SEE Characterization of the Samsung K4F660812 DRAM for the ST5 Project

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1 Introduction

In support of the ST5 project, the Single Event Effects (SEE) characteristics of the Samsung K4F660812 DRAM were measured by the JPL Radiation Effects Group [1]. All tests were carried out with heavy ion beams provided by the Texas A&M University Cyclotron Radiation Effects Facility (TAM) [2] and with proton beams provided by the University of California at Davis Crocker Nuclear Laboratory (DAVIS) [3]. The cross sections for Single Event Upsets (SEU) and Multiple Bit Upsets (MBU) cross sections were measured for a statistically significant sample of devices, culled from the ST5 flight lot as well as an identical commercial lot, at various heavy ion linear energy transfers (LETs) and proton energies. Also, the stuck bit, Single Event Latchup (SEL), and Single Event Functional Interrupt (SEFI) behavior of the devices were observed. The heavy ion measurements were performed between March 20-22, 2002, and the protons on April 19. This report summarizes the results of the tests.

2 Device

The Samsung K4F660812 is a 8×2^{23} bit Fast Page CMOS DRAM. The two-dimensional address space is organized into 2^{13} rows and 2^{10} columns. The plastic package contains 32 I/O pins, of which 31 used: 13 are dedicated to addressing, 8 for data, 3 for V_{SS}, 3 for V_{CC}, and 4 for the instruction set ($\overline{RAS}$,

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$\overline{\mathrm{CAS}}$, $\overline{\mathrm{W}}$, $\overline{\mathrm{OE}}$). More details can be obtained from the manufacturer's specification sheet, a copy of which can be found at [4].

3 Radiation Facilities

The two cyclotron facilities are detailed in the respective references found above. However, a few remarks regarding the beams used are presented here. The heavy-ions provided by TAM, although possessing similar LETs, are significantly less energetic than those found in the Galactic Cosmic Ray (GCR) spectrum. As a result, the ranges of the ion beams in silicon and plastic are limited, and the package, as well as the lead-frame must be removed before testing. This expensive and delicate delidding process is performed by the JPL hybrid lab.

TAM provides ions in a wide range of species and energies. However, to further increase the available LETs, the beams can be degraded with a system of foils, varying in thickness and rotation angles. The range of available LETs can be further increased by rotating the DUT, and to first order approximate the effective LET within the device (L_{eff}) by the cosine-law,

$$L_{\mathrm{eff}} = \frac{L_f}{\cos\theta}, \tag{1}$$

where L_f is the LET of the beam normal-incident on the part (downstream of the degrading foils). The ion beams used for these measurements are given in Table 1.

A note must be made regarding the beam counting provided by TAM. Four scintillators are placed on the perimeter of the beam spot, slightly upstream of the target. A removable scintillator is placed in the center of the beam spot. Prior to the device under test (DUT) exposure, the ratios of the four outer scintillators to the central one are measured (axial gain). During irradiation, the central scintillator is removed (so as to not degrade the beam further) and the axial gain, along with the beam counts in the four outer scintillators are used to infer the flux incident on the DUT. See reference [2] for further details. Over the course of the measurements, the experimenters noticed that the axial gain can fluctuate by a factor of 2 during a time period equal to that used to irradiate the device. These fluctuations limit the ability to determined the absolute beam normalization used to calculate upset cross sections. Using the raw data from the four outer scintillators, and the axial gain fluctuations, errors bars associated with the overall beam normalization ($\delta\sigma_{\mathrm{beam}}$) were determined. These errors can be as large as 30%. The axial gain fluctuations are thought to be a result of instabilities in the TAM beam line.

For the energy range available at DAVIS, the beam will penetrate the package, and no delidding is required for the proton measurements. However, before reaching the sensitive volume, the protons will lose a fraction of their kinetic energy, via Coulomb collisions with atomic electrons in the plastic. Therefore,

Ion	T_0 (MeV)	L_0	r_0 (μm)	T_f	L_f	r_f	L_{eff} $\left(\frac{\text{MeVcm}^2}{\text{mg}}\right)$
^{20}Ne	788	1.20	1615	788	1.20	1615	1.20, 2.10
^{20}Ne	788	1.20	1615	561	1.58	895	1.58, 2.75
^{40}Ar	1562	3.88	1038	1562	3.88	1038	3.88, 4.48, 6.81
^{40}Ar	1562	3.88	1038	1115	5.00	596	5.00
^{40}Ar	1562	3.88	1038	746	6.67	317	9.43, 11.70
^{40}Ar	1562	3.88	1038	717	6.85	299	6.85
^{129}Xe	2923	39.60	255	2923	39.60	255	39.60, 56.00, 69.00
^{129}Xe	2923	39.60	255	2112	45.70	173	45.70
^{78}Kr	2984	14.70	581	2984	14.70	581	14.70
^{78}Kr	2984	14.70	581	2069	18.50	340	18.50
^{78}Kr	2984	14.70	581	1609	21.50	240	21.50
^{78}Kr	2984	14.70	581	1283	24.20	178	24.20
^{78}Kr	2984	14.70	581	1050	26.70	139	26.70

Table 1: The ion beams used at TAM. T_0 is the initial kinetic energy, L_0 is the initial LET, and r_0 is the initial range in silicon. All initial values refer to the beam upstream of the degrader foils. T_f is the final kinetic energy, L_f if the final LET, and r_f if the final range. All final values refer to the beam at the surface of the delidded DUT. L_{eff} is the approximate (equation 1) effective LET achieved by rotating the device. LETs are given in units of MeV cm^2/mg.

the kinetic energy of the proton in the silicon die must be corrected for. These corrections were performed with SRIM [5] and it was assumed the proton travels through 400 μm of plastic with a mass density of $\rho = 1.68$ g/cm^3, approximately that of PVC plastic. Table 2 lists the energy of the proton beams before entering the plastic package as well as the energy at the sensitive volume. Due to the high reproducibility of the proton measurements, the beam counting techniques used at DAVIS appear to be stable, and no attempt to attribute beam normalization error bars was made.

T_0 (MeV)	T_f (MeV)
14.6	12.6
21.4	19.7
41.4	40.5
63.3	62.7

Table 2: The kinetic energy of the proton beams used at DAVIS (T_0), as well as energy of the beam at the sensitive volume of the DUT (T_f).

4 Experimental Apparatus and Procedure

The testing apparatus consisted of two PCs, a HP6629A power supply, and a specialized test circuit board. One PC, running Windows, was used to operate the HP6629A, which supplied power to the test board and DUT. High-level software, developed by the JPL group, was used to remotely operate and monitor the GPIB compatible power supply, as well as logging the current consumed by the DUT. The other PC, which ran a minimized Linux kernel, exercised and evaluated the DUT's performance, using a commercial PLX PCI I/O card to interface with the test board.

The test board was mounted directly downstream of the beam pipe, with the DUT centered on the beam. For the case of heavy ions, the DUT can also be rotated to vary L_{eff} (equation 1. Because humans cannot be in close proximity to the DUT while being irradiated, a combination of commercial receiver/driver cards are used to propagate the signals along the 40 pin, 50 ft ribbon cables that physically connect the Linux PC and test board.

To measure the upset cross sections, as well as the SEL, SEFI, and stuck bit response, a minimum of 5 passes are made over the DUT's address space. A pass consists of accessing each of the 2^{23} words, reading the 8 bit pattern stored, comparing it with an expected pattern, and re-writing the expected pattern. For the initial, or fill pass, the patterns read from the words are disregarded, and a known, random 8×2^{23} bit pattern is used to fill the memory array.

A single address is accessed at a time, in a consistent sequence. The rows and columns are incremented separately, using two loops in a nested structure. The columns are incremented the fastest due to the fact that when a word is accessed, the entire column gets refreshed. It takes about 73 s to complete an entire read/write pass which results in an approximate refresh time of 70 ms.

After the fill pass, another pass is performed, to insure bit integrity. If no bit errors are found, another pass is begun, while simultaneously opening up the beam shutter. Beam is delivered to the DUT for approximately 60 s, and the beam shutter is closed before the third pass is completed. Next, a fourth pass is performed, and the total number of errors due to the presence of ionizing radiation is the sum of errors in pass three and four. Finally, a fifth pass is made to check for stuck bits. For SEL and other phenomena with relatively small cross sections (or in instances when the flux delivered by the cyclotron is small enough that it takes multiple passes to incur a statistically significant number of upsets), usually up to seven or eight passes are performed while delivering beam to the part to allow for a larger fluence. When errors are found, the specific address, as well as the pattern read and expected are logged. The JPL group wrote the low-level software that performed the reading/writing to the addresses, as well as the error checking and logging. The method of determining the instantaneous beam flux and integration to obtain the total fluence is facility dependent and details can be found in the references.

5 Analysis

The upset cross sections are calculated calculated using equation 2,

$$\sigma = \frac{N}{\Phi \cdot \eta}, \tag{2}$$

where N is the total number of upsets, η is the total number of bits (8×2^{23}), and Φ is the fluence,

$$\Phi = \int_0^T \phi(t)\,\mathrm{dt}, \tag{3}$$

where $\phi(t)$ is the instantaneous flux of the beam and T is the duration of the run.

In addition to the above mentioned beam normalization error, (σ_{beam}), the statistical errors bars are determined by equation 4,

$$\delta\sigma\mathrm{stat} = \frac{\sigma}{\sqrt{N-1}}. \tag{4}$$

The total error is written as

$$\delta\sigma = \sqrt{\left(\delta\sigma_{\mathrm{beam}}\right)^2 + \left(\delta\sigma_{\mathrm{stat}}\right)^2}. \tag{5}$$

The current consumed by the DUT is continuously monitored by the software controlling the power supply. A SEL event is characterized by significant jump in the current. These devices typically use around 17 mA and the latchup threshold was set at 50 mA. The software can cycle the power in < 1 s. A SEFI event is characterized by a large percentage of the device failing, typically on the order of 10^6 bits.

6 Results

6.1 Heavy Ion Results

Two types of cross sections were calculated from the heavy ion data: the bit upsets cross section, σ_{bit}, where N in equation 2 is defined as the total number of bits upset, and the multiple bit upset cross section, σ_{mbu}, where N is defined as the number of words with multiple (≥ 2) upset bits. It is assumed that if multiple bits are upset within a single 8 bit word, the source of the upsets must be a single ion. This assumption is justified considering the total number of upset bits is typically between 500 and 5000. The probability for two separate ions (out of 5000) to strike the same word (out of 2^{23}) is minimal. This assumption is further validated by considering the proton measurements, where the number of upsets is fairly equivalent, yet few multiple bit events are observed.

Cross Section	A (cm^2)	B (MeV cm^2/mg)
Single Bit	4.86×10^{-8}	42.45
Multiple Bit	1.91×10^{-8}	87.19

Table 3: The values of the Edmonds fitting parameters (equation 6) for the single bit (σ_{bit}) and multiple bit (σ_{mbu}) heavy ion upset cross sections.

Part	L_{eff}	Behavior	Run #
Y0959	24.20	SEFI	32
Y0959	26.70	SEFI	24
Y0907	69.00	SEFI	64
Y0907	69.00	SEL	66
Y0907	69.00	SEL	67

Table 4: Non-SEU error modes induced by heavy ions. The serial number, along with the effective LET and upset mode are shown. Also listed in the run number where the error mode occurred.

Both variants of cross sections, as a function of LET, for 4 delidded parts measured with heavy ions are given in Tables 7 thru 14. Also, shown in the tables are the errors associated with the beam normalizations and statistics, as well as the species of beam used, and rotation of the DUT. The parts have been serialized by the JPL group for accounting purposes, and are referenced as Y0907, P0806, Y0956, and Y0959. Part Y0907 was taken from a commercial lot, while the other three were taken from the flight lot. The date code stamped on the die for the two lots are identical, and no significant deviations in the SEU response between the two were found. The LETs ranged between 1.20 thru 69.00 MeV·cm^2/mg.

The heavy ion σ_{bit} and σ_{mbu} measurements for all four parts are combined in Figures 1 and 2, respectively. The Edmonds two parameter fit [6],

$$\sigma\left(L_{\text{eff}}\right) = A \cdot e^{-\frac{B}{L_{\text{eff}}}}, \tag{6}$$

where A and B are the two fitting parameters. The values of the fitting parameters for both cross section curves are given in Table 3.

One of the tested parts (Y0959) experienced SEFIs at a relatively low LET ($\approx$ 25 MeV cm^2/mg) and another (Y0907) experienced both a SEFI and SEL, but only at the highest LET. Both devices returned to normal operating states after power cycling. Table 4 lists the runs, L_{eff}, and mode of the non-SEU malfunctions. There is no accurate method to determine the fluence was delivered to the DUT before the error modes occurred, thus no cross section is calculated. No stuck-bits were observed with the heavy ion beams.

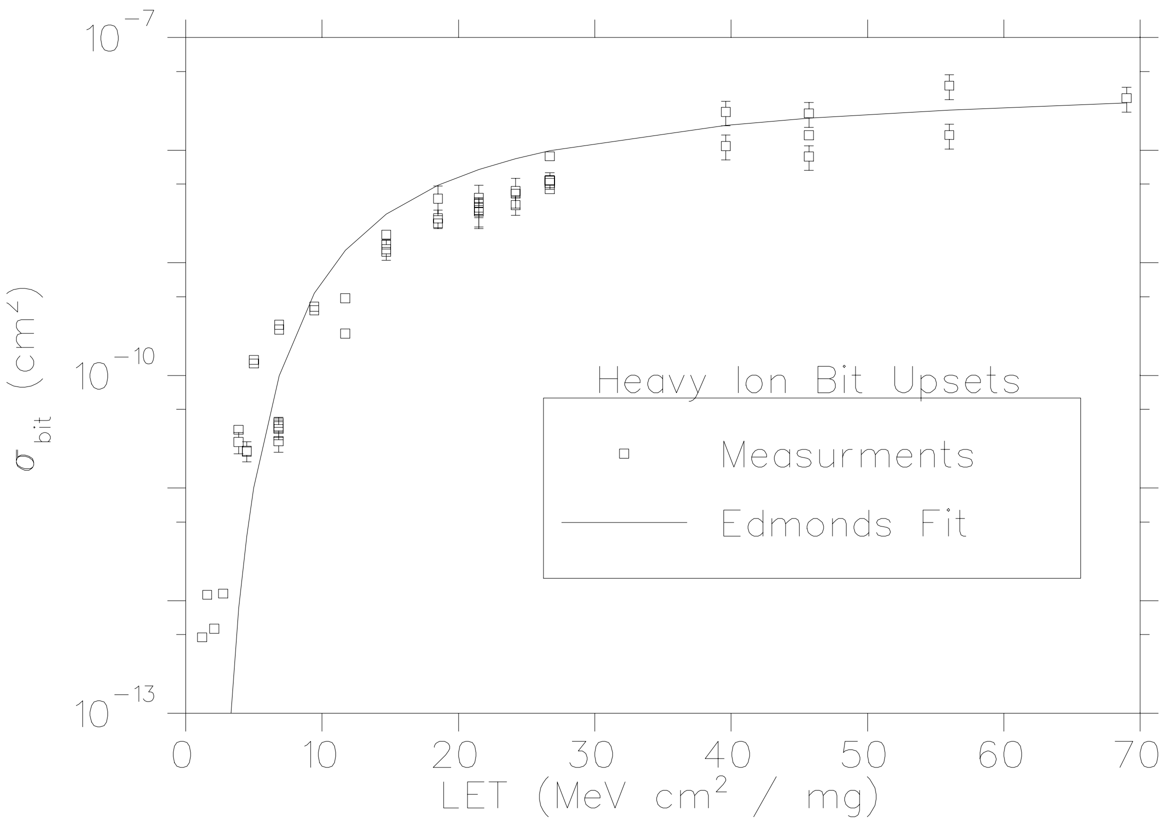

Figure 1: The single bit ($\sigma_{\rm bit}$) heavy ion upset cross section data, as measured as a function of beam LET, for all four delidded parts. The curve represents the two parameter Edmonds fit and the parameter values are given in Table 3.

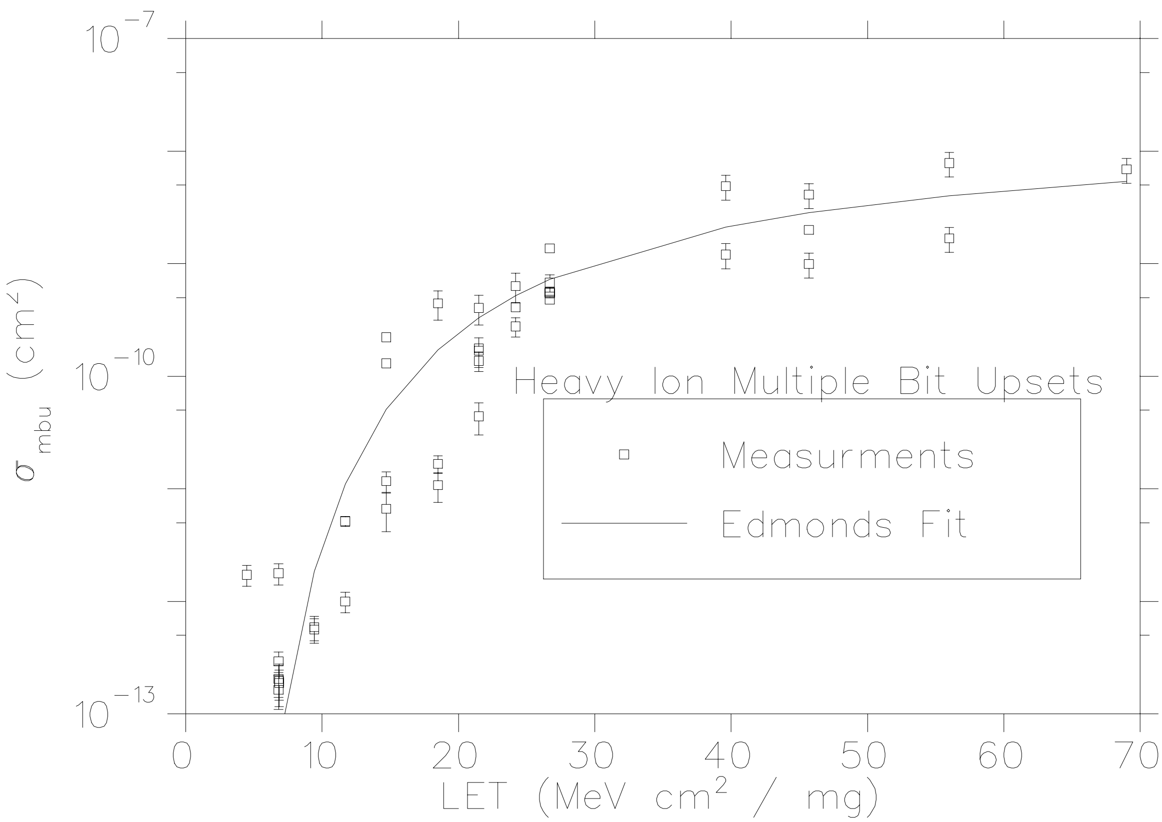

Figure 2: The multiple bit (σ_{mbu}) heavy ion upset cross section data, as measured as a function of beam LET, for all four delidded parts. The curve represents the two parameter Edmonds fit and the parameter values are given in Table 3.

Part	# MBUs	# Bit Errors	Fluence (/cm^2)	Run #
Y0949	1079	12571	2.06×10^{11}	3
X4705	3	8994	1.99×10^{11}	4
X4706	3	8502	1.94×10^{11}	5
X4706	5	8681	2.09×10^{11}	6
Y0953	4	7897	2.10×10^{11}	8

Table 5: The proton induced multiple bit errors observed. MBUs were observed only with the 62.7 MeV beam. The part number, fluence, and run are shown, along with the number of MBUs and single bit errors.

6.2 Proton Results

Five parts encapsulated in their original plastic package were irradiated from the front side at four different proton energies (see Table 2). A sixth part, with the plastic lapped off the underside, in order to expose the backside of the die, was also irradiated. As stated above, only statistical error bars are associated with the proton measurements. Proton induced multiple bit upsets were observed only with the highest energetic beam available at DAVIS. Furthermore only one of the six parts exhibited a significant number of MBUs, and only single bit cross sections were calculated. Table 5 lists the parts, runs, fluence, and number of MBUs and total bit upsets observed with the high energy proton beam. The proton single bit upset cross sections for the five front side parts are given in Tables 15 thru 19 and the backside part in Table 20. It should be noted that the only energy where the results between the frontside and backside irradiated parts differ considerably is at 19.7 MeV. All the proton data are shown in Figure 3. No attempt to fit a parameterized curve to the data was attempted, and a linear segment was drawn between successive points for each part.

A small number of stuck bits induced by protons were observed, all of which annealed in ≈ 90 s (at room temperature) upon which the device returned to 100% operational. Table 6 lists the devices, kinetic energies, number of stuck bits, total number of upset bits, fluence, and run numbers associated with these temporary stuck bits.

7 Conclusions

This report summarizes the SEE test results for the Samsung K4F660812 8×8M DRAM. Heavy ion tests were performed on three devices from the flight lot, and a single device from an identical commercial lot. The effective LET was varied between 1.20 and 69.00 MeV cm^2/mg. All the devices were delidded to expose the sensitive volume to the beam. Single and multiple bit upset cross sections are tabulated and parameterized curves are given that model the data. One device experienced a SEFI at 24 MeV cm^2/mg, and another experienced both

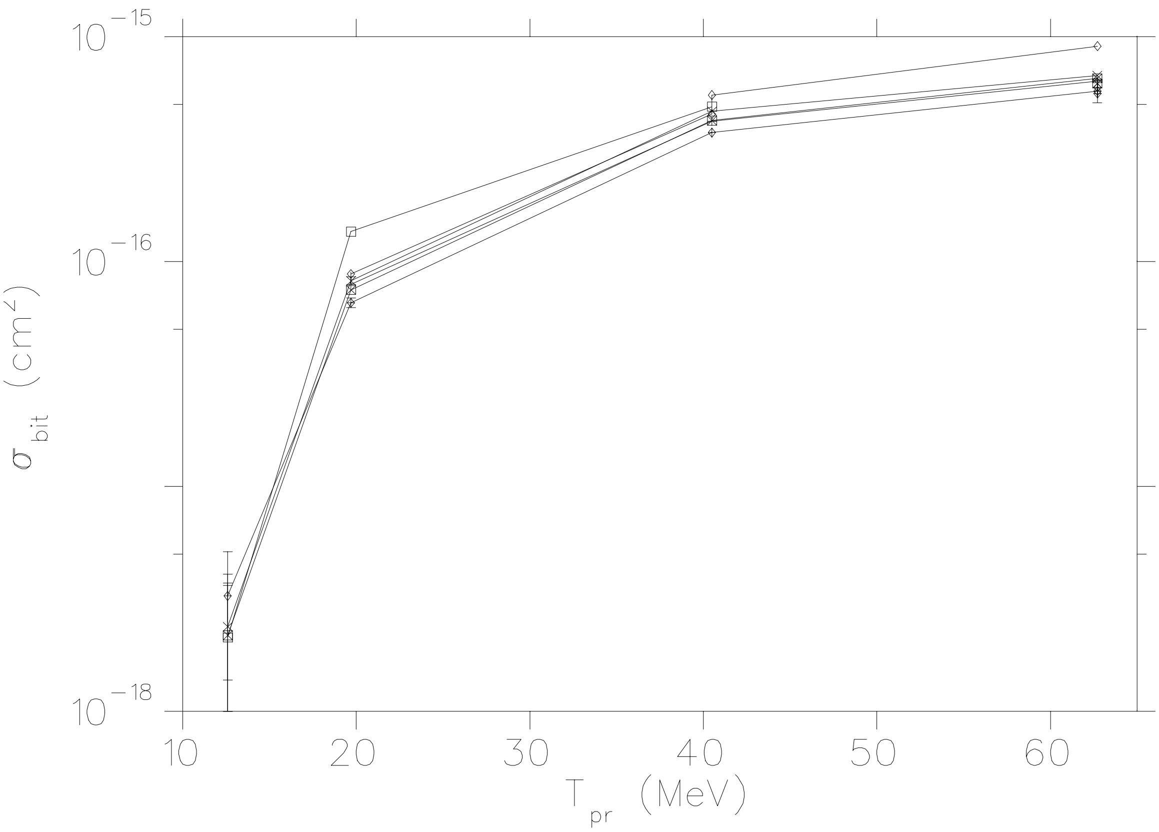

Figure 3: The single bit (σ_{bit}) proton upset cross section data, as measured as a function of kinetic energy, for all six parts. Linear segments are drawn connecting the points for each device.

Part	T_{pr} (MeV)	Stucks	Bit Errors	Fluence ($/cm^2$)	Run #
Y0953	12.6	1	3	1.37×10^{10}	23
X4707	19.7	1	549	1.03×10^{11}	22
X4707	19.7	3	587	1.02×10^{11}	21
X4705	19.7	2	551	1.00×10^{11}	19
Y0949	19.7	1	597	1.01×10^{11}	18
Y0953	19.7	2	441	1.00×10^{11}	17
X4686	19.7	1	937	1.03×10^{11}	16
X4707	40.5	1	1468	5.18×10^{10}	13
X4706	62.7	2	8681	2.09×10^{11}	6
X4705	62.7	3	8994	1.99×10^{11}	4
Y0949	62.7	1	12571	2.06×10^{11}	3

Table 6: Proton induced stuck bit events. The part seriel number, along with the beam kinetic energy, fluence, run number, and number of stuck bits and total number of upset bits are given. All stuck bits annealed within 90 s.

L_{eff}	σ_{bit} (cm^2)	$\delta\sigma_{bit}$ (cm^2)	$\frac{\delta\sigma_{stat}}{\sigma}$	$\frac{\delta\sigma_{beam}}{\sigma}$	Beam	θ_{DUT}	Run #
14.7	1.78×10^{-9}	1.16×10^{-10}	1.08	6.40	^{78}Kr (40)	0.0	2
14.7	1.46×10^{-9}	9.61×10^{-11}	1.57	6.40	^{78}Kr (40)	0.0	8
18.5	3.71×10^{-9}	1.09×10^{-9}	0.91	29.19	^{78}Kr (40)	0.0	3
21.5	2.84×10^{-9}	8.30×10^{-10}	1.45	29.19	^{78}Kr (40)	0.0	4
21.5	3.78×10^{-9}	2.20×10^{-10}	0.96	29.19	^{78}Kr (40)	0.0	5
21.5	2.94×10^{-9}	8.60×10^{-10}	1.09	29.19	^{78}Kr (40)	0.0	6
24.2	4.34×10^{-9}	1.27×10^{-9}	0.93	29.19	^{78}Kr (40)	0.0	7
26.7	8.85×10^{-9}	7.41×10^{-10}	0.83	8.33	^{78}Kr (40)	0.0	1
26.7	5.37×10^{-9}	4.48×10^{-10}	0.94	8.30	^{78}Kr (40)	0.0	11
26.7	5.37×10^{-9}	4.51×10^{-10}	1.29	8.30	^{78}Kr (40)	0.0	12
26.7	5.11×10^{-9}	4.52×10^{-10}	0.22	8.30	^{78}Kr (40)	0.0	13

Table 7: The heavy ion induced single bit upset cross section for commercial lot part Y0907. The effective LET is given in units of MeV cm^2/mg and the cross sections in cm^2. The total error as well as the beam and statistical contributions (percentile) are also given. Also shown is the beam and kinetic energy/AMU (MeV) used to make the measurement, as well as the rotation angle of the DUT. The run number is given for reference.

L_{eff}	σ_{bit} (cm^2)	$\delta\sigma_{\text{bit}}$ (cm^2)	$\frac{\delta\sigma_{\text{stat}}}{\sigma}$	$\frac{\delta\sigma_{\text{beam}}}{\sigma}$	Beam	θ_{DUT}	Run #
3.88	2.57×10^{-11}	5.53×10^{-12}	8.03	20.00	^{40}Ar (40)	0.0	33
4.48	2.15×10^{-11}	4.30×10^{-12}	1.53	20.00	^{40}Ar (40)	30.0	40
5.00	1.28×10^{-10}	7.99×10^{-12}	2.33	5.79	^{40}Ar (40)	0.0	34
6.81	6.43×10^{-13}	1.47×10^{-13}	10.98	20.00	^{40}Ar (40)	55.2	39
6.81	3.36×10^{-11}	6.74×10^{-12}	1.87	20.00	^{40}Ar (40)	55.2	46
6.81	3.53×10^{-11}	7.10×10^{-12}	1.85	20.00	^{40}Ar (40)	55.2	47
6.81	2.61×10^{-11}	5.24×10^{-12}	1.98	20.00	^{40}Ar (40)	55.2	51
6.85	2.56×10^{-10}	1.70×10^{-11}	0.78	6.57	^{40}Ar (40)	0.0	38
9.43	3.79×10^{-10}	2.51×10^{-11}	0.91	6.57	^{40}Ar (40)	45.0	53
11.70	4.85×10^{-10}	3.21×10^{-11}	0.87	6.57	^{40}Ar (40)	55.2	48
11.70	2.36×10^{-10}	1.57×10^{-11}	1.18	6.57	^{40}Ar (40)	55.2	50
14.70	1.32×10^{-9}	2.66×10^{-10}	2.25	20.00	^{78}Kr (40)	0.0	19
18.50	2.48×10^{-9}	4.62×10^{-10}	1.51	18.55	^{78}Kr (40)	0.0	20
21.50	3.09×10^{-9}	5.74×10^{-10}	1.40	18.55	^{78}Kr (40)	0.0	21
24.20	3.26×10^{-9}	6.06×10^{-10}	1.40	18.55	^{78}Kr (40)	0.0	22
26.70	4.51×10^{-9}	2.89×10^{-10}	1.56	6.21	^{78}Kr (40)	0.0	23

Table 8: The heavy ion induced single bit upset cross section for flight lot part P0806. The effective LET is given in units of MeV cm^2/mg and the cross sections in cm^2. The total error as well as the beam and statistical contributions (percentile) are also given. Also shown is the beam and kinetic energy/AMU (MeV) used to make the measurement, as well as the rotation angle of the DUT. The run number is given for reference.

L_{eff}	σ_{bit} (cm^2)	$\delta\sigma_{\text{bit}}$ (cm^2)	$\frac{\delta\sigma_{\text{stat}}}{\sigma}$	$\frac{\delta\sigma_{\text{beam}}}{\sigma}$	Beam	θ_{DUT}	Run #
1.20	4.73×10^{-13}	2.51×10^{-14}	4.66	2.55	^{20}Ne (40)	0.0	58
1.58	1.13×10^{-12}	6.05×10^{-14}	4.73	2.51	^{20}Ne (40)	0.0	57
2.10	5.66×10^{-13}	4.26×10^{-14}	7.05	2.62	^{20}Ne (40)	55.0	55
2.75	1.16×10^{-12}	7.08×10^{-14}	5.49	2.57	^{20}Ne (40)	55.0	56
39.60	1.09×10^{-8}	2.70×10^{-9}	1.61	24.75	^{129}Xe (25)	0.0	68
45.70	2.19×10^{-8}	5.42×10^{-9}	0.89	24.75	^{129}Xe (25)	0.0	74
45.70	8.78×10^{-9}	2.18×10^{-9}	1.24	24.75	^{129}Xe (25)	30.0	70
45.70	2.12×10^{-8}	5.26×10^{-9}	0.94	24.75	^{129}Xe (25)	30.0	72
45.70	1.36×10^{-8}	1.48×10^{-10}	1.07	0.20	^{129}Xe (25)	0.0	75
56.00	1.36×10^{-8}	3.38×10^{-9}	1.18	24.75	^{129}Xe (25)	45.0	71
56.00	3.75×10^{-8}	9.29×10^{-9}	0.80	24.75	^{129}Xe (25)	45.0	73
69.00	2.90×10^{-8}	7.19×10^{-9}	0.88	24.75	^{129}Xe (25)	55.0	69

Table 9: The heavy ion induced single bit upset cross section for flight lot part Y0956. The effective LET is given in units of MeV cm^2/mg and the cross sections in cm^2. The total error as well as the beam and statistical contributions (percentile) are also given. Also shown is the beam and kinetic energy/AMU (MeV) used to make the measurement, as well as the rotation angle of the DUT. The run number is given for reference.

L_{eff}	σ_{bit} (cm^2)	$\delta\sigma_{\text{bit}}$ (cm^2)	$\frac{\delta\sigma_{\text{stat}}}{\sigma}$	$\frac{\delta\sigma_{\text{beam}}}{\sigma}$	Beam	θ_{DUT}	Run #
3.88	3.30×10^{-11}	1.46×10^{-12}	1.87	4.02	^{40}Ar (40)	0.0	36
4.48	2.11×10^{-11}	9.17×10^{-13}	1.64	4.02	^{40}Ar (40)	30.0	42
5.00	1.38×10^{-10}	1.97×10^{-12}	1.14	0.87	^{40}Ar (40)	0.0	35
6.85	2.83×10^{-10}	5.88×10^{-12}	1.08	1.78	^{40}Ar (40)	0.0	37
6.81	3.81×10^{-11}	1.67×10^{-12}	1.76	4.02	^{40}Ar (40)	55.2	45
9.43	4.08×10^{-10}	8.30×10^{-12}	0.92	1.81	^{40}Ar (40)	45.0	54
14.70	1.25×10^{-9}	2.75×10^{-11}	2.02	0.86	^{78}Kr (40)	0.0	28
18.50	2.24×10^{-9}	1.10×10^{-10}	1.50	4.69	^{78}Kr (40)	0.0	29
21.50	3.38×10^{-9}	8.06×10^{-11}	1.42	1.92	^{78}Kr (40)	0.0	30
24.20	4.12×10^{-9}	7.27×10^{-11}	1.46	1.00	^{78}Kr (40)	0.0	31
26.70	5.41×10^{-9}	9.12×10^{-10}	1.53	16.79	^{78}Kr (40)	0.0	26

Table 10: The heavy ion induced single bit upset cross section for flight lot part Y0959. The effective LET is given in units of MeV cm^2/mg and the cross sections in cm^2. The total error as well as the beam and statistical contributions (percentile) are also given. Also shown is the beam and kinetic energy/AMU (MeV) used to make the measurement, as well as the rotation angle of the DUT. The run number is given for reference.

L_{eff}	σ_{MBU} (cm^2)	$\delta\sigma_{\text{MBU}}$ (cm^2)	$\frac{\delta\sigma_{\text{stat}}}{\sigma}$	$\frac{\delta\sigma_{\text{beam}}}{\sigma}$	Beam	θ_{DUT}	Run #
14.7	2.22×10^{-10}	1.58×10^{-11}	3.07	6.40	^{78}Kr (40)	0.0	2
14.7	1.31×10^{-10}	1.08×10^{-11}	5.26	6.40	^{78}Kr (40)	0.0	8
18.5	4.45×10^{-10}	1.31×10^{-10}	2.64	29.19	^{78}Kr (40)	0.0	3
21.5	4.41×10^{-11}	1.38×10^{-11}	11.63	29.19	^{78}Kr (40)	0.0	4
21.5	4.05×10^{-10}	1.19×10^{-10}	2.93	29.19	^{78}Kr (40)	0.0	5
21.5	1.69×10^{-10}	5.00×10^{-11}	4.55	29.19	^{78}Kr (40)	0.0	6
24.2	6.35×10^{-10}	1.86×10^{-10}	2.42	29.19	^{78}Kr (40)	0.0	7
26.7	1.37×10^{-9}	1.18×10^{-10}	2.11	8.33	^{78}Kr (40)	0.0	1
26.7	5.61×10^{-10}	4.93×10^{-11}	3.90	8.30	^{78}Kr (40)	0.0	11
26.7	5.49×10^{-10}	5.07×10^{-11}	4.03	8.30	^{78}Kr (40)	0.0	12
26.7	5.63×10^{-10}	4.68×10^{-11}	0.646	8.30	^{78}Kr (40)	0.0	13

Table 11: The heavy ion induced multiple bit upset cross section for commercial lot part Y0907. The effective LET is given in units of MeV cm^2/mg and the cross sections in cm^2. The total error as well as the beam and statistical contributions (percentile) are also given. Also shown is the beam and kinetic energy/AMU (MeV) used to make the measurement, as well as the rotation angle of the DUT. The run number is given for reference.

a SEFI and a SEL at 69 MeV cm^2/mg. The latches were mitigated within 1 s and the devices were not permanently damaged. No ion induced stuck bits were observed.

Proton tests were performed on five parts from the flight lot, with their original package intact, and a sixth part with the plastic package shaved off the backside to expose the underside of the die to the beam. The kinetic energy of the beam ranged from 12.6 to 62.7 MeV. The single bit upset cross sections are tabulated. Multiple bit upsets were observed only with the most energetic beam, and only one part experienced a significant number. A small number of stuck bits that annealed within 90 s were also observed, after which the parts returned to being full operational. The devices appear to be immune to proton induced SEFIs and SELs.

References

[1] http://parts.jpl.nasa.gov

[2] http://cyclotron.tamu.edu/ref/

[3] http://media.cnl.ucdavis.edu/Crocker/Website/default.php

[4] http://www.samsung.com

[5] http://www.srim.org

L_{eff}	σ_{MBU} (cm^2)	$\delta\sigma_{\text{MBU}}$ (cm^2)	$\frac{\delta\sigma_{\text{stat}}}{\sigma}$	$\frac{\delta\sigma_{\text{beam}}}{\sigma}$	Beam	θ_{DUT}	Run #
3.88	0.00×10^{0}	0.00×10^{0}	100.00	20.00	^{40}Ar (40)	0.0	33
4.48	1.73×10^{-12}	3.58×10^{-13}	5.41	20.00	^{40}Ar (40)	30.0	40
5.00	0.00×10^{0}	0.00×10^{0}	100.00	5.79	^{40}Ar (40)	0.0	34
6.81	0.00×10^{0}	0.00×10^{0}	100.00	20.00	^{40}Ar (40)	55.2	39
6.81	1.64×10^{-13}	5.48×10^{-14}	26.73	20.00	^{40}Ar (40)	55.2	46
6.81	2.05×10^{-13}	6.43×10^{-14}	24.25	20.00	^{40}Ar (40)	55.2	47
6.81	1.78×10^{-12}	3.81×10^{-13}	7.56	20.00	^{40}Ar (40)	55.2	51
6.85	1.89×10^{-13}	5.60×10^{-14}	28.87	6.57	^{40}Ar (40)	0.0	38
9.43	5.63×10^{-13}	1.38×10^{-13}	23.57	6.57	^{40}Ar (40)	45.0	53
11.70	9.99×10^{-13}	2.03×10^{-13}	19.25	6.57	^{40}Ar (40)	55.2	48
11.70	5.17×12^{-12}	5.32×10^{-13}	7.93	6.57	^{40}Ar (40)	55.2	50
14.70	6.67×10^{-12}	2.50×10^{-12}	31.62	20.00	^{78}Kr (40)	0.0	19
18.50	1.08×10^{-11}	3.18×10^{-12}	22.94	18.55	^{78}Kr (40)	0.0	20
21.50	1.37×10^{-10}	2.70×10^{-11}	6.64	18.55	^{78}Kr (40)	0.0	21
24.20	2.77×10^{-10}	5.32×10^{-11}	4.81	18.55	^{78}Kr (40)	0.0	22
26.70	4.80×10^{-10}	3.76×10^{-11}	4.79	6.21	^{78}Kr (40)	0.0	23

Table 12: The heavy ion induced multiple bit upset cross section for flight lot part P0806. The effective LET is given in units of MeV cm^2/mg and the cross sections in cm^2. The total error as well as the beam and statistical contributions (percentile) are also given. Also shown is the beam and kinetic energy/AMU (MeV) used to make the measurement, as well as the rotation angle of the DUT. The run number is given for reference.

$L_{\rm eff}$	$\sigma_{\rm MBU}$ (cm^2)	$\delta\sigma_{\rm MBU}$ (cm^2)	$\frac{\delta\sigma_{\rm stat}}{\sigma}$	$\frac{\delta\sigma_{\rm beam}}{\sigma}$	Beam	$\theta_{\rm DUT}$	Run #
1.20	2.06×10^{-15}	1.45×10^{-15}	70.71	2.55	^{20}Ne (40)	0.0	58
1.58	0.00×10^{0}	0.00×10^{0}	100.00	2.51	^{20}Ne (40)	0.0	57
2.10	2.82×10^{-15}	2.82×10^{-15}	100.00	2.62	^{20}Ne (40)	55.0	55
2.75	0.00×10^{0}	0.00×10^{0}	100.00	2.57	^{20}Ne (40)	55.0	56
39.60	1.21×10^{-9}	3.04×10^{-10}	4.85	24.75	^{129}Xe (25)	0.0	68
45.70	4.90×10^{-9}	1.22×10^{-9}	1.88	24.75	^{129}Xe (25)	0.0	74
45.70	9.93×10^{-10}	2.49×10^{-10}	3.68	24.75	^{129}Xe (25)	30.0	70
45.70	4.12×10^{-9}	1.02×10^{-9}	2.13	24.75	^{129}Xe (25)	30.0	72
45.70	2.00×10^{-9}	5.58×10^{-11}	2.78	0.20	^{129}Xe (25)	0.0	75
56.00	1.68×10^{-9}	4.21×10^{-10}	3.35	24.75	^{129}Xe (25)	45.0	71
56.00	7.84×10^{-9}	1.94×10^{-9}	1.74	24.75	^{129}Xe (25)	45.0	73
69.00	6.92×10^{-9}	1.72×10^{-9}	1.80	24.75	^{129}Xe (25)	55.0	69

Table 13: The heavy ion induced multiple bit upset cross section for flight lot part Y0956. The effective LET is given in units of MeV cm^2/mg and the cross sections in cm^2. The total error as well as the beam and statistical contributions (percentile) are also given. Also shown is the beam and kinetic energy/AMU (MeV) used to make the measurement, as well as the rotation angle of the DUT. The run number is given for reference.

$L_{\rm eff}$	$\sigma_{\rm MBU}$ (cm^2)	$\delta\sigma_{\rm MBU}$ (cm^2)	$\frac{\delta\sigma_{\rm stat}}{\sigma}$	$\frac{\delta\sigma_{\rm beam}}{\sigma}$	Beam	$\theta_{\rm DUT}$	Run #
3.88	3.30×10^{-11}	1.46×10^{-12}	1.87	4.02	^{40}Ar (40)	0.0	36
4.48	2.11×10^{-11}	9.17×10^{-13}	1.64	4.02	^{40}Ar (40)	30.0	42
5.00	1.38×10^{-10}	1.97×10^{-12}	1.14	0.87	^{40}Ar (40)	0.0	35
6.85	2.83×10^{-10}	5.88×10^{-12}	1.08	1.78	^{40}Ar (40)	0.0	37
6.81	3.81×10^{-11}	1.67×10^{-12}	1.76	4.02	^{40}Ar (40)	55.2	45
9.43	4.08×10^{-10}	8.30×10^{-12}	0.92	1.81	^{40}Ar (40)	45.0	54
14.70	1.25×10^{-9}	2.75×10^{-11}	2.02	0.86	^{78}Kr (40)	0.0	28
18.50	2.24×10^{-9}	1.10×10^{-10}	1.50	4.69	^{78}Kr (40)	0.0	29
21.50	3.38×10^{-9}	8.06×10^{-11}	1.42	1.92	^{78}Kr (40)	0.0	30
24.20	4.12×10^{-9}	7.27×10^{-11}	1.46	1.00	^{78}Kr (40)	0.0	31
26.70	5.41×10^{-9}	9.12×10^{-10}	1.53	16.79	^{78}Kr (40)	0.0	26

Table 14: The heavy ion induced multiple bit upset cross section for flight lot part Y0959. The effective LET is given in units of MeV cm^2/mg and the cross sections in cm^2. The total error as well as the beam and statistical contributions (percentile) are also given. Also shown is the beam and kinetic energy/AMU (MeV) used to make the measurement, as well as the rotation angle of the DUT. The run number is given for reference.

$T_{\rm pr}$ (MeV)	$\sigma_{\rm bit}$ (cm^2)	$\delta\sigma_{\rm bit}$ (cm^2)	Run #
12.6	3.26×10^{-18}	1.88×10^{-18}	23
19.7	6.57×10^{-17}	3.13×10^{-18}	17
40.5	3.75×10^{-16}	1.03×10^{-17}	9
62.7	5.74×10^{-16}	6.54×10^{-17}	1
62.7	5.95×10^{-16}	6.68×10^{-18}	2
62.7	5.60×10^{-16}	6.31×10^{-18}	8

Table 15: The proton induced single bit upset cross section for flight lot part Y0953. The kinetic energy is given in units of MeV and the cross sections in cm^2. The error (statistical only) and run number are also given.

$T_{\rm pr}$ (MeV)	$\sigma_{\rm bit}$ (cm^2)	$\delta\sigma_{\rm bit}$ (cm^2)	Run #
12.6	0.00×10^{0}	0.00×10^{0}	24
19.7	8.81×10^{-17}	3.60×10^{-18}	18
40.5	4.53×10^{-16}	1.12×10^{-17}	10
40.5	5.51×10^{-16}	1.12×10^{-17}	14
62.7	9.09×10^{-16}	8.11×10^{-18}	3

Table 16: The proton induced single bit upset cross section for flight lot part Y0949. The kinetic energy is given in units of MeV and the cross sections in cm^2. The error (statistical only) and run number are also given.

$T_{\rm pr}$ (MeV)	$\sigma_{\rm bit}$ (cm^2)	$\delta\sigma_{\rm bit}$ (cm^2)	Run #
12.6	2.38×10^{-18}	1.69×10^{-18}	25
19.7	8.21×10^{-17}	3.50×10^{-18}	19
40.5	4.67×10^{-16}	1.17×10^{-17}	11
62.7	6.73×10^{-16}	7.10×10^{-18}	4

Table 17: The proton induced single bit upset cross section for flight lot part X4705. The kinetic energy is given in units of MeV and the cross sections in cm^2. The error (statistical only) and run number are also given.

$T_{\rm pr}$ (MeV)	$\sigma_{\rm bit}$ (cm^2)	$\delta\sigma_{\rm bit}$ (cm^2)	Run #
12.6	2.18×10^{-18}	1.54×10^{-18}	28
19.7	7.48×10^{-17}	3.31×10^{-18}	20
40.5	4.24×10^{-16}	1.11×10^{-17}	12
62.7	6.53×10^{-16}	7.08×10^{-18}	5
62.7	6.19×10^{-16}	6.64×10^{-18}	6

Table 18: The proton induced single bit upset cross section for flight lot part X407. The kinetic energy is given in units of MeV and the cross sections in cm^2. The error (statistical only) and run number are also given.

T_{pr} (MeV)	σ_{bit} (cm^2)	$\delta\sigma_{\text{bit}}$ (cm^2)	Run #
19.7	8.58×10^{-17}	3.54×10^{-18}	21
19.7	7.94×10^{-17}	3.39×10^{-18}	22
40.5	4.22×10^{-16}	1.10×10^{-17}	13
62.7	6.35×10^{-16}	6.91×10^{-18}	7

Table 19: The proton induced single bit upset cross section for flight lot part X4707. The kinetic energy is given in units of MeV and the cross sections in cm^2. The error (statistical only) and run number are also given.

T_{pr} (MeV)	σ_{bit} (cm^2)	$\delta\sigma_{\text{bit}}$ (cm^2)	Run #
12.6	2.13×10^{-18}	1.51×10^{-18}	26
19.7	1.36×10^{-16}	4.43×10^{-18}	16
40.5	4.89×10^{-16}	1.21×10^{-17}	15

Table 20: The proton induced single bit upset cross section for flight lot part X4686. The kinetic energy is given in units of MeV and the cross sections in cm^2. The error (statistical only) and run number are also given. This is the part that was irradiated from the backside.

[6] "SEU Cross Sections Derived from a Diffusion Analysis," IEEE Trans. Nucl. Sci., no. 6, pp. 3207-3217, Dec. 1996.