Università di Padova - Dipartimento di Ingegneria dell'Informazione,
via Gradenigo 6/b 35131 Padova (Italy)
Tel. +39.049.827.7600
Fax +39.049.827.7699

Destructive SEE Report on Micron MT29F32G08ABAAA Single-Level-Cell NAND Flash Memory

Authors: Marta Bagatin, Simone Gerardin, Alessandro Paccagnella, Università di Padova

The work described in this report was done under
ESA Contract 2011-2012 RFQ3-13074/10/NL/PA CCN1
“Studies of radiation effects in new generation of non-volatile memories”

Technical officer: Véronique Ferlet-Cavrois

Date: October 2014

TABLE OF CONTENTS

FIGURES

TABLES

1 Introduction

Under Contract Change Notice 1 to ESA Contract 2011-2012 RFQ3-13074/10/NL/PA “Studies of Radiation Effects in New Generation of Non-volatile Memories”, we investigated the occurrence of destructive Single Event Effects (SEE) in Micron Single-Level-Cell (SLC) Flash Memories through micro beam and broad beam experiments.

NAND Flash memories are based on Floating Gate (FG) cells and they are currently the leading technology in the market of large-size non-volatile memories.

2 Applicable and Reference Documents

- ESCC22900 Total Ionizing Dose (TID) Testing
- ESCC25100 Single Event Effects (SEE) Testing
- Micron Technology MT29F32G08ABAAA Single-Level-Cell Flash Memory datasheet

3 Tested Devices

For this work we used one-bit-per-cell 32-Gbit SLC NAND Flash memories manufactured by Micron Technology with a 25-nm feature size. The details of the tested samples are reported in **Table 1**.

Internal reference number	MQ26, MN34, MN38, MN41, MN45 MN46, MN47, MN48	MN31, MN8, MQ21, MQ22, MQ23	MN7, MN4, MP7, MP6
Part number	MT29F32G08ABAAA	MT29F32G08ABAAA	MT29F32G08ABAAA
Supply voltage	2.7V-3.6V	2.7V-3.6V	2.7V-3.6V
Density	32 Gbit	32 Gbit	32 Gbit
ECC requirements	8-bit ECC per 540 bytes of data	8-bit ECC per 540 bytes of data	8-bit ECC per 540 bytes of data
Package	48-pin TSOP	48-pin TSOP	48-pin TSOP
Operating temperature	0°C to +70°C	0°C to +70°C	0°C to +70°C
Lot code	Unknown	Unknown	Unknown
Package markings	MNxx: 1304 2-2 29F32G08ABAAA WP ITZ A MQxx: 1334 1-2 29F32G08ABAAA WP Z A	MNxx: 1304 2-2 29F32G08ABAAA WP ITZ A MQxx: 1334 1-2 29F32G08ABAAA WP Z A	MPxx: 1336 29F32G08ABAAA WP ITZ A
Die markings	n.a.	n.a.	n.a.
Test	Microprobe SEE tests @ GSI	1-mm beam SEE tests @ LNL	Broad beam SEE tests @ LNL

Table 1: Details of the SLC NAND memories used for this work.

The plastic package of the devices to be irradiated with heavy ions was etched with a combination of mechanical grinding and nitric acid attack, to expose the die.

4 GSI Microprobe SEE Tests

4.1 Experimental Conditions

Microprobe SEE irradiations were carried out at GSI, Darmstadt, Germany. Two SEE test campaigns were performed, one in April 2014 and the other one in May 2014.

The used test setup consists of an FPGA motherboard controlled by a host PC and a daughterboard with an open-top socket, where the Device Under Test (DUT) is placed for irradiation. The connection between the two boards is implemented through a couple of high-speed connectors and a ribbon cable, which was necessary to fit both the motherboard and the daughter board inside the vacuum chamber.

The supply current drawn by the memory under test was constantly monitored through a PC-controlled power analyzer and stored on log.

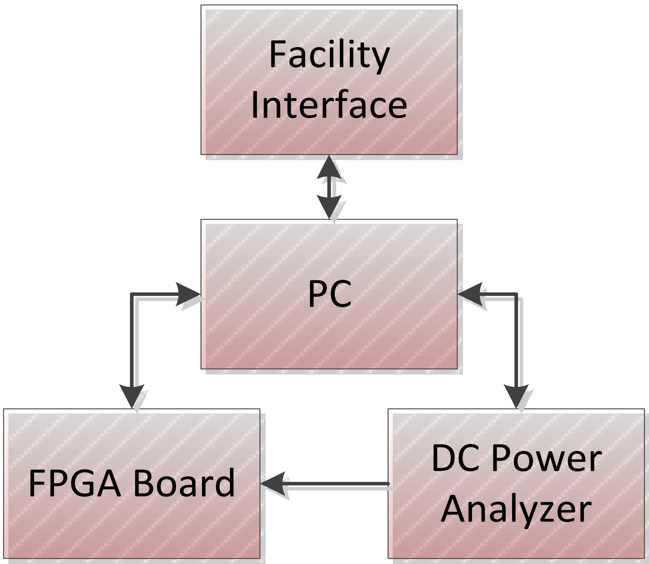

Figure 1: Irradiation setup.

An additional FPGA board was used to interface with the facility. The board issued hit requests, and sent a run number, while recording hit acknowledgments supplied by the facility acquisition hardware. This allowed synchronization between the ion strikes and the memory operations.

A schematic illustration of the irradiation setup is shown in **Fig. 1**.

During and after the irradiation (either multiple or single ion strikes), part of the memory was exercised with an Erase/Read/Program/Read (E/R/P/R) loop at maximum speed. For some runs, read operations were removed from the loop, to maximize the time spent erasing and programming the memory.

After each erase, program, and read operation, different parameters/signals were monitored.

- The Status Register (SR), which signals if erase and program operations are successfully performed.
- The Ready/Busy (RB), which is a device output that indicates if the memory is busy (active) or is ready to accept new commands (inactive). For instance, during a program operation

the RB signal is active (low); as soon as the operation is completed, the RB becomes inactive (high).

In detail:

- After erase operations we logged:
  - SR, to detect erase fails;
  - RB low time, to measure the erase time;
- After each program operation we logged:
  - SR, to detect program fails;
  - RB low time, to measure the program time;
- After each read operation we logged:
  - RB low time, to measure the read time;
  - Number and location of errors.

Two different modes were used for the microprobe experiments:

1. initially, a large scan (coarse scan) was performed on the peripheral circuitry, with the beam set to the maximum size and the motorized sample holder used to move the DUT and irradiate the whole area. At each position, a given number of ions were delivered and then the memory functionality was tested. As soon as a functional interrupt was detected or after the desired number of ions was reached, the beam was stopped and the memory was powered-off and then checked. The goal of this test was to identify the sensitive areas where destructive events could originate;
2. afterwards, on the sensitive spots identified during the previous phase, ions were delivered one by one (fine scan), and after each strike the memory was tested and power-cycled. The goal of this test was to make sure that the observed destructive events were due to a single ion and did not result from an accumulation of consecutive events.

The irradiation campaign at GSI microprobe was done in two runs, using the following ions:

- Au (4.8 MeV/u), LET 94 $\text{MeV}\cdot\text{mg}^{-1}\cdot\text{cm}^2$, beam size 432 μm by 342 μm, during the first run;
- Ti (6.05 MeV/u), LET 17.4 $\text{MeV}\cdot\text{mg}^{-1}\cdot\text{cm}^2$, beam size 675 μm by 559 μm, during the second run.

4.2 Experimental Results

Three different types of permanent effects were observed during the test runs with the GSI microprobe:

1. Failure to erase one or more blocks;
2. Complete failure to operate the memory;
3. Failure to program one or more pages.

Effect 1 was observed on only one sample (MQ26), during a coarse scan using Au ions (LET = 94 $\text{MeV}\cdot\text{mg}^{-1}\cdot\text{cm}^2$), and could not be reproduced on other samples and with the other ion (LET = 17.4 $\text{MeV}\cdot\text{mg}^{-1}\cdot\text{cm}^2$).

Effects 2 and 3 were observed initially during large scans, but could also be replicated in ion-by-ion mode, by shooting to the sensitive areas identified during the large scans.

The sample that experienced the erase failure (effect 1) was continuously operated under heavy-ion irradiation. Several 432 by 342 μm areas of the peripheral circuitry were irradiated with 1000 ions each (equivalent to a fluence of $6.77\cdot10^5$ ions/cm^2), before the permanent event was observed. During the scan, numerous SEFIs, recoverable with power cycles (to save beam time, repeat and reset were not tried to restore functionality), were observed. Finally, the memory became unable to erase 10 blocks, belonging to four different groups of addresses, namely 0xB6-

B7, 0x300-301, 0x400-401, 0x800-803. This occurred when shooting the area illustrated in **Fig. 2**, which is located close to the power supply pad of the memory. The event occurred after about 42 ion strikes ($2.84 \cdot 10^4$ ions/cm^2). This destructive failure was likely due to an 'unlucky' accumulation of events (the sample was irradiated multiple times before observing the failure). Moreover, this erase failure could not be reproduced in other samples. In fact, the same area and its vicinity were irradiated in other samples (MNxx) belonging to a different lot, but the effect was not observed anymore.

Complete failure to operate the memory (effect 2) was recorded only with Au (LET 94 MeV·mg^{-1}· cm^2), but was not observed with Ti (LET = 17.4 MeV·mg^{-1}· cm^2). This effect was experienced by three different memories belonging to the same lot, both in large-scan mode (MN34 after 233 ion strikes, i.e. $1.58 \cdot 10^5$ ions/cm^2) and ion-by-ion mode (MN38 after 37 ions, i.e. $2.5 \cdot 10^4$ ions/cm^2 and MN41 after 298 ions, i.e. $2.02 \cdot 10^5$ ions/cm^2). Results are summarized in Table 2.

Sample	**Irradiation mode**	**Ions to failure**	**Cross section [cm^2]**	**LET [MeV·mg^{-1}· cm^2]**
MN34	Coarse scan	233	$6.33 \cdot 10^{-6}$	94
MN38	Fine scan	37	$4 \cdot 10^{-5}$	94
MN41	Fine scan	298	$4.95 \cdot 10^{-6}$	94
Average		**189**	$\mathbf{7.81 \cdot 10^{-6}}$	94

Table 2: Samples that experienced complete loss of functionality.

Device cross sections were calculated as:

$$\sigma_{DEVICE} = \frac{\#events}{fluence} \tag{1}$$

These destructive events rendered the memory completely inoperable and the area of the die where effect 2 originated is shown in **Fig. 3**. In all three samples, no operation could be carried out (not even readout of the ID code) after striking the area indicated in **Fig. 3**. The likely reason for this severe loss of functionality is the corruption of the embedded microcontroller firmware and the effect is clearly due to a single ion. No event was observed by irradiating the same sensitive spots (and their vicinity) with the other ion at an LET of 17.4 MeV·mg^{-1}· cm^2. The threshold LET for this kind of event is then located between 17.5 and 94 MeV mg^{-1} cm^2.

The third observed effect (effect 3), i.e., failure to program one or more pages, was consistently observed in four devices (MN45, MN46, MN47, and MN48) at both the tested LETs. Details on these fails are reported in Table 3.

Cross sections for events 3 in Table 3 were calculated per page, i.e., dividing the number of program fails by the total number of pages exercised during the test:

$$\sigma_{PAGE} = \frac{\#\,page\,program\,fails}{fluence \cdot \#exercised\,pages} \tag{2}$$

The cross section per device can be obtained multiplying σ_{PAGE} by the total number of pages in the memory (i.e. 524288):

Sample	# page program fails	Tot pages read	Ions to failure	Page program fail cross section [cm^2]	LET [MeV·mg^{-1}·cm^2]
MN46	1	128	10000	$2.95 \cdot 10^{-9}$	17.4
MN45	619	32768	10000	$7.13 \cdot 10^{-9}$	17.4
MN47	43	32768	7107	$6.97 \cdot 10^{-10}$	17.4
MN48	126	32768	9070	$1.60 \cdot 10^{-09}$	17.4
Average				$\mathbf{8.4 \cdot 10^{-10}}$	

Table 3: Samples that experienced page program fails. Cross sections have been calculated considering the number of failed pages divided by the number of programmed pages.

$$\sigma_{DEVICE} = \frac{\#\,page\,program\,fails \cdot \#total\,pages}{fluence \cdot \#exercised\,pages} \qquad (3)$$

Data in Table 3 refer to irradiations with Ti ions in large-scan mode, whereas data relative to type-3 events during Au irradiations are not reported. In fact, during Au exposure, type-3 events occurred simultaneously with events of type 1, on which we mostly focused our analysis (see Table 2).

The areas where effect 3 originated are shown in **Fig. 4**. When striking any part of the four areas highlighted in **Fig. 4**, a number of page program fails increasing with fluence was observed in a certain range of addresses. The status register value of failed page program operations was E1, even though a read on the affected pages showed that the correct values were stored.

4.3 Annealing after irradiation

All irradiated samples were annealed after heavy-ion exposure. Annealing was performed for one week at room temperature and for one additional week at 100°C with unbiased samples (with shorted pins). None of the tested samples recovered its functionality after annealing. Only very small changes in the memory behavior were observed after the annealing process.

In particular:

- Concerning sample MQ26, featuring effect 1 (i.e., failure to erase one or more blocks), the number of blocks failing to erase increased after high-temperature annealing and the behavior was not stable with time. In fact, the number of blocks failing after erase changed over time if the memory was repeatedly exercised.
- As far as MN34, MN38, and MN41 are concerned, featuring effect 2 (i.e., complete loss of functionality), no change at all was observed after annealing. The memories were still unable to perform any operation, including the read of the device ID.
- Finally, samples MN45, MN46, MN47, and MN48, featuring effect 3 (i.e., failure to program one or more pages) showed only slight changes after annealing. In fact, the number of pages that could not be programmed decreased after annealing and some new pages failing to program showed up.

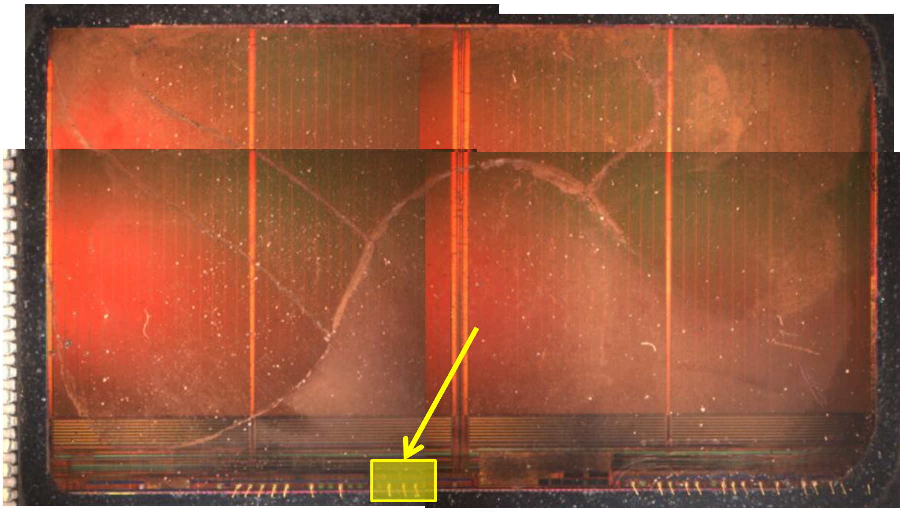

Figure 2: Heavy-ion struck location where erase failures originated in sample MQ26.

Figure 3: Heavy-ion struck location where complete loss of functionality originated in MN34, MN38, and MN41.

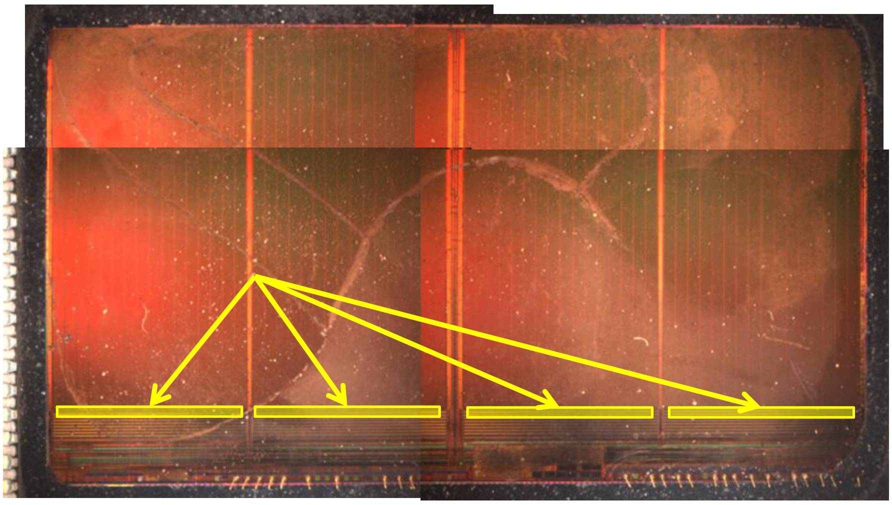

Figure 4: Heavy-ion struck location where page program fails originated in MN46, MN45, MN47, MN48.

5 LNL SEE Tests

5.1 Experimental conditions

Broad-beam heavy-ion irradiations and exposures using a collimated beam with a 1-mm diameter were performed at the SIRAD line of the Legnaro National Laboratories (LNL) in Italy, using the beams listed in **Table 4**.

Ion Species	Energy [MeV]	LET [MeV cm^2/mg]	Beam type
I	266.7 MeV	59.2	Broad and collimated
Cl	171 MeV	12.5	Broad

Table 4: Heavy-ion beams and test conditions used at LNL.

The test setup for heavy ions consisted of an FPGA motherboard controlled by a host PC and a daughterboard with an open-top socket, where the DUT was placed. No ribbon cables were used in this case, since there were no particular constraints on the size of the board to be put in the vacuum chamber.

The conditions during the exposure were practically identical to those used for the GSI microbeam experiments. In addition to irradiation during Erase/Read/Program/Read (E/R/P/R) loops, the samples were also irradiated in unbiased conditions.

5.2 Experimental Results

Out of the three permanent effects observed during the GSI microprobe sessions, only the program page fails (effect 3) were recorded at LNL, both using a broad beam (2 by 2 cm) and a round collimated beam with a diameter of 1 mm.

Noticeably, page program fails were observed even on samples irradiated in unbiased conditions (a condition not tested at GSI).

The failures were immediately recorded upon beam delivery. As a result, we cannot provide an accurate measurement of the number of ions to failure or cross section.

The absence of the total loss of functionality is probably due to the lower maximum LET available at LNL, as compared to GSI (59.2 MeV·mg^{-1}· cm^2 vs. 94 MeV·mg^{-1}· cm^2).

6 Cross Section for destructive events

Fig. 5 shows the cross section per device versus ion LET for the observed events.

Destructive events (event 2, complete loss of functionality) are illustrated with blue diamonds. The empty symbol represents the observability limit when no events are reported.

The device cross section for events of type 3 is shown with red squares. The device cross section was calculated as described in section 4.2 (equation (3)).

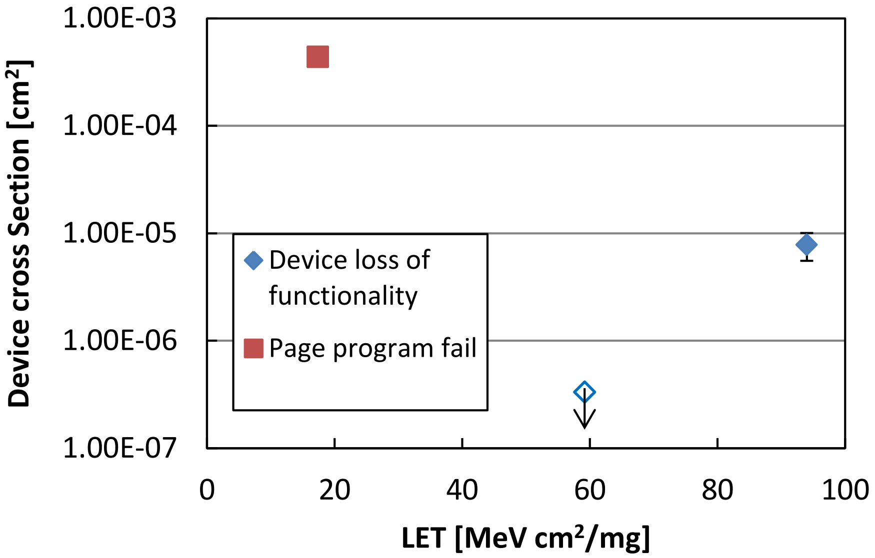

Figure 5: Device cross section versus LET for permanent loss of functionality. When not reported, errors bars are smaller than the symbols.

Finally, for the event of type 1 it is not meaningful to plot the cross section: in fact, only one event was observed during our tests and it was likely due to the accumulation of ions during multiple irradiation runs.

7 Conclusions

Three different kinds of permanent effects were observed following heavy-ion exposure.

Failure to erase some blocks in the memory was observed only on one sample and at the highest LET. This was likely due to the accumulation of 'unlucky' events during multiple irradiations and it originated close to the power supply pad of the memory.

Destructive events leading to a complete loss of functionality were observed at an LET of 94 $MeV \cdot mg^{-1} \cdot cm^2$ during microprobe experiments at GSI. The sensitive area was clearly identified and may be related to corruption of the embedded microcontroller firmware, leading to the inability to perform all operations, including reading the device ID. The threshold LET for these events is located between 59 $MeV \cdot mg^{-1} \cdot cm^2$ and 94 $MeV \cdot mg^{-1} \cdot cm^2$.

Less severe events leading to permanent failure to program some pages were observed also at lower LET, during both microbeam and broad beam experiments. This class of events occurs also on unpowered devices, when the border region of the cell array is struck by heavy ions. The exact origin of this kind of effects still remains unclear.

None of the three effects has been observed to recover after annealing (1 week at room temperature followed by 1 week at 100 °C).