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Technical Overview of Magnetoresistive Random Access Memory (MRAM)

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Outline

Overview of Toggle MRAM
Writing
Reading
Reliability
Extended temperatures
Scaling
Summary
### MRAM Advantages

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<th>Nonvolatile</th>
<th>Data Retention - ( \geq 20 \text{ years} )</th>
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<td>Fast</td>
<td>Symmetrical Read/Write – 35ns</td>
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<tr>
<td>Unlimited Cycling</td>
<td>Unlimited Endurance - ( \geq 10^{16} )</td>
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<td>Modular Integration</td>
<td>Easily Integrates in Back End Compatible with Embedded Designs</td>
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<td>Extended Temperatures</td>
<td>-40 °C &lt; T &lt; 150 °C Operation Demonstrated</td>
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<td>Highly Reliable</td>
<td>Intrinsic Reliability Exceeds 20 Year Lifetime at 150 °C Continuous Use</td>
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First Commercial MRAM now in Volume Production

4 Mb Toggle MRAM

- 35ns symmetrical read/write
- Unlimited endurance
- Data retention > 20 Years
- 256Kx16bit organization
- 3.3V single power supply
- Fast SRAM pinout
- Consumer temperature range (0 °C – 70 °C)
- Extended Industrial temperature range (-40 °C – 105 °C)
  - Available now
How MRAM Works

Information stored as magnetic polarization
- Detected as a resistance state

Isolation transistor can be logic device, no high on/off ratio needed
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Free Layer Field Response

Conventional MRAM
*Single Layer*

- $H=0$
  - Aligns with applied field

- $H \neq 0$
  - Rotates perpendicular to applied field

Toggle MRAM
*Coupled Trilayer*

- $H=0$
  - pinned

- $H \neq 0$
  - Rotates perpendicular to applied field
Advantages: Eliminates disturb - Large operating window
Toggle-bit Array Characteristics

4Mb, March-6N Toggle Map

Current 1
- No switching
- Switching Region
- Bit Saturation

Current 2
- No switching

100% toggle

No switch
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Read Distribution within an Array

Resistance of bits in a 4Mb array

- Low State
- High State

\[ \Delta R/\sigma = 30 \text{ typical} \]

\[ \sigma \approx 0.8\% \]

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

Optimized for MRAM

10 nm  \[ V_{1/2} \approx +0.7/-0.55 \text{ V} \]
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Tunnel Junction Reliability: Read

**Dielectric Breakdown**  
(catastrophic)

**Resistance Drift**  
(gradual)

- **Number of Bits @ R**
- **Resistance [Ω]**
- **Time [s]**

- **T=175 C**
- **1.0V**
- **0.8V**
- **0.6V**

- **Low State**
- **High State**

- **Margin before drift**
- **Necessary margin for spec. read-out speed**
- **Margin after drift**
Intrinsic Reliability vs. Temperature

MTJ failure modes as a function of address cycles

- Resistance Drift = Change in resistance of the magnetic cell materials (2% resistance change criteria)
- TJ TDDB = Time Dependant Dielectric Breakdown of the Tunnel Junction Oxide
- EM = Time to Failure by Electromigration in the copper write lines (10% resistance change criteria)
- Magn bridging = Interlayer bridging in the magnetic materials that would cause the magnetic properties to change
MRAM: Unlimited Read/Write Endurance

MRAM Endurance Tested to 58 Trillion Cycles with No Change in Critical Parameters.
Data from >2800 bits from 900 devices
8 orders of magnitude more cycles than current Flash technology
No known failure modes are seen or expected.
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Write Operating Region at 125 °C

- $H_{sat}$, $H_{sw}$ decrease linearly with Temp, reducing window
Read Signal vs. Temperature

MR decreases with temperature

Less read margin at 150 °C, but distributions are still well separated

MR (%)

T (°C)

Normalized $R_{\text{cell}}$

“0”

“1”

25 °C

150 °C
Read access time strobe for temperatures -40 to 125 °C

Meets specifications over industrial temperature range
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Historical Trend of TMR

Room temperature TMR values reported in the literature

- Year
- TMR at RT (%)
- Tunnel Barriers
  - AIOx
  - MgO
- Institutions
  - Tohoku
  - MIT
  - IBM
  - Tohoku & Hitachi
  - AIST
  - Anelva
  - Freescale
  - IBM
  - CNRS
  - IBM
  - AIST
  - Anelva
  - MIT
  - IBM
  - Tohoku
  - Sony
  - MPI
  - CSIC

Values reported in the literature include:
- Tohoku
- MIT
- IBM
- Tohoku & Hitachi
- AIST
- Anelva
- Freescale
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Read Margin with MgO Tunnel Barrier

Much higher MR with MgO replacing AlOx in tunnel barrier
- $\frac{MR}{\sigma} = 2\times$ AlOx

Demonstration in 4Mb circuit

- $\sigma \approx 1.5\%$
- $49 \sigma$

AlOx → MgO
MRAM Cell Integration in 90nm BEOL

Full integration of MgO-based MRAM devices with 90nm front end CMOS.

MRAM process with clad Cu write lines.

8 kb arrays of memory cells

Cell Size $0.29 \, \mu m^2$ – Linear shrink from 180nm

MTJ resistance of $1kohm-\mu m^2$

Toggle write characteristics

*IEDM 2005*
Large Operating Window at 90nm

Operating region where the bit toggles when both write currents are over their threshold values.

Scalability of the toggle MRAM concept to 90nm is demonstrated.
Spin-Torque MRAM

Each spin flip produces $\Delta S = \hbar$

$$\frac{\Delta S}{\Delta t} = \text{Torque}$$

Advantages: Smaller cell size, lower write current

$J_c \approx 10^7 \text{ A/cm}^2$
Distribution Considerations

- For Small Cell – \( I_{\text{switch}} = \frac{V_{\text{switch}}}{R_{\text{cell}}} \) must be \(<<1\text{mA}\)
- \( V_{\text{switch}} << V_{\text{breakdown}} \) for good Endurance
- \( V_{\text{read}} << V_{\text{switch}} \) to avoid Disturb
- \( V_{\text{read}} >> \) transistor mismatch requirement
- 10 Yr Data Retention requires \( \frac{E_b}{k_B T} \geq 50 \)
High MR at Low RA MTJ Material

TMR vs. RA for Optimized Lowest-RA MTJ Material

Best process gives good MR down to < 2 Ω-µm²
Batch Fabrication of MgO Tunnel Junction Nanopillars

- 200 mm Si wafer
- Optical lithography:
  - 100 nm x 200 nm bits

RA (Ω−µm²) | MR (%) | $I_c^{P→AP}$ (mA)
---|---|---
| 7 | 6 | 5 | 4 | 3 | 2 |
| 8.97 | 8.92 | 8.09 | 8.89 | 8.28 | 8.32 |
| 8.59 | 6.87 | 7.27 | 7.62 | 8.09 | 8.85 |
| 7.1 | 7.33 | 8.28 | 7.68 | 7.63 | 8.26 |
| 8.36 | 8.99 | 8.73 | 7.33 | 7.86 | 7.18 |
| 6.19 | 7.18 | 7.92 | 7.1 | 7.14 | 7.61 |
| 7.78 | 6.74 | 6.51 | 7.76 |

Quasistatic $J_c^{P→AP}$: ~4.5x10⁶ A/cm²
Summary

• Advances in magnetic materials and devices have enabled in the first commercial MRAM

• Toggle MRAM is the only MRAM technology shipping today
  • High-performance, high-endurance and highly reliable non-volatile memory
  • Extendable to industrial and automotive applications
    ▪ -40 °C – 105 °C operation available now

• New materials and devices show the potential for advanced scaling and further performance improvements
  • High TMR from MgO enables high-speed and scaling
  • Spin-Torque has potential to achieve high densities