Technology, Manufacturing and Markets of Magnetoresistive Random Access Memory (MRAM)

Brad Engel, VP - Product Development & Quality
Everspin – Electron Spin is Forever

- **Industry-first and leading MRAM supplier**
  - Technology leader in **Toggle MRAM** and **ST-MRAM**
  - Shipped over **2.5M** units with over **300** active customers to date
  - Over 15 years of design and production experience with **MRAM**

- **Break through non-volatile memory products and IP**
  - 70 Products in 3 Memory Families
  - Asynchronous x8, x16 and Serial SPI
  - 600 Active Patents and Applications WW
  - 176 Issued / 47 Pending US Patents

- **Backed by leading VC Investors** *(Spin-out from Freescale in June, 2008)*

- **Global Footprint**
  - Headquarters: Chandler, AZ, USA
  - Manufacturing: USA, Singapore, Thailand, China
  - Sales Offices: USA, Europe, China, Japan
  - Design Center: Austin, TX, USA

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What is MRAM Technology?

- Simple 1 transistor + 1 MTJ memory cell
- Magnetic polarization stores data
- Resistance levels represent bit values compared to electron charge levels
- Highly reliable non-volatile memory
- Unlimited cycling endurance
- Low latency enabling instant on/off
**Toggle Write**

- Write accomplished by magnetic fields from current passing through bit and word lines.
- In volume production

**Spin-Torque Write**

- Write accomplished by spin polarized current passing through the MTJ.
- In development
## Everspin MRAM Advantages

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Capability</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Non-volatile capability</strong></td>
<td>Data retention of the bit cell &gt; 20 years</td>
</tr>
<tr>
<td><strong>Performance</strong></td>
<td>Symmetric read/write – 35ns / 40MHz Serial</td>
</tr>
<tr>
<td><strong>Endurance</strong></td>
<td>Unlimited cycling endurance</td>
</tr>
<tr>
<td><strong>CMOS integration</strong></td>
<td>Easily integrates into back-end process</td>
</tr>
<tr>
<td></td>
<td>Compatible with embedded designs → No effect on CMOS</td>
</tr>
<tr>
<td></td>
<td>Allows for flexible manufacturing</td>
</tr>
<tr>
<td><strong>Temperature range</strong></td>
<td>-40°C &lt; T &lt; 150°C operation demonstrated</td>
</tr>
<tr>
<td><strong>High Temp Storage</strong></td>
<td>Intrinsic reliability &gt; 20 years lifetime at 125°C</td>
</tr>
<tr>
<td><strong>Soft error immunity</strong></td>
<td>Alpha radiation soft error rate too low to measure (&lt;0.1 FIT per Mb) → Everspin partners offer radiation hardened MRAM</td>
</tr>
<tr>
<td><strong>Environmentally friendly</strong></td>
<td>No battery/caps, RoHS/REACH compliant, instant-on</td>
</tr>
</tbody>
</table>
How is MRAM made?

- **Leverage CMOS semiconductor ecosystem**
  - Everspin MRAM layer added to standard CMOS
  - Standard packages with protective internal shield

- **Common standard package types**
  - Drop in replacement fits footprints for existing printed circuit board designs

- **Pin for Pin functionally equivalent**
  - BBSRAM, SPI NVM, nvSRAM and FeRAM
## Current Toggle MRAM Products

### 16-bit I/O

<table>
<thead>
<tr>
<th>Part Number</th>
<th>Density</th>
<th>Configuration</th>
<th>Temp</th>
</tr>
</thead>
<tbody>
<tr>
<td>MR4A16B</td>
<td>16Mb</td>
<td>1M x 16</td>
<td>C, I, A</td>
</tr>
<tr>
<td>MR2A16A</td>
<td>4Mb</td>
<td>256K x 16</td>
<td>C, I, E, A</td>
</tr>
<tr>
<td>MR0A16A</td>
<td>1Mb</td>
<td>64K x 16</td>
<td>C, I, E, A</td>
</tr>
</tbody>
</table>

### 8-bit I/O

<table>
<thead>
<tr>
<th>Part Number</th>
<th>Density</th>
<th>Configuration</th>
<th>Temp</th>
</tr>
</thead>
<tbody>
<tr>
<td>MR4A08B</td>
<td>16Mb</td>
<td>2M x 8</td>
<td>C, I, A</td>
</tr>
<tr>
<td>MR2A08A</td>
<td>4Mb</td>
<td>512K x 8</td>
<td>C, I</td>
</tr>
<tr>
<td>MR0A08B</td>
<td>1Mb</td>
<td>128K x 8</td>
<td>C, I</td>
</tr>
<tr>
<td>MR256A08B</td>
<td>256Kb</td>
<td>32K x 8</td>
<td>C, I</td>
</tr>
<tr>
<td>MR0D08B</td>
<td>1Mb</td>
<td>128K x 8, 1.8V I/O</td>
<td>C</td>
</tr>
<tr>
<td>MR256D08</td>
<td>256Kb</td>
<td>32K x 8, 1.8V I/O</td>
<td>C</td>
</tr>
</tbody>
</table>

### SPI I/O

<table>
<thead>
<tr>
<th>Part Number</th>
<th>Density</th>
<th>Configuration</th>
<th>Temp</th>
</tr>
</thead>
<tbody>
<tr>
<td>MR25H40</td>
<td>4Mb</td>
<td>512K x 8</td>
<td>I, A</td>
</tr>
<tr>
<td>MR25H10</td>
<td>1Mb</td>
<td>128K x 8</td>
<td>I, A</td>
</tr>
<tr>
<td>MR25H256</td>
<td>256Kb</td>
<td>32K x 8</td>
<td>I, A</td>
</tr>
</tbody>
</table>

### 48-BGA
- x8 Asynchronous parallel I/O
- x16 Asynchronous parallel I/O
- x8 Asynchronous parallel 1.8V I/O

### 44-TSOPII, 54-TSOP
- x8 Asynchronous parallel I/O
- x16 Asynchronous parallel I/O

### 8-DFN
- SPI-compatible serial I/O
- 40 MHz; No write delay

### 32-SOIC
- x8 Asynchronous parallel I/O

### Temperatures

<table>
<thead>
<tr>
<th></th>
<th>Commercial</th>
<th>Industrial</th>
<th>Extended</th>
<th>Automotive</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 to +70 °C</td>
<td>-40 to +85 °C</td>
<td>-40 to +105 °C</td>
<td>-40 to +125 °C</td>
</tr>
</tbody>
</table>

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MRAM Markets & Applications

Storage Systems & Servers
Industrial Automation & Robotics

Automotive & Transportation
Energy Management

Telecom & Datacom
Consumer, POS, Gaming

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Toggle MRAM Used by Top Companies

Siemens Recognizes Everspin Technologies for Perfect MRAM Quality - May, 2009
“After two years of high volume production and more than 100K systems in the field, we are very happy with the perfect quality and reliability of Everspin’s products in our industrial automation systems”
http://www.semiconductor.net/article/CA6658902.html

Everspin’s automotive-temperature MRAM meets harsh environment demands in BMW S1000 RR racing bike
Everspin introduces AEC-Q100 MRAM products to serve broad automotive applications; 4Mb MRAM stores critical calibration data for BMW Motorsport Super Bike

Everspin Technologies’ MRAM Selected by Emerson Network Power to Deliver Critical Storage for Industrial Computing Boards
Non-volatile MRAM technology provides a robust, reliable memory solution for VME and Compact PCI boards.

Everspin Technologies to provide Airbus with MRAM products for advance wide body aircraft
Flight Control Computer on A350 XQB aircraft uses MRAM for critical program and data storage in extreme environment applications.

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**MRAM Writes and Reads**

- Write Current Flows Down Write Line 1 & 2
- Magnetic Tunnel Junction (MTJ) At Cross-Point Is Polarized
- Polarization State Is Read By Selecting Pass Transistor to Sense Resistance of Specific MTJ
MRAM Integration

MRAM module

Metal 5
Cu
Via 3
Metal 4
Cu
Metal 3
Via 2
Metal 2
Via 1
Metal 1
Contact
Bit cell

MTJ
Metal 5
Metal 4
MTJ
MTJ Bit Materials

Free Synthetic Antiferromagnet (SAF)
- Free M2
- Ru
- Free M1
- AlOx
- Fixed
- Ru
- Pinned
- AF pinning layer
- Seed
- Base electrode

Tunnel barrier

Pinned Synthetic Antiferromagnet (SAF)

Materials:
- Ta
- Eg, NiFe, CoFe, CoFeB
- Eg, NiFe, CoFe, CoFeB
- Eg, PtMn, IrMn
- Ta/TaN
Ultra-thin layers require precision control for manufacturing
Toggle MRAM: Write Mechanism

- Toggle MRAM is a unique approach that provides both robust switching performance and manufacturability
  - Response of synthetic antiferromagnetic free layer is the key.

Conventional MRAM

- Single Layer
- H=0: Aligns with applied field
- H≠0: Rotates perpendicular to applied field

Toggle MRAM

- Synthetic Antiferromagnet
- H=0: Aligns with applied field
- H≠0: Rotates perpendicular to applied field


**Toggle Write Operation**

- **Low-R State**
  - MTJ
  - Pinned
  - $I_1$
  - $H_1$

- **High-R State**
  - MTJ
  - Pinned
  - $H_2$

- **Advantages:**
  - Eliminates disturb
  - Large operating window

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Robust Toggle-Bit Selection

- Robust bit disturb margin
- All bits along $\frac{1}{2}$-selected current lines have increased energy barrier during programming
Toggle Switching Characteristics

Current $I_1$

No switching

Switching Region

Current $I_2$

No switching

Bit Saturation
Toggle-bit Array Characteristics

4Mb, March6N Toggle Map

0% switching region (no disturbs)
Write Operating Region at 125 °C

- Large write window at Automotive temperatures

- $H_{sat}, H_{sw}$ decrease linearly w/Temp, reducing window

\[ H_{sat}, H_{sw} \text{ decrease linearly w/Temp, reducing window} \]
Capacitance at node Integrates Current Difference

\[ I_{\text{Ref}} = (I_{\text{High}} + I_{\text{Low}})/2 \]

Local references created from two MTJ: one high and one low resistance state
**Magnetoresistance and Distributions**

\[
MR = \frac{\Delta R}{R_{\text{low}}} , \quad \Delta R = R_{\text{high}} - R_{\text{low}}
\]

- **Signal** = \( R_{\text{cell}} - R_{\text{ref}} \)
  - \( \frac{1}{2} \) of \( \Delta R \) available for sensing
- **Circuit works at finite bias**
  - MR is reduced by bias dependence of MR
- **Must sense all bits in the array**
  - Circuit must work with bits in tails of the R distribution

Resistance distribution reduces useable MR.

For six-sigma yield in the array, need: \( \Delta R/2 > 6\sigma \)
Read Distribution within an Array

Critical Factors:
1. Tunnel barrier quality
2. Pattern fidelity

Optimized for MRAM

$V_{1/2} \sim +0.7/-0.55$ V

$\Delta R/\sigma = 30$ typical

$\sigma \sim 0.8\%$
## MTJ Deposition on 200mm Wafers

### Measured uniformity—200 mm

<table>
<thead>
<tr>
<th>MR=45%, σ=2%</th>
<th>RA=10.4 kΩ-μm², σ=6%</th>
</tr>
</thead>
<tbody>
<tr>
<td>43.9 44.5 44.6 44.8 44.5 43.1</td>
<td>11.3 11.0 10.5 10.5 10.9 12.3</td>
</tr>
<tr>
<td>44.4 45.0 45.2 46.0 45.8 46.0 44.6 43.1</td>
<td></td>
</tr>
<tr>
<td>44.1 45.4 42.9 45.6 45.6 45.8 44.5</td>
<td></td>
</tr>
<tr>
<td>44.5 46.1 44.3 45.1 45.5 45.8 46.0 45.0</td>
<td></td>
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<tr>
<td>44.5 45.8 43.4 45.4 45.9 45.7 45.9 44.7</td>
<td></td>
</tr>
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<td></td>
</tr>
</tbody>
</table>

Manufacturable wafer level uniformity and wafer-to-wafer repeatability

- optimization of deposition tool, process, and material stack
Toggle MRAM High Reliability

- Predicted lifetime from accelerated testing
- Robust reliability at Automotive temperatures
MRAM is a highly reliable, high-performance, nonvolatile memory IC, with unlimited endurance

- Has the unique characteristics of a working memory while providing non-volatility

Current MRAM products are used in a wide variety of applications

- Data Storage, Industrial Control, Medical Systems, Transportation, Metering and Gaming

Everspin Continues MRAM leadership:

- Expanding MRAM into new markets and applications
- On track to deliver the industry’s first ST-MRAM