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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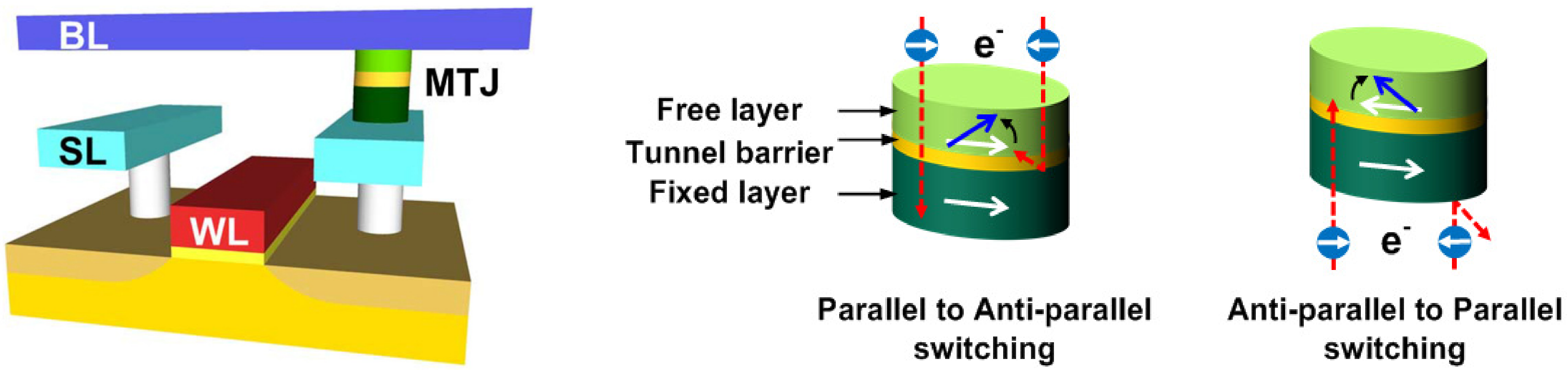
Overview

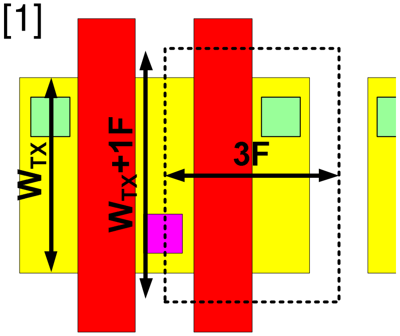
- Spin-Transfer Torque (STT) MRAM: Basic Concepts
- Magnetic Tunnel Junction (MTJ): Key Physics to Be Modeled
- Model Framework and Implementation
- Case Study: STT-MRAM Scalability and Variability Simulations
- Summary

STT-MRAM Basics

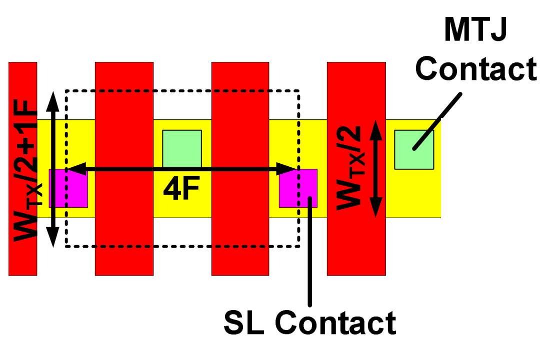


STT-MRAM bit-cell structure and STT switching

[1]



1T-1MTJ layout



2T-1MTJ layout

* SRAM: ~$120F^2$

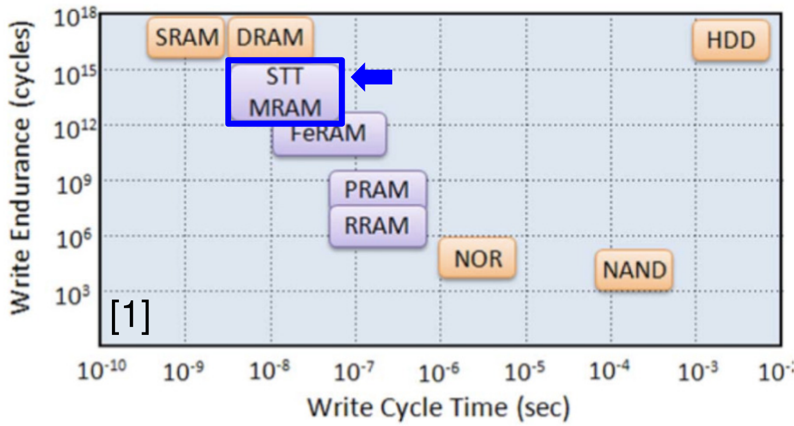
Type	Stand-alone	Embedded
W_{TX}	Minimum	18F
1T-1MTJ	$6F^2$	$57F^2$
2T-1MTJ	$8F^2$	$40F^2$

Bit-cell area comparison

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

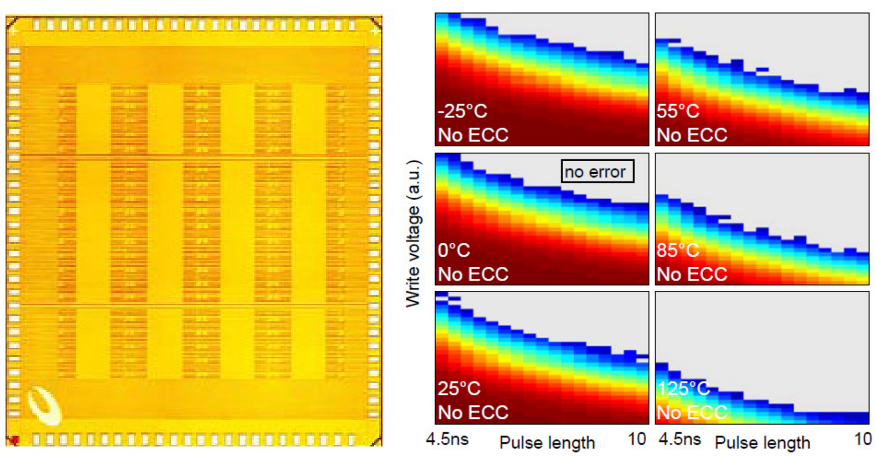
[1] R. Takemura, JSSC 2010 (Hitachi)

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

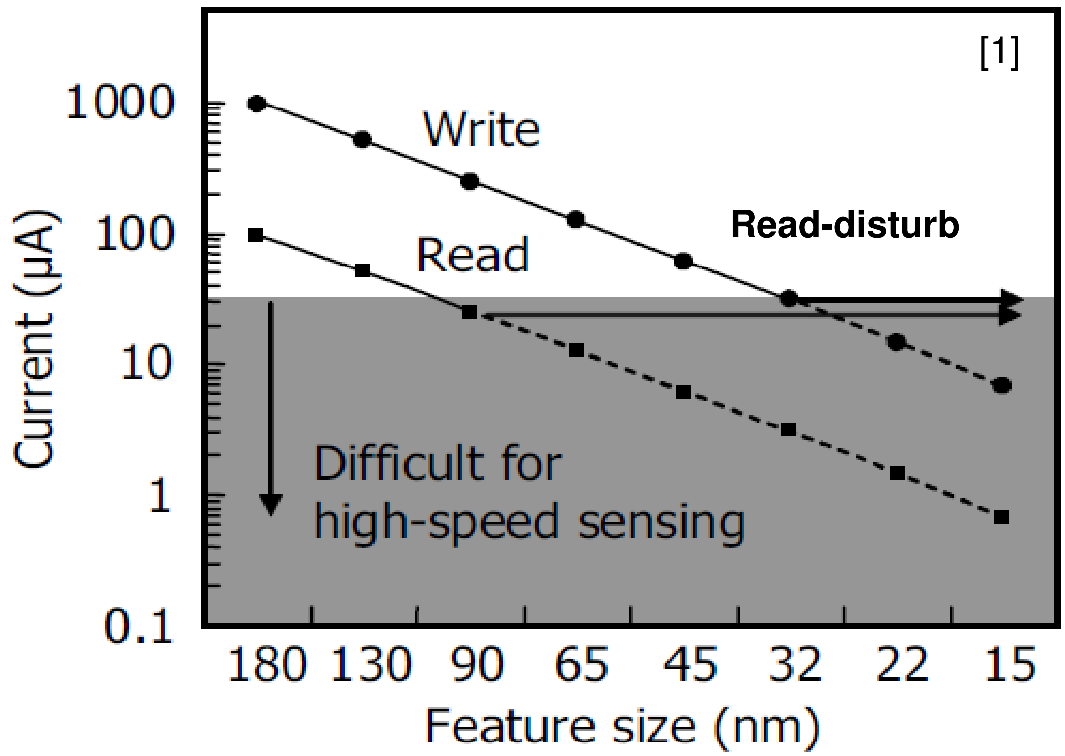
- **Recent demonstration by TDK** [2]
  - 8Mbits embedded STT-MRAM
  - 90nm CMOS/ 50F^2 1T-1MTJ
  - 150% TMR, 4/5ns Read/Write
  - Less than 1ppm bit error rate for 10yr retention/125C



Chip micrograph and write shmoos

[1] K. Lee, TMAG 2011 (Qualcomm) [2] G. Jan, VLSI 2014 (TDK)

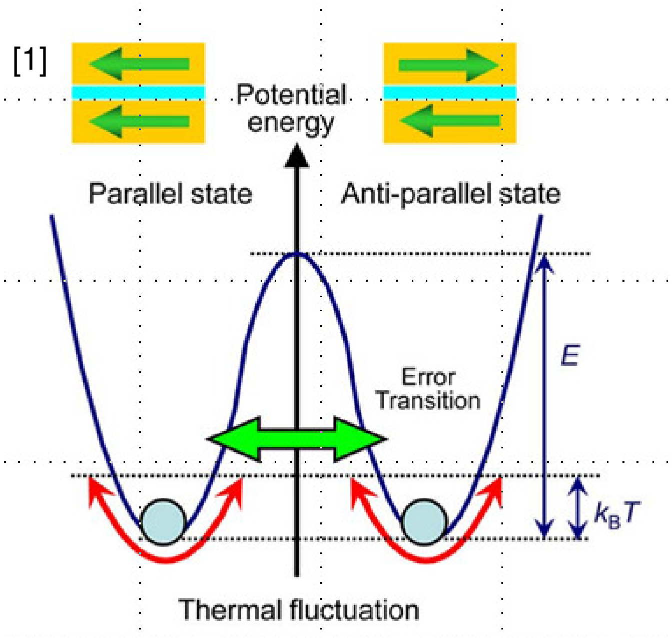
STT-MRAM Scaling Challenges



- 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

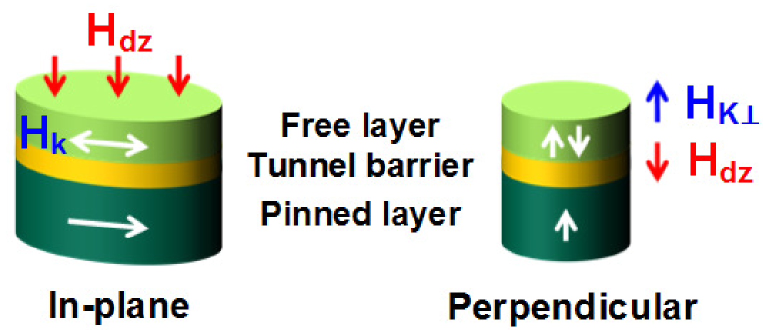
[1] K. Ono, IEDM 2009 (Hitachi)

Key MTJ Physics to Be Modeled



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

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

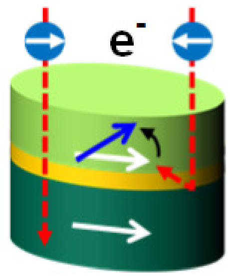


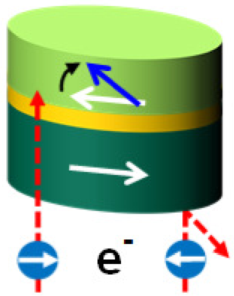
Thermal stability and magnetic anisotropy

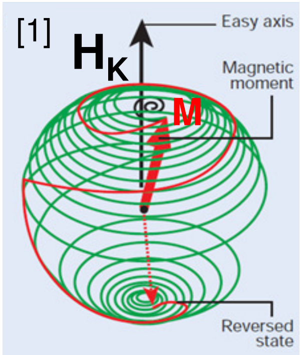
- Thermal stability (Δ) determines the degree of nonvolatility
- Thermal stability is defined as E_b with respect to thermal fluctuation
- H_k decides the energetic preference of spin direction (i.e. easy axis): In-plane or perpendicular magnetic anisotropy

[1] R. Takemura, JSSC 2003 (Hitachi)

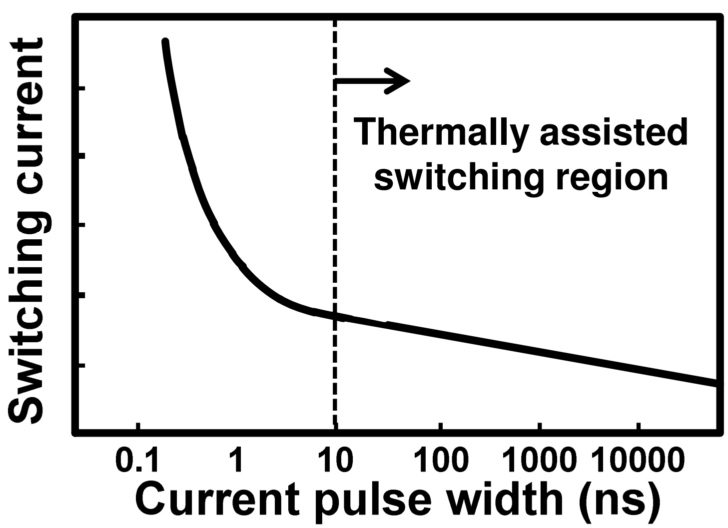
Key MTJ Physics to Be Modeled



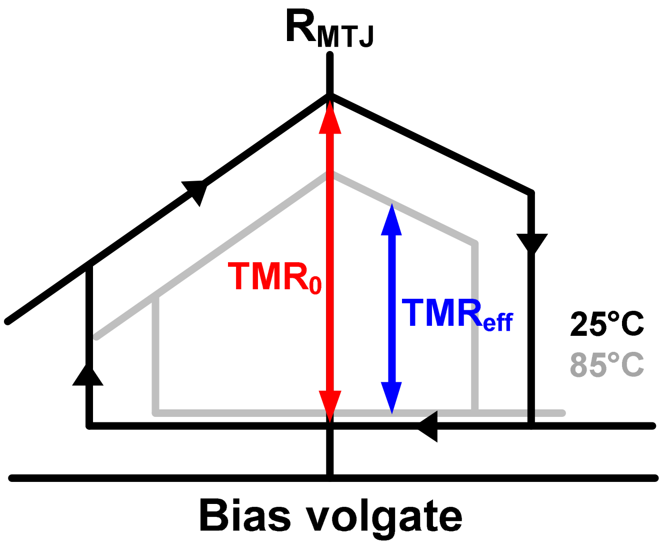




STT-induced dynamic spin motion



Switching current vs. pulse width

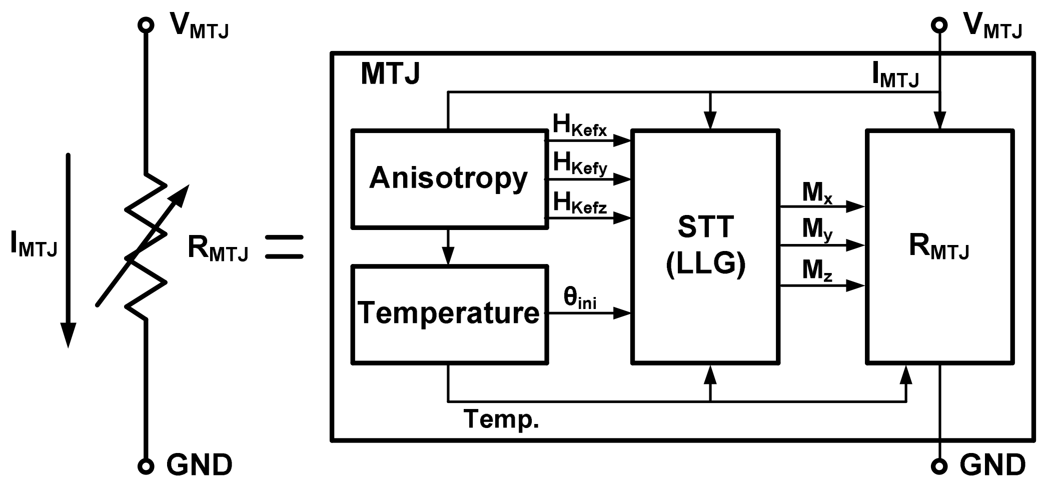


Temperature-dependent R-V curve

*TMR: Tunneling magnetoresistance ratio

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

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

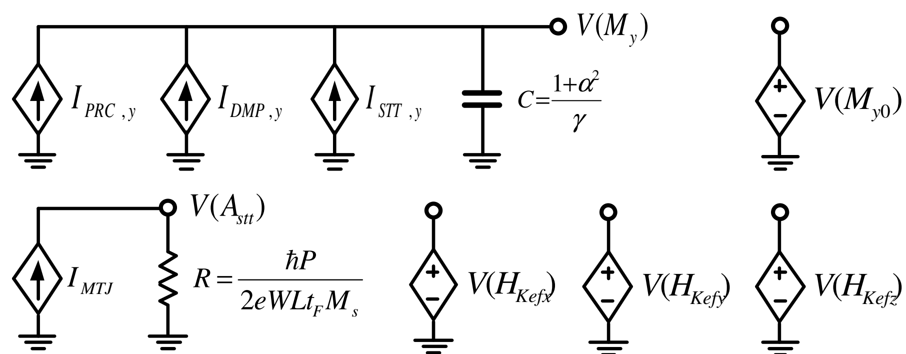
- Covers all types of anisotropy sources (shape, crystal, and interface)
- Dimension-dependent anisotropy field enables scalability and variability analyses
- Changing the initial angle parameter allows convenient simulation of MTJ switching probability

SPICE Implementation

Numerical form:

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

Circuit implementation (y-coordinate):



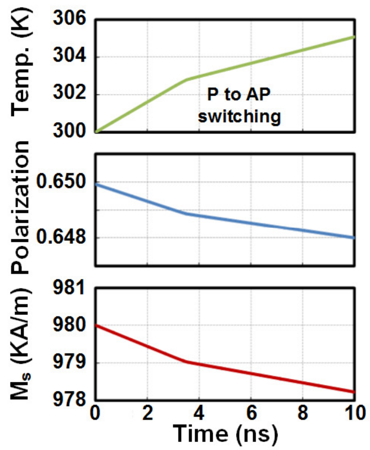
HSPICE script (y-coordinate):

C_M_y M_y 0 '$(1+\alpha^2)/\gamma$'
$G\_dM_{y\_prc}$ 0 M_y cur='$-(v(M_z)\cdot v(H_{Kefx})-v(H_{Kefz})\cdot v(M_x))$'
$G\_dM_{y\_dmp}$ 0 M_y cur='$-\alpha\cdot(v(M_z)\cdot(v(M_{y0})\cdot v(H_{Kefz})-v(H_{Kefy})\cdot v(M_z))-(v(M_x)\cdot v(H_{Kefy})-v(H_{Kefx})\cdot v(M_{y0}))\cdot v(M_x))$'
$G\_dM_{y\_stt}$ 0 M_y cur='$v(A_{stt})\cdot(v(M_z)\cdot(v(M_{y0})\cdot M_{pz}-M_{py}\cdot v(M_z))-(v(M_x)\cdot M_{py}-M_{px}\cdot v(M_{y0}))\cdot v(M_x))$'
E_M_{y0} M_{y0} 0 vol='$v(M_y)$' max='$\cos(v(\theta_c))$' min='$-\cos(v(\theta_c))$'

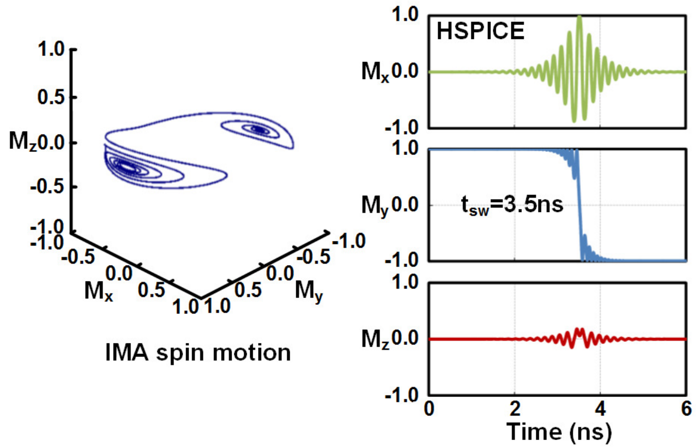
SPICE implementation of LLG equation (only y-coordinate shown for simplicity)

- 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·dV/dt*

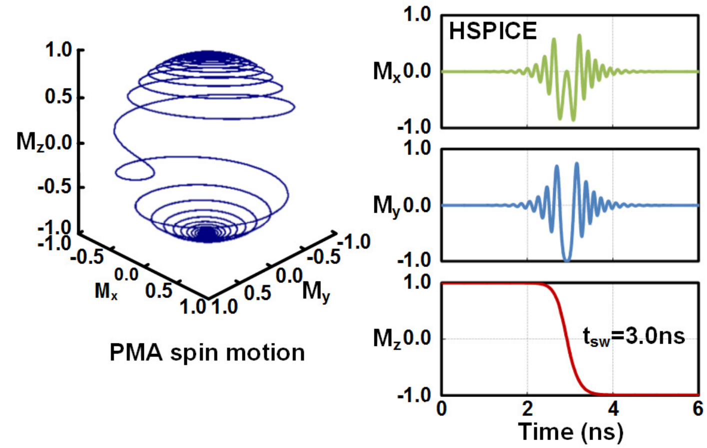
Model Verification



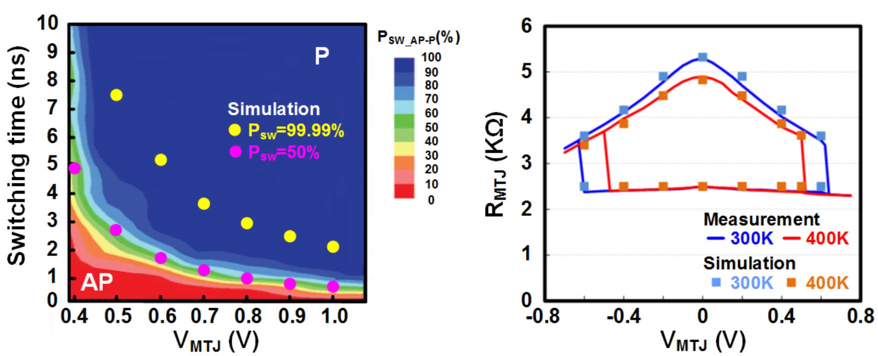
Temp. dependency of material parameters



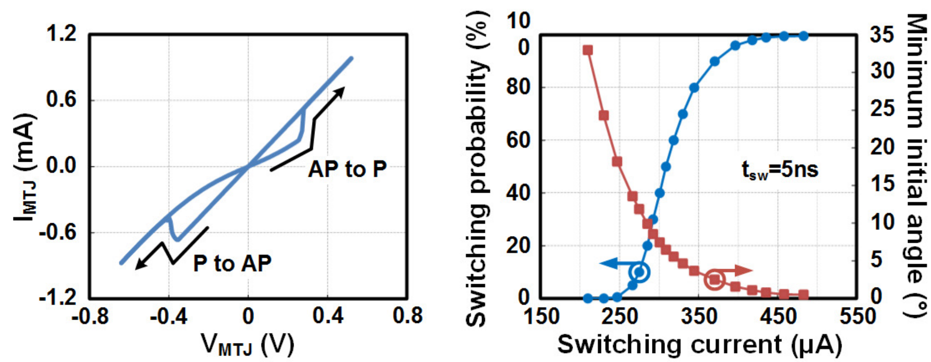
In-plane switching



Perpendicular switching



Comparison with measurement data [1], [2]



MTJ switching characteristics

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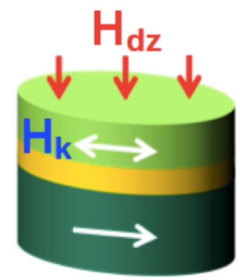
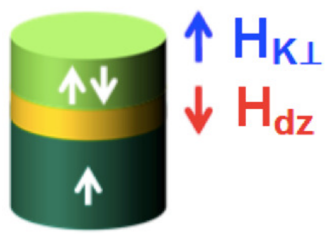
Scalability Study: MTJ Options

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)

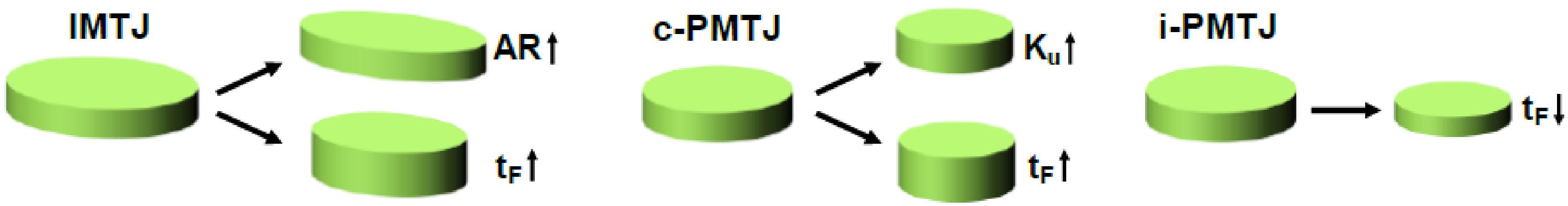
- Crystal perpendicular anisotropy from high-K_u materials (FePt, FePd, etc)
- H_{dz} reduces switching current
- Low polarization, high damping

3. Interface perpendicular MTJ (i-PMTJ)

- Interface perpendicular anisotropy in thin CoFeB
- CoFeB turns from in-plane to perpendicular when $t_F < t_c$ (~1.5nm)

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

Scalability Study: I_c Scaling Trend

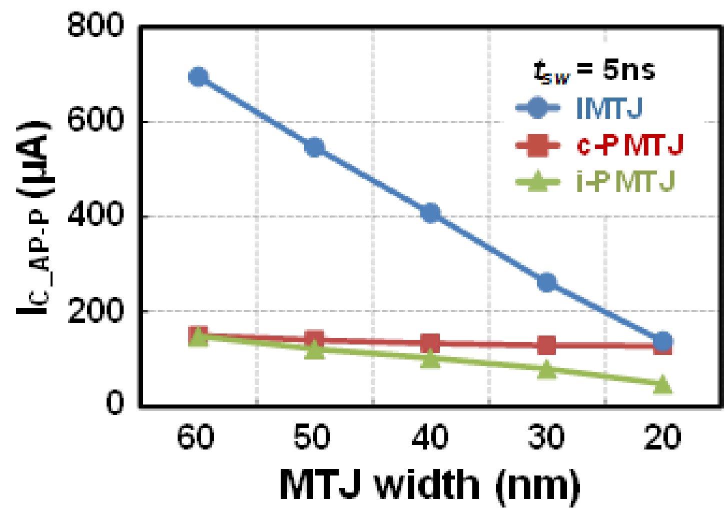


MTJ scaling methods under iso-retention condition

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 ↑		t_F ↑ , t_F dependent α		
c-PMTJ (FePdX)	M_s=1077, P=0.51, α=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 ↑				t_F ↑
i-PMTJ (CoFeB)	Ms=1077, P=0.6, t_c=1.5nm	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 ↓, t_F dependent α			Dual interface	

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

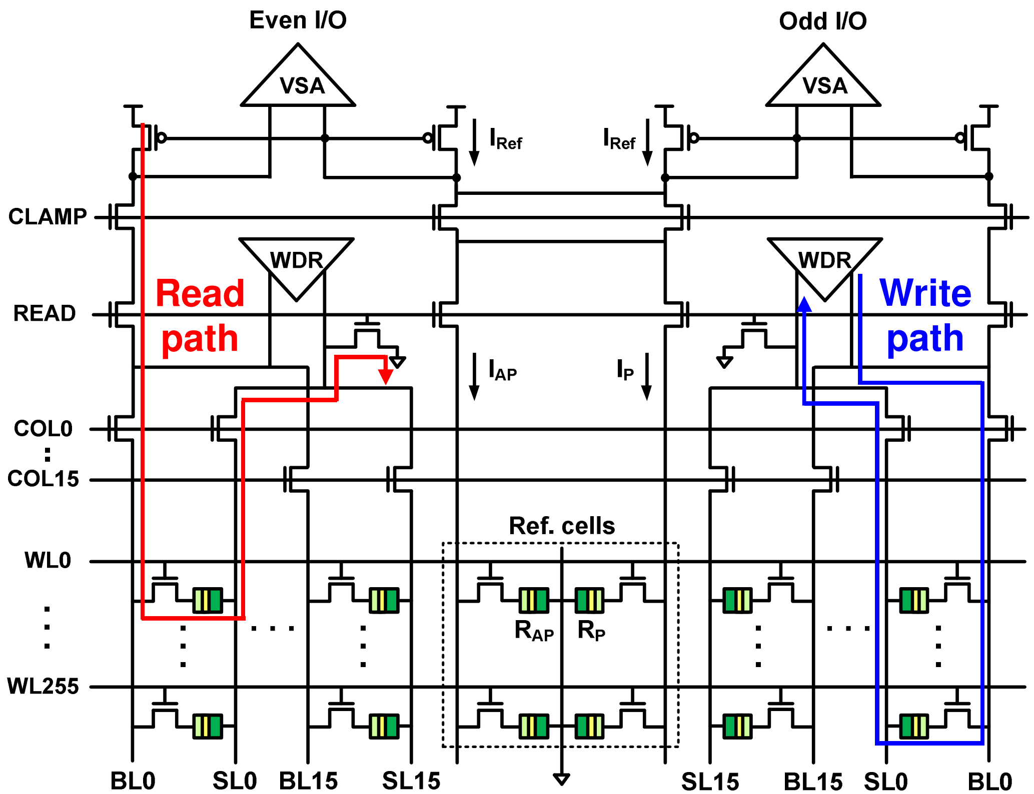
MTJ scaling scenario



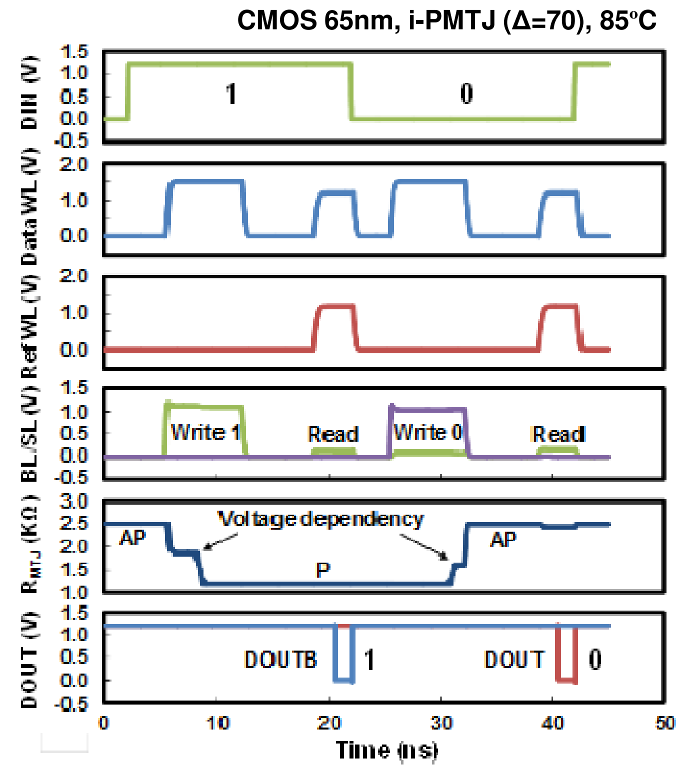
Critical switching current (I_c) trend

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

Variability Study: Simulation Setup



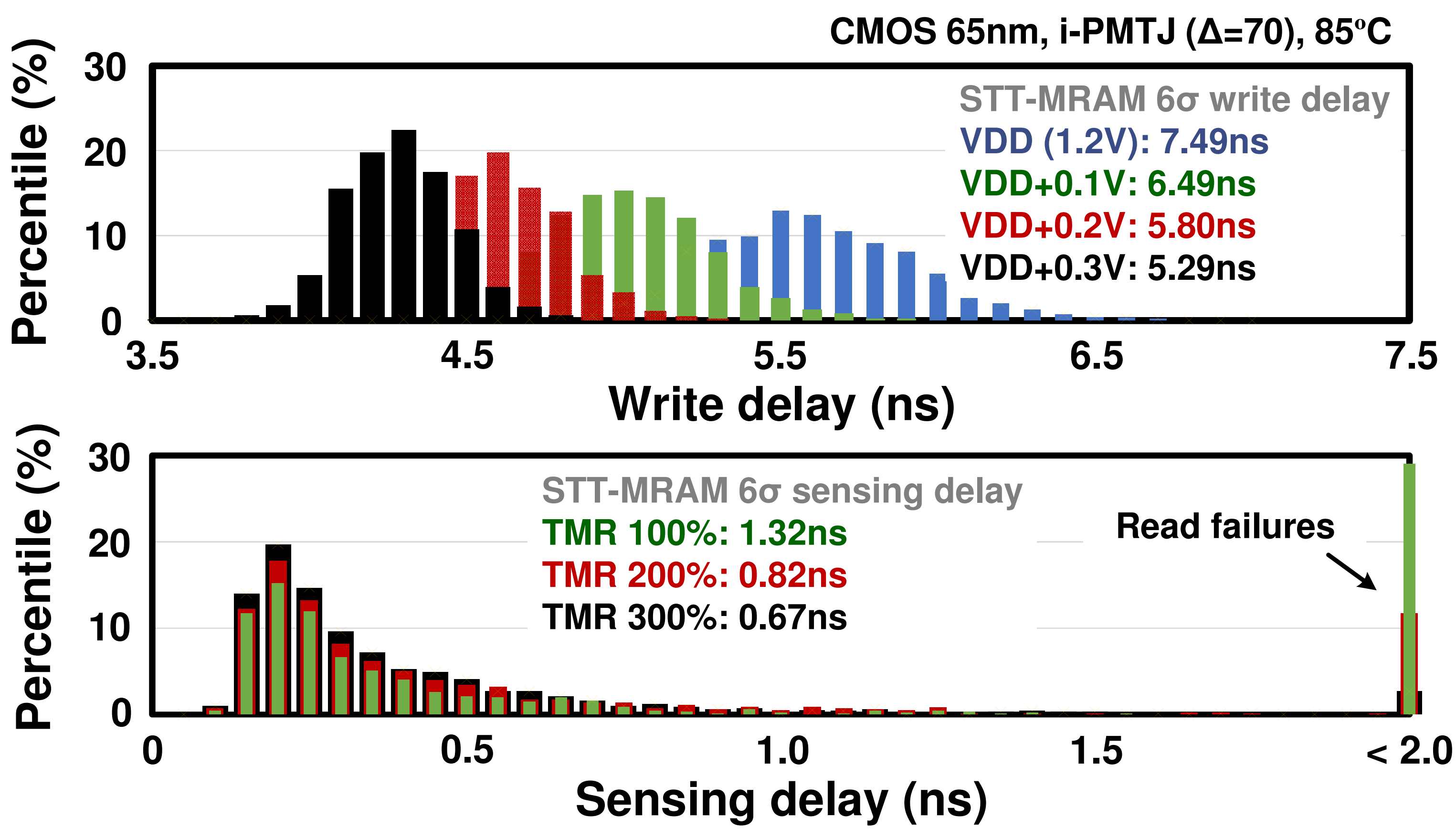
STT-MRAM column circuit



Overall memory operation

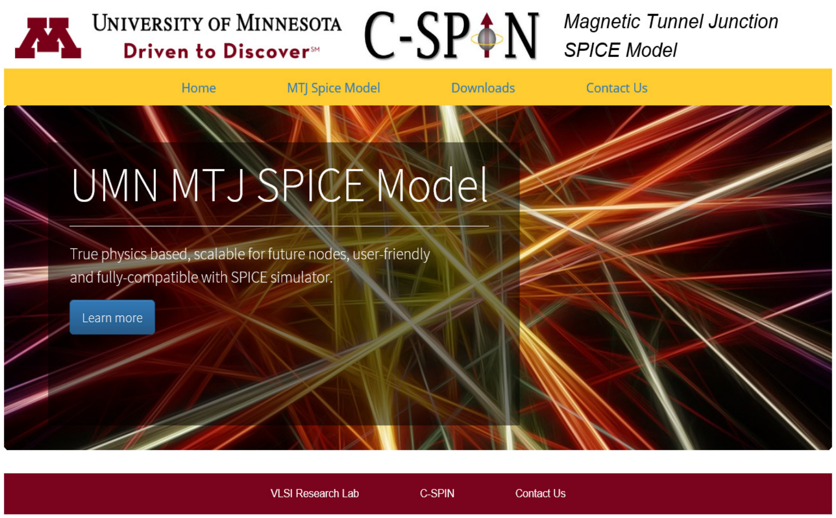
- Optimized bit-cell connection for symmetric current driving
- Bi-directional write current driver, dual-voltage WL driver
- Parallelizing read current, Mid-point reference circuit using $I_{Ref}=(I_{AP}+I_P)/2$

Variability Study: Write and Read Delays

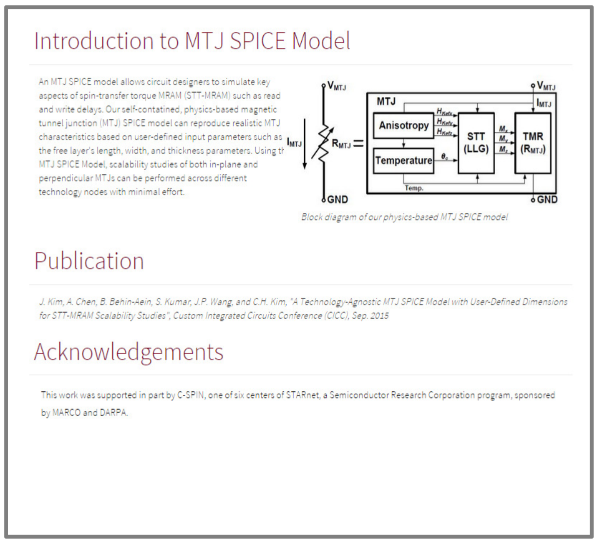


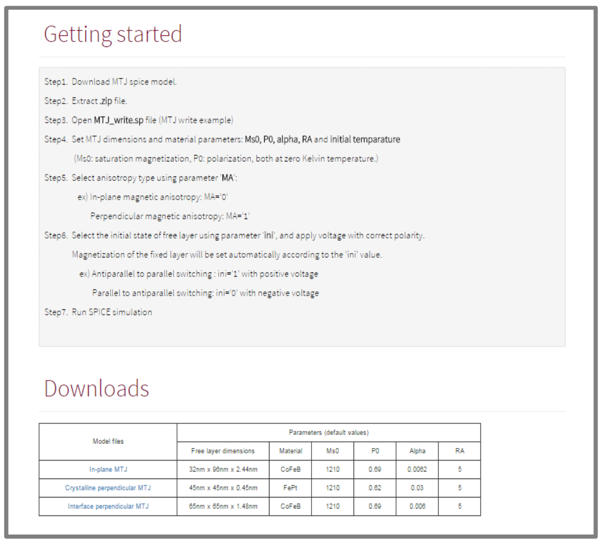
- Write and sensing delay distributions with 6σ values
- Includes realistic variation for both MTJ (i.e. *W*, *L*, t_F, RA) and CMOS (i.e. transistor *W*, *L*, V_{th}, T_{ox})

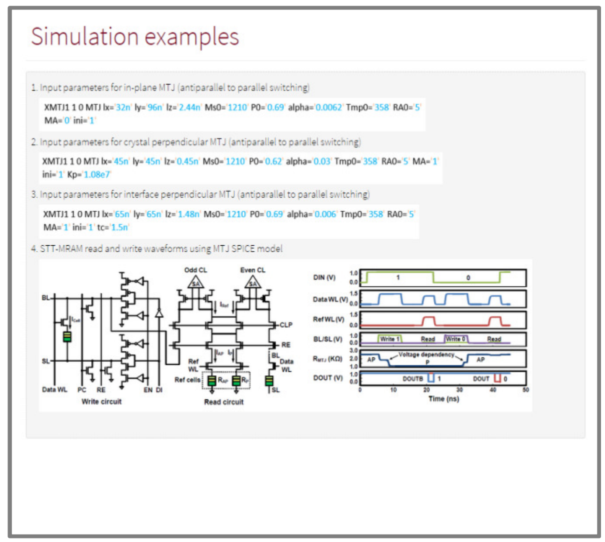
Model Download Website



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

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