Radiation Hard Memory

Radiation testing of candidate memory devices for Laplace mission
ESTEC Contract No.: 4000101358/10/NL/AF

H. Schmidt¹, M. Hermann², K. Grürmann², F. Gliem² & V. Ferlet-Cavrois³

¹ Airbus DS GmbH Friedrichshafen, Germany
² IDA, TU Braunschweig, Germany
³ ESA/ESTEC Noordwijk, The Netherlands

CNES/ESA Radiation Effects Final Presentation Days
10th March 2015
Context
Context

RHM Overview

- Radiation test program for commercial DRAM and NV memories for application in harsh radiation environment (EJSM Laplace / JUICE mission), focus on TID behaviour and severe SEE (SEFI, destructive failure, etc.)

- Collaboration between Airbus DS GmbH (former Astrium GmbH) as prime and IDA (Institut für Datentechnik und Kommunikationsnetze), TU Braunschweig

- Technical Officer (ESA): Véronique Ferlet-Cavrois

- ESTEC Contract No.: 4000101358/10/NL/AF
Context
EJSM Laplace / JUICE Mission

- ESA’s Cosmic Vision 2015-2025 plan

- 2012: Selection of JUICE (Jupiter Icy Moon Explorer) for L1 launch slot of ESA Cosmic Vision science programme
  - Launch planned for 2022 with Ariane 5
  - Mission until > 2033 (>4000 days)
  - 7.5 years cruise towards Jupiter
  - Jupiter orbit insertion in 01/2030
  - Tour in the Jupiter system including several flybys of Callisto and two flybys of Europa
  - Callisto gravity assist sequence to raise orbit inclination to observe Jupiter polar regions and to transfer to Ganymede
  - Polar orbit insertion around Ganymede in 9/2032
Very high fluxes and high energies of electrons.

Very high fluxes of lower energy protons, low fluxes of higher energy protons.
## Context

**JUICE Radiation Environment - TID**

### Table: Total Ionising Dose in Si for Spherical Al Shielding

<table>
<thead>
<tr>
<th>Shielding Thickness [mm]</th>
<th>Total</th>
<th>Electrons</th>
<th>Bremsstrahlung</th>
<th>Trapped Protons</th>
<th>Solar Protons</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>1.75E+08</td>
<td>1.67E+08</td>
<td>3.90E+05</td>
<td>6.15E+06</td>
<td>9.14E+05</td>
</tr>
<tr>
<td>0.1</td>
<td>1.02E+08</td>
<td>1.00E+08</td>
<td>2.56E+05</td>
<td>1.21E+08</td>
<td>4.60E+05</td>
</tr>
<tr>
<td>0.2</td>
<td>6.03E+07</td>
<td>5.96E+07</td>
<td>1.68E+05</td>
<td>2.43E+05</td>
<td>2.45E+05</td>
</tr>
<tr>
<td>0.4</td>
<td>3.60E+07</td>
<td>3.57E+07</td>
<td>1.12E+05</td>
<td>4.87E+04</td>
<td>1.35E+05</td>
</tr>
<tr>
<td>0.6</td>
<td>2.53E+07</td>
<td>2.51E+07</td>
<td>8.53E+04</td>
<td>1.93E+04</td>
<td>9.11E+04</td>
</tr>
<tr>
<td>0.8</td>
<td>1.81E+07</td>
<td>1.79E+07</td>
<td>6.83E+04</td>
<td>1.00E+04</td>
<td>8.88E+04</td>
</tr>
<tr>
<td>1</td>
<td>1.26E+07</td>
<td>1.28E+07</td>
<td>5.21E+04</td>
<td>6.04E+03</td>
<td>5.54E+04</td>
</tr>
<tr>
<td>1.5</td>
<td>6.33E+06</td>
<td>6.25E+06</td>
<td>3.27E+04</td>
<td>2.44E+03</td>
<td>3.69E+04</td>
</tr>
<tr>
<td>2</td>
<td>3.84E+06</td>
<td>3.78E+06</td>
<td>2.41E+04</td>
<td>1.25E+03</td>
<td>2.72E+04</td>
</tr>
<tr>
<td>2.5</td>
<td>2.63E+06</td>
<td>2.58E+06</td>
<td>1.96E+04</td>
<td>7.59E+02</td>
<td>2.11E+04</td>
</tr>
<tr>
<td>3</td>
<td>1.92E+06</td>
<td>1.88E+06</td>
<td>1.67E+04</td>
<td>5.04E+02</td>
<td>1.69E+04</td>
</tr>
<tr>
<td>4</td>
<td>1.17E+06</td>
<td>1.14E+06</td>
<td>1.32E+04</td>
<td>2.62E+02</td>
<td>1.19E+04</td>
</tr>
<tr>
<td>5</td>
<td>7.96E+05</td>
<td>7.75E+05</td>
<td>1.13E+04</td>
<td>1.59E+02</td>
<td>9.02E+03</td>
</tr>
<tr>
<td>7</td>
<td>4.44E+05</td>
<td>4.28E+05</td>
<td>9.16E+03</td>
<td>7.50E+01</td>
<td>5.85E+03</td>
</tr>
<tr>
<td>10</td>
<td>2.36E+05</td>
<td>2.23E+05</td>
<td>7.02E+03</td>
<td>3.90E+01</td>
<td>3.65E+03</td>
</tr>
<tr>
<td>14</td>
<td>1.25E+05</td>
<td>1.16E+05</td>
<td>6.52E+03</td>
<td>1.58E+01</td>
<td>2.28E+03</td>
</tr>
<tr>
<td>17</td>
<td>8.50E+04</td>
<td>7.73E+04</td>
<td>6.02E+03</td>
<td>1.03E+01</td>
<td>1.71E+03</td>
</tr>
<tr>
<td>20</td>
<td>6.06E+04</td>
<td>5.37E+04</td>
<td>5.64E+03</td>
<td>7.12E+00</td>
<td>1.33E+03</td>
</tr>
<tr>
<td>25</td>
<td>3.71E+04</td>
<td>3.10E+04</td>
<td>5.14E+03</td>
<td>4.33E+00</td>
<td>9.44E+02</td>
</tr>
<tr>
<td>30</td>
<td>2.41E+04</td>
<td>1.86E+04</td>
<td>4.71E+03</td>
<td>2.88E+00</td>
<td>7.05E+02</td>
</tr>
<tr>
<td>40</td>
<td>1.18E+04</td>
<td>7.35E+03</td>
<td>4.05E+03</td>
<td>1.50E+00</td>
<td>4.37E+02</td>
</tr>
<tr>
<td>50</td>
<td>7.29E+03</td>
<td>3.41E+03</td>
<td>3.57E+03</td>
<td>9.10E-01</td>
<td>3.03E+02</td>
</tr>
<tr>
<td>60</td>
<td>5.32E+03</td>
<td>1.89E+03</td>
<td>3.22E+03</td>
<td>6.03E-01</td>
<td>2.22E+02</td>
</tr>
<tr>
<td>80</td>
<td>3.62E+03</td>
<td>8.09E+02</td>
<td>2.68E+03</td>
<td>3.13E-01</td>
<td>1.33E+02</td>
</tr>
<tr>
<td>100</td>
<td>2.64E+03</td>
<td>4.30E+02</td>
<td>2.14E+03</td>
<td>1.86E-01</td>
<td>8.78E+01</td>
</tr>
</tbody>
</table>

### Graph: 4pi TID in Si at Center of Al Spheres

- **Total**
- **Electrons**
- **Bremsstrahlung**
- **Trapped Protons**
- **Solar Protons**

10 March 2015
## Context

**JUICE Radiation Environment - TID**

### TID Mission Profile:

<table>
<thead>
<tr>
<th>Phase</th>
<th>Duration [days]</th>
<th>1mm [krad]</th>
<th>2mm [krad]</th>
<th>4mm [krad]</th>
<th>7mm [krad]</th>
<th>10mm [krad]</th>
<th>14mm [krad]</th>
<th>20mm [krad]</th>
<th>40mm [krad]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cruise</td>
<td>2711</td>
<td>55</td>
<td>27</td>
<td>12</td>
<td>6</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>To Europa</td>
<td>458</td>
<td>1040</td>
<td>338</td>
<td>113</td>
<td>46</td>
<td>25</td>
<td>14</td>
<td>7</td>
<td>2</td>
</tr>
<tr>
<td>Europa Phase</td>
<td>38</td>
<td>383</td>
<td>160</td>
<td>65</td>
<td>29</td>
<td>17</td>
<td>10</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Jupiter HL to Callisto</td>
<td>248</td>
<td>767</td>
<td>236</td>
<td>72</td>
<td>26</td>
<td>14</td>
<td>7</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>To Ganymede</td>
<td>311</td>
<td>1660</td>
<td>465</td>
<td>127</td>
<td>41</td>
<td>20</td>
<td>10</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Ganymede science</td>
<td>318</td>
<td>8957</td>
<td>2613</td>
<td>782</td>
<td>296</td>
<td>156</td>
<td>82</td>
<td>39</td>
<td>7</td>
</tr>
<tr>
<td>Total</td>
<td>4084</td>
<td>12863</td>
<td>3839</td>
<td>1171</td>
<td>443</td>
<td>234</td>
<td>125</td>
<td>61</td>
<td>12</td>
</tr>
<tr>
<td>1 Europa Flyby</td>
<td>14</td>
<td>189</td>
<td>78</td>
<td>32</td>
<td>14</td>
<td>8</td>
<td>5</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

**TID Level of interest: > 400 krad**
Parts Selection
Parts Selection
Selection Criteria - Radiation

- Radiation performance – to be investigated
  - TID: level of interest > 400 krad, minimum >> 50 krad
  - SEL LET threshold > 60 MeV·cm²·mg⁻¹
  - Good SEFI behaviour
Parts Selection
Selection Criteria - Mission Demands (SSR/SSMM)

- Exponential increase of demands on storage size & data rate
  → 10 Tbit
  → 14 Gbps

- SDRAM (8 x 512 Mb) “State-of-the-art” but storage size limited to < 2 Tb

- First flight heritage with NAND Flash
Parts Selection
Selection Criteria - Performance

- Radiation performance – to be investigated
  - TID: level of interest > 400 krad, minimum >> 50 krad
  - SEL LET threshold > 60 MeV·cm²·mg⁻¹
  - Good SEFI behaviour

- Density ≥ 4 Gb (MCM of 8 x 512 Mb “state-of-the-art”)

- High speed, low power

- Easy I/F
Parts Selection

**DRAM**
- Computing DRAM
  - PM, EDO DRAM
  - SDR SDRAM ("state-of-the-art")
  - DDR, DDR2, DDR3, DDR4 SDRAM
- Mobile DRAM
- Graphic DRAM

**Non-volatile Memory**
- Flash
  - NOR (1 bit, 2 bits)
  - NAND (SLC, MLC, TLC, 3-D)
- MRAM
  - MTJ
  - STT
- PCRAM
- FeRAM
- ReRAM, …
Parts Selection
DDR3 SDRAM

- Focus on latest DDR3 SDRAM technology with monolithic densities up to 4 Gb. Additional tests with 2 Gb DDR3 parts.

4 Gb DDR3:
- Elpida EDJ4208BASE-DJ-F (obsolete)
- SK Hynix H5TQ4G83MFR-H9C
- Micron MT41J512M8RH-093:E
- Samsung K4B4G0846B-HCH9
- Nanya NT5CB512M8CN-EK

2 Gb DDR3:
- SK Hynix H5TQ2G83BFR-H9C
- Nanya N5CB256M8BN-CG
- Micron MT41J256M8HX-15E:D
- Samsung K4B2G0846B
- Samsung K4B2G0846D
## Parts Selection

### NAND Flash

- Only SLC NAND flash technology provides sufficient endurance (50k…100k EPC), data retention, and speed. Test of heritage SLC parts as reference + latest SLC technology available.

**Reference:**
- Samsung K9WBG08U1M (SLC, 4 x 8 Gb, 51 nm)
- Micron MT29F8G08AAAWP-ET:A (SLC, 8 Gb, 50 nm)

**Focus on state-of-the-art technology:**
- Micron MT29F16G08ABACAWP-IT:C (SLC, 16 Gb, 25 nm)
- Micron MT29F32G08ABAAAWP-IT:A (SLC, 32 Gb, 25 nm)
Performed Test Campaigns

TID:
- October 2012: 1st in-situ TID testing of 4 Gb DDR3
- March 2013: Unbiased pre-selecting TID tests on DDR3
- October 2013: Unbiased pre-selecting TID tests on DDR3
- January 2014: In-situ TID testing of NAND flash and DDR3

SEE / Heavy Ions:
- May 2011: 1st SEE tests of 2 Gb DDR3 and angular tests on NAND flash, RADEF
- January 2012: SEE characterisations of Micron 16/32 Gb NAND flash & 2/4 Gb DDR3, RADEF
- April 2012: Further SEE characterisations of NAND flash and DDR3, RADEF
- December 2012: High range SEE testing on DDR3 (including SEL) and angular characterisation of Micron 16 Gb NAND flash, TAMU

SEE / Protons
- March 2014: SEE characterisations of 4 Gb DDR3, PSI
- April 2014: SEE characterisations of 16/32 Gb NAND flash
Detailed Radiation Test Results
Main results

- Tolerance dose:
  - State-of-the-art NAND Flash: ≈ 30 krad
  - State-of-the-art DDR3 SDRAM: ≈ 400 krad (Hynix)

- Both types suffer from SEE error mechanisms with data loss:
  - NAND Flash: destructive failure (DF)
  - DDR3 SDRAM: device SEFI

- Both types are latch-up free

- Parts with good test coverage:
  - NAND Flash: 16/32-Gbit Micron, no other parts procurable
  - DDR3 SDRAM: 4-Gbit Hynix, other parts have substantial errors
Outline

- NAND-Flash
  - Test equipment, error classification
  - Test Results
    - Heavy-ion SEE
    - Proton SEE
    - $^{60}$Co TID
- DDR3 SDRAM
  - Test equipment
  - DUT preparation
  - Test Results
    - Heavy-ion SEE
    - Proton SEE
    - $^{60}$Co TID
- Comparison
NAND-Flash: TID (+ SEE Protons)

TID ≤ 300 krad

52 wire Ribbon Cable ≤ 30cm

DUT Carrier

Co-60 Source

Shielding Box

Remote Control PC: Pattern Verification, Error Vector Storage

Ethernet

HS Controller Board (FPGA H/W): Pattern Generation

Irradiation Vault
NAND-Flash: Standard SEE Tests

Functional Block Diagram

- Capability to operate up to 16 DUTs
NAND-Flash: Enhanced SEE Tests

Functional Block Diagram

- Heating and cooling
- Tilting
- Current Measurement (Remote controlled Digital Oscilloscope)
NAND-Flash: Heating of the DUT

- PCB with DUT, Peltier element and temperature sensor
NAND-Flash: Tilting of the DUT

Tilting setup

Definition of Azimuth and Elevation Angle

Pin 1 Memory Array

Samsung 4x8-Gbit

Micron 16-Gbit

State Machine, HV Pulser

State Machine, HV Pulser

(long package axis)

(long package axis)

(short package axis)

(short package axis)
NAND-Flash: TID and Proton Tests

Functional Block Diagram

- Capability to operate up to 16 DUTs
NAND-Flash: TID shielding box

- 16 DUTs mounted above the shielding box
NAND-Flash: Error Classification

SEE error pattern

Class A
- SEU
  - Single Bit Error
  - Multiple Bit Error
  - Single Symbol Error
  - Stuck bit, etc.

Class B
- Transient SEFI
  - Page Error (PE)
  - Column Error (CE)
  - Block Error (BE)

Class C
- Persistent SEFI
  - PE
  - CE
  - BE
  - Device Error

Class D
- Device Failure
NAND-Flash: Error Image

![Graph showing error density and address distribution.](image)

Error Density [1k / pixel]

Column Address [%]

Page Address [%]
NAND-Flash results

Heavy Ion SEE
TAMU cross section points are a bit below the RADEF measurement

Effect of temperature?
NAND-Flash SEE HI: SEFI

- classified into Column Errors, Row Errors and Block Errors
- measured individually for each mode
- the influence of the respective mode is rather minor
- Marching Mode 5 (without PC) delivers nearly the same cross section than Marching Mode 1 (with PC) in contrast to early NAND-Flash generations
- all row errors are transient
- all column errors are persistent
- one out of 2000 xenon ions generates a Class C Persistent SEFI (resolvable by PC)
NAND-Flash SEE HI: Class B Transient SEFI

Column Errors

Row Errors

Block Errors

All Errors
1.00E-08 1.00E-07 1.00E-06 1.00E-05 1.00E-04 1.00E-03
0 1 02 03 04 05 06 07 08 0
σ SEFI [cm²·die⁻¹]

LET [MeV·cm²·mg⁻¹]

Class C Persistent SEFI: Column Errors, Read Mode M2R

16-Gbit Micron 25nm SLC
32-Gbit Micron 25nm SLC

The 32-Gbit Micron data points are shifted to the right by LET=1 MeV·cm²·mg⁻¹ to improve readability.

Class C Persistent SEFI: Row Errors, Read Mode M2R

16-Gbit Micron 25nm SLC
32-Gbit Micron 25nm SLC

The 32-Gbit Micron data points are shifted to the right by LET=1 MeV·cm²·mg⁻¹ to improve readability.

Class C Persistent SEFI: Block Errors, Read Mode M2R

16-Gbit Micron 25nm SLC
32-Gbit Micron 25nm SLC

The 32-Gbit Micron data points are shifted to the right by LET=1 MeV·cm²·mg⁻¹ to improve readability.

Class C Persistent SEFI: All Errors, Read Mode M2R

16-Gbit Micron 25nm SLC
32-Gbit Micron 25nm SLC

The 32-Gbit Micron data points are shifted to the right by LET=1 MeV·cm²·mg⁻¹ to improve readability.
Class B+C Transient+Persistent SEFI, Read Mode M2R

The 32-Gbit Micron data points are shifted to the right by LET=1 MeV cm² mg⁻¹ to improve readability.
- permanent damage with definite data loss
- no flux dependence found (flux between 30 and 8000 cm\(^{-2}\) s\(^{-1}\))
- therefore we conclude that the DF is triggered by a single hit and not by the coincidence of several hits
- 16 Gbit Micron shows also other DF types affecting the on-chip microcontroller
Increase of write and erase current but
No SEL found
Short term and long term SEU annealing, 4 Gbit ST Microelectronics
Short term and long term SEU annealing, Micron 16/32-Gbit NAND-Flash feature size 25 nm
Annealing depends strongly on the feature size.
Micron 16-Gbit SLC NAND-Flash, MBUs at normal incidence, Xe, LET=60
- hard SEUs accumulate over the mission time
- soft SEUs accumulate only over the data storage time, which is only of some days
- hard SEUs survive scrubbing and can therefore be more harmful
With increasing LET the number of SEUs related to MBUs increases
Cross section of soft and hard SEUs, directly after exposure and 20 days later, 16-Gbit Micron SLC NAND-Flash
Cross section of soft and hard SEUs, directly after exposure and 20 days later, 16-Gbit Micron SLC NAND-Flash
**NAND-Flash SEE HI: Annealing of Hard SEUs**

- Short term / long term Hard Error annealing, Micron 16/32Gbit NAND-Flash DUTs unbiased
NAND-Flash SEE HI: Annealing of Hard SEUs

Development of the hard SEU count after repeated erase-write-read cycles

- Xe, $F = 2\times10^5$ 1/sq cm
- Kr, $F = 1\times10^5$ 1/sq cm
- Fe, $F = 1\times10^5$ 1/sq cm
- Ar, $F = 1\times10^7$ 1/sq cm
- Ne, $F = 1\times10^8$ 1/sq cm
NAND-Flash SEE HI: Omni directional ion incidence

- Samsung 4x8-Gbit, Kr, TAMU, Texas
- strong angular dependence
Micron 16-Gbit, Kr, TAMU, Texas
weak angular dependence
NAND-Flash results

Proton SEE
25 nm NAND-Flash is by three orders of magnitude more sensitive to proton SEUs than 51 nm NAND-Flash

- increase of SEUs towards low energies
- should be investigated further to exclude peculiarities of the source
- The SEFI count is very low.
- To get more SEFI events a higher fluence is needed.
- Limited beam time.
- Limited total dose.

The 32 Gbit Micron data points are shifted to the right by 3 MeV to improve readability.
the SEFI count is very low

to get more SEFI events a higher fluence is needed

limited beam time

limited total dose
the SEFI count is very low

to get more SEFI events a higher fluence is needed

limited beam time

limited total dose

No Destructive Failure or SEL observed
NAND-Flash results

$^{60}$Co TID
- Class A SEUs and Class D Destructive Failures were observed
- no Class B or C SEFIs
- functional breakdown of each DUT is marked with dotted line
- first random data errors already between 5 and 10 krad(Si)
- Destructive Failure between 32 and 64 krad (Si)
NAND-Flash TID: Error Share in Refresh Mode

- Refresh every 2.5 krad(Si)
- first random data errors already between 3 and 30 krad(Si)
- periodic refresh keeps the error share below $1 \cdot 10^{-5}$, tolerable before ECC
- Refresh has no influence on the Destructive Failure
- with periodic refresh the Destructive Failure occurrence determines the total dose

Samsung 51nm: first SEUs after 70 krad(Si), no functional breakdown until end of test at 90 krad(Si)
NAND-Flash TID: Standby Current

- no correlation between standby current increase and Destructive Failure
- standby current remains below the specified datasheet value at DF
- After DF the standby current increases further or drops again in some cases
- Standby current of DUTs operated at 3.6V is by a factor of 5 higher compared to the 3.3V DUTs
DDR3 – Overview

- Test equipment
- DUT preparation
- Test procedures
- Test results
  - Heavy-ion SEE
  - Proton SEE
  - $^{60}$Co TID
DDR3 – Test equipment
DDR3 – Test equipment

- FPGA (Xilinx Virtex6)
- DDR3 device (opened)
- Custom SODIMM
- Water cooler
- Power switching
- ZIF socket
- Custom DDR3 SDRAM controller
- Special feature: software conditioning
  - Rewrite mode registers
  - Reset DLL
  - Calibrate ZQ
- Interfaces with Xilinx’ PHY
Test equipment – shielding

- DUTs
- Water
- Electrical
- Source
- Lead
- Steel
Test equipment – shielding

Source

ML605

Dosimeter

Cooler

DUTs

Current measurement

USB adapter
Thinning was performed by Fraunhofer Institute for Applied Optics and Precision Engineering, Jena
DDR3 – SEE error classification

- SEUs
  - Stuck bits
- Row SEFIs
- Column SEFIs
- Device SEFIs
DDR3 SDRAM results

Heavy ion SEE
DDR3 results – heavy ion SEE - Overview

- 4 tests:
  - 3 × RADEF, Jyväskylä
  - 1 × TAMU, College Station
- 7 tested parts:
  - 2 Gbit: Samsung, Hynix, Micron, Nanya
  - 4 Gbit: Samsung, Hynix, Elpida
DDR3 results – heavy ion SEUs

![Graph showing the relationship between LET (Mev cm$^2$/mg) and SEU cross-section ($\sigma_{SEU}$ [cm$^2$/bit]). The graph includes lines for different memory types and manufacturers, such as 4-Gbit Elpida, 4-Gbit Samsung, 2-Gbit Samsung (D), 2-Gbit Hynix, and 2-Gbit Micron. The graph indicates few MBUs for LET values ranging from 0 to 70.](image)
DDR3 results – heavy ion row SEFIs

![Graph showing σ_{row} vs. LET for different memory types.](image)

- Red: 4-Gbit Elpida
- Blue: 4-Gbit Samsung
- Green: 2-Gbit Samsung (D)
- Yellow: 2-Gbit Hynix
- Pink: 2-Gbit Micron
DDR3 results – heavy ion column SEFIs
Without software conditioning

With software conditioning

\[ \sigma_{\text{device}} \left[ \text{cm}^{-2} / \text{device} \right] \]

\[ \text{LET} \left[ \text{MeV cm}^2 / \text{mg} \right] \]

- 4-Gbit Elpida
- 4-Gbit Samsung
- 2-Gbit Samsung (D)
- 2-Gbit Hynix
- 2-Gbit Micron
DDR3 results – SEL

- **Setup:**
  - 4 Gbit, Samsung and Hynix
  - 80 °C
  - $10^7 \text{ cm}^{-2}$ Xenon, 61.1 MeV cm$^2$ / mg
  - Write/read mode

- **Result:**
  - No SEL
  - Current returns to original value after irradiation
DDR3 results – hard SEUs

- Hard SEUs: cannot be removed by rewriting
No soft SEU annealing for DRAM due to refresh

<table>
<thead>
<tr>
<th>Wire</th>
<th>Vacuum</th>
<th>Room temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neon</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Argon</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Iron</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Krypton</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Xenon</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Samsung, 2 Gbit

Time since irradiation [h]
DDR3 results – heavy ion SEE – SEFI mitigation

- **C1**
  - Rewrite mode registers
  - DLL reset
  - ZQ calibration
  - No data loss

- **C2**
  - Reset DDR3 device
  - Reset memory controller (recalibrates line delays)
  - Data retention not guaranteed

- **C3**
  - Power cycle
  - Data loss
DDR3 results – heavy ion SEE – SEFI mitigation

Power cycle may be necessary!
DDR3 results – heavy ion SEE – current

4-Gbit Hynix devices, LET 60 MeV cm² / mg, 80 °C

Current [mA]

Time [s]

Hynix, sample 1
Hynix, sample 2
Hynix, sample 3
Baseline idle
DDR3 SDRAM results

Proton SEE
DDR3 results – proton SEUs

![Graph showing the relationship between proton energy and SEU cross-section for different memory brands.](image-url)
DDR3 results – proton row SEFIs

![Graph showing proton row SEFIs](image)

- Hynix
- Samsung
- Micron
- Nanya
DDR3 results – proton column SEFIs
DDR3 results – proton device SEFIs

![Graph showing proton device SEFIs versus proton energy]
DDR3 results – proton SEU polarity

![Graph showing share of 0 → 1 errors vs. proton energy (MeV) for different memory brands: Hynix, Samsung, Micron, and Nanya. The graph illustrates the variation in error rates across different proton energies.]
DDR3 SDRAM results

$^{60}$Co TID
DDR3 results – TID - Overview

- 4 tests:
  - 2 × In-Situ
  - 2 × Unbiased
- 3 + 7 parts tested:
  - In-Situ, 4 Gbit: Samsung, Hynix, Micron
  - Unbiased, 4 Gbit: Samsung, Hynix, Micron, Nanya, Elpida
  - Unbiased, 2 Gbit: Samsung, Hynix, Micron, Nanya
DDR3 results – TID – error density

Samsung, 4 Gbit, in-situ, room temperature

Error density

Dose [krad]

DUT 0
DUT 1
DUT 2
DUT 3
DUT 4
DUT 5
DUT 6
DUT 7

Radiation Hard Memory – Final Presentation

March, 10, 2015
DDR3 results – TID – error density

Micron, 4 Gbit, in-situ, room temperature

This part looked good in an unbiased test, but bad in an in-situ test!
4-Gbit Hynix device: no errors up to >400 krad at room temperature
DDR3 results – TID – error annealing

Samsung, 4 Gbit, in-situ, 422 krad, room temperature

Remaining bit errors vs. Time [h]

- DUT 0
- DUT 1
- DUT 2
- DUT 3
- DUT 4
- DUT 5
- DUT 6
- DUT 7
DDR3 results – TID – current

Average idle current per device [mA]

Dose [krad]

- Micron
- Samsung
- Hynix
SDRAM operation:

1. Open page
2. Write/read page buffer
3. Close page

Array
Page buffer
DDR3 results – TID – Band error pattern (4-Gbit Samsung)

512 pages

< $10^{-5}$ errors

20% errors

5% errors
DDR3 results – TID – Band error pattern – background

- Last accessed page is repeatedly opened after the test
- Errors appear on the last page and other pages
- Observed for:
  - 4-Gbit Samsung (in-situ)
  - 2-Gbit Samsung (revision D, unbiased)
  - 2-Gbit Micron (unbiased)
  - 2-Gbit Hynix (unbiased)
- Not observed for:
  - 4-Gbit Hynix (in-situ/unbiased)
  - 4-Gbit Elpida (unbiased)
  - 2-Gbit Samsung (revision B, unbiased)
  - 2-Gbit Nanya (unbiased)
- Mechanism not understood so far
- Can be mitigated by appropriate controller design
DDR3 results – summary

- **SEE:**
  - No SEL (LET=60, normal incidence)
  - Software conditioning reduces SEFI sensitivity for some part types
  - \(\approx 10\%\) hard SEUs
  - Significant hard SEU annealing

- **TID:**
  - DDR3 SDRAM is useful for \(\geq 400\) krad (Hynix)
  - Other parts: band error pattern – triggered by mode of operation
  - Significant annealing
  - Idle current increase: none (Hynix) to extreme (Micron)
  - In-situ results can be worse than unbiased results (example: 4-Gbit Micron)
    - In-situ tests are required
    - Unbiased preselection tests may be useful
Comparison between NAND-Flash and DDR3 SDRAM

Test Results
The 25 nm NAND-Flash cross section at low LET is about two orders of magnitude higher compared to the DDR3 SDRAM cross section and the 4x8 Gbit NAND-Flash cross section.
The column SEFI cross section of the 2 Gbit Micron DDR3 SDRAM is two orders of magnitude higher compared to the respective 16/32 Gbit NAND-Flash cross section.
There are big differences among the DDR3 SDRAM Row SEFI cross sections.

The 2 Gbit Micron cross section is about two orders of magnitude above the favourable DDR3 parts.

The 16/32 Gbit NAND-Flash cross section is similar to the favourable DDR3 SDRAM cross sections.
Comparison SEE HI: Block SEFI

Class B: Transient

Class C: Persistent

- NAND-Flash only
Comparison SEE HI: Device SEFI

- DDR3 SDRAM only
- The effectiveness of software conditioning depends on the manufacturer.
NAND-Flash only

The NAND-Flash Destructive Failure is permanent damage with definite data loss.

Neither NAND-Flash nor DDR3 SDRAM suffered from SEL
25 nm NAND-Flash is by the factor of 400 more sensitive to proton SEUs than DDR3 SDRAM (feature size ≈ 35 nm). NAND-Flash and DDR3 SDRAM show an increase of SEUs towards low energies. This should be investigated further to exclude peculiarities of the source.
In most cases the SEFI count is very low. To get more SEFI events the fluence a higher fluence is needed, which is hard to realize because of the limited beam time and in case of NAND-Flash because of the limited total dose.
Comparison SEE Proton: Row SEFI

NAND-Flash

- Page Errors, Storage Mode M3a, 25nm
- Page Errors, Storage Mode M3a, 25nm

The 32 Gbit Micron data points are shifted to the right by 3 MeV to improve readability.

DDR3 SDRAM

- Hynix
- Samsung
- Micron
- Nanya
Neither NAND-Flash nor DDR3 SDRAM suffered from permanent damaging effects like Destructive Failure or SEL
Recent Publications


Conclusions
Results
TID

DDR3 SDRAM
- DDR3 technology in general low sensitive to TID
- Outstanding TID performance of SK Hynix 4 Gb and Samsung 4 Gb devices:
  - H5TQ4G83MFR-H9C: almost insensitive to TID > 400 krad
  - K4B4G0846B-HCH9: 1st data errors at TID > 150 krad
- Very promising candidates for JUICE mission regarding TID

NAND Flash
- Heritage parts with good TID performance > 90 krad, well suitable for JUICE mission
- Scaled technologies show much lower TID tolerance:
  - Functional failures at TID > 30 krad (HDR) independent from applied intermediate refresh
  - Suitable for TID level ≤ 25 krad
  - High amount of shielding mandatory for use in JUICE mission
Results
SEE

DDR3 SDRAM
- Less sensitive to SEU than former technologies and NAND flash
- Increased sensitivity to SEFI leads to the need of further mitigation techniques
- Increase of SEE sensitivity to protons with scaling - direct ionisation?
- No Single Event Latch-up at LET > 60 MeVcm\(^2\)mg\(^{-1}\) and T > 80°C

NAND Flash
- Very good SEU and SEFI performance of heritage parts
- Scaled technologies show increased SEU and SEFI sensitivity compared to heritage parts, but still reasonable
- No data loss in case of SEFI due to non-volatility
- Increase of SEE sensitivity to protons with scaling, 25 nm technology - direct ionisation?
- No Single Event Latch-up at LET > 60 MeVcm\(^2\)mg\(^{-1}\) and T > 80°C
  BUT destructive events at LET < 15 MeVcm\(^2\)mg\(^{-1}\) (LET ≈ 30 MeVcm\(^2\)mg\(^{-1}\) for heritage parts):
  \(\lambda_{\text{destructive}} \approx 4.3 \text{ FIT (< 0.1 FIT for heritage parts)}\)
# Results

## SEE Rates

<table>
<thead>
<tr>
<th>SEU [day^{-1}bit^{-1}]</th>
<th>Quiet (JUICE)</th>
<th>Solar flare (CREME96, Worst Week)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HI</td>
<td>p^+</td>
</tr>
<tr>
<td><strong>DDR3 SDRAM</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H5TQ4G83MFR</td>
<td>1.0E-14</td>
<td>1.6E-12</td>
</tr>
<tr>
<td>K4B4G0846B</td>
<td>5.0E-13</td>
<td>4.1E-13</td>
</tr>
<tr>
<td><strong>NAND Flash</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K9WBG08U1M</td>
<td>8.8E-12</td>
<td>5.2E-14</td>
</tr>
<tr>
<td>MT29F16G08ABACAWP-IT:C/MT29F32G08ABAAAWP-IT:A</td>
<td>5.7E-10</td>
<td>8.1E-10</td>
</tr>
<tr>
<td><strong>SEFI [day^{-1}]</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>HI</td>
<td>p^+</td>
</tr>
<tr>
<td><strong>DDR3 SDRAM</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H5TQ4G83MFR</td>
<td>6.6E-04</td>
<td>6.5E-05</td>
</tr>
<tr>
<td>K4B4G0846B</td>
<td>7.9E-05</td>
<td>7.2E-07</td>
</tr>
<tr>
<td><strong>NAND Flash</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K9WBG08U1M</td>
<td>1.3E-05</td>
<td>7.9E-07</td>
</tr>
<tr>
<td>MT29F16G08ABACAWP-IT:C/MT29F32G08ABAAAWP-IT:A</td>
<td>4.1E-04</td>
<td>4.5E-04</td>
</tr>
<tr>
<td><strong>Destructive Failure [day^{-1}]</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>NAND Flash</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K9WBG08U1M</td>
<td>2.5E-09</td>
<td>-</td>
</tr>
<tr>
<td>MT29F16G08ABACAWP-IT:C</td>
<td>1.0E-07</td>
<td>-</td>
</tr>
</tbody>
</table>
Questions