Heavy Ion Irradiation Test Report for the Samsung 850 PRO Series Solid State Drive

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I. Introduction

The purpose of this test was to determine the heavy ion-induced single-event effect (SEE) susceptibility of the Samsung solid state drive (SSD) containing the Vertical-NAND (VNAND) flash technology. This test was supported by the NASA Electronics Parts and Packaging (NEPP) Program.

II. Devices Under Test

The Samsung 840 PRO Series SSD features a standard 2.5" SATA 6 Gb/s interface. The SSD utilizes the latest VNAND flash technology. Each VNAND chip contains a stack of VNAND die. There are two types of VNAND chips on the drive. The K9PRGY8S7M, consists of 8 stacked die, and the K9HQGY8S5M consists of 4 stacked die. Each VNAND die is 86 Gb. The 256 GB SSD comprises of 2 chips of each type. We de-encapsulated two chips on each SSD for the heavy ion exposure. The other components on the SSD, including the DDR3, controller, and other active devices (amplifiers, voltage references, diodes, etc.) will not be exposed to irradiation.

The SSD specifications and features can be found on the Samsung website [1]. Basic device and test information is provided in Table I.

Table I
Device information.

Generic Part Number:	MZ7KE256HMHA
Full Part Number	MZ7KE256HMHA
Manufacturer:	Samsung
Lot Date Code (LDC):	Unknown (REAG ID # 14-055)
Quantity Tested:	4
Serial Numbers of Control Sample:	TBD
Serial Numbers of Radiation Samples:	S1SUNWAF602432F S1SUNWAF602011H S1SUNWAF602550Z S1SUNWAF602429B S1SUNWAF602546H
Part Function:	Solid state drive
Part Technology:	41 nm CMOS and vertical-NAND
Package Style:	SATA interface
Test Equipment:	PC, power supply, SATA 6.0 cable, current meter

III. Test Facility

The heavy ion testing was carried out at the Texas A&M University Cyclotron Facility. The beam information is given below.

Facility: Texas A&M University Cyclotron Facility
Cocktail: 25 MeV/amu
Flux: $< 1 \times 10^5$ ions/(cm^2·s)
Fluence: $\leq 1 \times 10^7$ ions/cm^2 (for a given run)
Ions: Shown in Table II

Table II
Heavy ion specie, energy, LET, and range in silicon.

Ion	Total Energy	Initial LET in air	Range in Si
	(MeV)	*(MeV·cm^2/mg)*	*(µm)*
Ne	545	1.8	799
Ar	991	5.5	493
Kr	2081	19.8	332

IV. Test Method

A. Irradiation procedure

Figure 1 shows a schematic of the test setup. The desktop PC for accessing the SSD was positioned in the irradiation chamber in close proximity to the device-under-test (DUT). The power supply was also positioned in the irradiation chamber. We remotely controlled the power supply via GPIB or USB interface.

The sequence of test procedures are described below in Table III. We evaluated the performance of the SSD during static test mode and dynamic test mode. In the static mode, we performed a read following the exposure and recorded the bad addresses. In dynamic mode, we actively read the SSD during the exposure, and recorded the bad addresses.

In the event of a functional interrupt, we allowed the SSD to self-clear the error, given that the device is not in a high current state. If functionality does not recover, we cycled power to the SSD.

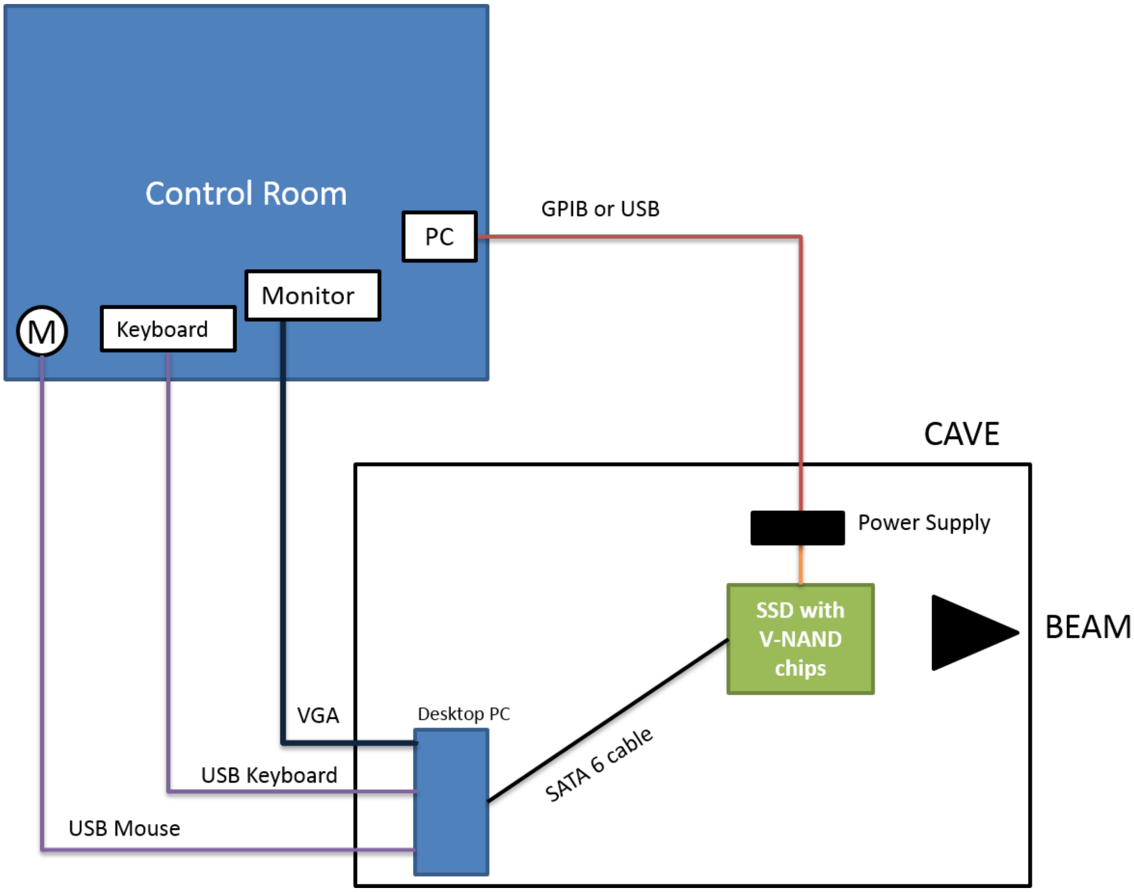

Figure 1. Schematic diagram of the test setup.

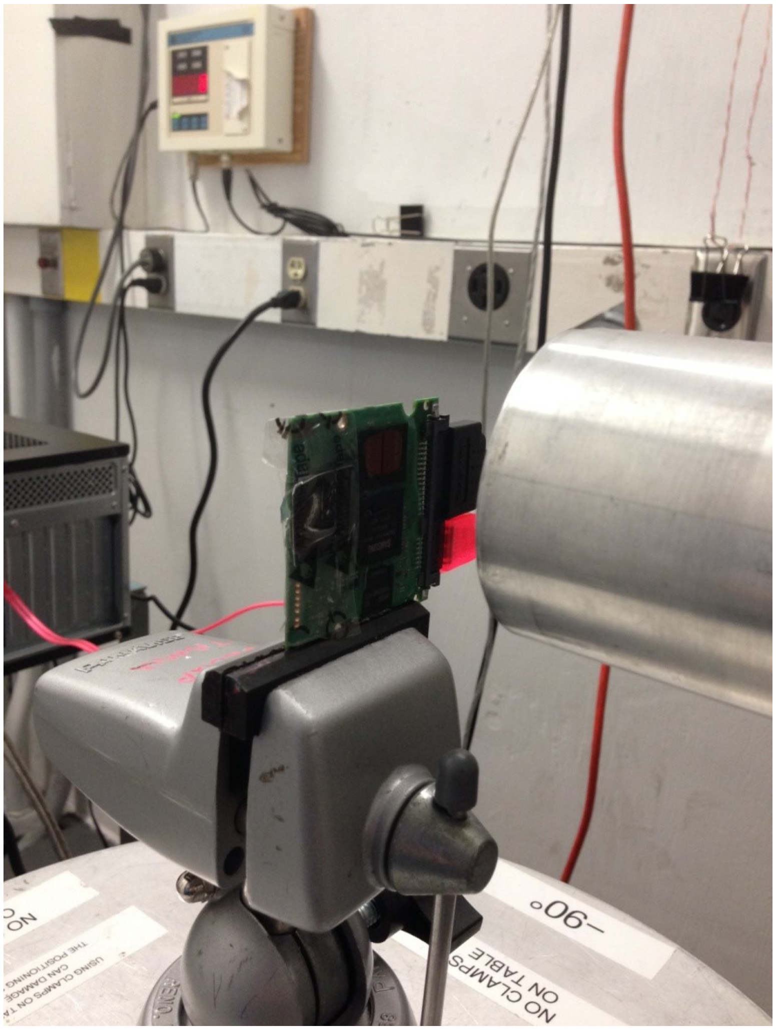

Figure 2. Photograph of the test setup at the Texas A&M University Cyclotron facility. The printed circuit board is taken directly from the SSD. The exposed die is located near the top of the board. The other etched chip (left side on the board) is covered with a lid to avoid incidental exposure.

Table III
Description of test modes.

Static test	• Write a pattern to entire memory • Beam on/off • Read with log of bad sectors, or • Read with image of entire memory
Dynamic read test	• Write to a range of sectors • Beam on • Continuously read the range of sectors with log of bad sectors, or • Continuously read with image of the target sectors • Beam off
Dynamic write/read	Similar as dynamic read
Dynamic write	Similar as dynamic read and write/read

B. Device characterization procedure

We utilized an open source software called “Caine” as the diagnostic tool to perform read and write operations to the SSD [2]. We used a 64-bit Ubuntu 14 Linux environment to run a collection of tools, including pipe viewer, 7-Zip archiver, a hash calculation tool, and “dd” (convert and copy tool), with its derivaties dcfldd, dc3dd.

The program interface also allowed us to examine the Self-Monitoring, Analysis and Reporting Technology (SMART) attributes, which includes a list of reliability parameters for the SSD.

C. Test conditions

Test Temperature:	Air ambient temperature
Operating Frequency:	Static bias: DC
	Sequential Read: 540 MB/s (max)
	Sequential Write: 530 MB/s (max)
Power Supply:	5 V
Angle:	0° (normal) to 75°
Parameters:	1) SSD supply voltage
	2) SSD supply current
	3) Bad sectors
	4) Bad bytes
	5) SMART attributes

V. Results

We observed single-event functional interrupts (SEFI) during the test. Three parts also showed permanent degradation and partial loss of functionality from the heavy ion irradiation. The run files are accessible through the attached file in the reference [3].

Figure 3 shows the SEFI cross section as a function of effective LET. The cross section data have significant Poisson error, due to the low count. We irradiated four parts with 25 MeV/amu Kr, Ar, and Ne, at various angles. The heavy ions likely penetrated multiple dies for some ion species (particularly Ne). Therefore, SEFI due to signal contention is possible. However, with that consideration, we carried out comparative runs with degraded beams, which reduced the ion penetration range, but still observed SEFIs with similar characteristics. For example, 25 MeV/amu Ar has a nominal range of 445 µm in Si, while a degraded beam has a range of 218 µm. We estimated that a degraded beam will limit the ion range to within one die, based on cross section images of the stacked-die dimensions from a Samsung 840 EVO SSD. A more thorough investigation may be necessary to precisely place the Bragg’s Peak within the stacked structure, if one desires to only evaluate single die effects.

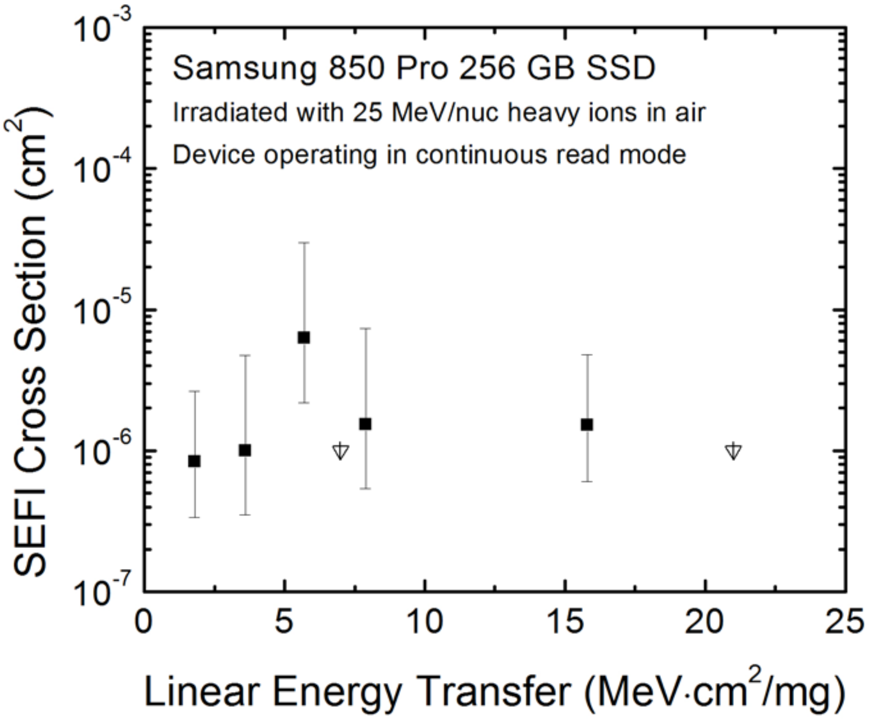

Figure 3. SEFI cross section vs. LET for the 256 GB Samsung SSD irradiated with 25 MeV/nuc heavy ions in air. Device was continuously read during irradiation. Arrows indicate maximum fluence levels without any observed error.

Table IV categorizes the functional interrupt errors according to the device response, recovery method, and test mode. We note that the errors during read/write tests occurred during the read cycle only. We did not detect write errors during the test.

Table IV
SEFIs categorized according to the test mode, event characteristics, and recovery method.

Test Mode	**Description**	**Recovery method**
Static on, Static off	SSD not responsive	Power cycle
Static on, Dynamic read	Read access errors	Power cycle, Self-cleared in one case
Dynamic read	Corrupt data errors with entire memory showing errors	Rewritten (Did not power cycle)
Dynamic read	Corrupt data errors with 8 continuous sectors showing errors	Self-cleared on next read

Static on/off tests are representative of typical application conditions for storage flash devices. All of the SEEs occurring during static mode testing caused the SSD to become nonresponsive. A power cycle was required to recover the SSD functionality following such a SEFI. Interestingly, the SEFI occurred even when the SSD is unpowered during irradiation. The stored data was unaffected from such events. We were able to successfully read the programmed data after a SEFI.

A read access error signifies an unsuccessful read operation, possibly due to input command errors. On the other hand, a corrupt data error represents an error from the memory array, due to either cell bit-flips, or corruption in the read-out buffer.

The heavy ion test results showed that the corruption errors are not necessarily caused by corrupt cells. For example, some SEEs corrupted 8 continuous sectors. These errors did not persist, but are cleared on the subsequent read. Thus, they are likely caused by SEUs in the data buffers. However, cell corruption was evident in other cases. The SMART attribute, “reallocated sector count,” indicated the number of sectors which were removed and replaced due to cell corruption. The error count increased due to SEE, even though the errors were not visible during read, since ECC detected and corrected the errant data, by replacing the bad sectors.

Both read access errors and data corruption errors affected 8 continuous sectors (4 KB) at a time. The errors repeated every 128 sectors in most cases. The trend may reflect the data organization of the SSD, which we are not yet familiar with at the time of this writing. The 256 GB SSD consists of two 8 die chips and two 4 die chips. We irradiated the 8 die chip during the test. Assuming that the controller reads 4 KB from one die at a time, once the SSD encounters a SEFI, it skips the other dies in that chip, and attempts to read from the next chip. Therefore, the total number of sectors from the other unirradiated chips should be 8×(4+4+8) = 128 sectors. Consequently, we repeatedly observed the patterns of 8 continuous bad sectors followed by 128 error-free sectors.

Three of the four irradiated samples failed functionally during the heavy ion test. The first device failed after a statically biased run with Kr. The second device showed write speed degradation prior to a SEFI, from nominal speed to 345 MB/s. Another device failed suddenly, after two error-free runs. That device continued to show read access errors after a power cycle. The degradation and functional failure were caused by a SEE in the flash memory peripheral control circuits. The second device recovered functionality after being shipped back to the GSFC laboratory. The other devices remained nonfunctional. The cause of the functional failures is unclear. The total ionizing dose received by the DUTs were relatively insignificant – 0.45, 1.8, and 3.6 krad(Si) (before recombination). We monitored the supply current of the SSD, which did not show excursions during irradiation. Although single-event gate rupture is possible, we do not have the precision for device-level access to characterize the transistor-level electrical parameters.

VI. Conclusion

We evaluated the heavy ion irradiation response of the 256 GB Samsung 850 Pro SSD, containing the VNAND flash. We targeted one flash chip at a time. SEFIs dominated the SEE response of the SSD. The SEFIs occurred down to a LET of 1.8 MeV·cm^2/mg. The SSD recovered functionality by power reset in most cases, and the errors self-cleared on the second read in other cases. Aside from SEFIs, the SMART attributes revealed possible heavy ion-induced cell corruption, which were corrected by ECC. We also found functional failures or permanent performance degradations during irradiation with each of the ions, Ne, Ar, and Kr. However, at this time, the failure mechanism is unknown.

VII. Reference

[1] Samsung corporation. (Aug. 2013). *Samsung 840 Pro Series SSD datasheet*. Available: http://www.samsung.com/global/business/semiconductor/minisite/SSD/global/download/Samsung_SSD_840_PRO_Series_Data_Sheet_rev_1_2.pdf

[2] Computer Aided INvestigative Environment (CAINE). Available: http://www.caine-live.net/

[3] Samsung 256G_TAMU_Oct2014.xls.