

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

Model download website: mtj.umn.edu

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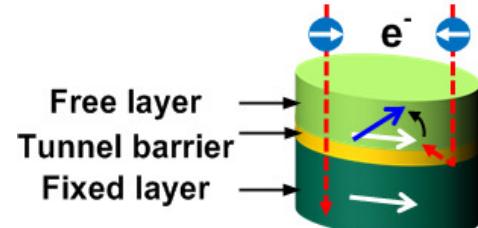
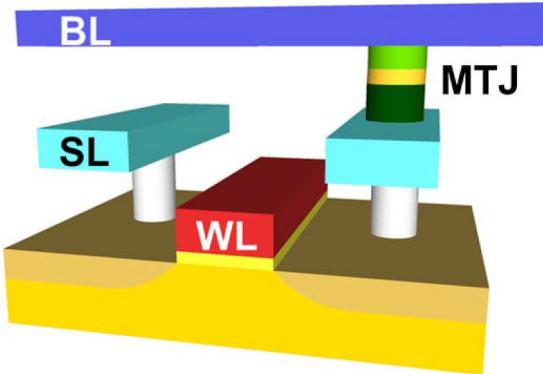
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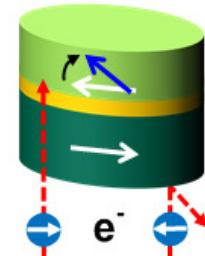
Overview

- **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

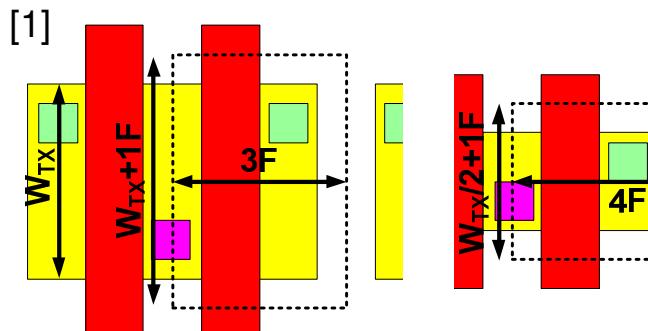


Parallel to Anti-parallel
switching



Anti-parallel to Parallel
switching

STT-MRAM bit-cell structure and STT switching



1T-1MTJ layout

2T-1MTJ layout

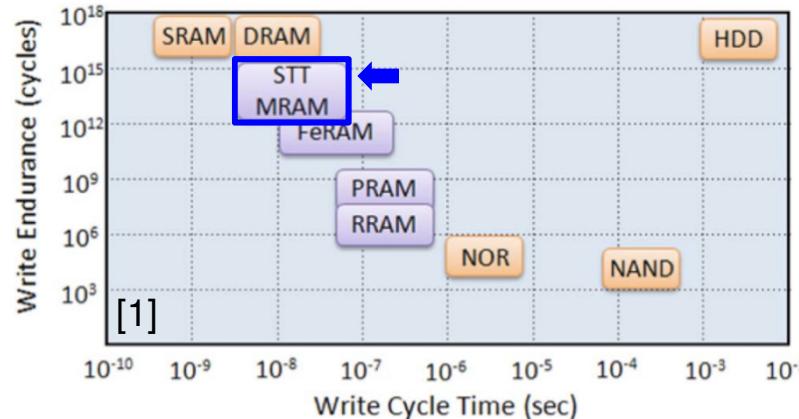
Type	Stand-alone	Embedded
W_{TX}	Minimum	$18F$
1T-1MTJ	$6F^2$	$57F^2$
2T-1MTJ	$8F^2$	$40F^2$

* SRAM: $\sim 120F^2$

Bit-cell area comparison

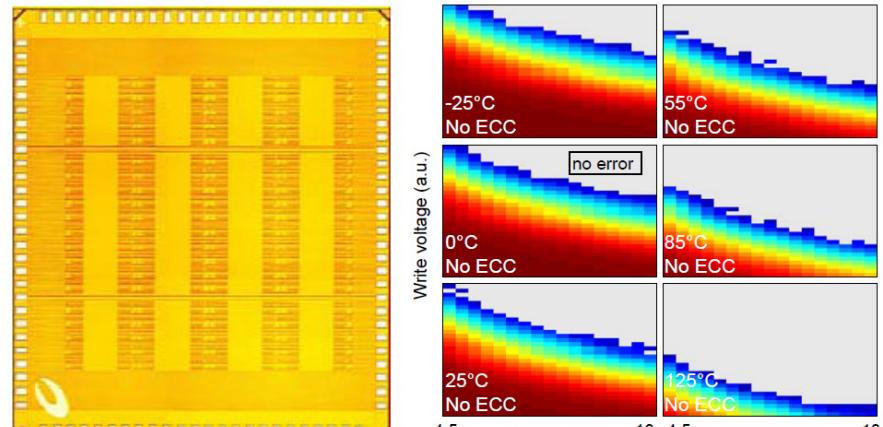
- Key features: Nonvolatile, compact, CMOS compatible, high endurance

Target Applications & Recent Progress



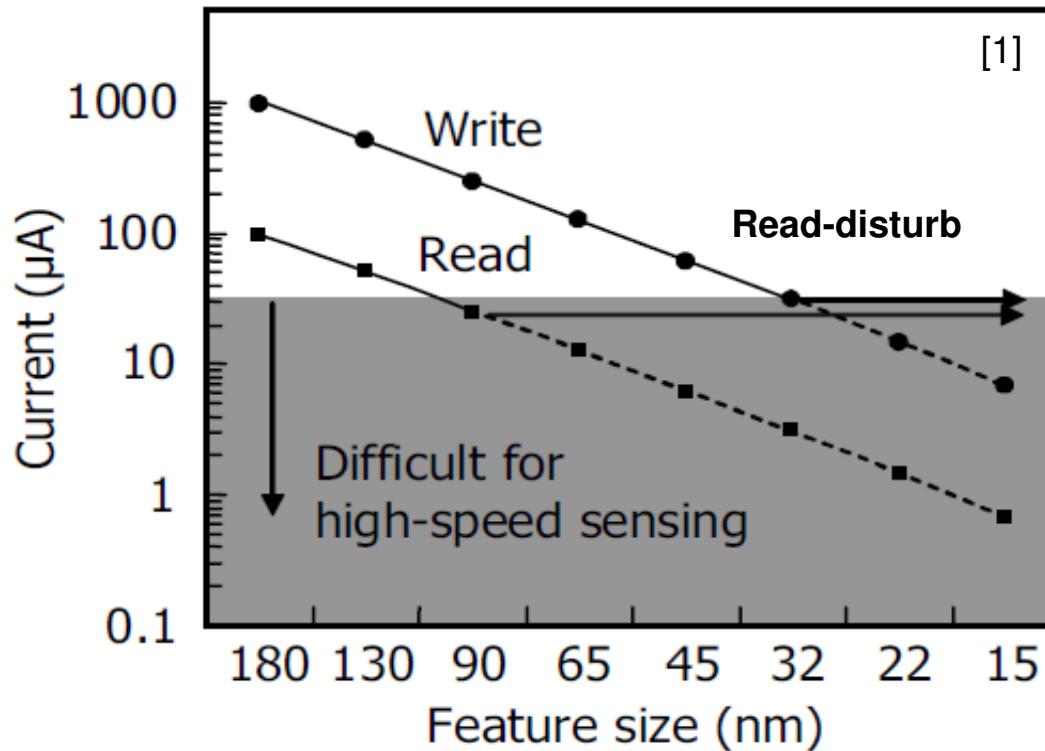
- **STT-MRAM target applications**
 - Low power main memory
 - Embedded cache memory:
 - No standby power, compact size
 - Low latency due to reduced global interconnect delay

- **Recent demonstration by TDK [2]**
 - 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



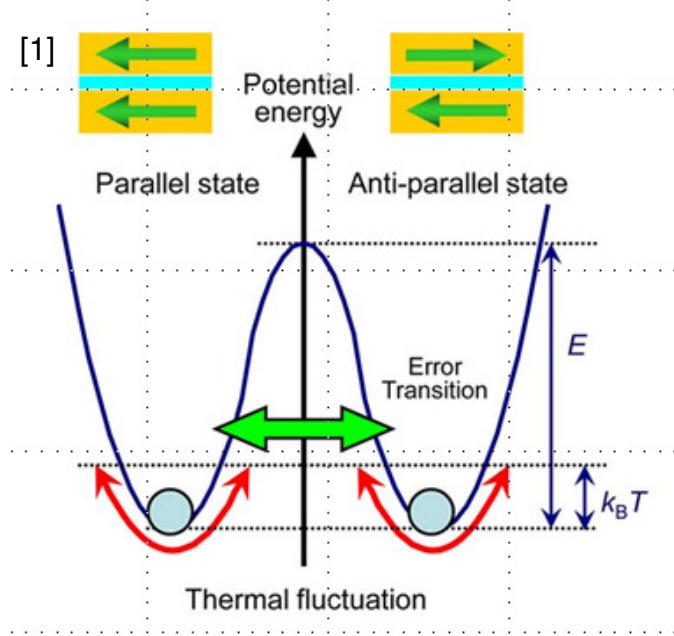
Chip micrograph and write shmoos

STT-MRAM Scaling Challenges



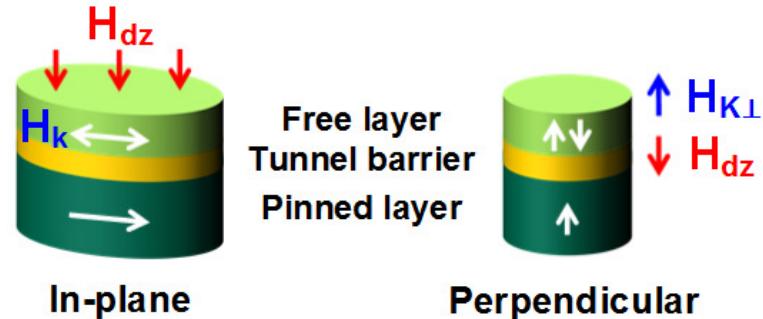
- One critical issue is the conflict between read and write operations which becomes more severe with MTJ scaling
- The development of a *scalable MTJ SPICE model* is a key aspect of exploring the potential of STT-MRAM in future technology nodes

Key MTJ Physics to Be Modeled



$$\Delta = \frac{E_b}{k_B T} = \frac{H_k M_s V}{2k_B T} : \text{Thermal stability factor}$$

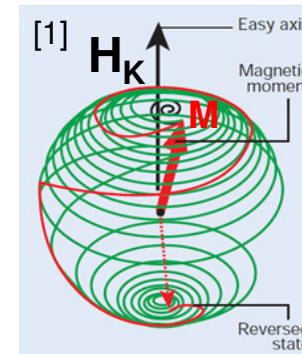
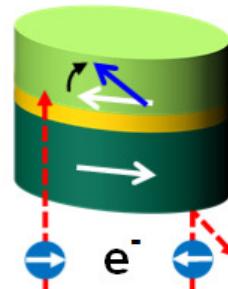
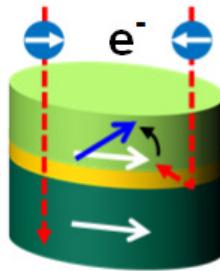
- E_b : Energy barrier, V : Magnet volume,
- H_k : Anisotropy field, M_s : Saturation magnetization



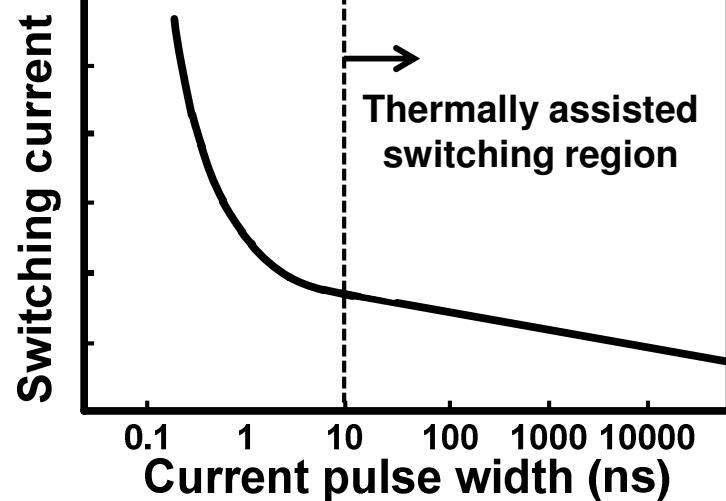
Thermal stability and magnetic anisotropy

- Thermal stability (Δ) 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

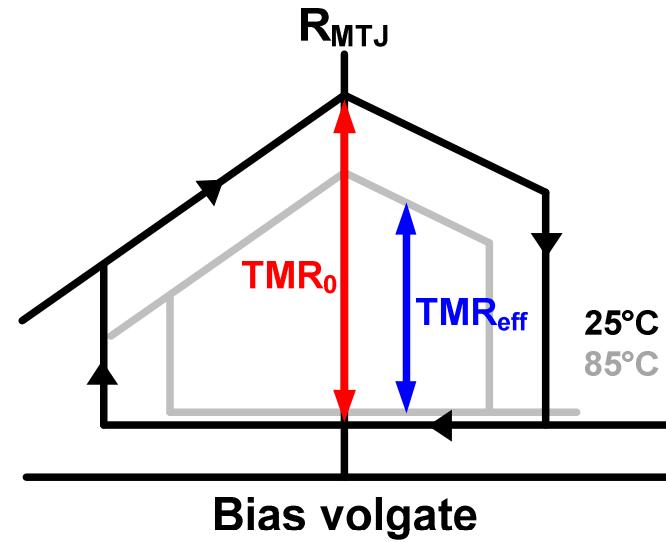
Key MTJ Physics to Be Modeled



STT-induced dynamic spin motion



Switching current vs. pulse width



Temperature-dependent R-V curve

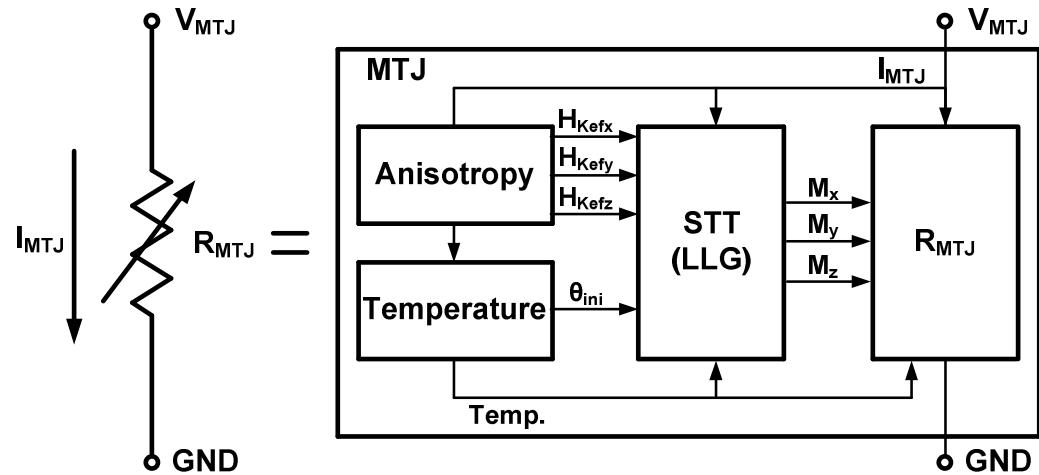
*TMR: Tunneling magnetoresistance ratio



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[1] J. Sun, Nature 2003 (IBM)

Proposed Technology-Agnostic SPICE-Compatible MTJ Model



Input	Description	Remark
W	Free layer width	Δ dependent
L	Free layer length	Δ dependent
t_F	Free layer thickness	Δ dependent
α	Magnetic damping factor	Material related
M_{s0}	Saturation magnetization, 0K	Material related
P_0	Polarization factor, 0K	Material related
K_u	Crystal anisotropy constant	for c-PMTJ
t_c	Critical thickness	for i-PMTJ
T_0	Initial temperature	Ambient
P_{sw}	Switching probability	by initial angle
RA	Resistance-area product	Measured data
$asym$	Bidirectional I_c asymmetry	Measured data
MA	In-plane/Perpendicular selection	0/1
$State$	Parallel/Anti-parallel selection	0/1

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

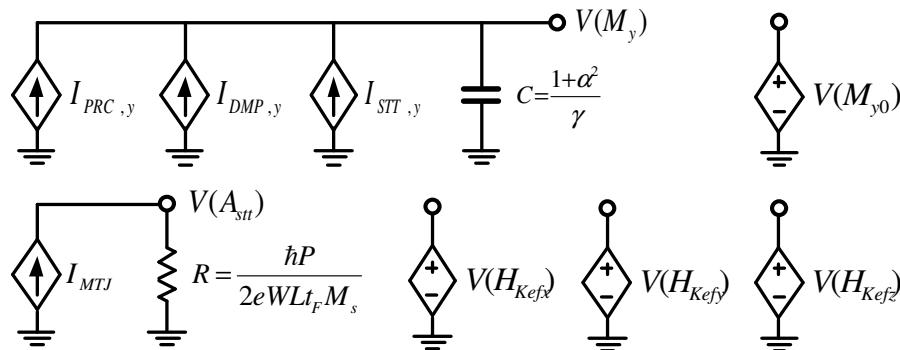
SPICE Implementation

Numerical form:

$$\frac{1+\alpha^2}{\gamma} \cdot \frac{d\bar{M}}{dt} = -\bar{M} \times \bar{H}_{Keff} - \alpha \cdot \bar{M} \times (\bar{M} \times \bar{H}_{Keff}) + A_{stt} \cdot \bar{M} \times (\bar{M} \times \bar{M}_p), A_{stt} = \frac{\hbar P J}{2et_F M_s}$$

Precession Damping Spin torque

Circuit implementation (y-coordinate):



HSPICE script (y-coordinate):

```

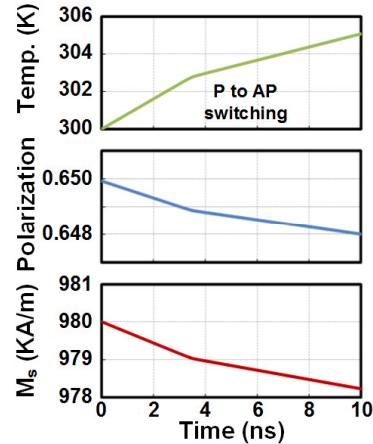
C_My      M_y  0  '(1+alpha^2)/gamma
G_dMy_pr  0  M_y  cur='-(v(M_z)*v(H_Kefx)-v(H_Kefz)*v(M_x))'
G_dMy_dmp 0  M_y  cur='-alpha*(v(M_z)*(v(M_y0)*v(H_Kefz)-v(H_Kefy)*v(M_z))-(v(M_x)*v(H_Kefy)-v(H_Kefx)*v(M_y0))*v(M_x))'
G_dMy_stt 0  M_y  cur='v(A_stt)*(v(M_z)*(v(M_y0)*M_pz-M_py*v(M_z))-(v(M_x)*M_py-M_px*v(M_y0))*v(M_x))'
E_My0     M_y0 0  vol='v(M_y)' max='cos(v(theta_c))' min='-cos(v(theta_c))'

```

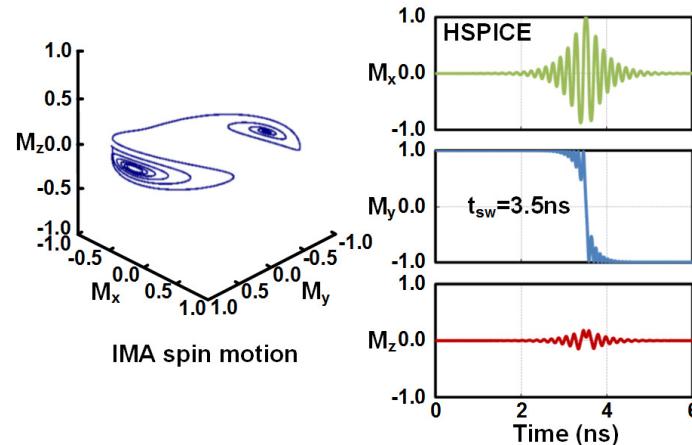
SPICE implementation of LLG equation (only y-coordinate shown for simplicity)

- 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: $I=C \cdot dV/dt$

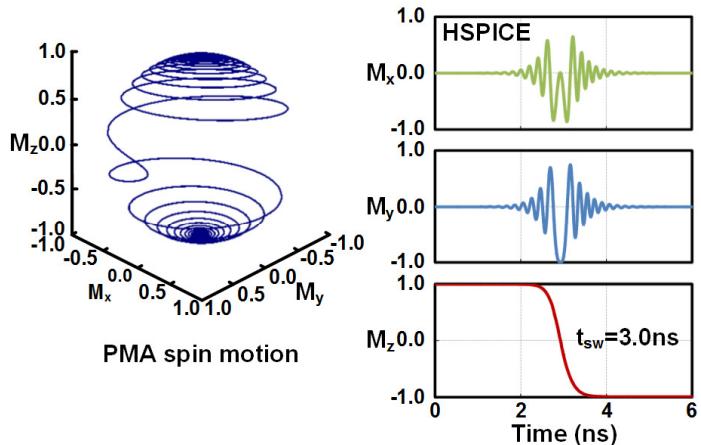
Model Verification



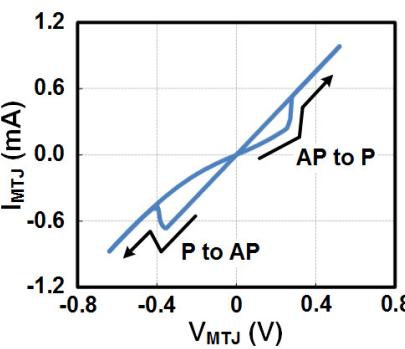
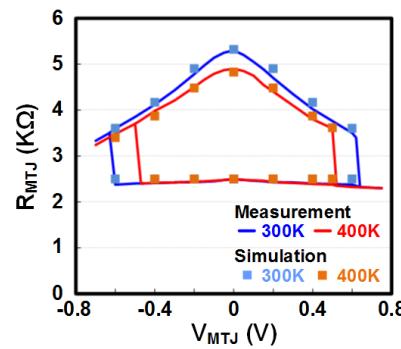
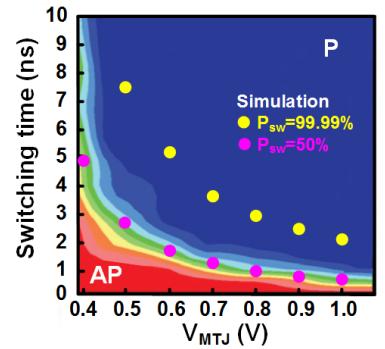
Temp. dependency of material parameters



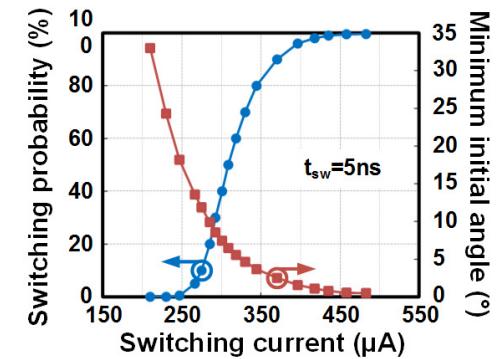
In-plane switching



Perpendicular switching



Comparison with measurement data [1], [2]



MTJ switching characteristics

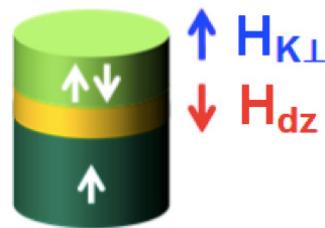
Overview

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- Summary

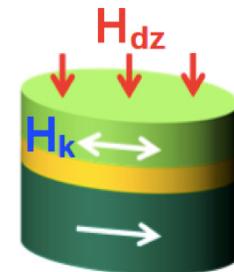
Scalability Study: MTJ Options

1. In-plane MTJ (IMTJ)

- Geometry dependent **shape anisotropy**
- Longer dimension → Easier magnetization
- high polarization but high switching current due to H_{dz}



$$J_{C0\perp} = \frac{2e\alpha M_S t_F (H_{K\perp} - 4\pi M_S)}{\hbar\eta}$$



$$J_{C0} = \frac{2e\alpha M_S t_F (H_K + 2\pi M_S)}{\hbar\eta}$$

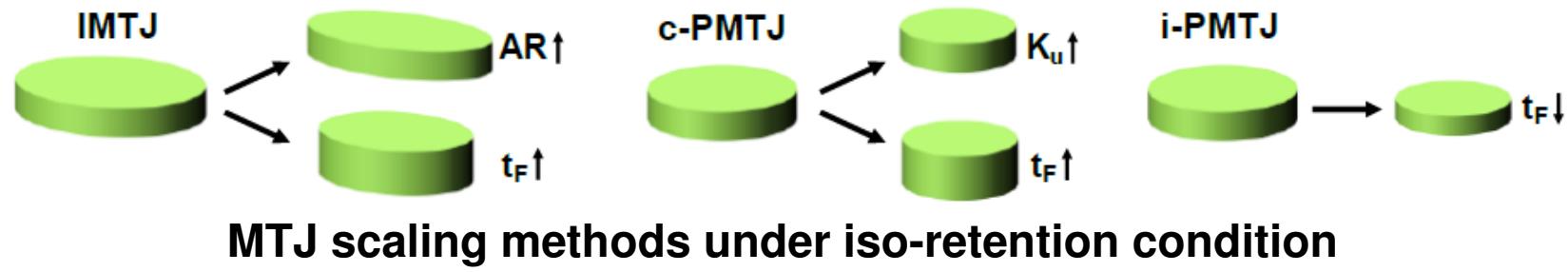
2. Crystal perpendicular MTJ (c-PMTJ)

- **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 $t_F < t_c$ ($\sim 1.5\text{nm}$)
- **Which MTJ technology is best from a scaling perspective?**

Scalability Study: I_c Scaling Trend

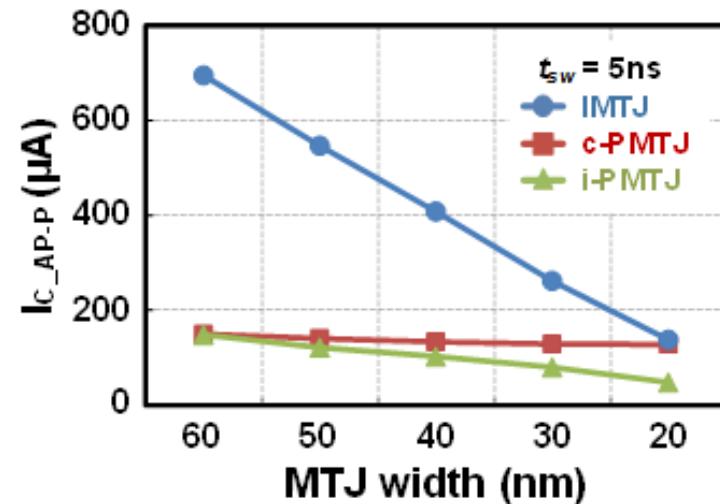


MTJ width (nm)		60	50	40	30	20	
IMTJ (CoFeB)	$M_s=1077$, $P=0.6$	AR	2.35	2.65	3	3	3
		t_F (nm)	2.00	2.00	2.10	2.58	3.50
		α	0.007	0.007	0.0068	0.006	0.0055
		Remark	AR \uparrow		$t_F \uparrow$, t_F dependent α		
c-PMTJ (FePdX)	$M_s=1077$, $P=0.51$, $\alpha=0.03$	K_u	0.92	1.01	1.18	1.55	2.00
		t_F (nm)	0.45	0.45	0.45	0.45	0.65
		Remark	constant t_F , $K_u \uparrow$			$t_F \uparrow$	
i-PMTJ (CoFeB)	$M_s=1077$, $P=0.6$, $t_c=1.5\text{ nm}$	t_F (nm)	1.47	1.42	1.32	2.99	2.31
		α	0.013	0.015	0.018	0.006	0.0062
		Remark	$t_F \downarrow$, t_F dependent α		Dual interface		

* $\Delta=70$ (85°C), M_s (10^3 A/m), K_u (10^6 J/m 3)

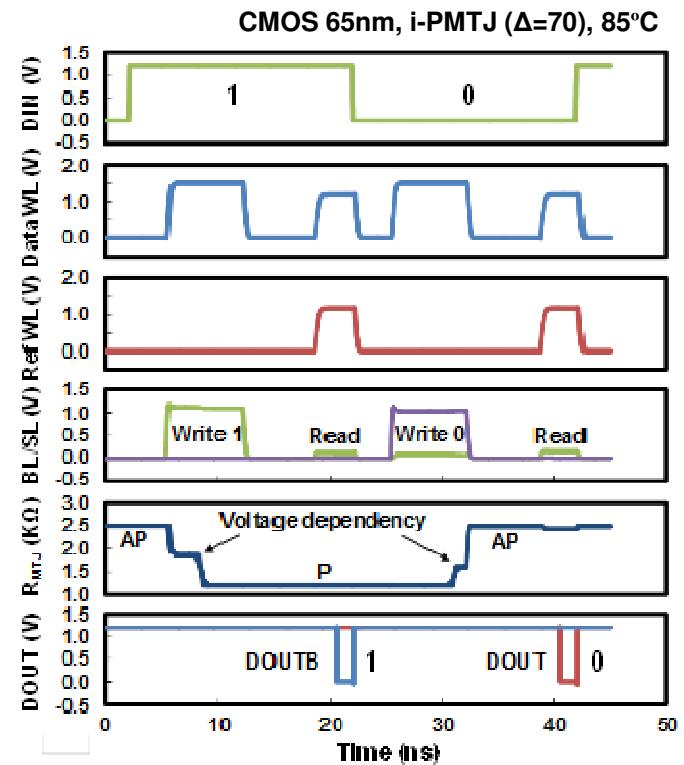
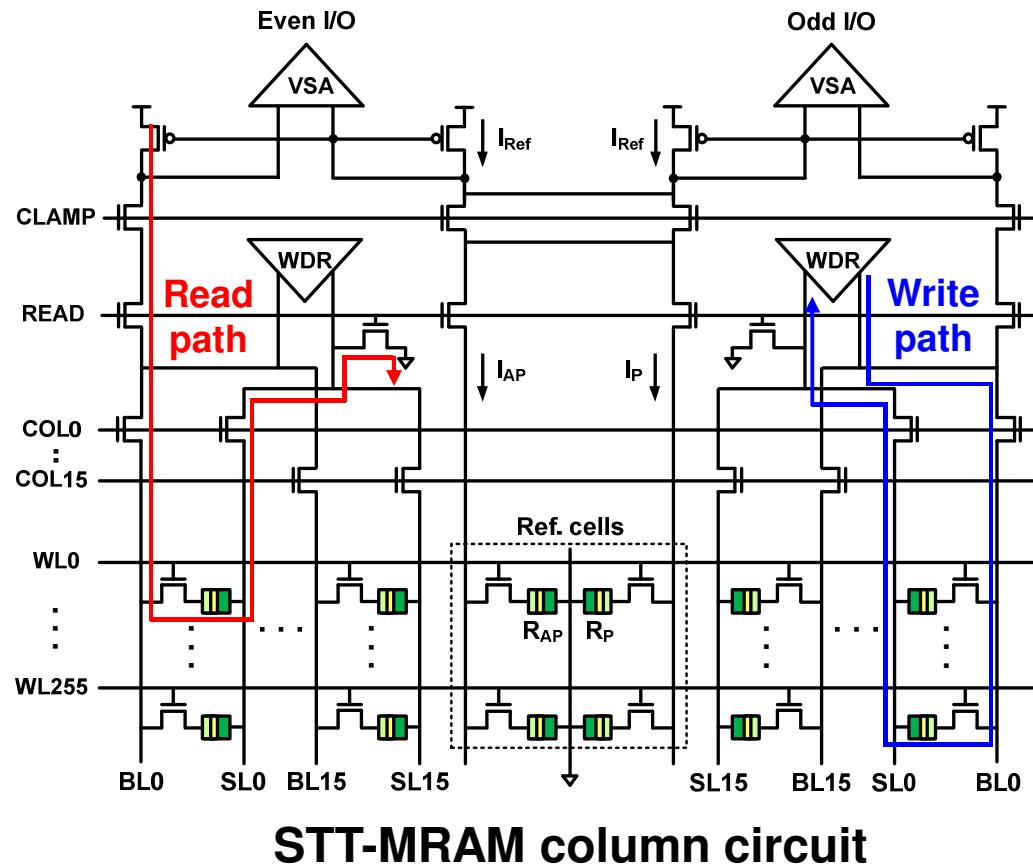
MTJ scaling scenario

- MTJ scaling based on iso-retention using realistic materials
- Interface PMTJ shows the superior switching efficiency over the scaling



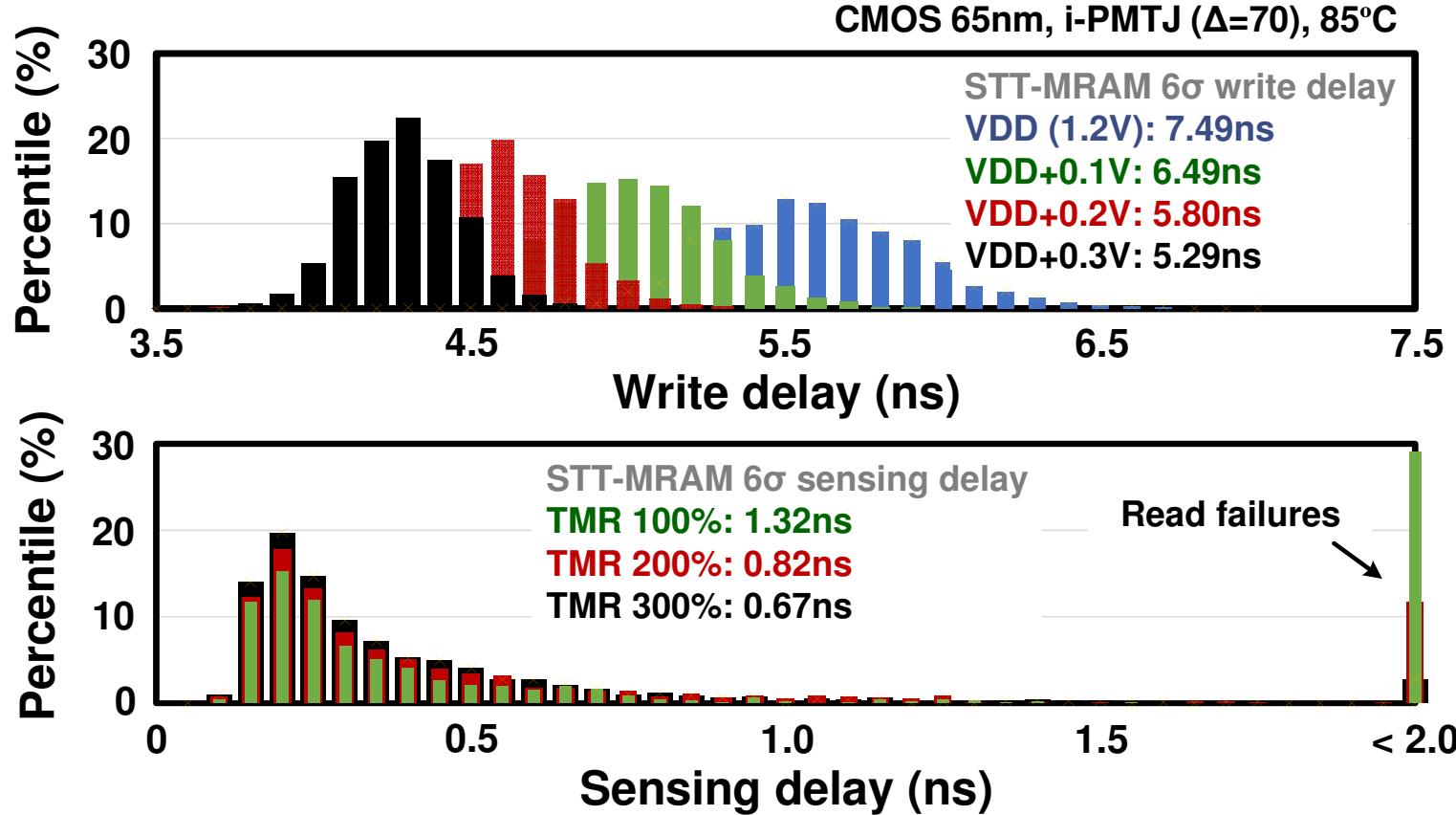
Critical switching current (I_c) trend

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 $I_{Ref} = (I_{AP} + I_P)/2$

Variability Study: Write and Read Delays



- Write and sensing delay distributions with 6 σ 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

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<http://mtj.umn.edu>

Introduction to MTJ SPICE Model

An MTJ SPICE model allows circuit designers to simulate key aspects of spin-transfer torque MRAM (STT-MRAM) such as read and write delays. Our self-contained, physics-based magnetic tunnel junction (MTJ) SPICE model can reproduce realistic MTJ characteristics based on user-defined input parameters such as the free layer's length, width, and thickness parameters. An MTJ SPICE model's scalability studies of both in-plane and perpendicular MTJs can be performed across different technology nodes with minimal effort.

Block diagram of our physics-based MTJ SPICE model:

Publication

J. Kim, A. Chen, B. Behm-Hein, S. Kumar, J.-P. Wang, and C.H. Kim, "A Technology-Hognostic MTJ SPICE Model with User-Defined Dimensions for STT-MRAM Scalability Studies", Custom Integrated Circuits Conference (CICC), Sep. 2015

Acknowledgements

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Getting started

Step1. Download MTJ spice model.
 Step2. Extract zip file.
 Step3. Open MTJ_write.spice file (MTJ write example)
 Step4. Set MTJ dimensions and material parameters: Mf0, P0, alpha, RA and initial temperature (Ms saturation magnetization, P0 polarization, both at zero Kelvin temperature).
 Step5. Select anisotropy type using parameter: MA:
 ex) In-plane magnetic anisotropy: MA=0
 Perpendicular magnetic anisotropy: MA=1
 Step6. Select the initial state of free layer using parameter: 'InI', and apply voltage with correct polarity.
 Magnetization of the fixed layer will be set automatically according to the 'InI' value.
 ex) Antiparallel to parallel switching: InI=1 with positive voltage
 Parallel to antiparallel switching: InI=0 with negative voltage
 Step7. Run SPICE simulation

Downloads

Model files	Parameters (default values)
In-plane MTJ	Free layer dimensions: 32nm x 96nm x 2.44nm; Material: CoFeB; Mf0: 1210; P0: 0.09; Alpha: 0.0002; RA: 5
Crystalline perpendicular MTJ	45nm x 45nm x 0.45nm; FePt; Mf0: 1210; P0: 0.02; Alpha: 0.03; RA: 5
Interface perpendicular MTJ	65nm x 65nm x 1.48nm; CoFeB; Mf0: 1210; P0: 0.09; Alpha: 0.005; RA: 5

Simulation examples

1. Input parameters for in-plane MTJ (antiparallel to parallel switching)

```
XMTJ11 1 0 MTJ bx=32n ly=96n lz=2.44n Ms0=1210 P0=0.09 alpha=0.0062 Tmp0=358 RAO=5
MA=0 inI=1
```

2. Input parameters for crystal perpendicular MTJ (antiparallel to parallel switching)

```
XMTJ13 1 0 MTJ bx=45n ly=45n lz=0.45n Ms0=1210 P0=0.62 alpha=0.03 Tmp0=358 RAO=5 MA=1
inI=1 Kp=1.00e7
```

3. Input parameters for interface perpendicular MTJ (antiparallel to parallel switching)

```
XMTJ1 1 0 MTJ bx=65n ly=65n lz=1.48n Ms0=1210 P0=0.09 alpha=0.006 Tmp0=358 RAO=5
MA=1 inI=1 tc=1.5n
```

4. STT-MRAM read and write waveforms using MTJ SPICE model

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

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