Qualification and Reliability of MRAM Toggle Memory Designed for Space Applications

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MRQW
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Outline

• Introduction
• Why MRAM for Space Applications
• MRAM Technology
• Development of an Emerging Technology
• MRAM Reliability Evaluation
• Status of Cobham MRAM
• Continuous Improvement for Reliability
Introduction

Emergence of MRAM Technology

- MRAM R&D has been ongoing for 25 years
- Commercial MRAM (Everspin) was introduced 14 years ago
- Space Qualified MRAM (Cobham) is now in its 6th year

MTJs based MRAM: 24 years of R&D

Graphical History of MTJ MRAM (B. Dieny)
Why MRAM for Space
Technology Evaluation and Selection

Traditional non-volatile technologies could not meet requested radiation targets

• Circa 2010 ... Repeated calls from the Space Community for a TID, SEL, SEGR and upset immune non-volatile memory for critical boot applications

• ... pushed industry toward emerging technologies

• MRAM Strengths
  – Bit Cell SEU Immune to >100 MeV·cm²/mg
  – Bit Cell TID Immune to >1 Mrad(Si)
  – Low Voltage (SEGR, SEB immune)
  – Unlimited Endurance
  – Retention beyond mission lifetimes
  – High speed
  – Symmetric Read & Writes

Commercial NVM Technology Survey

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Flash</th>
<th>nvSRAM</th>
<th>SONOS</th>
<th>FRAM</th>
<th>CRAM</th>
<th>MRAM</th>
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<tbody>
<tr>
<td>Endurance</td>
<td>$10^5$</td>
<td>$10^6$</td>
<td>$10^5$</td>
<td>$10^6$</td>
<td>$&gt;10^{12}$</td>
<td>$&gt;10^{12}$</td>
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<tr>
<td>Retention (yrs)</td>
<td>$&gt;10$</td>
<td>$&gt;10$</td>
<td>$&gt;10$</td>
<td>$&gt;10$</td>
<td>$&lt;1$</td>
<td>$&gt;10$</td>
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<tr>
<td>Destructive Read</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
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<tr>
<td>Read Time</td>
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<td>20ns</td>
<td>20ns</td>
<td>100ns</td>
<td>500ns</td>
<td>35ns</td>
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<tr>
<td>Erase/Write Time</td>
<td>10ms</td>
<td>20ns</td>
<td>10ms</td>
<td>100ns</td>
<td>70ns</td>
<td>35ns</td>
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<tr>
<td>High Voltage</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>SEL</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td>SEGR Sensitivity</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
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<tr>
<td>SEU Bit Cell</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
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<tr>
<td>SHE/RILC Bit Cell</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>SEFI (data lost)</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
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<tr>
<td>TID rad(Si)</td>
<td>$&lt;50k$</td>
<td>$&lt;50k$</td>
<td>100k</td>
<td>$&gt;200k$</td>
<td>$&gt;200k$</td>
<td>$&lt;100k$</td>
</tr>
<tr>
<td>Maturity</td>
<td>Good</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Poor</td>
<td>Moderate</td>
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</table>

Weaknesses in commercial MRAM fixable by RHBD techniques

Weaknesses in other commercial technologies were intrinsic
Magnetoresistive Random-Access Memory (MRAM) is a type of non-volatile random-access memory which stores data in magnetic domains.

- **Non-Volatile**: Months to decades of data retention without power or refresh
- **Fast**: Read/write similar to SRAM & DRAM
- **Endurance**: Handles memory workloads

Courtesy of Everspin Inc.
Electron Spin is the Basis of MRAM

A non-volatile memory not based on charge storage

- Spin is a fundamental quantum number
- Ferromagnetic materials contain unpaired electrons
- Alignment of spin results in magnetism
- Memory is stored in the spin of the electrons
- Spin does not "leak" like charge
- Spin is not affected by heavy ion irradiation
- Spin is not affected by accumulated dose (TID)
- Spin alignment achieved by magnetic fields
- Avoids wear out mechanisms of charge based devices

Spin Quantum Number

Fe

$4s$

$3d$

[Ar]$3d^64s^2$
Magneto-Tunnel Junctions

• MTJ = Magneto Tunnel Junction
• TMR = Tunnel Magnetoresistance (Ratio)

\[ TMR = \frac{R_{AP} - R_P}{R_P} = \frac{2P_1P_2}{1-P_1P_2} \]

• Ferromagnetic materials have an imbalance of spin up (e↑) and spin down (e↓) electrons
• Electron spin conserved during tunneling
• The total electron current for in a given state is constrained by the minimum number of available states on both sides of the barrier
• Therefore the total current is greater when the magnetic materials on both sides of the barrier are aligned
MRAM Bit Cell

Writing an MRAM Bit

- MRAM cell created from a Magnetic Tunnel Junction (MTJ)
- Information stored as magnetic polarization
- Data (polarization) is written by creating a magnetic field with two perpendicular metal lines
- Infinite endurance
- Fast access NVM (35ns to 50ns)
- Non Destructive Read


Magnetic layer 1 (free layer)
Magnetic layer 2 (fixed layer)

Magnetic vectors are parallel (Low Resistance “0”)
Magnetic vectors are anti-parallel (High Resistance “1”)
Toggle MRAM Operation

Same flow toggles bit from 1→0 or 0→1

- Long axis displays higher magnetic moment thus becomes “favored” orientation
- In actual device, MTJ is composed of a complex multi-layered Synthetic Anti-Ferromagnetic (SAF) structure
- Ferromagnetic layers resist alignment as would two permanent magnets
- Polarization within SAF layers is modulated by the combined magnetic field vectors $H_1$ and $H_2$
- Angled bit cell orientation allows the same pulse sequence to change a 1 to 0 or 0 to 1
- Three step toggle sequence mitigates disturbs

• Ken LaBel (NEPP 2010) ... Word of warning:
  – *There are ALWAYS more challenges in “qualifying” a new technology device than expected*

**Technology Selection**
- Remain objective
- Fall in love with the problem not the solution

**Technology Evaluation**
- Do existing techniques apply
- Can commercial data be leveraged
- Does target environment effect mechanisms
- What must be re-validated

**Define Mission Success**
- Performance requirements vs. wish list
- Reliability requirements vs. ideals
- Screens/Specs - value vs. false security
- Quantify Risks

**Design, Fab, Test and Qual**
- DFT (Techniques to evaluate mechanisms)
- Design for Reliability (including Radiation)
- Refine rationale behind specification limits
- Refinement of process, screens, flows

**13 Technologies Evaluated**
- Existing, Emerging & Exotic
- Sampled and Tested

**Expert Partners (Everspin)**
- Used all available data
- Extended Reliability Demo

**Government Input (AFRL,..)**
- Industry Input (Customers)
- Re-evaluate as Tech Matures

**Mil Standard QML-V flow**
- Monitor beyond Data Sheet
- Accelerated Life Test
# 16Mb & 64Mb RadHard MRAM

## Product Details

<table>
<thead>
<tr>
<th>Part Number</th>
<th>UT8MR2M8</th>
<th>UT8MR8M8</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMD#</td>
<td>5962-12227</td>
<td>5962-13207</td>
</tr>
<tr>
<td>Density</td>
<td>16Mb</td>
<td>64Mb, MCM</td>
</tr>
<tr>
<td>Interface</td>
<td>Asynchronous SRAM</td>
<td></td>
</tr>
<tr>
<td>Configuration</td>
<td>2M x 8 bit</td>
<td>8M x 8 bit</td>
</tr>
<tr>
<td>Supply Voltage</td>
<td>+3.3V</td>
<td></td>
</tr>
<tr>
<td>Access Time</td>
<td>45ns/45 ns</td>
<td>50ns/50ns</td>
</tr>
<tr>
<td>(read/write)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Write Endurance</td>
<td>Unlimited cycles &gt; 20 years</td>
<td></td>
</tr>
<tr>
<td>Data Retention</td>
<td>20 years</td>
<td></td>
</tr>
<tr>
<td>Process Technology</td>
<td>180nm LP TSMC</td>
<td></td>
</tr>
<tr>
<td>Temp Range</td>
<td>-40°C to 105°C</td>
<td></td>
</tr>
<tr>
<td>Typical Power¹</td>
<td>~10mW/MHz (read)</td>
<td>~15mW/MHz (read)</td>
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<tr>
<td>Package</td>
<td>40 pin CFP, 25 mil pitch</td>
<td>64 pin CFP, 50 mil pitch</td>
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<tr>
<td>Operational Environment</td>
<td>TID: 1Mrad(Si)</td>
<td>SEL: 112 MeV·cm²/mg @105°C</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SEU: 112 MeV·cm²/mg @25°C</td>
</tr>
<tr>
<td>Qualifications</td>
<td>QML-Q, -V</td>
<td></td>
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</tbody>
</table>

¹Nominal voltage at room temp

![Block Diagram of 16Mb MRAM](image)

- RHBD to achieve SEL immunity
- RHBD and Process to >1Mrad(Si) TID
- Bit cell immune to upset
- ECC protects against single bit SER
Reliability Evaluation
QML-V Qualification and Reliability Demonstration

- Cobham re-validated activation energies and expanded models
- Cobham added reliability mechanism specific burn-in screens to flow
- Cobham extended lifetime projections to > 15 years

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Method</th>
<th>Results</th>
<th>Data</th>
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<tbody>
<tr>
<td>Gate Oxide Integrity (core)</td>
<td>Constant Voltage TDDB</td>
<td>&gt; 15 yr</td>
<td>&lt; 1 PPM</td>
</tr>
<tr>
<td>Gate Oxide Integrity (IO)</td>
<td>Constant Voltage TDDB</td>
<td>&gt; 15 yr</td>
<td>&lt; 20 PPM</td>
</tr>
<tr>
<td>Hot Carrier Integrity (core)</td>
<td>Vd-accel Idsat Degradation</td>
<td>&gt; 15 yr</td>
<td>&lt;0.1% shift</td>
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<tr>
<td>Hot Carrier Integrity (IO)</td>
<td>Idsat Degradation</td>
<td>&gt; 15 yr</td>
<td>&lt;10% shift</td>
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<tr>
<td>NBTI</td>
<td>Constant Voltage Bias</td>
<td>&gt; 15 yr</td>
<td>&lt;10% shift</td>
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<tr>
<td>Electromigration (CMOS)</td>
<td>Constant Current Stress</td>
<td>&gt; 15 yr</td>
<td>&lt;1 PPM</td>
</tr>
<tr>
<td>Electromigration (MRAM)</td>
<td>Constant Current Stress</td>
<td>&gt; 15 yr</td>
<td>&lt;1 PPM</td>
</tr>
<tr>
<td>Tunnel Barrier Integrity</td>
<td>Constant Voltage TDDB</td>
<td>&gt; 15 yr</td>
<td>&lt;1 PPM</td>
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<tr>
<td>Bias-Driven Resistance Drift</td>
<td>Constant Voltage Bias/High Temperature</td>
<td>&gt; 15 yr</td>
<td>&lt; 1000 FIT</td>
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<tr>
<td>Thermal Resistance Shift</td>
<td>High Temperature Bake</td>
<td>&gt; 15 yr</td>
<td>&lt; 1000 FIT</td>
</tr>
<tr>
<td>Magnetic Layer Integrity</td>
<td>High Temperature Bake</td>
<td>&gt; 15 yr</td>
<td>&lt;0.1% shift</td>
</tr>
<tr>
<td>Data Retention</td>
<td>High Temperature Bake</td>
<td>&gt; 20 yr</td>
<td>&lt; 1 PPM</td>
</tr>
</tbody>
</table>


Select Subset of Evaluated Wear Out Mechanisms
Status of Cobham MRAM

Timeline of MRAM introduction in Space Applications

- MRAM transition from emerging to mainstream
- First launches 3/14/16 (EXOMARs, OSIRIS-REx)
- 144 Design In's, 71 Customers
- Cobham 64Mb MRAM QML-V qualified (1/08/2016)
- Cobham 16Mb MRAM QML-V qualified (12/22/2015)
- Cobham 16Mb MRAM QML-Q qualified (3/25/2014)
Qualification of Emerging Technologies

Continuous Improvement Applied to Reliability

- Is a standard QML-V qualification flow adequate for emerging technologies?

- Must Evaluate ...
  - Are there interactions between failure mechanisms?
  - Did intrinsic “bulk” property analysis comprehend full population?
  - How can process variation learning be accelerated?
  - Develop techniques to expose new mechanisms
  - Refine rationale behind specification limits
  - Refinement of process, screens, flows
  - Quantification of risk

How do we learn the answers to questions we don’t yet know to ask?

Case Study ... End of life accelerated HTOL testing on product
Continuous Improvement & Reliability

120,000 Hour Equivalent (EOL) Accelerated Stress – Reliability Growth

- Accelerated HTOL used to develop device wear out models
- Data used to determine guard bands at final test
- 60 worst case devices selected from 4 contemporary lots
- Additional 22 devices from original QML-V qual lot
- End of Life FIT rates (to internal ECC-off test limit) determined
- Post-stress Testing
  - All devices pass to all Data Sheet specs at EOL
  - No (ECC-on) failures at EOL or any read point

Internal ECC-off EOL Limit FIT Rate

<table>
<thead>
<tr>
<th>Lot No.</th>
<th>Avg. FIT Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lot A</td>
<td>67.7</td>
</tr>
<tr>
<td>Lot B</td>
<td>122.3</td>
</tr>
<tr>
<td>Lot C</td>
<td>455.3</td>
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<tr>
<td>QML-V Lot</td>
<td>180.5</td>
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<tr>
<td>Lot D</td>
<td>25.5</td>
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Continuous Improvement Quantifies and Validates QML-V Qualification
Summary

MRAM and Reliability of Emerging Technologies

• Cobham MRAM introduced at QML-Q level in 2014
  – TID hardened to >1Mrad(Si)
  – SEL Immune (100 MeV·cm²/mg)
  – SEU immune (100 MeV·cm²/mg)

• Reliability of an emerging technology can be enhanced through:
  – Thorough physics of failure characterization
  – “Design for Radiation” and “Design for Reliability” techniques
  – Screening coupled with understanding of mechanisms
  – A “Continuous Improvement” methodology approach
  – Accelerated lifetime characterization of product