

Comparison of TID Response and SEE Characterization of Single and Multi Level High Density NAND Flash Memories

Farokh Irom, Duc N. Nguyen, Reno Harboe-Sørensen and Ari Virtanen

Abstract— Heavy ion single-event measurements and TID response for 8Gb commercial NAND flash memories are reported. Radiation results of multi-level flash technology are compared with results from single-level flash technology. In general, these commercial high density memories appear to be much less susceptible to SEE and have better TID response compared to older generations of flash memories. The charge pump survived up to 600 krad.

Index Terms—nonvolatile memory, NAND flash, floating gate, single event effects, single event upset, total ionizing dose, gamma rays, x-ray

I. INTRODUCTION

In recent years there has been increased interest in the possible use of high density commercial nonvolatile flash memories in space because of their high density capabilities and non-volatile data. They are used in a wide variety of spacecraft subsystems. At one end of the spectrum, flash memories are used to store small amounts of mission critical data such as boot code or configuration files, and at the other end they are used to construct multi-gigabyte data recorders that record mission data.

Flash memory cells are not as sensitive to data loss, or bit upsets induced by single event effects (SEE), compared to those experienced by SRAMs and DRAMs. Information on floating gates (FGs) is embedded by the presence or absence of trapped charge on an electrically isolated conductor.

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Nevertheless, flash memories are susceptible to upset and degradation from radiation and more information is needed on their radiation characteristic before they can be used in space.

Flash memories have been the subject of several ionizing radiation effects studies in recent years, regarding both total ionizing dose (TID) [1-3] and SEE [4-9] experiments. In both cases, the complex control circuitry has been demonstrated to be the most vulnerable part of commercial devices. However, the degradation of the threshold voltage, V_{TH} of the single cell in the floating gate array after exposure to ionizing radiation is a non-negligible issue, as it may lead to the corruption of the stored code. Also, different functional failures have been detected in some commercial devices depending on the mode of operation during radiation exposure [5,6]. The functionality of flash memories begins to fail as TID accumulates during a space mission. In addition, direct strikes from galactic cosmic rays (GCR) and protons from a solar flare can upset internal circuitry associated with structures such as the charge pump, state buffers, cache, or internal microcontrollers, as well as FG arrays. These upsets can result in incorrect read/write operation or even cause the device not to function until it is power cycled, reinitializing all the internal circuitry.

At present, the industry trend is to continue with feature size scaling. In advanced flash memories one would expect the single event upset (SEU) cross section per bit to become smaller with shrinking feature sizes [2]. Also, decreasing feature size improves the possibility of increase in the density. Furthermore, the SEU cross section for the FG arrays is becoming comparable to, if not larger, than that of the control logic. The SEU cross section can be dominated by either the FG array or the control logic, depending on the particular application [4]. Also, because of thinner oxide layers, the total dose response is improved [2].

High density commercial nonvolatile flash memories with the NAND architecture are now available from different manufacturers. This paper examines SEE effects and TID response in multi-level cell (MLC) and single-level cell (SLC) 8Gb Samsung NAND flash memories. Also, we report TID response in SLC 8Gb Micron Technology NAND flash memory.

II. DEVICE DESCRIPTION

In this work we study commercial MLC and SLC 8Gb NAND flash memory manufactured by Samsung. Also, we study Micron Technology SLC 8Gb NAND flash memory.

These parts are built on a 51 nm process. The Samsung MLC part number is K9G8G08U0A and the Samsung SLC part number is K9F8G08U0M. The Micron Technology SLC part number is MT29F8G08AA. In general, the 8Gb Samsung NAND flash memories is a 8,448 Mb (8,858,370,048 bit). A NAND structure consists of 32 cells. For MLC devices a cell has 2-bit data, and 1,081,344 NAND cells reside in a block. For SLC devices a cell has 1-bit data, and 2,162,688 NAND cells reside in a block. The program and read operations are executed on a page basis, while the erase operation is executed on a block.

III. EXPERIMENTAL PROCEDURE

A) *SEE measurements*

Heavy ion SEU measurements were performed at two facilities. The SEU Test Facility located at the Brookhaven National Laboratory (BNL) and the cyclotron facility at Jyväskylä, Finland (RADEF). Both facilities provide a variety of ion beams over a range of energies for testing. Ion beams used in our measurements are listed in Table I for BNL and Table II for RADEF. LET and range values are for normal incident ions. At both BNL and RADEF, test boards containing the device under test (DUT) were mounted to the facilities test frame. Tests at BNL were done in vacuum with normal incident beam. Tests at RADEF were done in air with normal incident beam. The beam flux ranged from 1×10^3 to 1×10^5 ions/cm²sec. The radiation measurements for Samsung MLC and Micron Technology SLC devices were done at BNL facility and for Samsung SLC devices were done at RADEF facility. Also, for comparison purposes we repeated the measurements on Samsung MLC devices at RADEF.

The DUTs were etched to remove the plastic packaging and expose them to the ion beam. The SEE data for NAND flash memories at BNL and RADEF were taken using a commercial memory tester called JDI. The JDI tester is fully capable of performing high speed testing on memory systems. The DUT was powered with an HP6629 power supply.

All tests at BNL and RADEF were conducted by first loading the DUT with a random pattern and then verifying the pattern by reading it back from the device. During irradiation, the DUT was read continuously and checked for errors and logged. After the irradiation, the pattern was again verified and the device's power was cycled and the pattern was erased to make the device ready for the next run.

TABLE 1. List of the ion beams used in our SEE measurements at the BNL facility.

Ion	LET (MeV-cm ² /mg)	Range (μm)
¹⁹ F	3.4	120
²⁸ Si	8.0	74
⁴⁸ Ti	19.8	40
⁹ Br	37.3	36
¹⁰⁷ Ag	52.9	31
¹²⁷ I	59.7	31

TABLE II. List of the ion beams used in our SEE measurements at the RADEF facility.

Ion	LET (MeV-cm ² /mg)	Range (μm)
²⁰ Ne	4.0	146
⁴⁰ Ar	11.4	118
⁵⁶ Fe	20.7	97
⁸² Kr	35.2	94

B) *TID measurements*

Total dose measurements were done using the JPL Co-60 facility at a dose rate of 50 rad (SiO₂) per second at room temperature. Also, total dose measurements were performed using a 20keV x-ray source at the Air Force Research Laboratory (AFRL), with a dose rate of 100 rad/s (SiO₂). In all measurements the DUTs were under static biased during irradiation, but not actively exercised, because this corresponds to the actual operating condition during most of an extended space mission. TID measurements were performed in following two modes:

1. *EPR or Refresh Mode:*

- a. Erase, write, and read to validate programmed numbers.
- b. Irradiate DUTs with static biased.
- c. Read numbers to ensure data retention.
- d. Repeat a to c for each radiation increment.

2. *Read Only or No Refresh Mode:*

- a. Erase, write, and read to validate programmed numbers.
- b. Irradiate DUTs with static biased.
- c. Read numbers to ensure data retention.
- d. Repeat b to c for each radiation increment.

IV. SEE TEST RESULTS

Two types of radiation induced events were measured while performing read operations during irradiation: SEU and single event functional interrupt (SEFI).

A) *SEUs*

In Fig. 1, we show the SEU cross sections for the Samsung MLC and SLC 8Gb NAND flash memories. The error bars are ~ 2 sigma and result from Poisson statistics. For the data points where statistical error bars are not shown, they are smaller than the size of the plotting symbols. For comparison we display results of our measurements for Samsung MLC device at both BNL and RADEF facilities. There is excellent agreement between the two measurements. It is not surprising that the SLC devices are less sensitive to SEUs than MLC devices. This can be attributed to the fact that the voltage threshold V_{TH} changes are smaller in a MLC device. In general, this commercial high density device appears to be much less susceptible to SEUs than typical flash devices that have been tested recently [1,7,8,9]. The SEU cross section per bit for MLC and SLC devices are on the

order of 5×10^{-10} and 5×10^{-11} cm^2/bit , respectively. The GCR rate for MLC devices is about 1.0×10^{-9} events per bit per year (Worst case). The rate from solar flare is about 2.0×10^{-6} per bit per flare (Worst case) [10]. These low upset rates can be easily handled by the most rudimentary error detection and correction systems.

B) SEFIs

In Fig. 2, we show the SEFI cross section for Samsung 8Gb MLC and SLC NAND flash memory. The error bars are ~ 2 sigma and result from Poisson statistics. For comparison we display results of our measurements for MLC devices at both BNL and RADEF facilities. There is excellent agreement between the two measurements. The SEFI LET threshold is below $12 \text{ MeV}\cdot\text{cm}^2/\text{mg}$. The GCR rate for MLC devices is about 2.0×10^{-4} events per device per year (Worst case). The rate from solar flare is about 0.35 per device per flare (Worst case) [10]. An analysis of SEFIs was complicated because the signature, recovery mechanism, and consequence to the device operation varied greatly, depending upon exactly how the device functionality was altered. Typical SEFI events resulted in a large number of errors while trying to read the device. Some events will self-recover once the device is re-read. Other SEFIs require a power cycle and the part to be re-initialized to return to normal operations.

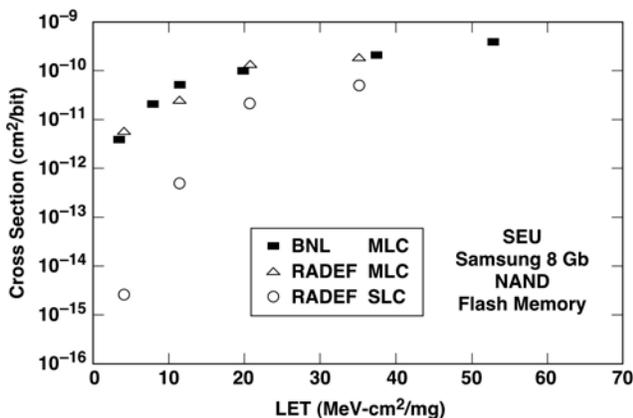


Fig. 1. SEU cross section for Samsung 8Gb MLC and SLC NAND flash memories. Measurements were performed at the BNL and RADEF facilities.

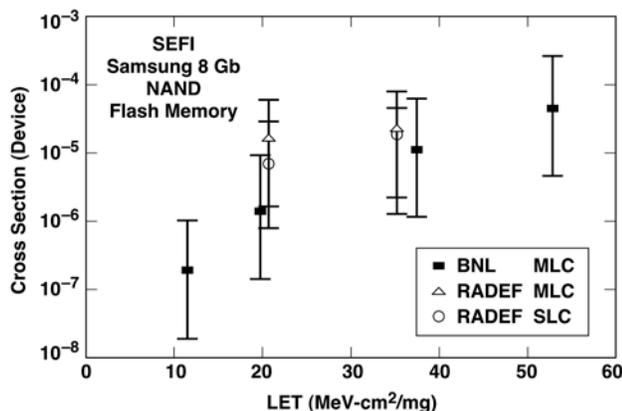


Fig. 2. SEFI cross section for Samsung 8Gb MLC and SLC NAND flash memories. Measurements were performed at the BNL and RADEF facilities.

V. TID TEST RESULTS

TID measurements were performed with programming the DUTs with two different patterns: sequential numbers or all zeros. For each pattern TID measurements were performed in Refresh and No Refresh mode.

A. Sequential Numbers Pattern

TID measurements were performed only on Samsung MLC parts in two modes: Refresh Mode (Erase/Program/Read) and No Refresh Mode (read only). The sample size for these measurements was three.

1 Refresh Mode

In Refresh Mode we irradiated three parts at 10, 20, 30, 50, 75, and 100 krad (SiO_2). All three devices only had a few read errors. Two fresh parts were irradiated at different doses: 125, 175, 200, and 225 krad (SiO_2). Both of the devices function and only one had 3,035 read errors out of 8 billion bits.

2 No Refresh Mode

In No Refresh Mode the DUTs were subjected only to read after irradiation. Three parts were irradiated up to 40 krad. Table III summarizes the TID results, and Fig. 3 displays the percentage of erroneous bits versus the dose. At 40 krad the error percentage is about 1. After 12 hours annealing at room temperature, all three parts were erased, programmed, and read to verify functionality. All three perform normally, and they have the following number of read errors: 13, 11, and 11, respectively.

Table III. Summary of TID results for Samsung 8Gb MLC NAND flash memory.

TID (Krad)	Errors (Sample #1)	Errors (Sample #2)	Errors (Sample #3)
10	8	9	5
20	908	8151	1868
30	498,486	269,831	757,053
40	23,602,768	85,978,925	95,856,256

B. All Zeros Pattern

The DUTs were programmed in all zeros. We performed Co-60 irradiations in Refresh and No Refresh Modes. The sample size for these measurements was three.

1 Refresh Mode

In Refresh Mode the Samsung 8Gb SLC failed to erase after 250 krad, compared to the Micron technology 8Gb SLC after 35 krad. Surprisingly, the Samsung 8Gb MLC still can be erased after 600 krad.

2 No Refresh Mode

In No Refresh Mode Co-60 irradiations were performed on Samsung MLC and SLC and Micron Technology SLC devices up to 600 krad. Also, x-ray irradiations were performed only on three de-lidded Samsung MLC devices up to 350 krad. The results are discussed below.

Fig. 4 shows the buildup of read errors during TID exposure of the DUTs that have been programmed to all zeros prior to irradiation. For Samsung MLC devices, the error number increases monotonically and saturates around 100 krad to half of the number of bits. After 100 krad almost half of the bits are read as a one and the charge pump still works properly. As a matter of fact, the charge pump was functional up to the level of 600 krad to which the DUTs were irradiated confirming that the charge pump still functions properly. For Samsung SLC devices the error number is negligible up to 200 krad and increases monotonically and saturates around 500 krad to all of the number of bits exposed to radiation. For Micron Technology 8Gb SLC devices the error number is negligible up to 100 krad and increases monotonically to 250 krad. The charge pump is not functional after 250 krad.

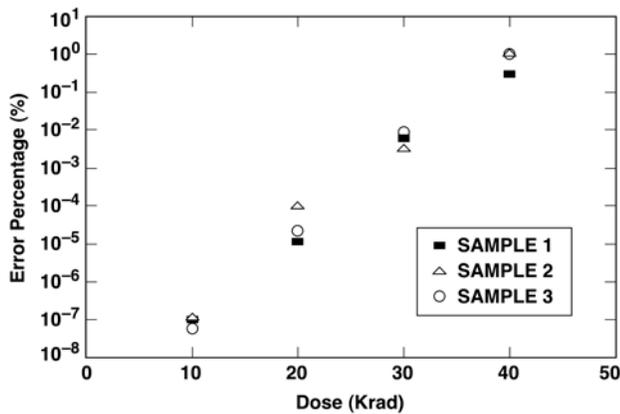


Fig. 3. Percentage of data errors versus dose for 8Gb MLC Samsung NAND flash.

Also, the Samsung MLC parts that have been programmed to all ones prior to irradiation did not show errors in an excessive way. There are few errors which are contributed to errors from circuitry and buffer regions and not from cells.

In the case of Co-60 irradiation we observed read errors starting around 50 krad (SiO_2). For x-ray irradiation the threshold was around 10 krad (SiO_2). These errors are caused when the V_{TH} of a programmed (zero) floating gate changes enough to shift from the programmed to the erased cell (one) distribution, and being read as an erased cell in read mode. As a result, the first cells to flip are those programmed at the lowest V_{TH} . While variations in V_{TH} occur below TID threshold, they may be too small to be detectable in read mode [11].

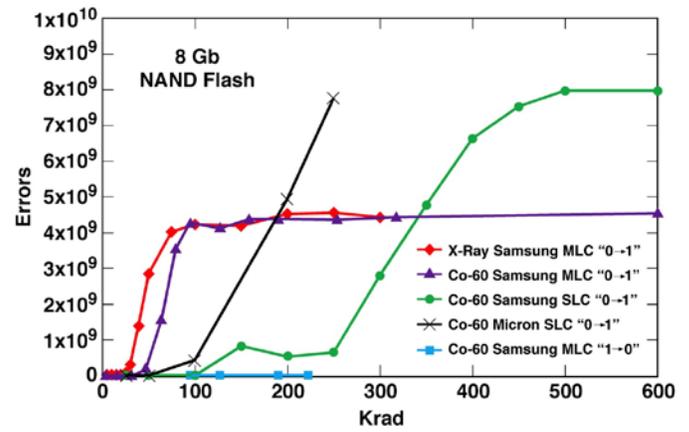


Fig. 4. Comparison of TID measurements of MLC and SLC devices with Co-60 and x-ray.

The Samsung MLC part shows more sensitivity to x-ray irradiation than Co-60. It has been shown that floating gates are more sensitive to x-ray than to γ -rays (Co-60 irradiation). This is likely due to dose enhancement effects [12].

Figs. 5 and 6 compare threshold voltage distribution and illustrate the comparative differences between MLC and SLC NAND flash cells, respectively. SLC NAND stores two binary states (either a binary 1 or a binary 0) in a single cell, whereas MLC NAND can store four states: 00, 01, 10, and 11. To recognize the four states "11", "10", "01", and "00", special circuitry must be added to allow the amount of charge stored in the floating gate to be controlled within narrow limits during the writing, and also to detect the different amounts of charge during reading. The programming circuits must deliver precise amounts of electrons to the floating gate, and the sense amps must distinguish between the four small threshold voltage regimes. There is considerably more design margin with SLC, which leads to greater radiation robustness, reliability, and endurance compared to MLC. Before irradiation, the V_{TH} distribution almost resembles the expected Gaussian shape. However, after irradiation, the threshold voltage of all floating gates programmed in the zero state uniformly moves toward lower V_{TH} . On the other hand, the threshold voltage of all floating gates programmed in the one state uniformly moves toward higher V_{TH} [13].

In Fig. 4, it is not surprising that at saturation only about half of the bits are read as a one for MLC devices. This might be contributed to a reduction in the voltage generated from the dedicated read charge pump circuitry. If the voltage generated by the read charge pump is lower than the designed value, all the cells belonging to the same string of 32 floating gates will be read as zero regardless of their actual status.

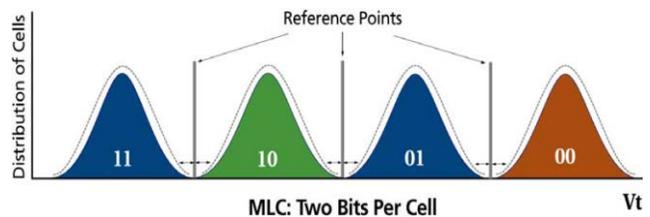


Fig. 5. Multi-level Flash Cells. The x-axis is cell threshold voltage.

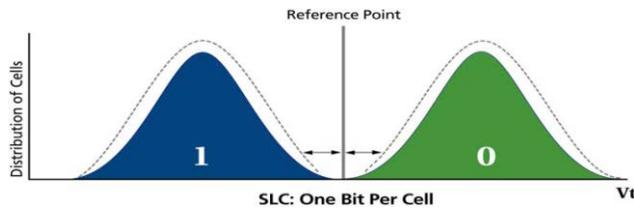


Fig. 6. Single-level Flash Cells. The x-axis is cell threshold voltage.

VI. DISCUSSION

Interpretation of radiation tests in the new generation of flash memories is difficult because of the very involved architecture and internal circuitry. In new advanced flash memory technology, the cells are n-channel transistors, where the floating gate is filled with electrons in the zero state, and empty of electrons in the one state. Since the effect of radiation is to introduce positive charges into the oxide, radiation tends to turn zeros into ones, but not the reverse. In the heavy ion tests, all the single bit errors in the floating gates are zeros-to-one errors. Upset in flash memories also occurred in the microcontroller, buffer and register regions, causing complex errors at the block level as well as address errors [1, 4, 5]. The radiation tests in the present study were more limited in scope and concentrated on determining whether the same general types of functional errors occurred in newer high density flash memories as well as investigating the possibility of destructive failures. SEU in the newer high density devices appears to be similar to that in the older technology. Functional failures caused by cell upset in the very complex control and state registers used in flash memory architecture continue to occur [6]. It is likely that page/block SEFI type of errors arise due to upsets in configuration registers in the memory array rather than upsets of the individual bits.

VII. CONCLUSION

We tested the advanced commercial high density 8Gb NAND flash memory from Samsung with heavy ions. The general conclusion is that the SEU per bit and SEFI cross sections in this study are smaller than the older generation of flash memories. Furthermore, The SLC devices are less sensitive to SEUs than MLC devices. We also investigated the TID response of 8Gb Samsung and Micron Technology NAND flash memories with x-ray and γ -ray irradiation. The parts were irradiated up to 600 krad and the charge pump was still functional at high dose levels. This is an improvement compared to the older generation of flash memories. Our TID results showed that the threshold voltage shift in irradiated devices depends on the radiation source. Dose enhancement phenomena were observed after x-ray irradiation.

More work needs to be done to increase the level of understanding as well as how it may affect highly scaled commercial devices.

VIII. ACKNOWLEDGMENT

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