Single Event Effect Measurements of Micron Technology 128Gb Single-Level NAND Flash Memory

Farokh Irom, Gregory R. Allen

***Abstract*— Heavy ion single-event measurements on 128Gb Micron Technology single-level NAND flash memory are reported. Two single event effect (SEE) phenomena were investigated: single bit upsets (SBUs) and single effect functional interrupts (SEFIs).**

***Index Terms*—**

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 data retention. 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 and science data.

Because of flash memories' complex structure, they can't be treated as just simple memories. Thus, it becomes quite challenging to determine how they will respond in radiation environments. The most radiation-sensitive part of flash memories is the complex circuitry external to the floating gate (FG) cell array. Different functional failures have been detected in some commercial devices depending on the mode of operation during radiation exposure [1-2]. The functionality of flash memories begins to fail as total ionizing dose (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. These upsets can result in incorrect READ/PROGRAM 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 (SBU) per bit cross section to scale down with shrinking feature sizes [3]. Decreasing feature size leads to increased device capacity. Furthermore, the SBU cross section for the FG arrays is becoming comparable to, if not larger than, that of the control logic. The SBU cross section can be dominated by either the FG array or the control logic, depending on the particular application [4-6]. Also, because of thinner oxide layers, the total dose response is improved [3].

High-density commercial nonvolatile flash memories are now available from different manufacturers. This report examines SBUs and SEFIs in single-level cell (SLC) 128Gb Micron Technology NAND flash memories.

II. DEVICE DESCRIPTION

This report examines commercial SLC 128Gb NAND flash memory manufactured by Micron technology. The Micron Technology SLC 128Gb part number is MT29F128G08CJAAA and the date code is 1852. It is built by stacking of 4 Micron Technology 32Gb SLC NAD flash memory. The part number is MT29F32G08ABAAA. The 32Gb NAND flash memory is built on a 25 nm process. In general, the 32Gb Micron Technology NAND flash memories is a 36,238,786,560 bit device. A NAND structure consists of 32 cells. For SLC devices, a cell has 1-bit data, and 1,081,344 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. Test Facilities

Heavy ion SEE measurements were performed at the

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cyclotron facility at Texas A&M University (TAMU). This facility provides a variety of ion beams over a range of energies for testing. Ion beams used in the measurements are listed in Table I. LET and range values are for normal incident ions. Tests were done in air. The devices under test (DUTs) were etched to remove the plastic packaging and expose them to the ion beam. The ranges and LETs listed in the table apply after the particles have penetrated the 3 cm of air. Test boards containing the device under test (DUT) were mounted to the facilities test frame. The beam flux ranged from 2×10^2 to 5×10^3 ions/cm^{2}sec.

TABLE I
LIST OF THE ION BEAMS USED IN OUR SEE MEASUREMENTS AT TAMU.

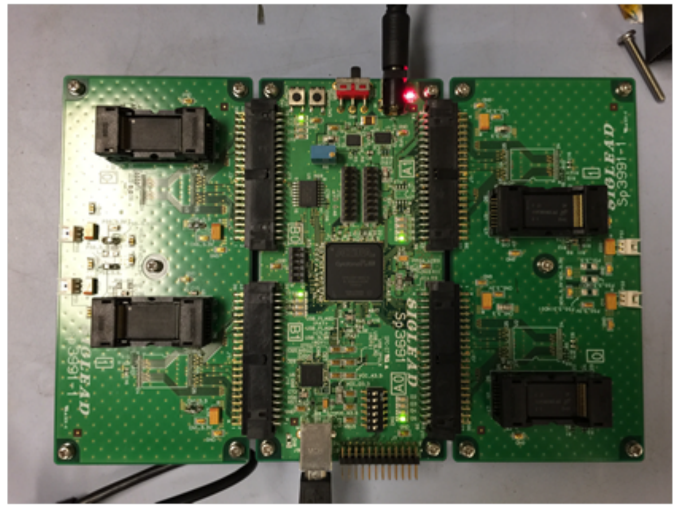
Ion	LET (MeV-cm2/mg)	Range (µm)
^{4}He	0.1	1386
^{14}N	1.3	392
^{20}Ne	2.7	279
^{40}Ar	8.3	192
^{63}Cu	19.6	136
^{129}Xe	51.5	120
^{165}Ho	71.3	114
^{181}Ta	78.2	113

B. *Experimental Methods*

The DUTs were etched to remove the plastic packaging and expose them to the ion beam. For all SEE measurements, the single bit upset (SBU) and single effect functional interrupts (SEFI) measurements were taken using a commercial memory tester called SIGNAS-II. The SIGNAS-II consists of a motherboard with an FPGA (Altera Cyclone III); a daughter board with TSOP socket for NAND; and Windows-based analysis software. The maximum operating frequency of the SIGNAS-II is 20MHz cycle time, which is the operating frequency used during the measurements. During the heavy ion and proton SEE measurements, Vcc was set to 3.3 V. The electron SEE measurements were done while DUTs were unbiased.

The majority of the SEE tests were conducted by first loading all 8Gb of the DUT with an all “0” pattern (which puts the FGs in a charged state) and then verifying the pattern by reading it back from the device. The complete READ cycle for the Micron 32Gb SLC devices is around 5 minutes. During irradiation, all 32Gb of the DUT were dynamically operated in READ mode. After irradiation and the completion of the final READ cycle that was started during irradiation, the device’s power was cycled, the DUT was read again, checked for errors, and logged. This final check after a power cycle reveals errors that are from bit upsets in the floating gates. Some heavy ion measurements were performed while the DUT was dynamically read, erased and programmed during irradiation. Other measurements were performed while the DUT was in static mode during irradiation. A limited number of dynamic read measurements were performed on the DUT that were programed with a pseudo random pattern prior to irradiation with heavy ion and proton beams.

In general, occurrence of a typical SEFI event results in a large number of errors and a spike in the device current. 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 operation. For SEFI measurements, the DUT current was monitored during the irradiation, and the beam was stopped after a sharp spike in the current, which is a signature of a SEFI event. Typical current during irradiation is 2 mA. The occurrence of SEFI increased the current to 25-40 mA.



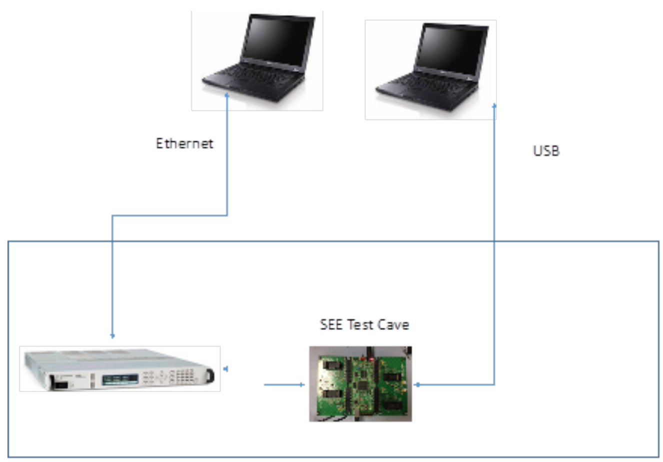


Fig. 1. Test board (top) and test setup (bottom).

IV. TEST RESULTS

Two types of radiation-induced events were measured while performing read operations during irradiation: SBU and SEFI. The sample size for these measurements was three.

A. *SBUs*

Fig. 1 shows the FG SBU cross sections for the Micron SLC 32Gb NAND flash memory. The error bars in Fig. 2 are smaller than the size of the plotting symbols. For comparison, the figure includes results of the measurements for the Micron SLC previously tested at TAMU. The two measurements show excellent agreement.

The SBU LET threshold is below 0.105 MeV-cm2/mg. The saturation SBU cross section per bit for the SLC device is on the order of 2.9×10^{-10} cm^2/bit, which is the approximate physical area of an FG. The SBU cross-section is the same for both static and either type (read mode or read/erase/program mode) of dynamic measurements.

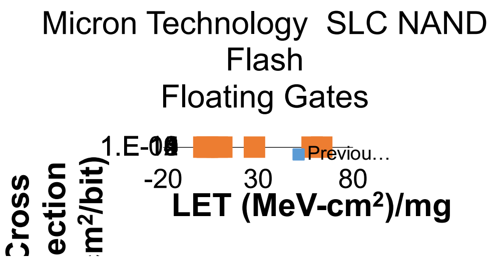


Fig. 2. SBU cross section for Micron 32Gb SLC NAND flash memory.

An SBU rate calculation has been performed to estimate the probability of occurrence of FG bit flip in READ mode for GCR interplanetary space environment. Based on this calculation, the rate is 7.2×10^{-7} per bit per year. The rate for the worst week CREME96 model flare is equal to 3.8×10^{-6} per bit per flare. Details of these calculations are presented in Appendix A.

Fig. 3 shows the SEFI cross section for Micron 32Gb SLC NAND flash memory. The error bars are ~2 sigma (95%) and result from Poisson statistics. For comparison, this figure includes results from previous measurements of the SLC at the TAMU facility. The two measurements show agreement to within the error bars. SEFIs were observed at a LET of 3.2 MeV-cm^2/mg, but no SEFIs were observed at a LET of 2.7 MeV-cm2/mg at a fluence of 1×10^7. The SEFI LET threshold is between 2.7 and 3.2 MeV-cm^2/mg. 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. 3 presents SEFIs cross sections for the Micron SLC 32Gb NAND flash memory During SEFI measurements, the beam was stopped immediately after occurrence of the first SEFI. Because it was unclear exactly how much beam was delivered to the device before the SEFI occurred, we estimate 10% error in the fluence measurement of each SEFI and this error was included in the error bars.

An SEFI rate calculation has been performed to estimate the probability of occurrence of a SEFI for Pysche environment. Based on this calculation, the rate is 0.037 per year per device GCR interplanetary space environment. The rate for the worst week CREME96 model flare is equal to 0.29 per flare. Details of these calculations are presented in Appendix A.

During the heavy ion measurements, we have noticed failure to program some of the blocks in the flash memory after exposing the DUT to certain amount of ions fluence. For higher LETs the amount of fluence is less than lower LETs. We have calculated the block failure cross section σ_{Block} by the dividing the number of block program fails to fluence multiply the number of exercised blocks.

$$\sigma_{Block} = \text{\# block program fails} / (\text{fluence} . \text{\#exercised blocks})$$

The σ_{device} can be obtained by σ_{Block} times the number of blocks in each device. The rate for failure of one block to program in each device is 3.6×10^{-2} per day.

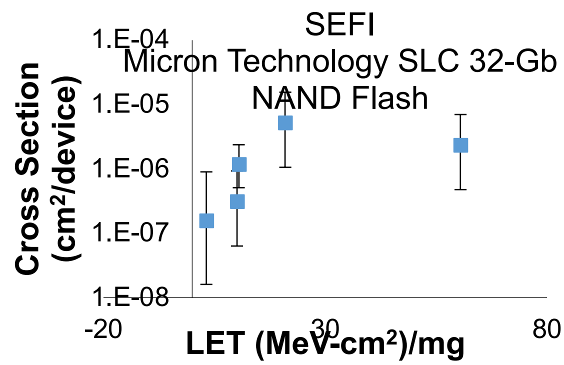


Fig. 3. SEFI cross section for Micron 32Gb SLC NAND flash memory.

V. DISCUSSION AND CONCLUSION

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]. SBU in the newer high-density devices appears to be similar to that in the older technology. 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.

Our heavy ion measurements showed failure of blocks to program. In order to prevent this issue we recommend performing ERASE/PROGRAM function very often during the mission. A conservative estimate is to scrub the flash memories every month to prevent the block program failure.

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APPENDIX A

The Micron Technology 32Gb single-level NAND flash memory was found to be susceptible to SBU and SEFI. In this Appendix we calculates the rates for these events in the environments relevant to GCR in interplanetary space while assuming a spacecraft shielding equivalent to 100 mils of aluminum. If the mission is unlucky, it might also encounter a solar particle event (loosely called "solar flare" here). A flare may or may not be encountered. The CERME96 Model Solar Flare (protons and heavy ions) in interplanetary space is used to calculate the solar flares. The model is evaluated at 1 AU.

Three different descriptions characterize the same solar event in the CREME96 model; peak flux (a.k.a., worst 5-minutes), worst day, and worst week. The worst-day flux is a time average over the worst day, and the worst-week flux is a time average over the worst week (actually, 7.5 days). The peak flux represents the peak in the solar flare in interplanetary space. The "stormy" magnetic field option was selected because the flare not only supplies particles that can cause SBU and SEFI, it can also interfere with the magnetic field in such a way as to reduce the magnetic protection.

Unlike GCR, the abundance of protons compared to heavy ions in a solar flare is large enough for protons to be important. Hence, protons and heavy ions are both included. The number of upsets accumulated over the duration of the flare, if the mission is unlucky enough to encounter a flare of the CREME96 variety, is calculated by multiplying the worst-week rate by 7.5 days.

Heavy-ion SBU and SEFI data are plotted in the Figs. 3-4, which also includes fitting curves. The fitting parameters are listed in Table II. Heavy-ion rate estimates require a model describing the directional dependence of device susceptibility. This dependence is rarely measured, so two models are typically used to produce two rate estimates. One is the "Best Estimate Model", which is probably close to reality but is not guaranteed. The other is the "Worst Case Model", which is recommended for design purposes.

The environments considered include solar flare protons. We do not have proton cross section data for SBU or SEFI for this part, so the method in [7] was used to estimate proton cross sections from the heavy-ion parameters. The last column in Table II lists the estimated proton cross sections. These cross sections were calculated for 200MeV protons. A slightly conservative integration with environmental data is obtained by using the 200 MeV cross section for all protons having energies greater than 7 MeV at the part location. Proton susceptibility is taken to be isotropic. Past experience indicates that the model in [7] tends to be conservative for SEFI. Furthermore, the SBU mechanism for flash devices is different than assumed by the model, so it is likely that the model is inaccurate for SBU in this device. However, this is the best that can be done at this time. If the calculated solar flare proton rates are excessively conservative, the heavy-ion rates still remain and the end result is not greatly affected by this conservatism.

TABLE II:
HEAVY-ION DATA (EXPONENTIAL PARAMETERS) AND PROTON CROSS SECTIONS (200 MEV) FOR THE 32GB MICRON NAND FLASH MEMORY.

Mode	Heavy-Ion Fitting Parameters From Test Data		Estimated σproton
	$L_{1/e}$ (MeV-cm^2/mg)	σsat	
SBU	1.25	2.7x10^{-10} cm^2/bit	1.5x10^{-16} cm^2/bit
SEFI		2.4x10^{-6} cm^2/device	6.1x10^{-12} cm^2/device

Rate estimates using the Best Estimate directional model (which is not recommended for design purposes) are listed in Table III, while rate estimates using the Worst Case directional model (which is recommended for design purposes) are listed in Table IV. The "per-year" units for GCR refer to Earth years. As a reminder, the calculated proton contribution to the flare rate is likely to be conservative. It is possible that the actual proton contribution is very small, in which case the flare rate reduces to the heavy-ion contribution.

TABLE II: RATES CALCULATED USING THE **BEST ESTIMATE** MODEL FOR DIRECTIONAL EFFECTS

Environment		SBU rate per bit	SEFI rate per device
Inter. Space (100 mils, 1AU)	GCR (solar min.)	2.3x10^{-7}/year	0.031/year
	Flare Heavy Ions	1.2X10^{-6}/flare	0.12/flare
	Flare Protons	1.7x10^{-6}/flare	0.07/flare
	Flare Total*	2.9x10^{-6}/flare	0.19/flare

TABLE III: RATES CALCULATED USING THE **WORST CASE** MODEL FOR DIRECTIONAL EFFECTS

Environment		SBU rate per bit	SEFI rate per device
Inter. Space (100 mils, 1AU)	GCR (solar min.)	7.2x10^{-7}/year	0.037/year
	Flare Heavy Ions	2.1x10^{-6}/flare	0.22/flare
	Flare Protons	1.7x10^{-6}/flare	0.07/flare
	Flare Total*	3.8x10^{-6}/flare	0.29/flare