A Technology-Agnostic MTJ SPICE Model with User-Defined Dimensions for STT-MRAM Scalability Studies

Model download website: mtj.umn.edu

Jongyeon Kim¹, An Chen², Behtash Behin-Aein², Saurabh Kumar¹, Jian-Ping Wang¹, and Chris H. Kim¹

¹University of Minnesota, Minneapolis, MN 55455 USA
²GLOBALFOUNDRIES, Sunnyvale, CA 94085 USA

kimx2889@umn.edu
Overview

• Spin-Transfer Torque (STT) MRAM: Basic Concepts
• Magnetic Tunnel Junction (MTJ): Key Physics to Be Modeled
• Model Framework and Implementation
• Case Study: STT-MRAM Scalability and Variability Simulations
• Summary
STT-MRAM Basics

STT-MRAM bit-cell structure and STT switching

[1T-1MTJ layout] [2T-1MTJ layout]

MTJ Contact

SL Contact


- Key features: Nonvolatile, compact, CMOS compatible, high endurance

<table>
<thead>
<tr>
<th>Type</th>
<th>Stand-alone</th>
<th>Embedded</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W_{TX}$</td>
<td>Minimum</td>
<td>18F</td>
</tr>
<tr>
<td>1T-1MTJ</td>
<td>6F$^2$</td>
<td>57F$^2$</td>
</tr>
<tr>
<td>2T-1MTJ</td>
<td>8F$^2$</td>
<td>40F$^2$</td>
</tr>
</tbody>
</table>

* SRAM: ~120F$^2$
Target Applications & Recent Progress

- **STT-MRAM target applications**
  - Low power main memory
  - Embedded cache memory:
    - No standby power, compact size
    - Low latency due to reduced global interconnect delay

- **Recent demonstration by TDK**
  - 8Mbits embedded STT-MRAM
  - 90nm CMOS/ 50F² 1T-1MTJ
  - 150% TMR, 4/5ns Read/Write
  - Less than 1ppm bit error rate for 10yr retention/125C

---

One critical issue is the conflict between read and write operations which becomes more severe with MTJ scaling. The development of a scalable MTJ SPICE model is a key aspect of exploring the potential of STT-MRAM in future technology nodes.
Key MTJ Physics to Be Modeled

Thermal stability and magnetic anisotropy

- Thermal stability ($\Delta$) determines the degree of nonvolatility
- Thermal stability is defined as $E_b$ with respect to thermal fluctuation
- $H_k$ decides the energetic preference of spin direction (i.e. easy axis): In-plane or perpendicular magnetic anisotropy

\[ \Delta = \frac{E_b}{k_B T} = \frac{H_k M_s V}{2 k_B T} \]

- $E_b$: Energy barrier, $V$: Magnet volume,
- $H_k$: Anisotropy field, $M_s$: Saturation magnetization

Key MTJ Physics to Be Modeled

STT-induced dynamic spin motion

Switching current vs. pulse width

Temperature-dependent R-V curve

Thermally assisted switching region

*TMR: Tunneling magnetoresistance ratio

Proposed Technology-Agnostic SPICE-Compatible MTJ Model

Overall model framework

- Covers all types of anisotropy sources (shape, crystal, and interface)
- Dimension-dependent anisotropy field enables scalability and variability analyses
- Changing the initial angle parameter allows convenient simulation of MTJ switching probability

User-defined input parameters

<table>
<thead>
<tr>
<th>Input</th>
<th>Description</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>Free layer width</td>
<td>Δ dependent</td>
</tr>
<tr>
<td>L</td>
<td>Free layer length</td>
<td>Δ dependent</td>
</tr>
<tr>
<td>tF</td>
<td>Free layer thickness</td>
<td>Δ dependent</td>
</tr>
<tr>
<td>α</td>
<td>Magnetic damping factor</td>
<td>Material related</td>
</tr>
<tr>
<td>M0</td>
<td>Saturation magnetization, 0K</td>
<td>Material related</td>
</tr>
<tr>
<td>P0</td>
<td>Polarization factor, 0K</td>
<td>Material related</td>
</tr>
<tr>
<td>Kn</td>
<td>Crystal anisotropy constant</td>
<td>for c-PMTJ</td>
</tr>
<tr>
<td>tc</td>
<td>Critical thickness</td>
<td>for i-PMTJ</td>
</tr>
<tr>
<td>T0</td>
<td>Initial temperature</td>
<td>Ambient</td>
</tr>
<tr>
<td>Psw</td>
<td>Switching probability</td>
<td>by initial angle</td>
</tr>
<tr>
<td>RA</td>
<td>Resistance-area product</td>
<td>Measured data</td>
</tr>
<tr>
<td>asym</td>
<td>Bidirectional L asymmetry</td>
<td>Measured data</td>
</tr>
<tr>
<td>MA</td>
<td>In-plane/Perpendicular selection</td>
<td>0/1</td>
</tr>
<tr>
<td>State</td>
<td>Parallel/Anti-parallel selection</td>
<td>0/1</td>
</tr>
</tbody>
</table>
SPICE Implementation

Numerical form:
\[
\frac{1 + \alpha^2}{\gamma} \cdot \frac{dM}{dt} = -M \times H_{K_{eff}} - \alpha \cdot M \times (M \times H_{K_{eff}}) + A_{sst} \cdot M \times (M \times M_p), \quad A_{sst} = \frac{\hbar P J}{2eT_f M_s}
\]

Precession        Damping        Spin torque

Circuit implementation (y-coordinate):

HSPICE script (y-coordinate):

SPICE implementation of LLG equation (only y-coordinate shown for simplicity)

- Internal variables are represented as node voltages using circuit elements
- Differential behavior of magnetization by emulating an incremental charge build-up over time in a capacitor: \( I = C \cdot dV/dt \)
Model Verification

In-plane switching

Perpendicular switching

Temp. dependency of material parameters

Comparison with measurement data [1], [2]

MTJ switching characteristics

Overview

• Spin-Transfer Torque (STT) MRAM: Basic Concepts
• Magnetic Tunnel Junction (MTJ): Key Physics to Be Modeled
• Model Framework and Implementation
• Case Study: STT-MRAM Scalability and Variability Simulations
• Summary
Scalability Study: MTJ Options

1. **In-plane MTJ (IMTJ)**
   - Geometry dependent **shape anisotropy**
   - Longer dimension $\rightarrow$ Easier magnetization
   - High polarization but high switching current due to $H_{dz}$

   
   
   $J_{c01} = \frac{2e\alpha M_s t_F (H_{K \perp} - 4\pi M_s)}{\hbar \eta}$

2. **Crystal perpendicular MTJ (c-PMTJ)**
   - Crystal perpendicular anisotropy from high-$K_u$ materials (FePt, FePd, etc)
   - $H_{dz}$ reduces switching current
   - Low polarization, high damping

3. **Interface perpendicular MTJ (i-PMTJ)**
   - Interface perpendicular anisotropy in thin CoFeB
   - CoFeB turns from in-plane to perpendicular when $t_F < t_c$ ($\sim 1.5$nm)

   \[ J_{c0} = \frac{2e\alpha M_s t_F (H_{K} + 2\pi M_s)}{\hbar \eta} \]

**Which MTJ technology is best from a scaling perspective?**
Scalability Study: $I_c$ Scaling Trend

MTJ scaling methods under iso-retention condition

<table>
<thead>
<tr>
<th>MTJ scaling scenario</th>
<th>Critical switching current ($I_c$) trend</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTJ scaling based on iso-retention using realistic materials</td>
<td>Interface PMTJ shows the superior switching efficiency over the scaling</td>
</tr>
</tbody>
</table>

![Graph showing $I_c$ versus MTJ width for different MTJ types.](image)

**Table: MTJ Scaling Parameters**

<table>
<thead>
<tr>
<th>MTJ Type</th>
<th>Width (nm)</th>
<th>AR</th>
<th>$t_F$ (nm)</th>
<th>$K_u$</th>
<th>Rem.</th>
<th>$I_c$ (μA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMTJ (CoFeB)</td>
<td>60-20</td>
<td>2.35-3</td>
<td>2.00-2.58</td>
<td>0.92-2.00</td>
<td>AR ↑, $t_F$ ↑, $K_u$ ↑</td>
<td>IMTJ, c-PMTJ, i-PMTJ</td>
</tr>
<tr>
<td>c-PMTJ (FePdX)</td>
<td>60-20</td>
<td>0.007-0.0055</td>
<td>0.45-0.65</td>
<td>0.45-2.00</td>
<td>constant $t_F$, $K_u$ ↑</td>
<td>IMTJ, c-PMTJ, i-PMTJ</td>
</tr>
<tr>
<td>i-PMTJ (CoFeB)</td>
<td>60-20</td>
<td>0.013-0.007</td>
<td>1.47-1.52</td>
<td>1.42-3.29</td>
<td>$t_F$ ↓, $t_F$ dependent $\alpha$</td>
<td>IMTJ, c-PMTJ, i-PMTJ</td>
</tr>
</tbody>
</table>

*Δ=70 (85°C), $M_s$ (10^5/A/m), $K_u$ (10^5/J/m³)
Variability Study: Simulation Setup

- Optimized bit-cell connection for symmetric current driving
- Bi-directional write current driver, dual-voltage WL driver
- Parallelizing read current, Mid-point reference circuit using $I_{\text{Ref}} = (I_{\text{AP}} + I_{\text{P}})/2$
Variability Study: Write and Read Delays

- Write and sensing delay distributions with $6\sigma$ values
- Includes realistic variation for both MTJ (i.e. $W$, $L$, $t_F$, RA) and CMOS (i.e. transistor $W$, $L$, $V_{th}$, $T_{ox}$)
Model Download Website

http://mtj.umn.edu
Summary

- We have developed a technology-agnostic MTJ model for benchmarking future STT-MRAMs
- The proposed compact model is useful for studying the scalability and variability of different MTJ devices and material options.
- Model available online at mtj.umn.edu

Acknowledgements

- This work was supported in part by C-SPIN, one of six centers of STARnet, a Semiconductor Research Corporation program, sponsored by MARCO and DARPA.