

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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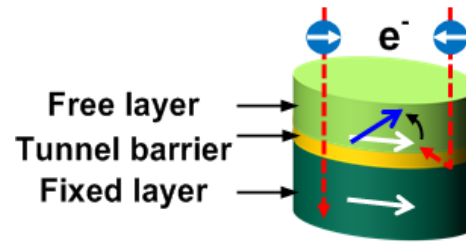
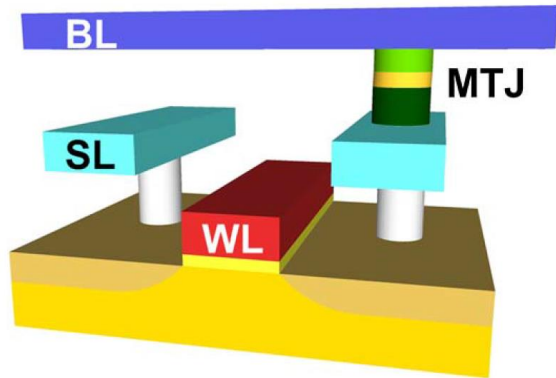
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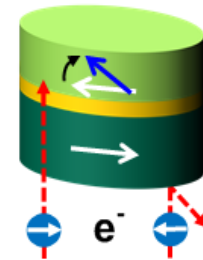
Overview

- **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

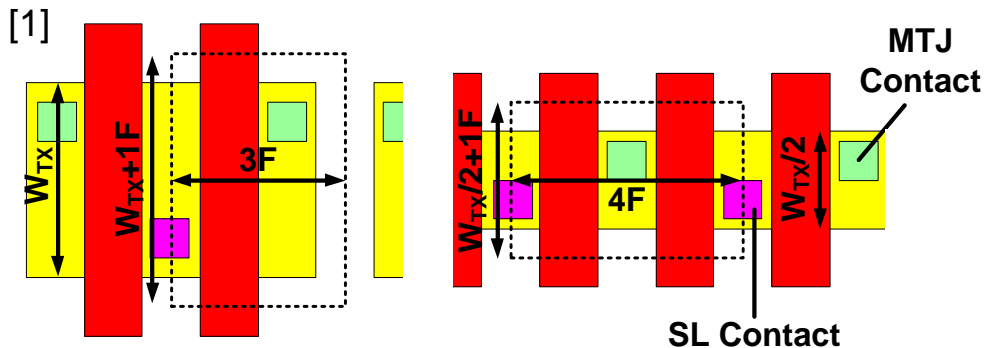


Parallel to Anti-parallel switching



Anti-parallel to Parallel switching

STT-MRAM bit-cell structure and STT switching



1T-1MTJ layout

2T-1MTJ layout

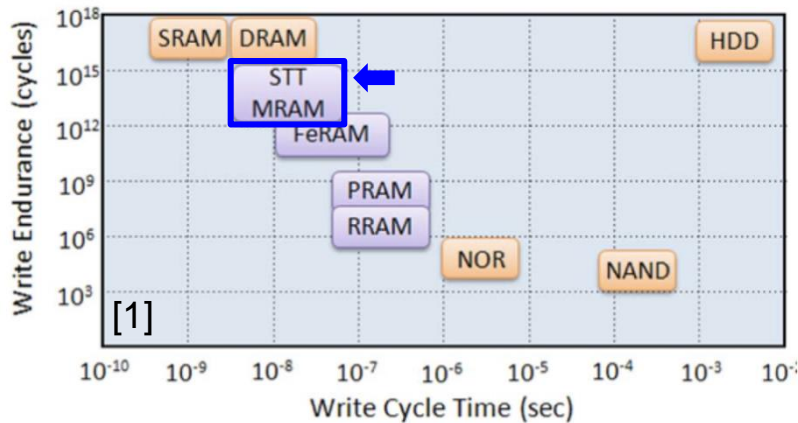
* SRAM: $\sim 120F^2$

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

Bit-cell area comparison

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

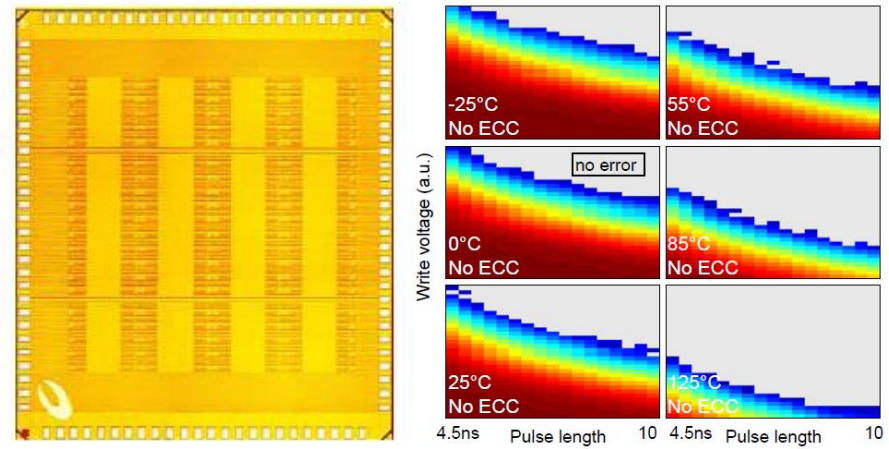
Target Applications & Recent Progress



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

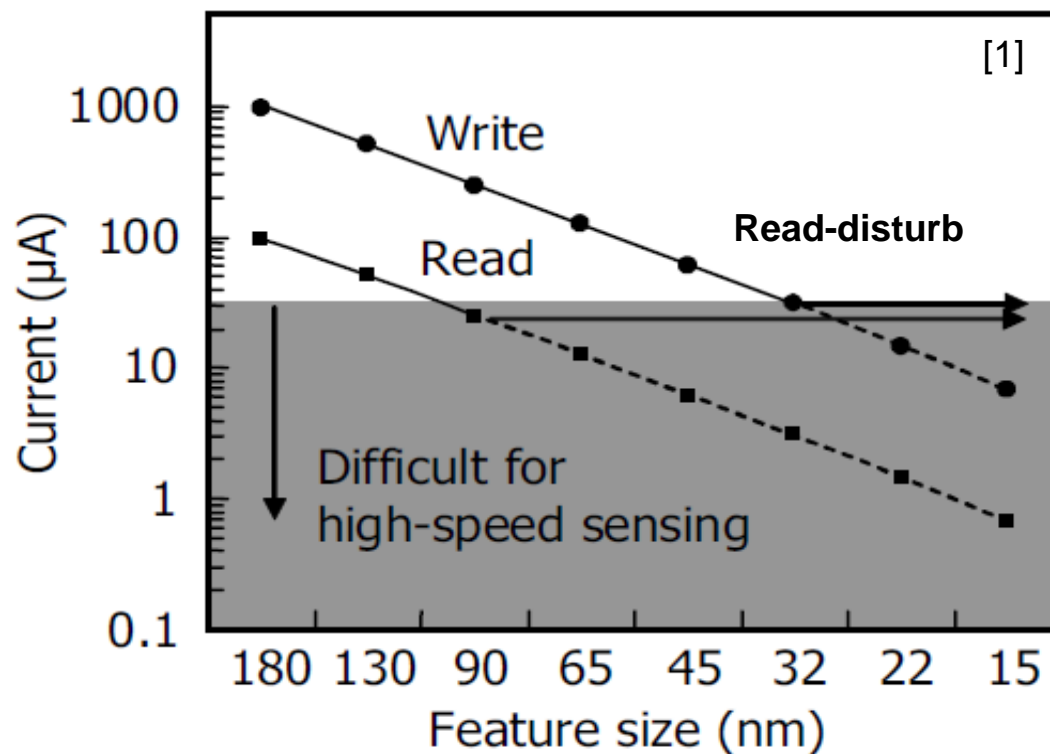
- **Recent demonstration by TDK [2]**

- 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



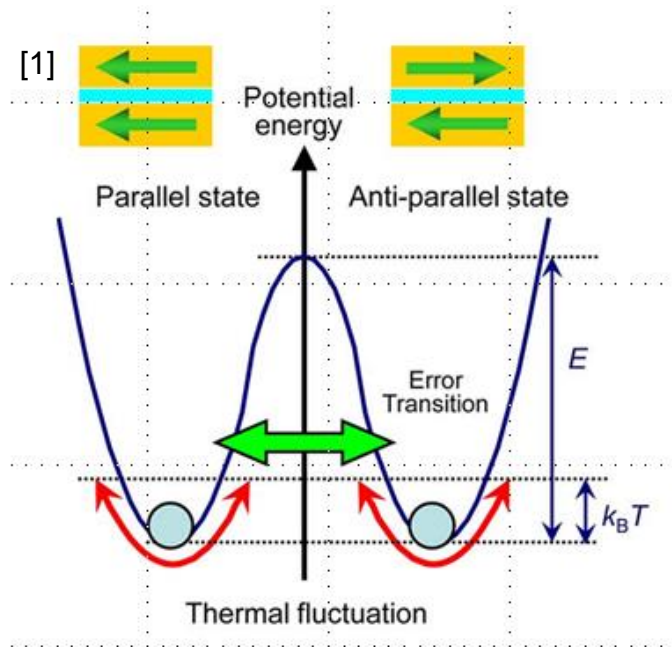
Chip micrograph and write shmoos

STT-MRAM Scaling Challenges



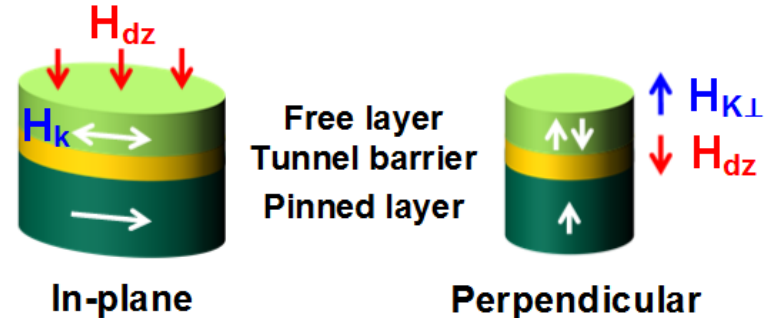
- One critical issue is the conflict between read and write operations which becomes more severe with MTJ scaling
- The development of a **scalable MTJ SPICE model** is a key aspect of exploring the potential of STT-MRAM in future technology nodes

Key MTJ Physics to Be Modeled



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

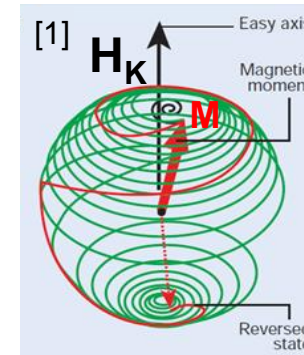
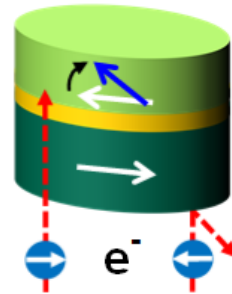
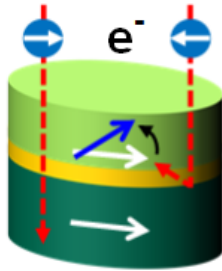
- E_b : Energy barrier, V : Magnet volume,
- H_k : Anisotropy field, M_s : Saturation magnetization



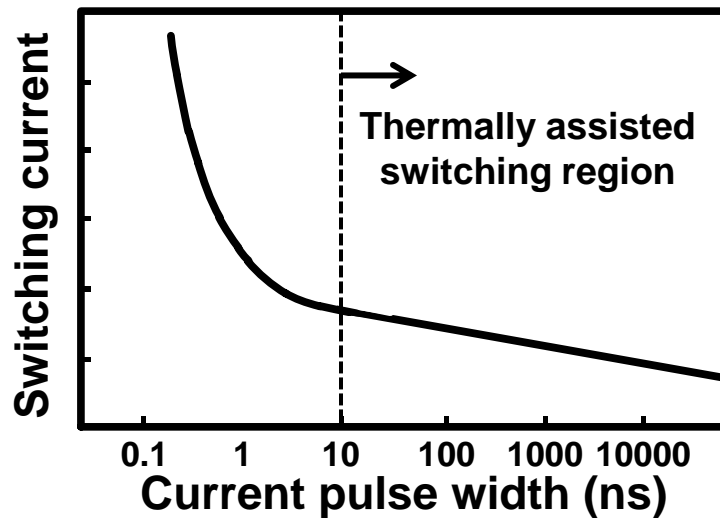
Thermal stability and magnetic anisotropy

- 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

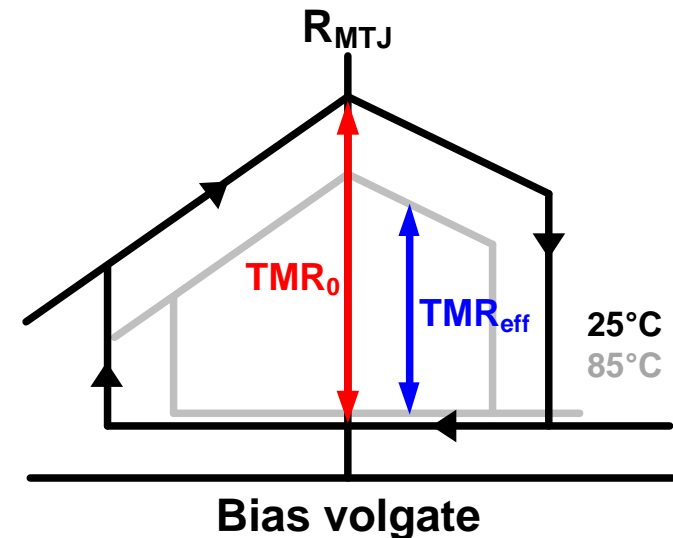
Key MTJ Physics to Be Modeled



STT-induced dynamic spin motion



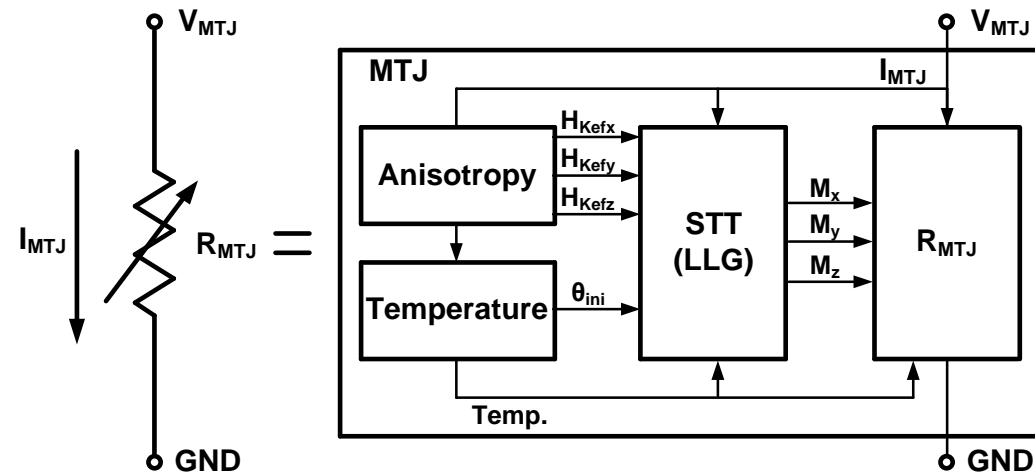
Switching current vs. pulse width



Temperature-dependent R-V curve

*TMR: Tunneling magnetoresistance ratio

Proposed Technology-Agnostic SPICE-Compatible MTJ Model



Overall model framework

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

User-defined input parameters

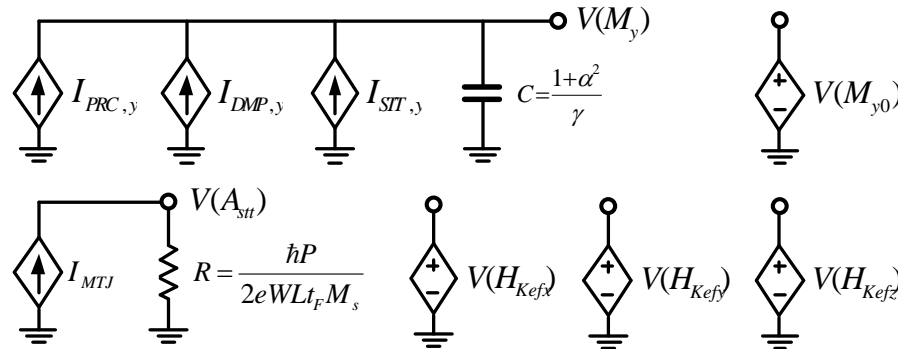
- Covers all types of anisotropy sources (shape, crystal, and interface)
- Dimension-dependent anisotropy field enables scalability and variability analyses
- Changing the initial angle parameter allows convenient simulation of MTJ switching probability

SPICE Implementation

Numerical form:

$$\frac{1+\alpha^2}{\gamma} \cdot \frac{d\bar{M}}{dt} = \underbrace{-\bar{M} \times \bar{H}_{Keff}}_{\text{Precession}} - \underbrace{\alpha \cdot \bar{M} \times (\bar{M} \times \bar{H}_{Keff})}_{\text{Damping}} + \underbrace{A_{stt} \cdot \bar{M} \times (\bar{M} \times \bar{M}_p)}_{\text{Spin torque}}, \quad A_{stt} = \frac{\hbar P J}{2e t_F M_s}$$

Circuit implementation (y-coordinate):



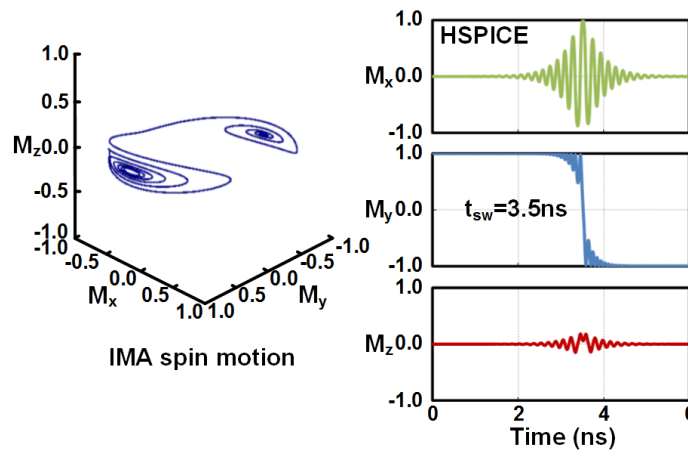
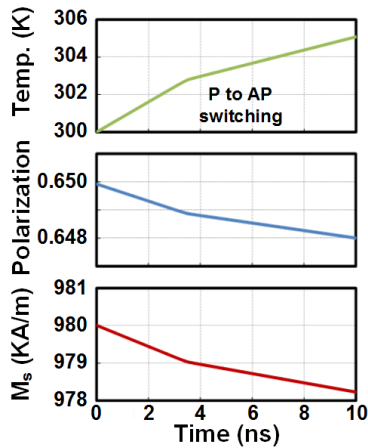
HSPICE script (y-coordinate):

```
C_My      My 0  '(1+alpha^2)/gamma'
G_dMy_prc 0 My cur='-(v(Mz)*v(HKfx)-v(HKfx)*v(Mx))'
G_dMy_dmp 0 My cur='-\alpha*(v(Mz)*(v(My0)*v(HKfx)-v(HKfx)*v(Mz))-(v(Mx)*v(HKfy)-v(HKfx)*v(My0))*v(Mx))'
G_dMy_stt 0 My cur='v(Astt)*(v(Mz)*(v(My0)*Mpz-Mpy*v(Mz))-(v(Mx)*Mpy-Mpx*v(My0))*v(Mx))'
E_My0     My0 0  vol='v(My)' 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: $I = C \cdot dV/dt$

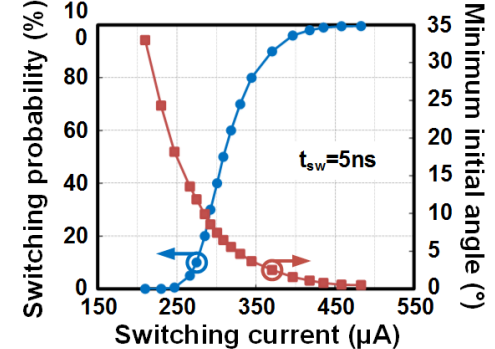
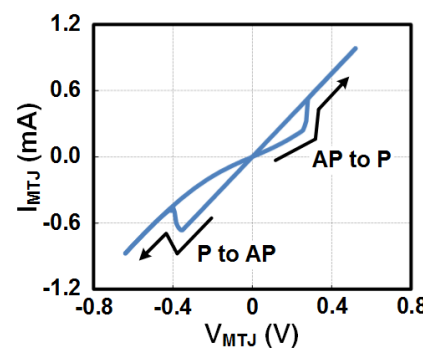
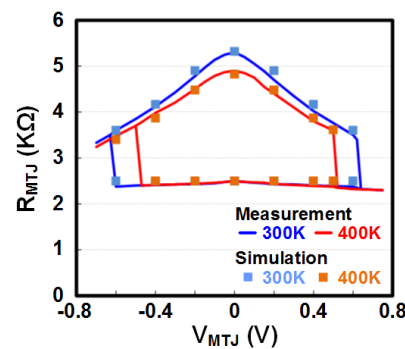
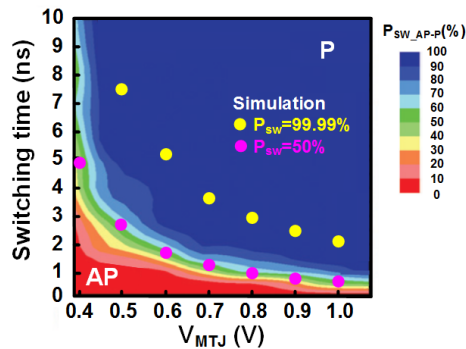
Model Verification



Temp. dependency of material parameters

In-plane switching

Perpendicular switching



Comparison with measurement data [1], [2]

MTJ switching characteristics

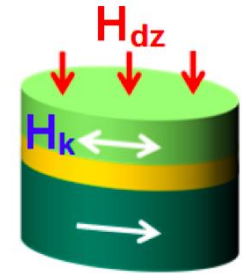
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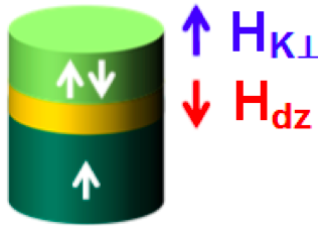
Scalability Study: MTJ Options

1. In-plane MTJ (IMTJ)

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



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



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

2. Crystal perpendicular MTJ (c-PMTJ)

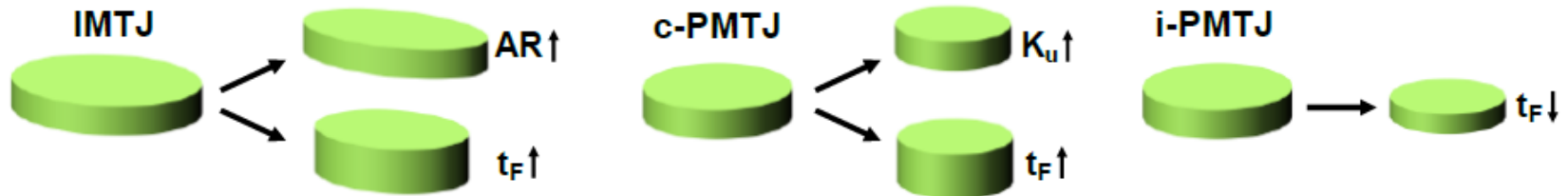
- **Crystal perpendicular anisotropy** from high- K_u materials (FePt, FePd, etc)
- H_{dz} reduces switching current
- Low polarization, high damping

3. Interface perpendicular MTJ (i-PMTJ)

- **Interface perpendicular anisotropy** in thin CoFeB
- CoFeB turns from in-plane to perpendicular when $t_F < t_c$ ($\sim 1.5\text{nm}$)

- **Which MTJ technology is best from a scaling perspective?**

Scalability Study: I_c Scaling Trend

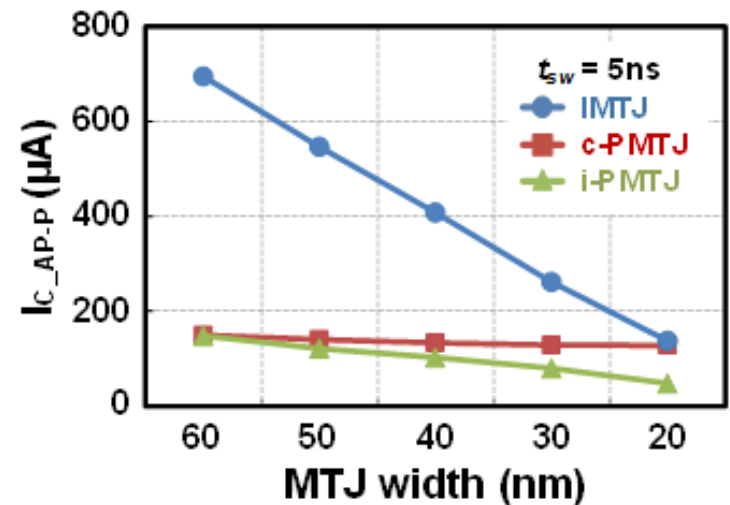


MTJ scaling methods under iso-retention condition

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 , $K_u \uparrow$				
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/m³)

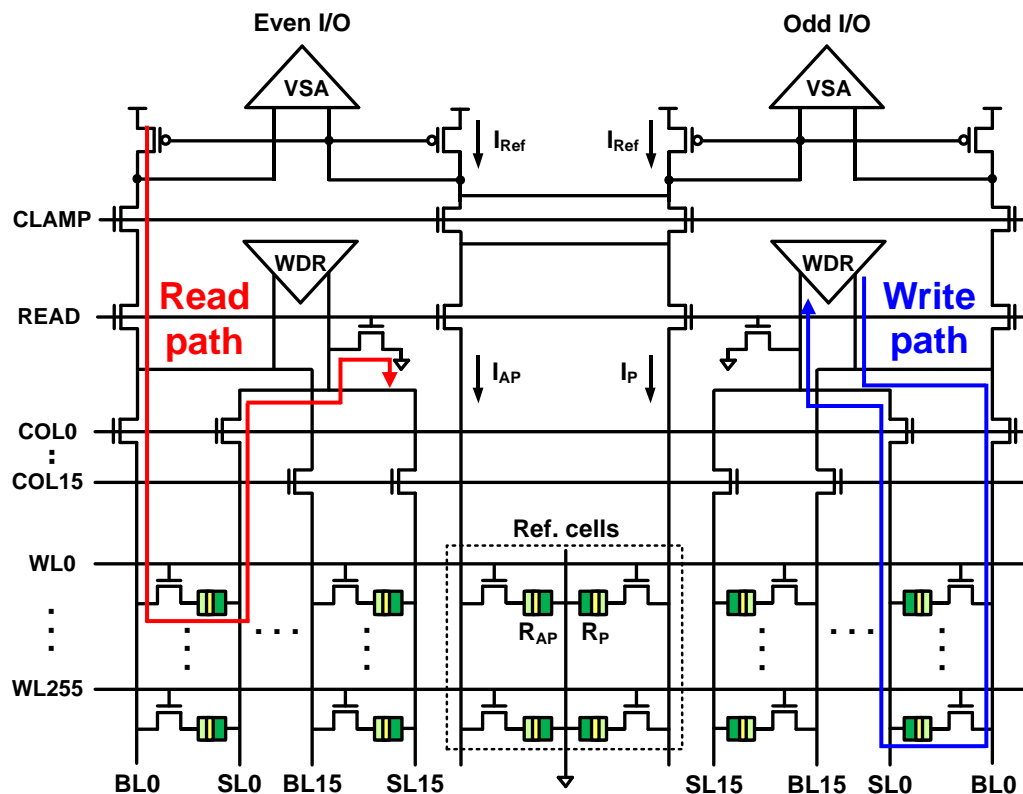
MTJ scaling scenario



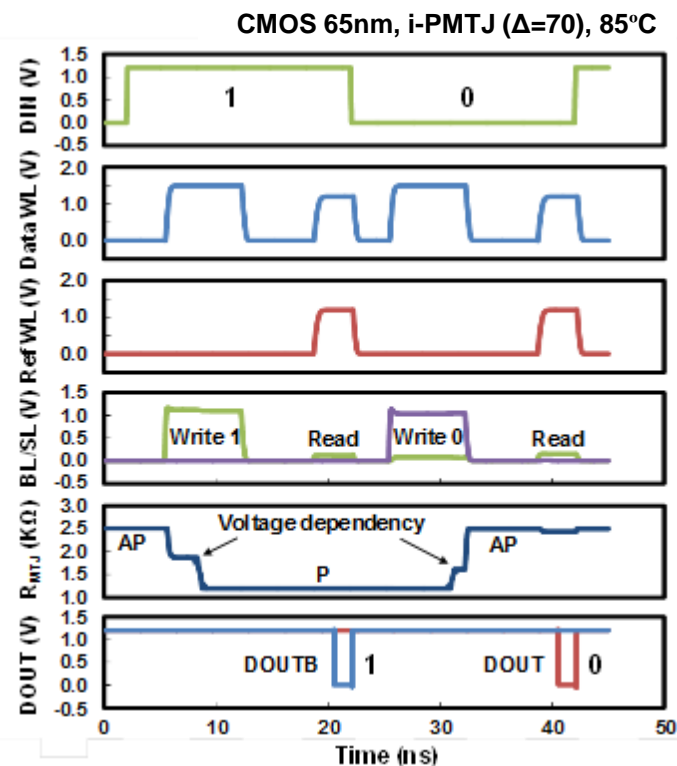
Critical switching current (I_c) trend

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

Variability Study: Simulation Setup



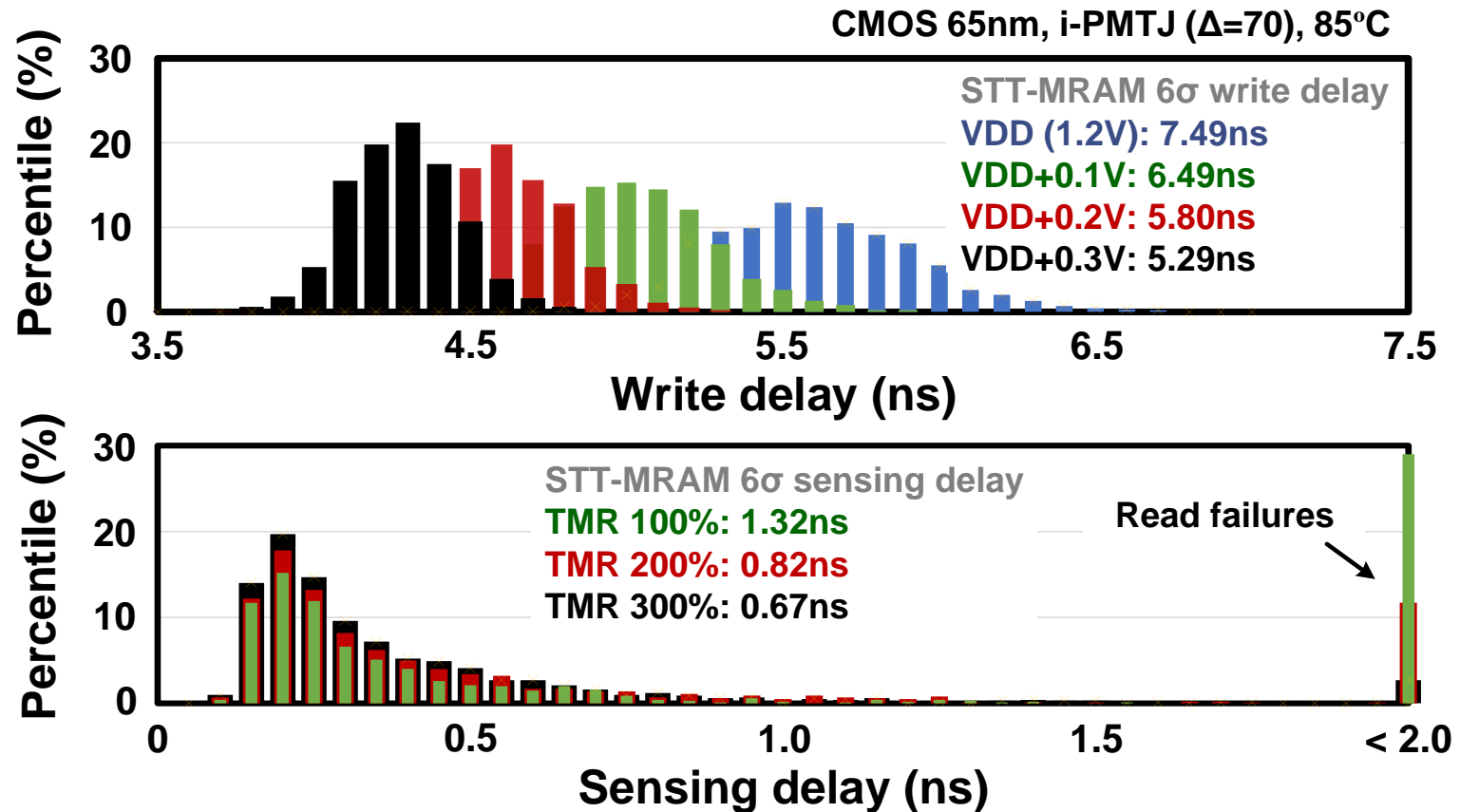
STT-MRAM column circuit



Overall memory operation

- 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})

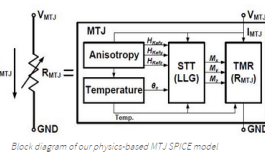
Model Download Website



<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 delay. 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. Using the MTJ SPICE Model, 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. Behin-Aein, S. Kumar, J.P. Wang, and C.H. Kim, "A Technology-Agnostic MTJ SPICE Model with User-Defined Dimensions for STT-MRAM Scalability Studies", Custom Integrated Circuits Conference (CICC), Sep. 2015

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.

Getting started

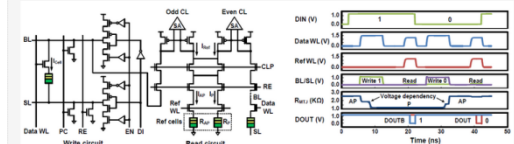
- Step1. Download MTJ spice model.
- Step2. Extract zip file.
- Step3. Open MTJ_write.sp file (MTJ write example).
- Step4. Set MTJ dimensions and material parameters: M_0 , P_0 , α , RA and initial temperature (M_0 : saturation magnetization, P_0 : polarization, both at zero kelvin temperature.)
- Step5. 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)				
	Free layer dimensions	Material	M_0	P_0	α
In-plane MTJ	32nm x 96nm x 2.44nm	CoFeB	1210	0.59	0.0062
Crystalline perpendicular MTJ	45nm x 45nm x 0.45nm	FeB	1210	0.62	0.03
Interface perpendicular MTJ	65nm x 65nm x 1.48nm	CoFeB	1210	0.59	0.006

Simulation examples

1. Input parameters for in-plane MTJ (antiparallel to parallel switching)
 $XMTJ1\ 1\ 0\ MTJ\ lx=32n\ ly=96n\ lz=2.44n\ M_0=1210\ P_0=0.59\ alpha=0.0062\ Tmp0=358\ RA0=5\ MA=0\ ini=1$
2. Input parameters for crystal perpendicular MTJ (antiparallel to parallel switching)
 $XMTJ1\ 1\ 0\ MTJ\ lx=45n\ ly=45n\ lz=0.45n\ M_0=1210\ P_0=0.62\ alpha=0.03\ Tmp0=358\ RA0=5\ MA=1\ ini=1\ Kp=1.08e7$
3. Input parameters for interface perpendicular MTJ (antiparallel to parallel switching)
 $XMTJ1\ 1\ 0\ MTJ\ lx=65n\ ly=65n\ lz=1.48n\ M_0=1210\ P_0=0.59\ alpha=0.006\ Tmp0=358\ RA0=5\ MA=1\ ini=1\ tc=1.5n$
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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