SEE Testing of the 4 Gb Samsung and Spansion Flash NAND

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Abstract—**Single event effect (SEE) testing was performed on the Samsung and Spansion 4 Gb NAND flash devices. Testing was performed up to LET = 41 MeV cm^2/mg. The parts were characterized for a variety of SEE. Testing and analysis showed that MBU became more prevalent at higher LET values.**

Index Terms—**SEU, single event upset, heavy ion**

I. Introduction

THE increasing demand for higher memory densities in space electronics has generated significant interest in the use of flash NAND devices on orbit [1]. However, like most semiconductor devices flash memories are susceptible to single-event effects (SEE) that arise from the creation of electron-hole pairs following energy transfer between an incident ion and the semiconductor material. These effects have been the subject of a number of different studies [2]-[5].

In this paper we report data from SEE testing of two 4 Gb flash NAND devices. The testing was performed to determine their SEE characteristics. Additionally the upset data was analyzed to determine if multiple-bit upsets within a single word were the result of a single ion corrupting multiple bits, or if they resulted from multiple, single upsets accumulating as a result of the high fluences used in testing. This is especially important to know since most NAND flash devices use some form of error correction code which may be defeated by a sufficient number of bad bits.

II. Testing

The devices under test (DUT) were 4 Gb flash NAND memories from Samsung (part number K9F4G08U0D) and Spansion (part number S34ML04G100TFI000). The Spansion devices were TSOPs that were depotted prior to irradiation, while the Samsung parts were procured as die, then wire bonded and assembled on to the test board at Maxwell Technologies. Following assembly all parts were functionally tested and operating current was recorded to ensure nominal operating conditions in the beam.

Testing was performed at the Texas A&M Cyclotron Institute Radiation Effects Facility. Various ion beams provide for a wide range of LET. The 15 MeV / nucleon beams were used for this test. All tests were performed with the beam at normal incidence and room temperature. The beam flux was varied between 1.7E3 ion/cm^2/s and 6.4E5 ion/cm^2/s. The target exposure was typically set for a total accumulated fluence 1E7 ions/cm^2, however the beam was manually stopped when SEL or SEFI were observed.

The SEE tester software runs on a laptop with PCI Express as the interface to the test board. This allows the configuration to be programmable and interface to a variety of DUTs mounted on the test board by means of daughter cards. BNC connectors on the test board enable the use of an oscilloscope to detect current transients and allow the software to record beam is on. All tests are run at room temp and utilize an "address as data" pattern where unique 32 bit values are stored every 32 bits. The device was tested in three different modes.

In the static test, the device was programmed prior to irradiation, and the pattern was verified immediately prior to irradiation. The DUT was powered on statically. That is no reads or writes were performed. The DUT was irradiated to a fluence of 1E7 ion/cm^2 and monitored for SEL. Following irradiation, the device was read again, and a final EWV performed to verify functionality.

During read-only testing, the device was programmed prior to irradiation, and the pattern was verified immediately prior to irradiation. The DUT was powered on and read continually during the test. The log file recorded the number of blocks that were read during the test. During irradiation the device was monitored to determine if a SEL / SEFI has occurred. If a SEL / SEFI had occurred, the beam was stopped. The current was recorded and an attempt was made to recover the device, first through software intervention, and eventually by cycling device power. Following irradiation, the device was read again, and a final EWV was performed to verify functionality

For erase-write-verify (EWV) testing, the DUT was powered on and a pattern was continually erased, written, and verified in each block in the device The log file recorded the number of blocks that were accessed during the test. During irradiation the device was monitored to determine if a SEL / SEFI had occurred. Following a SEL /SEFI the beam was stopped. The current was recorded and an attempt was made to recover the device to recover the device; first through software intervention, and eventually by cycling device power. Following irradiation, a final EWV is performed to verify functionality.

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III. Results

A. SEL / SEFI

The functional characteristic of SEL is an increase in the device current following irradiation that can only be removed by a power cycle. Previous testing on NAND devices has shown increases in current exceeding the typical operating levels can also be caused by contention on the data signal lines [3]. Thus clearly distinguishing between the two effects proves difficult, especially in the case of dynamic tests where the current level is constantly changing during irradiation due to the changes in function associated with a particular operating mode. For example in EWV mode, erasing, writing and reading each require a different amount of current in the part thus creating a dynamic current signature. In the case of these tests currents recorded were not out of the normal operating range for the part. In the case of static testing, the device was biased and irradiated to a fluence of 1E7 ions/cm^2. No increase in current was observed during irradiation, suggesting a SEL threshold > 40 MeV cm^2/mg.

To measure the SEL/SEFI cross sections, the beam was manually stopped when an event was observed, and the cross section was calculated as the inverse of the recorded fluence except for a few select runs where the part was power cycled, and the beam re-started allowing multiple SEFIs to be recorded on the same part during a single beam run. However, because of the time to reboot the software following a SEFI this was not the typical procedure.

In Fig. 1 the error bars represent the uncertainty due to Poisson statistics. Because of the small number of counts, the lower error bar would terminate well below the vertical minimum of the graph, so only the upper error bars are shown. In addition, the latency between the time when the event occurs and the point where the beam is shut off adds additional uncertainty to the cross section. However the uncertainty due to this latency is small compared to the Poisson fluctuations of the cross section.

Following irradiation, all tested devices were subjected to a final EWV cycle to determine their functionality. Because of the time required for this test, the devices were returned to Maxwell prior to testing. All parts operated normally during this post-beam EWV, thus indicating that under the conditions tested, there were no permanent SEFI (PSEFI). However, we note that because of the high SEFI cross section we were unable to test for PSEFI at higher fluences typically required for hardness assurance.

TABLE I
SUMMARY OF STUCK BITS FOLLOWING IRRADIATION FOR THE SPANSION DEVICE

LET (MeV cm^2/mg)	Mode	Number Of Stuck Bits	Cross Section (cm^2)
32	EWV	2	2.0E-4
40	static	5	1.0E-4
40	read	3	6.4E-5

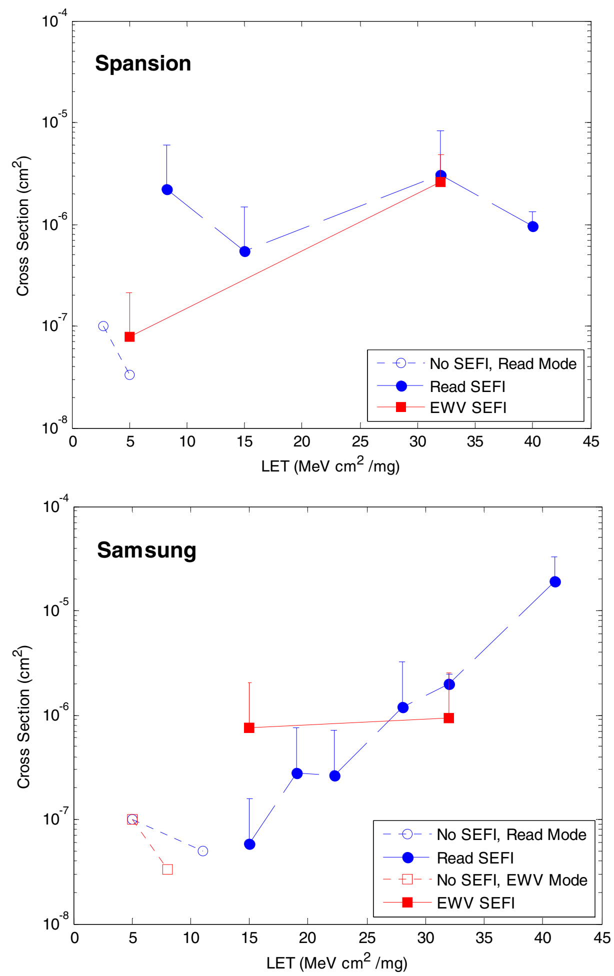

Fig. 1. Cross section as a function of LET for SEFI. For the "Read No SEFI" point, part did not SEFI during irradiation. The cross section is the upper bound, calculated as the inverse of the fluence. Absence of lower bound error bars indicates a lower bound of 0.

B. Permanent Errors

All irradiated devices were returned to Maxwell for a final EWV after the end of the beam run. Data that was corrupted after the final, post-beam EWV cycle were considered to be stuck bits. The results are summarized in Table I for the Spansion devices and in Table II for the Samsung devices.

TABLE II
SUMMARY OF STUCK BITS FOLLOWING IRRADIATION FOR THE SAMSUNG DEVICE

LET (MeV cm^2/mg)	Mode	Number Of Blocks Affected	Cross Section (cm^2/block)	Max Stuck Bits / Block
22.2	read	55	1.5E-5	82
32	read	72	8.7E-6	829440
40	static	108	1.1E-5	500008

We note that the two devices had significantly different failure modes. For the Spansion devices, only single bits per block were stuck. Thus the number of stuck bits listed in Table I is identical to the number of blocks with stuck bits. In contrast the permanent failures for the Samsung typically involved more blocks, and more bits per block (Table II).

C. Upset Testing

Fig. 2 shows the cross section for single event upsets as a function of LET. The data was collected by irradiating the devices in read-only or static mode. A final, post beam read was performed on the devices and all bits corrupted were counted as SEUs. Upsets in the device were predominantly transitions from 0 to 1. At low LET, the cross section for 0 to 1 transitions was several orders of magnitude higher than the cross section for transitions from 1 to 0 (Fig. 3). However as the LET increased to 30 MeV cm^2/mg the cross section for 1 to 0 transitions increased. In the case of the Samsung device, the 1 to 0 cross section eventually exceeded the cross section for 0 to 1 transitions.

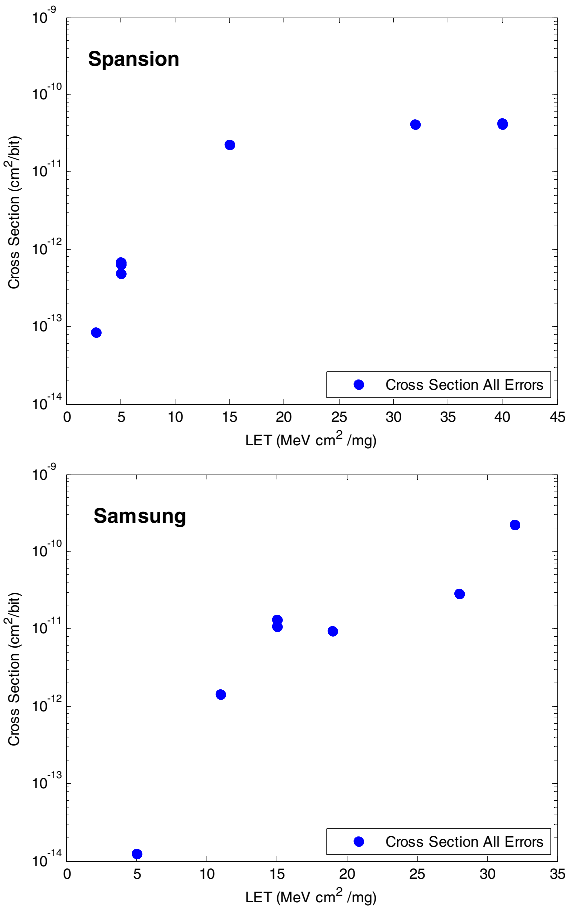

Fig. 2. Cross section as a function of LET. Data represent read-only mode irradiation.

The cross section for number of bits corrupted in a byte is plotted in Fig. 4. Single-bit upsets (SBU) are the most common, with the cross section for SBU being several orders of magnitude greater than the cross section for double-bit upsets (DBU) at low LET. At the LET = 40 MeV cm^2/mg the SBU cross section still dominates the cross section for MBUs in the Spansion device. However, for the Samsung device, the MBU cross section is nearly the same as the SBU cross section.

To analyze the MBU cross sections further, in Fig. 5 we plot the same data as in Fig. 4 but only include the cross section for SBU, DBU, and 3 bit / byte upsets (3BU). In

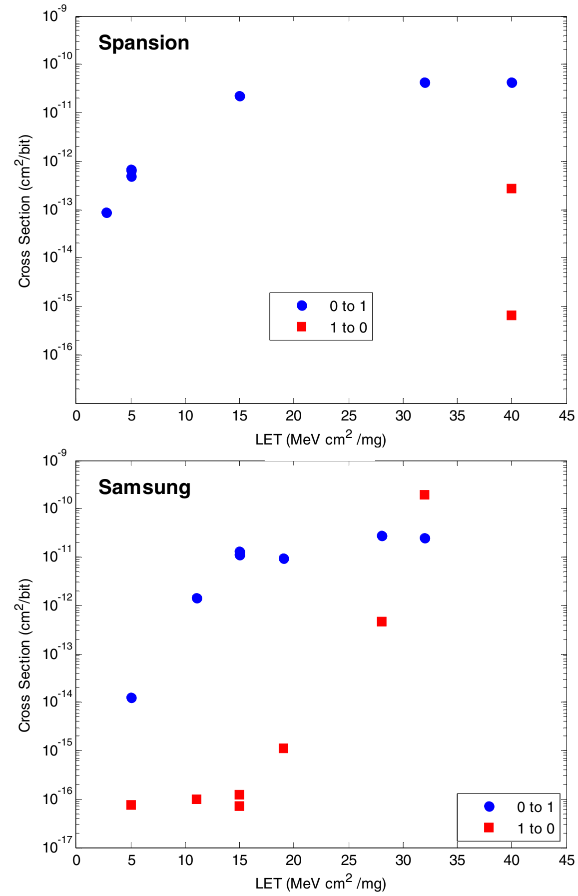

Fig. 3. Cross section for 0 to 1 and 1 to 0 errors during read-only irradiation.

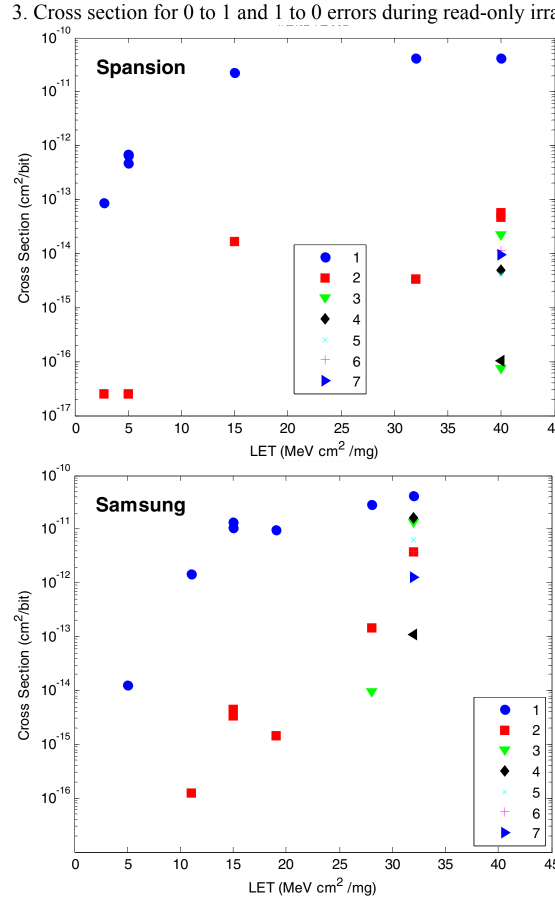

Fig. 4. Number of bits corrupted per byte during read-mode irradiation.

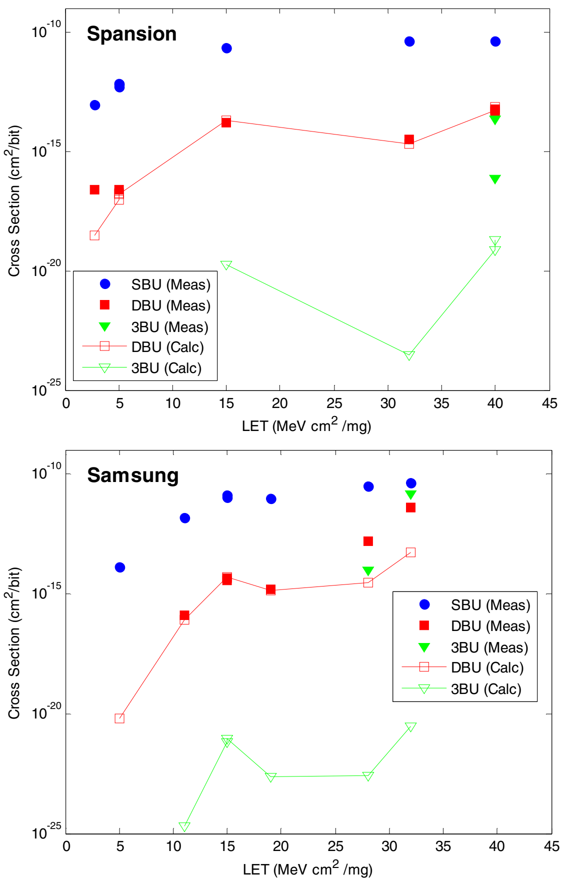

Fig. 5. Number of bits corrupted per byte following read mode irradiation (solid symbols) and the calculated cross section for MBU resulting from accumulated SBU (open symbols). Measured data is the same as in Fig. 4

addition, using the method found in [6] we calculate the expected cross sections for DBU and 3BU assuming that all multi-bit errors are the result of an accumulation of SBU, rather than resulting from a single ion corrupting multiple bits. In comparing the measured and calculated data, we note that there is fairly good agreement between the values at low LET indicating that most DBU and 3BU are the result of an accumulation of SBU. At LET = 40 MeV cm^2/mg for the Spansion device and LET= 28 MeV cm^2/mg for the Samsung device, we see the measured cross section for DBU and 3BU exceeds the calculated cross section for an accumulation of SBU. Thus indicating that the MBU cross section is dominated by a single ion corrupting multiple bits at these LET.

IV. Conclusion

Single event effect testing was performed on Spansion and Samsung 4Gb flash devices from LET= 2.7 MeV cm^2/mg up to LET = 41 MeV cm^2/mg. During irradiation no SEL or permanent SEFI, were observed. All SEFI observed could be cleared by a power cycle. The Spansion device had a lower threshold for SEFI however, the Samsung was more susceptible to stuck bits. In both devices, most upsets recorded corrupted single bits, however some higher order MBU were measured at higher LET.

Acknowledgment

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