Radiation Effects of Commercial Resistive Random Access Memories

Dakai Chen, Kenneth LaBel, NASA Goddard Space Flight Center, Greenbelt, MD 20771

Melanie Berg, Edward Wilcox, Hak Kim, Anthony Phan, ASRC Space and Defense, Inc., Seabrook, MD 20706

Marco Figueiredo, Orbital Science corp., Greenbelt, MD 20770

Stephen Buchner, Ani Khachatrian, Nicolas Roche, Naval Research Laboratory, Washington, DC 29375
Acknowledgement

• Sponsors:
  • NASA Electronics Parts and Packaging (NEPP) Program
  • Defense Threat Reduction Agency (DTRA)
  • National Reconnaissance Office (NRO)
• Adesto and Panasonic for providing technical support
Acronyms

• 1T1R – 1 transistor 1 resistor
• BEOL – Back-end-of-line
• CBRAM – Conductive-bridge random access memory
• CMOS – Complimentary metal-oxide-semiconductor
• EEPROM – Electrically erasable programmable read only memory
• LCDT – Low cost digital tester
• LBNL – Lawrence Berkeley National Laboratory
• LET – Linear energy transfer
• RAM – Random access memory
• ROM – Read-only memory
• ReRAM – Reduction-oxidation random access memory
• RRAM – Resistive Random Access Memory
• SEE – Single-event effect
• SEFI – Single-event functional interrupt
• SEU – Single-event upset
• SOIC – Small Outline Integrated Circuit
• TAMU – Texas A&M University
Motivation

- Limited availability of radiation tolerant flash memories
- Radiation performance of state-of-the-art flash is generally good but include some weaknesses
- Flash already reaching scaling limits
- Resistive random access memory (RRAM) has shown very good tolerance to radiation*
- Published radiation test results only from test chips
- A first look at the SEE performance of two commercial production-level RRAMs


Panasonic Embedded ReRAM

Panasonic MN101L
- 16 bit microcontroller with embedded ReRAM
- Industry’s first mass production-level ReRAM

1T1R array architecture, with CMOS transistor as access transistor to each ReRAM stack
- TaOₓ as switching layer
- Minimum device width ~ 0.5 μm
- Fabricated back-end-of-line in a 180 nm CMOS process

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Memory Size</td>
<td>64 KB</td>
</tr>
<tr>
<td>Program Endurance</td>
<td>Program area (62 KB): ≥ 10³</td>
</tr>
<tr>
<td></td>
<td>Data area (2 KB): ≥ 10⁵</td>
</tr>
<tr>
<td>Programming Voltage</td>
<td>1.8 to 3.6 V</td>
</tr>
<tr>
<td>Reading Voltage</td>
<td>1.1 to 3.6 V</td>
</tr>
<tr>
<td>Data Retention</td>
<td>10 years</td>
</tr>
</tbody>
</table>


ReRAM – Reduction-Oxidation Random Access Memory
1T1R – 1 transistor 1 resistor

To be published on nepp.nasa.gov previously presented by Dakai Chen at the NASA Electronic Parts and Packaging (NEPP) Electronics Technology Workshop (ETW), Greenbelt, MD, June 17-19, 2014.
Heavy Ion Testing

- Kovar lid collimator (254 μm) exposed ReRAM array and peripheral control circuits
- Used Panasonic’s evaluation card as test vehicle
- ROM operating conditions: \( V_{cc} = 3.3 \) V, Frequency = 8 MHz or DC
- Test modes: static, dynamic read, read/compare/write, and write
- Data patterns: 00, FF, 55, and AA
- 15 MeV/amu heavy ions in air at Texas A&M University
- 16 MeV/amu heavy ions in vacuum at Lawrence Berkeley National Laboratory

ROM – Read-Only Memory
Heavy Ion Test Results

- No SEU from static test
  - 1 functional error following Xe irradiation, during read-back, recovered by a reset
- Dynamic read and write produced mostly SEFIs
  - 1 locked mode event
- Similar SEFI cross sections for read and write test mode
- Angular irradiation
  - Beam shadowing from the collimator likely contributed to reduced cross section

SEU – Single-Event Upset
SEFI – Single-Event Functional Interrupt
SEE Characteristics

- **Functional interrupts**
  - Microcontroller stops reading/writing
  - Flash vulnerable to large scale page and block errors

- **Bit upsets**
  - Include single-bit and multiple-bit upsets
  - Error address locations distributed throughout the microcontroller memory bank
  - 8 SEUs in the ROM

Pulsed-Laser Testing

• Pulsed-laser testing was carried out at the Naval Research Laboratory

• Laser characteristics
  – Wavelength = 590 nm
  – 1/e penetration range = 2 μm in silicon
  – Beam diameter = 1.7 μm for 20× lens, 0.9 μm for 100× lens

• We probed the ReRAM array and surrounding peripheral circuits with a 20× lens to identify the sensitive regions

• Sensitive areas were further investigated with a 100× lens, and the energy was fine-tuned to determine the upset energy threshold

• Equivalent LET values are based on empirical data from previous studies on other device types

LET – Linear Energy Transfer
Sensitive Locations

- **Bit upsets**
  - Did not originate from the ReRAM array
  - Location sensitive to SEUs also susceptible to SEFIs

- **Functional interrupt**
  - Stops reading/writing
  - Continuously reading out errors from the ROM
  - Stuck reading at end of Bank0 (FFFF)
  - Continuously reading errors from other address locations beside the ROM
Upset Sensitivity in the Most Sensitive Location

- Determine upset energy threshold at the most sensitive location using 100× lens
- Location 1:
  - Read mode: 5.5 pJ (17 MeV·cm²/mg)
  - Write mode: 8.6 pJ (26.5 MeV·cm²/mg)
- Location 2:
  - Read mode: 71 pJ (220 MeV·cm²/mg)
- Location 3:
  - Read mode: 105 pJ (320 MeV·cm²/mg)
SEE Characteristics

- Compare SEE characteristics with heavy ion results
- Memory address of errors from laser test are similar to those from heavy ion test
- SEFI modes from laser and heavy ion test are also similar
  - Although limited information was gained from SEFIs that caused immediate cease of operation
- Sensitive region consists of sense amplifier circuit
  - SEU in the sensing circuit of flash devices lead to SEFI*

SF Register – Special function register
IO Register – Input/Output register


To be published on nepp.nasa.gov previously presented by Dakai Chen at the NASA Electronic Parts and Packaging (NEPP) Electronics Technology Workshop (ETW), Greenbelt, MD, June 17-19, 2014.
Adesto CBRAM

- 128 kb EEPROM from Adesto
- Ag/GeS2/W conductive bridge memory (CBRAM)
- 1T1R structure
- Back-end-of-line 130 nm CMOS

EEPROM – Electrically Erasable Programmable Read-Only Memory

To be published on nepp.nasa.gov previously presented by Dakai Chen at the NASA Electronic Parts and Packaging (NEPP) Electronics Technology Workshop (ETW), Greenbelt, MD, June 17-19, 2014.
Adesto CBRAM

- Heavy ion test carried out at LBNL in vacuum
- 8-pin SOIC packages were chemically etched to expose die
- 16 MeV/nuc cocktail
- Test conditions:
  - NASA’s LCDT tester
  - Vcc = 3.3 V
  - Frequency = 1 kHz or DC
  - Mode: static random read, static sequential read, continuous random read, write all/random read, write all/sequential read
  - Patterns: 00, FF, AA, and counter

LBNL – Lawrence Berkeley National Laboratory
SOIC – Small Outline Integrated Circuit
LCDT – Low Cost Digital Tester

To be published on nepp.nasa.gov previously presented by Dakai Chen at the NASA Electronic Parts and Packaging (NEPP) Electronics Technology Workshop (ETW), Greenbelt, MD, June 17-19, 2014.
SEE Characteristics

- Static “On” and dynamic test modes produced mostly SEFIIs
- Most (if not all) bit upsets due to acknowledgement fails, indicative of control circuit errors and not array errors
- SEFI modes
  - Stuck address, accumulating acknowledgement failures
    - Occurred during read and write/read test modes
    - Reset usually required
  - Read errors in continuous addresses
    - Column, page, or entire memory read out 00FF
    - Errors may clear by itself, or reset required
- No Apparent pattern sensitivity for FF, 00, AA, and Counter
SEE Characteristics

- Column errors (0000 to 000F) during read; memory still functional
SEE Characteristics

- Column errors (0000 to 00CF) during read; memory still functional
SEE Characteristics

- Entire memory reading 00FF during read
- Column errors (0000 to 00CF) during read
- Stuck at single address; reset required
SEE Characteristics

Irradiated with 16 MeV/nuc heavy ions
Frequency = 100 kHz, \( V_{CC} = 3.6 \) V

Cross Section (\( cm^2/device \))

Effective LET (MeV\cdot cm^2/mg)

- **Read**
- **Write/Random Read**
- **Write/Sequential Read**
Conclusion

- RRAM array immune to heavy ions with LET as high as 75 MeV·cm²/mg
  - SEU in CMOS access transistor not enough to cause bit flip
- SEFI is the dominant error mode
  - Panasonic MN101L embedded ReRAM’s SEFIs originate from sense amplifier circuits
  - Adesto CBRAM showed column/page errors, mass read errors from entire memory, and stuck address errors
- Lack of charge pump reduces sensitivity to erase or program failure
  - Eliminates block erase failures (issue for flash)