	9.96E+04	1.00E+07	0	0	CB, 2MHz
174	#2	3.0/1.4	Cl-35	13.54	-30	0	1.22E+05	1.00E+07	0	1	CB, 2MHz
175	#2	3.0/1.4	Cl-35	13.54	30	-89	1.23E+05	1.00E+07	0	0	CB, 2MHz
176	#2	3.0/1.4	Cl-35	16.59	45	-89	1.01E+05	1.00E+07	0	0	CB, 2MHz
177	#2	3.0/1.4	Cl-35	16.59	-45	-89	1.01E+05	1.00E+07	0	0	CB, 2MHz
178	#2	3.0/1.4	Cl-35	13.54	-30	-89	1.25E+05	1.00E+07	0	0	CB, 2MHz
179	#3	3.0/1.4	Cl-35	11.73	0	0	1.45E+05	1.01E+07	0	0	CB, 2MHz
180	#3	3.0/1.4	Cl-35	16.59	45	0	1.03E+05	1.00E+07	0	0	CB, 2MHz
181	#3	3.0/1.4	Cl-35	13.54	30	0	1.26E+05	1.00E+07	0	0	CB, 2MHz
183	#4	3.0/1.4	Cl-35	16.59	45	0	1.03E+05	1.00E+07	0	0	CB, 2MHz
184	#4	3.0/1.4	Cl-35	13.54	30	0	1.28E+05	1.00E+07	0	0	CB, 2MHz
185	#4	3.0/1.4	Cl-35	11.73	0	0	1.47E+05	1.00E+07	0	0	CB, 2MHz
186	#4	3.0/1.4	Ni-58	26.58	0	0	1.14E+05	1.06E+07	0	0	CB, 2MHz
187	#4	3.0/1.4	Ni-58	30.69	30	0	1.03E+05	1.00E+07	0	0	CB, 2MHz
188	#4	3.0/1.4	Ni-58	37.59	45	0	8.49E+04	1.00E+07	0	0	CB, 2MHz
189	#4	3.0/1.4	Ni-58	37.59	-45	0	8.83E+04	1.00E+07	1	0	CB, 2MHz
190	#4	3.0/1.4	Ni-58	30.69	-30	0	1.05E+05	1.00E+07	0	1	CB, 2MHz
191	#3	3.0/1.4	Ni-58	26.58	0	0	1.32E+05	1.00E+07	1	0	CB, 2MHz
192	#3	3.0/1.4	Ni-58	30.69	30	0	1.10E+05	9.99E+06	0	0	CB, 2MHz
193	#3	3.0/1.4	Ni-58	30.69	-30	0	1.07E+05	1.00E+07	1	1	CB, 2MHz
194	#2	3.0/1.4	Ni-58	30.69	-30	0	1.11E+05	1.00E+07	0	0	CB, 2MHz
195	#2	3.0/1.4	Ni-58	26.58	0	0	1.25E+05	1.00E+07	0	0	CB, 2MHz
196	#2	3.0/1.4	Ni-58	30.69	30	0	1.05E+05	1.00E+07	0	1	CB, 2MHz
197	#2	3.0/1.4	Ni-58	30.69	30	0	1.05E+05	1.00E+07	0	0	CB, 2MHz
198	#1	3.0/1.4	Ni-58	30.69	-30	0	6.16E+04	1.01E+07	0	0	CB, 2MHz
199	#1	3.0/1.4	Ni-58	26.58	0	0	7.24E+04	1.00E+07	0	1	CB, 2MHz
200	#1	3.0/1.4	Ni-58	30.69	30	0	4.31E+04	1.00E+07	0	1	CB, 2MHz
201	#1	3.0/1.4	Ni-58	30.69	30	0	3.89E+04	1.00E+07	0	0	CB, 2MHz
202	#1	3.0/1.4	Ni-58	26.58	0	0	3.60E+04	1.00E+07	0	0	CB, 2MHz

Table IV. Group-C Test Data

TAMU Run	DUT	Bias (V) V_{CCI}/V_{CCA}	Ion	LET (MeV•cm^2/mg)	Tilt	Flux (Ions/cm^2/s)	Fluence (Ions/cm^2)	Upset		Comments
								SH1	SH2	
1	35546	3.3/1.5	Ag	44.4	0	1.00E+05	1.00E+07	1	0	zero pattern 2MHz
2	35546	3.3/1.35	Ag	44.4	0	1.00E+05	1.00E+07	1	0	CB 2MHz
3	35546	3.0/1.35	Ag	44.4	0	1.00E+05	1.00E+07	0	0	CB 2MHz
4	35546	3.6/1.7	Ag	44.4	0	1.00E+05	1.00E+07	0	0	CB 2MHz
5	35546	3.6/1.7	Ag	62.8	45	1.00E+05	1.00E+07	2	2	CB 2MHz
6	35546	3.6/1.7	Ag	69	50	1.00E+05	1.00E+07	0	0	CB 2MHz
7	35546	3.0/1.35	Ag	69	50	1.00E+05	1.00E+07	1	1	CB 2MHz
8	35546	3.0/1.35	Ag	62.8	45	1.00E+05	1.00E+07	0	0	CB 2MHz
9	35546	3.0/1.35	Ag	51.3	30	1.00E+05	1.00E+07	1	0	CB 2MHz
10	35546	3.0/1.35	Ag	51.3	30	1.00E+05	1.00E+07	0	0	CB 500kHz
11	35546	3.0/1.35	Ag	51.3	30	1.00E+05	1.00E+07	0	0	CB 100kHz
12	35546	3.0/1.35	Ag	62.8	45	1.00E+05	1.00E+07	1	28	CB 100kHz, clock upset?
13	35546	3.0/1.35	Ag	62.8	45	1.00E+05	1.00E+07	1	1	CB 100kHz, clock upset?
14	35475	3.0/1.35	Ag	44.4	0	1.00E+05	1.00E+07	0	0	Zero 2MHz
15	35475	3.0/1.35	Ag	44.4	0	1.00E+05	1.00E+07	0	0	CB 2MHz
16	35475	3.6/1.7	Ag	44.4	0	1.00E+05	1.00E+07	0	2	CB 2MHz
17	35475	3.6/1.7	Ag	62.8	45	1.00E+05	1.00E+07	0	0	CB 2MHz
18	35475	3.0/1.35	Ag	62.8	45	1.00E+05	1.00E+07	0	0	CB 2MHz
19	35475	3.0/1.35	Ag	62.8	45	1.00E+05	1.00E+07	0	0	CB 100kHz
20	35475	3.0/1.35	Ag	51.3	30	1.00E+05	1.00E+07	0	0	CB 100kHz
21	35475	3.0/1.35	Ag	44.4	0	1.00E+05	1.00E+07	0	0	CB 100kHz
22	35551	3.0/1.35	Ag	44.4	0	1.00E+05	1.00E+07	0	0	Zero 100kHz
23	35551	3.0/1.35	Ag	44.4	0	1.00E+05	1.00E+07	0	0	CB 100kHz
24	35551	3.6/1.7	Ag	44.4	0	1.00E+05	1.00E+07	0	0	CB 100kHz
25	35551	3.6/1.7	Ag	62.8	45	1.00E+05	1.00E+07	0	0	CB 100kHz
26	35551	3.6/1.7	Ag	62.8	45	1.00E+05	1.00E+07	0	0	CB 100kHz
27	35551	3.0/1.35	Ag	62.8	45	1.00E+05	1.00E+07	0	0	CB 100kHz
28	35551	3.0/1.35	Ag	62.8	45	1.00E+05	1.00E+07	1	1	CB 2MHz, clock upset?
29	35551	3.6/1.7	Ag	62.8	45	1.00E+05	1.00E+07	0	0	CB 2MHz
30	35551	3.6/1.7	Ag	44.4	0	1.00E+05	1.00E+07	1	0	CB 2MHz
31	35551	3.0/1.35	Ag	44.4	0	1.00E+05	1.00E+07	0	0	CB 2MHz
63	35475	3.0/1.35	Xe	54	0	6.00E+04	1.00E+07	1	1	CB 2MHz
64	35475	3.0/1.35	Xe	54	0	6.00E+04	6.00E+06	0	0	CB 2MHz
65	35475	3.6/1.7	Xe	54	0	6.00E+04	1.00E+07	0	0	CB 2MHz
66	35475	3.6/1.7	Xe	76.4	45	6.00E+04	1.00E+07	0	0	CB 2MHz
67	35475	3.0/1.35	Xe	76.4	45	6.00E+04	1.00E+07	0	1	CB 2MHz
68	35475	3.0/1.35	Xe	84	50	6.00E+04	1.00E+07	0	1	CB 2MHz
69	35475	3.6/1.7	Xe	84	50	6.00E+04	1.00E+07	0	1	CB 2MHz
70	35546	3.6/1.7	Xe	54	0	6.00E+04	1.00E+07	2	0	CB 2MHz
71	35546	3.0/1.35	Xe	54	0	5.00E+04	1.00E+07	0	1	CB 2MHz
72	35546	3.0/1.35	Xe	84	50	5.00E+04	1.00E+07	0	0	CB 2MHz
73	35546	3.6/1.7	Xe	84	50	5.00E+04	1.00E+07	0	1	CB 2MHz
74	35551	3.6/1.7	Xe	54	0	5.00E+04	1.00E+07	0	0	CB 2MHz
75	35551	3.6/1.7	Xe	84	50	5.00E+04	1.00E+07	0	1	CB 2MHz

B. Single Event Upset and Rate Prediction

Group-B test data acquired are used to obtain the SEU cross-section because this group has the most complete data. Figure 2 shows the cross-section per flip-flop calculated from the upsets measured for each specific LET. Each data point is the average upset of the four DUTs. The measured errors may include facility noises (e.g. mechanical noises). Nevertheless, all the measured errors are counted for a worst-case scenario. The Weibull-curve fit of these data obtains: $L_0 = 10$ MeV•cm2/mg; width = 35 MeV•cm2/mg; shape = 2; saturation cross-section = 9×10^{-10}cm^2. The approximate device parameters for simulation are: active volume depth = 0.15 µm, and funnel depth = 0.3 µm. Using Space Radiation 4.5 simulator with Weibull and device parameters, the SEU rate at GEO for 100 mil Aluminum shielding and Solar minimum condition is obtained as 1.96×10^{-11} upsets/bit•day.

Group-A and Group-C test data are consistent with the above data. Group-C test data also includes upsets measured both at 100-kHz and 2-MHz clock speed. Except the outlier of Run 12, the 100-kHz upsets are significantly less than the 2-MHz upsets; this indicates that the measured upsets are mostly single-event-transient induced.

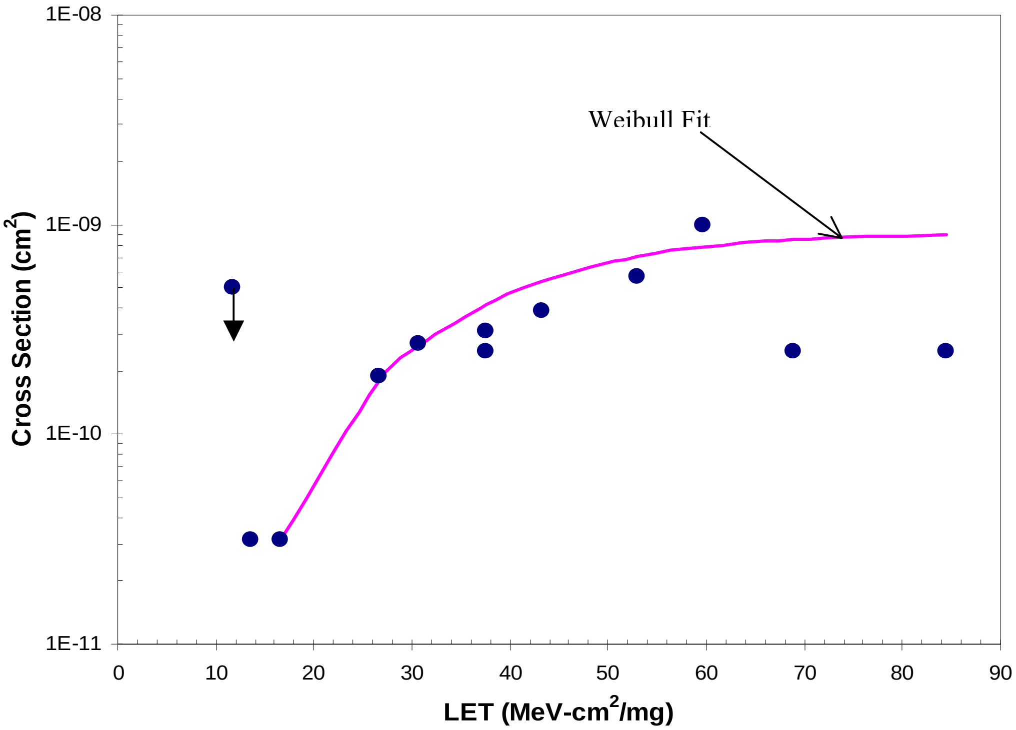

Figure 3 Group-B test data plotted as the SEU Cross-section of the TMR flip-flop with respect to the heavy-ion LET, each data point represents the average of four DUTs. The data point with an arrow pointed down-ward indicates the cross-section derived from test data is below this point. The curve is a Weibull fit for SEU rate predictions.

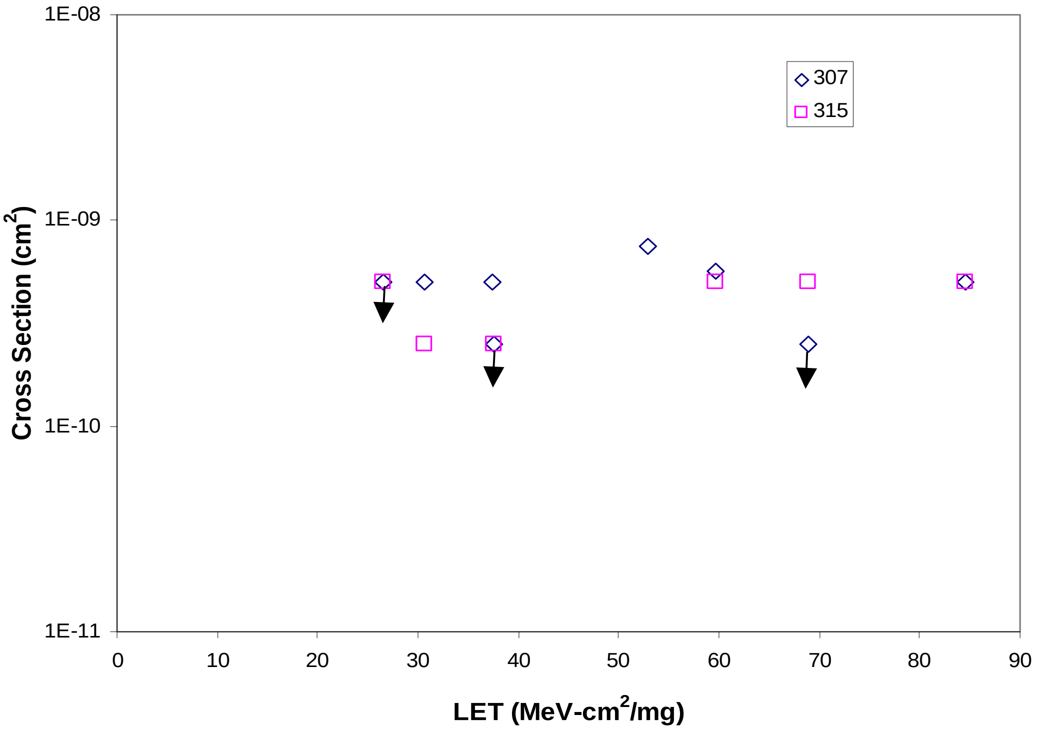

Figure 4 Group-A test data plotted as the SEU cross-section of the TMR flip-flop with respect to the heavy ion LET.

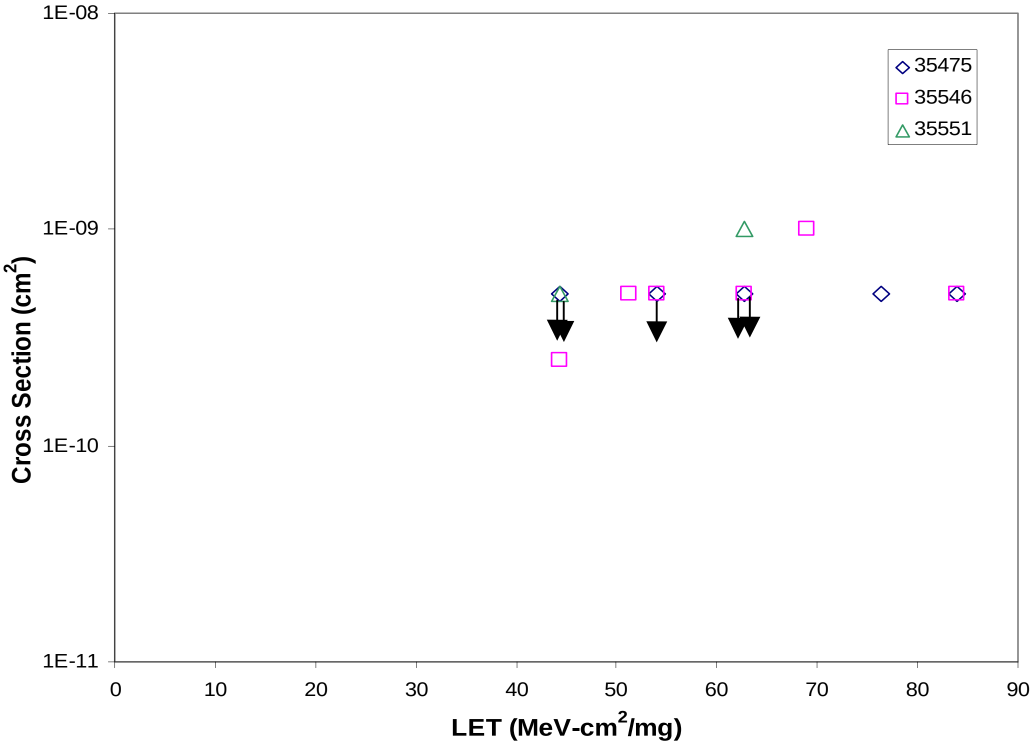

Figure 5 Group-C test data plotted as the SEU cross-section of the TMR flip-flop with respect to the heavy ion LET.

C. *Single Event Latch-up*

There is no occurrence of SEL in any Group-A, Group-B or Group-C test run. Table V lists the SEL testing limits for each test Group.

Table V SEL Testing Limits

	Group A	Group B	Group C
Facility	BNL	BNL	TAMU
V_{CCI}/V_{CCA}	3.3V/1.5V	3.6V/1.65V	3.6V/1.7V
Temperature	Room	Room	Room
Max Effective LET (MeV•cm^2/mg)	104 (320-MeV Iodine tilted 55°)	104 (320-MeV Iodine tilted 55°)	84 (1.253-GeV Xe tilted 50°)
Quantity Tested	2	4	3

D. *Single Event Dielectric Rupture*

The signature of the occurrence of a SEDR is a permanent power-supply current jump. Based on previous experiences the resistance of the antifuse after SEDR is approximately 500-1000 Ω, so the current jump is 1.5 V (V_{CCA})/500-1000 Ω, which is 3 mA-1.5 mA. Since the antifuse can only be biased by V_{CCA}, the in-flux I_{CCA} is examined throughout the test run. Figures 5-8 show the in-flux I_{CCA} for the Group-B SEDR testing runs, and Figures 9-11 show the in-flux I_{CCA} for the Group-C SEDR testing runs. No signature permanent current jump is observed in any run. The maximum LET for Group-B testing is 60 MeV•cm^2/mg (Iodine), and for Group-C testing is 54 MeV•cm^2/mg (Xe). The worst case for SEDR is with the ion beam perpendicular to the antifuse surface; an ion with small LET striking at a tilting angle cannot be used to simulate the effect of an ion-strike with a large LET. Since the antifuse surface is not completely perpendicular to the surface, tilting test runs with high LET ions are performed for completeness. The antifuse is between the top two layers of metal, so the penetration of heavy ions is not an issue.

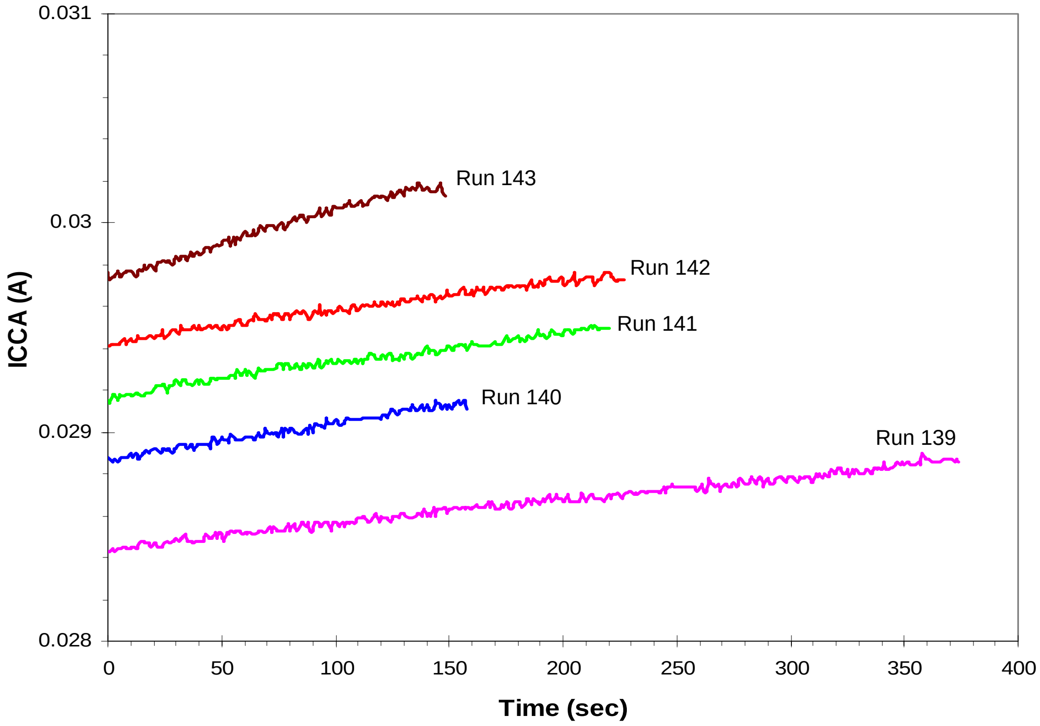

Figure 6 Group-B DUT #4 in-flux I_{CCA} current, V_{CCA} = 1.65 V. I_{CCA} increases continuously because of total dose effect. I_{CCA} also has small fluctuation but no significant jumps, which would be the signature of SEDR.

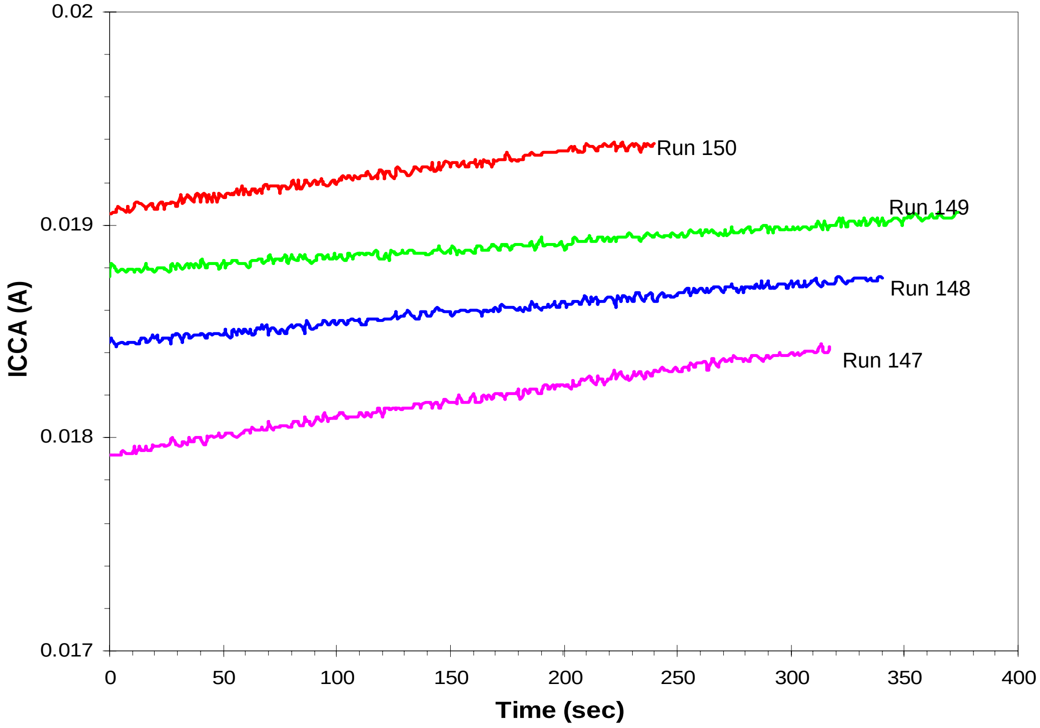

Figure 7 Group-B DUT #3 in-flux I_{CCA} current, V_{CCA} = 1.65 V. I_{CCA} increases continuously because of total-dose effect. I_{CCA} also has small fluctuations but no significant permanent jumps, which would be the signature of SEDR.

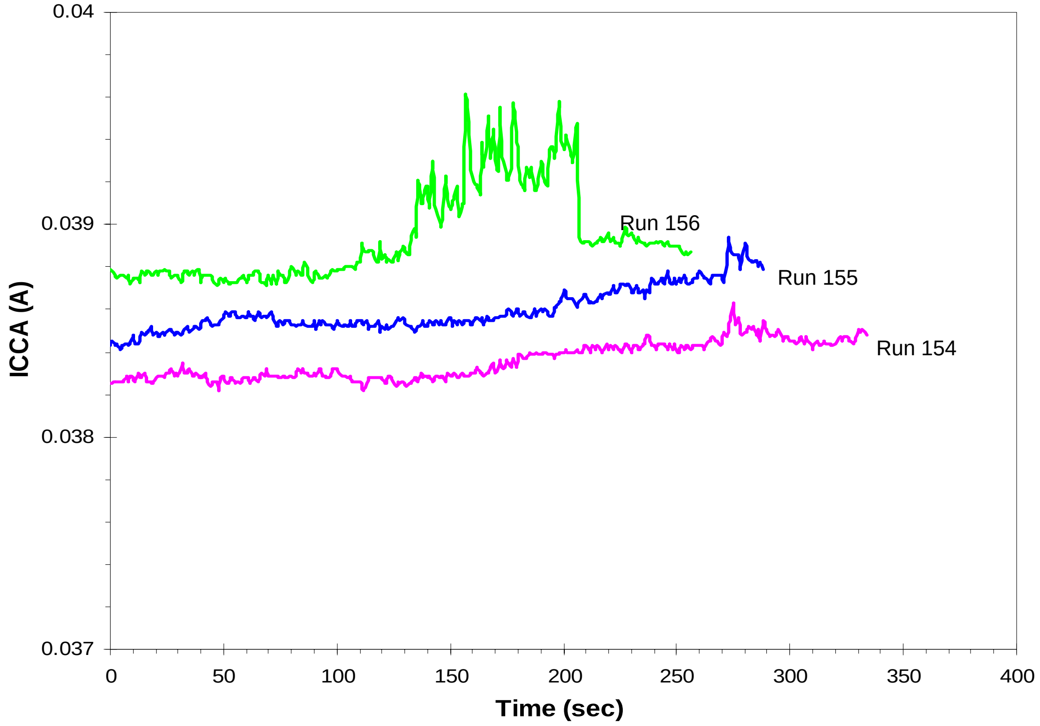

Figure 8 Group-B DUT #2 in-flux I_{CCA} current, V_{CCA} = 1.65 V. I_{CCA} increases continuously because of total-dose effect. I_{CCA} also has small fluctuations but no significant permanent jumps, which would be the signature of SEDR. Run-156 has small temporary current-pulse of ~0.5 mA, which may due to charging/discharging effects.

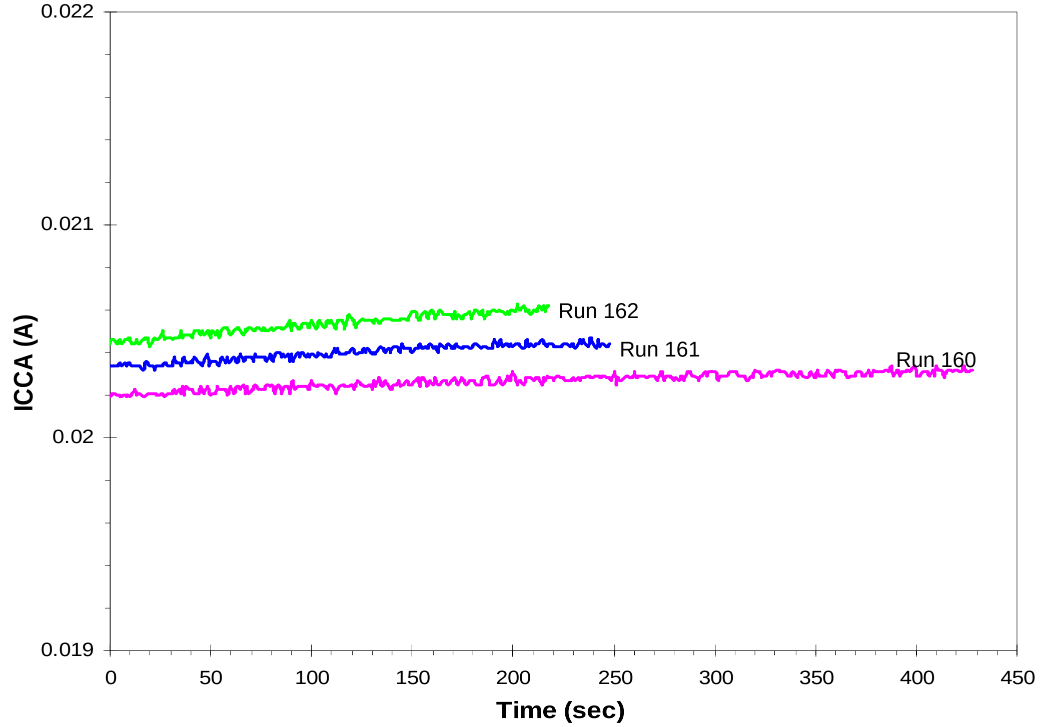

Figure 9 Group-B DUT #1 in-flux I_{CCA} current, V_{CCA} = 1.65 V. I_{CCA} increases continuously because of total-dose effect. I_{CCA} also has small fluctuations but no significant permanent jumps, which would be the signature of SEDR.

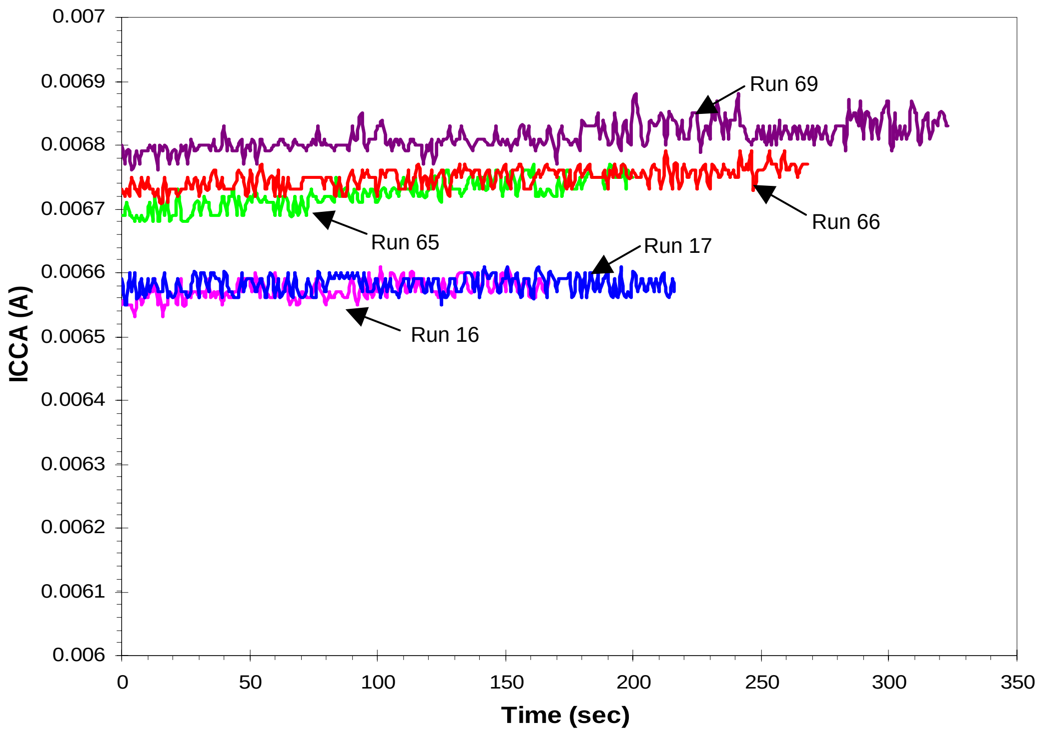

Figure 10 Group-C DUT 34475 in-flux I_{CCA} current, $V_{CCA} = 1.7$ V. I_{CCA} increases continuously because of total-dose effect. I_{CCA} also has small fluctuations but no significant permanent jumps, which would be the signature of SEDR.

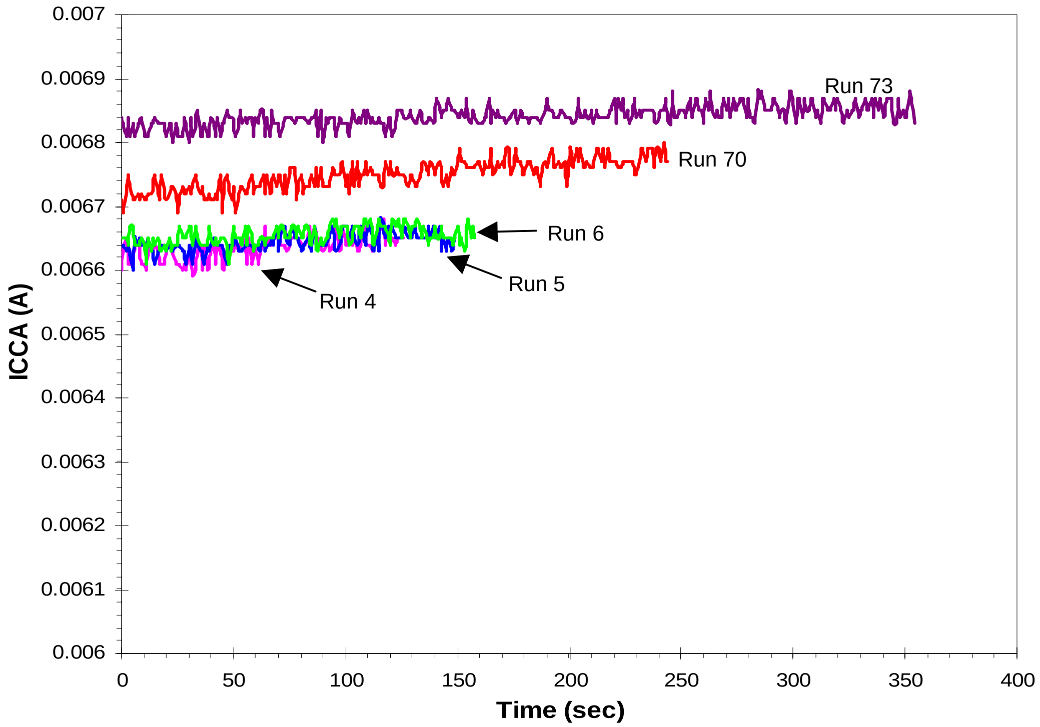

Figure 11 Group-C DUT 35546 in-flux I_{CCA} current, $V_{CCA} = 1.7$ V. I_{CCA} increases continuously because of total-dose effect. I_{CCA} also has small fluctuations but no significant permanent jumps, which would be the signature of SEDR.

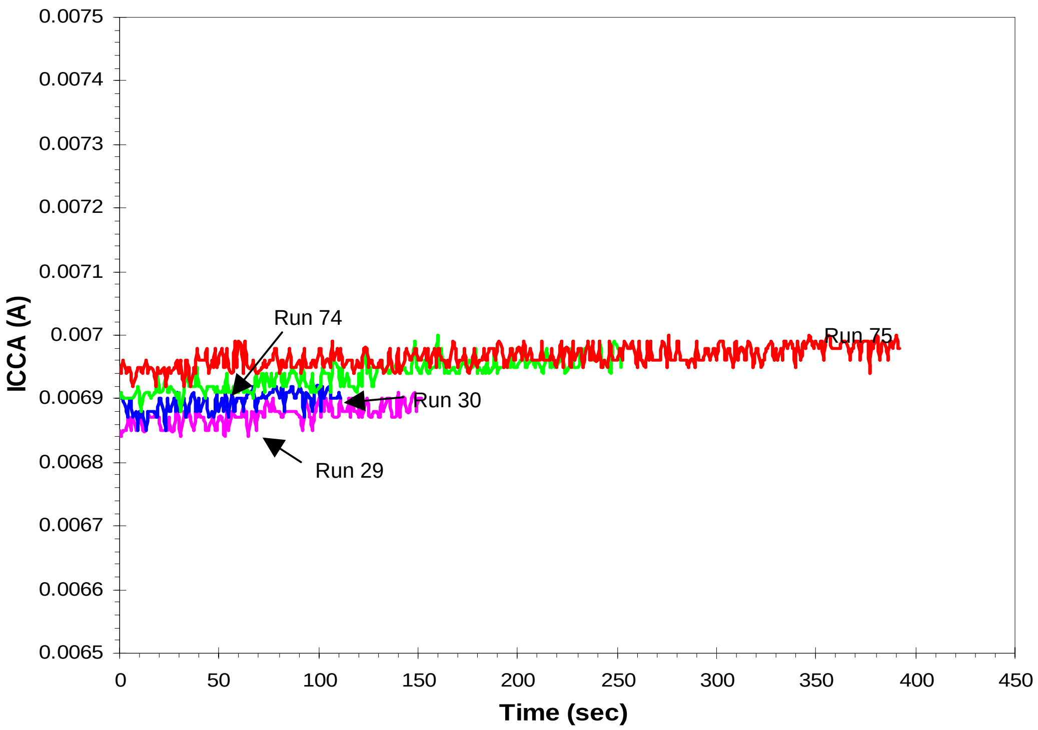

Figure 12 Group-C DUT 35551 in-flux I_{CCA} current, $V_{CCA} = 1.7$ V. I_{CCA} increases continuously because of total-dose effect. I_{CCA} also has small fluctuations but no significant permanent jumps, which would be the signature of SEDR.