

# **SPICE Modeling of STT-RAM for Resilient Design**

**Zihan Xu, Ketul Sutaria, Chengen Yang,  
Chaitali Chakrabarti, Yu (Kevin) Cao  
School of ECEE, ASU**



# OUTLINE

- **Heterogeneous Memory Design**
  - **A Promising Candidate: STT-RAM**
    - Fundamentals of STT-RAM
    - Previous approaches
    - [Hierarchical Modeling](#) Solution
  - **SPICE Model of STT-RAM**
    - Equivalent Circuit Model
    - Device Parameter Model
  - **STT-RAM Single Cell Simulation**
  - **Summary and Future Work**
-

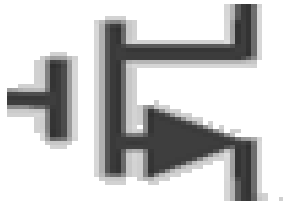
# Trend of Technology Scaling

Bulk/SOI  
MOSFET

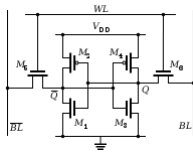
Strained  
MOSFET

HKMG  
MOSFET

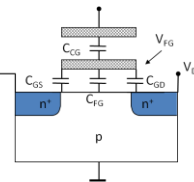
MG  
MOSFET



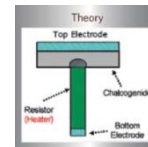
SRAM



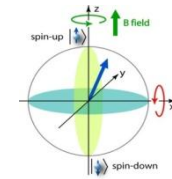
Flash



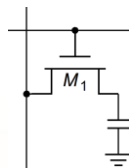
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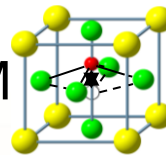
STT



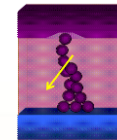
DRAM



FRAM



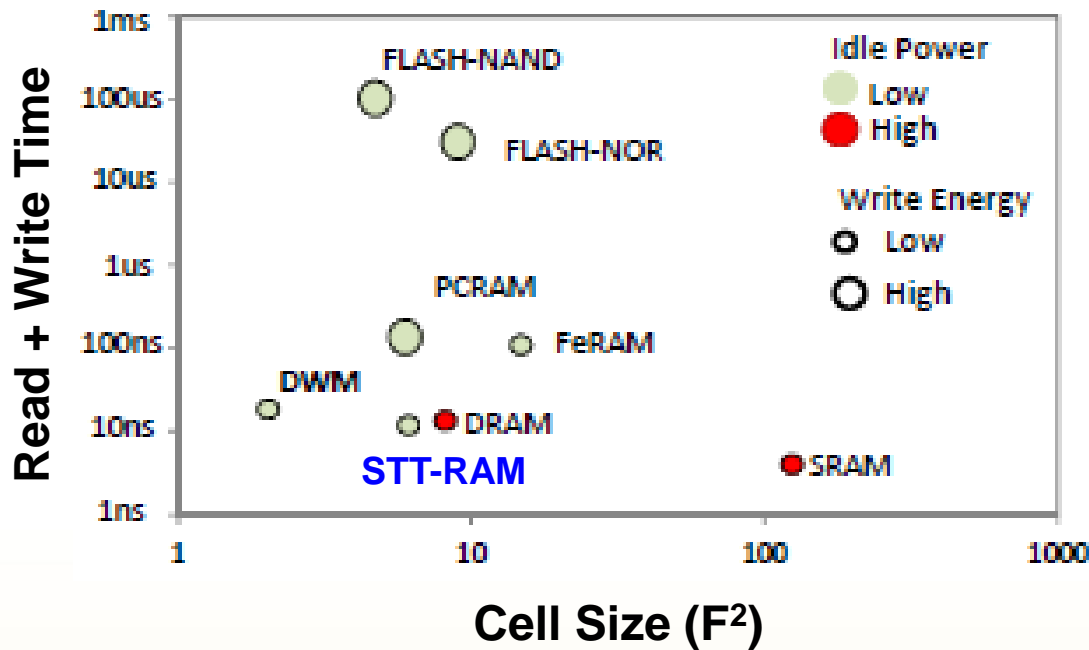
RRAM



- **Tremendous variety in memory** physics, materials, structures, and devices!

# Tremendous Diversity

## ■ Performance



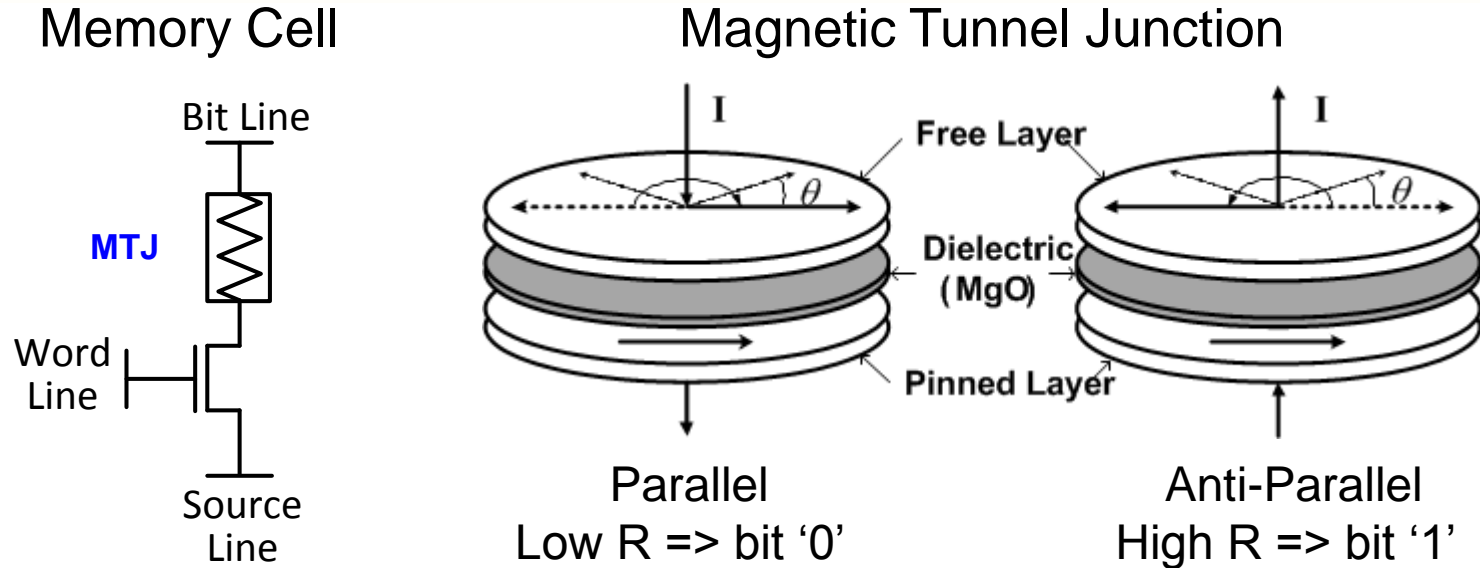
[R. Venkatesan, ISLPED 2012]

## ■ STT-RAM

### Advantages:

- Access time comparable to SRAM
- Density comparable to DRAM
- Low standby power
- High endurance ( $>10^{16}$ )
- Scalable to lower technology nodes
- Can be used for logic design

# STT-RAM Fundamental



- Magnetic Tunnel Junction (MTJ) consists of thin insulating layer (Dielectric-MgO) about  $\sim 1$  nm thick, sandwiched between two layers of ferromagnetic material.
- Magnetization of one layer is fixed while that of other layer is free. Direction of magnetization angle in free layer governs the resistance of MTJ.
- Resistance is translated to logical value of the data that is stored. Parallel state corresponds to bit '0' being stored and anti-parallel state corresponds to bit '1'.

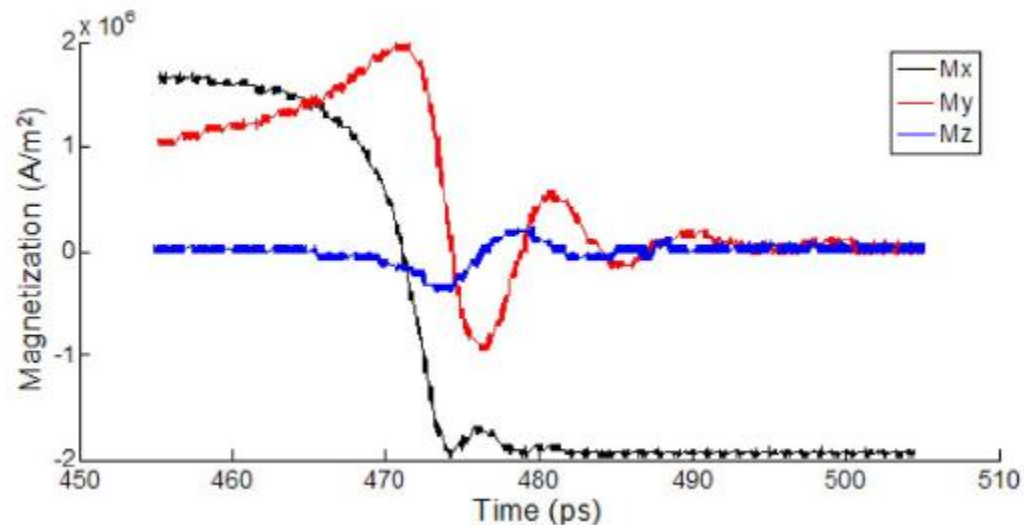
# LLG Equation

$$\frac{d\vec{M}}{dt} = \underbrace{-\gamma\mu_0 \cdot \vec{M} \times \vec{H}}_{\text{Zeeman (external)}} + \underbrace{\frac{\alpha}{M_s} \cdot \vec{M} \times \frac{d\vec{M}}{dt}}_{\text{Damping (internal)}} + \underbrace{\gamma \frac{K}{M_s^2} \cdot (\vec{M} \cdot \vec{u}_{ea}) \cdot (\vec{M} \times \vec{u}_{ea})}_{\text{Anisotropic (internal)}}$$

- Zeeman energy tends to align the magnetization field with the applied field.
- Damping energy is the energy loss of the precession of magnetization.
- Anisotropic energy is responsible for self-alignment of magnetization along easy axis  $\vec{u}_{ea}$ .
- $\gamma \approx 1.76 \times 10^{11} \text{ rad} \cdot \text{s}^{-1} \cdot \text{T}^{-1}$  gyromagnetic ratio
- $\mu_0 = 4\pi \times 10^{-7} \text{ N} \cdot \text{A}^{-2}$  permeability constant
- K is anisotropy constant dependent on material

# Numerical Method

- Numerically solve 3D LLG equation
- Capture both static and transient behavior of magnetization
- Difficult implementation and low efficiency



[J. B. Kammerer, TED 2010]

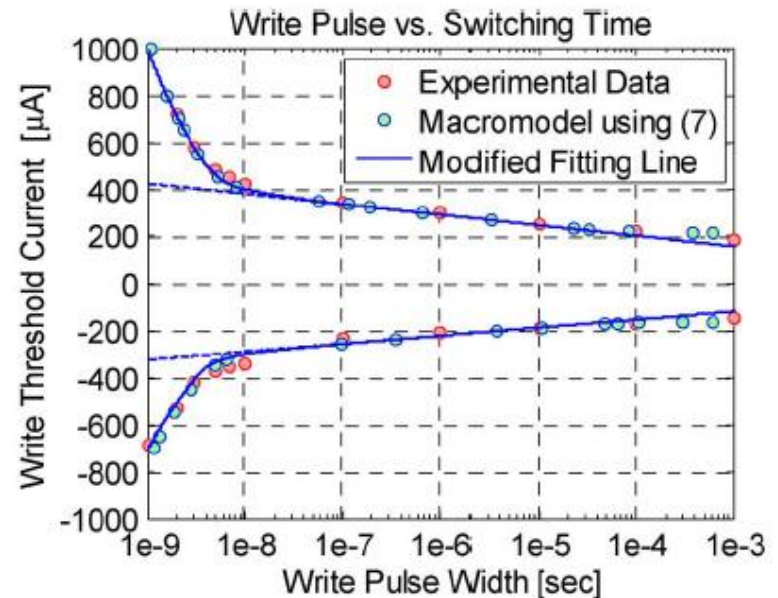
# Macro Model

- Based on calculated switching (threshold) current

$$- J_{C0} = \frac{\alpha\gamma eM_s t_{FL}}{\mu_B g} \times \left( H_{ext} \pm H_{ani} \pm \frac{H_d}{2} \right)$$

$$- J_c = J_{C0} \left[ 1 - \left( \frac{k_B T}{E} \right) \ln \frac{\tau}{\tau_0} \right]$$

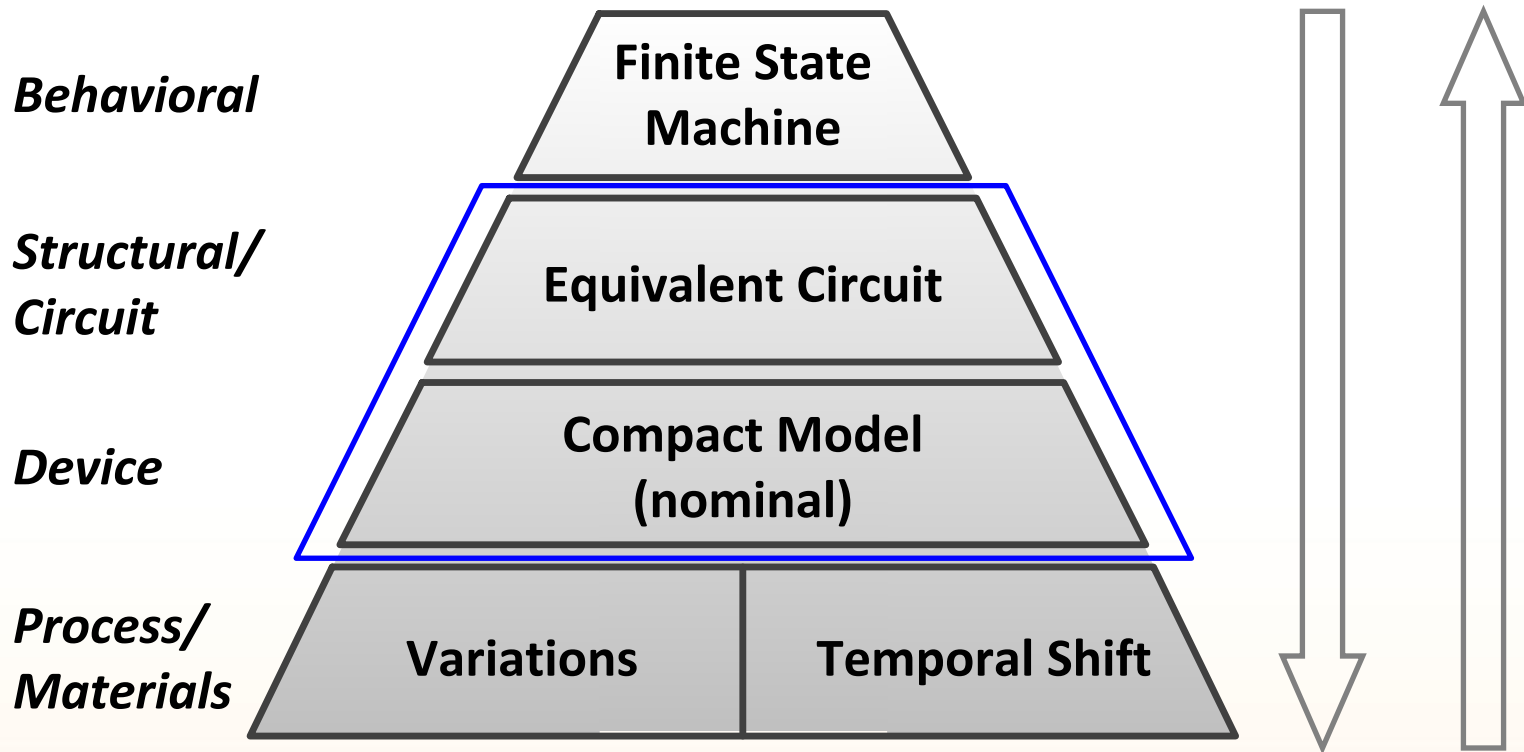
- Capture the relation of switching current amplitude and pulse width
- Cannot capture transient behavior and variation issues



[J. D. Harms, TED 2010]

# Hierarchical Memory Model

- Multi-level modeling for design analysis, optimization and path-finding / inverse path-finding

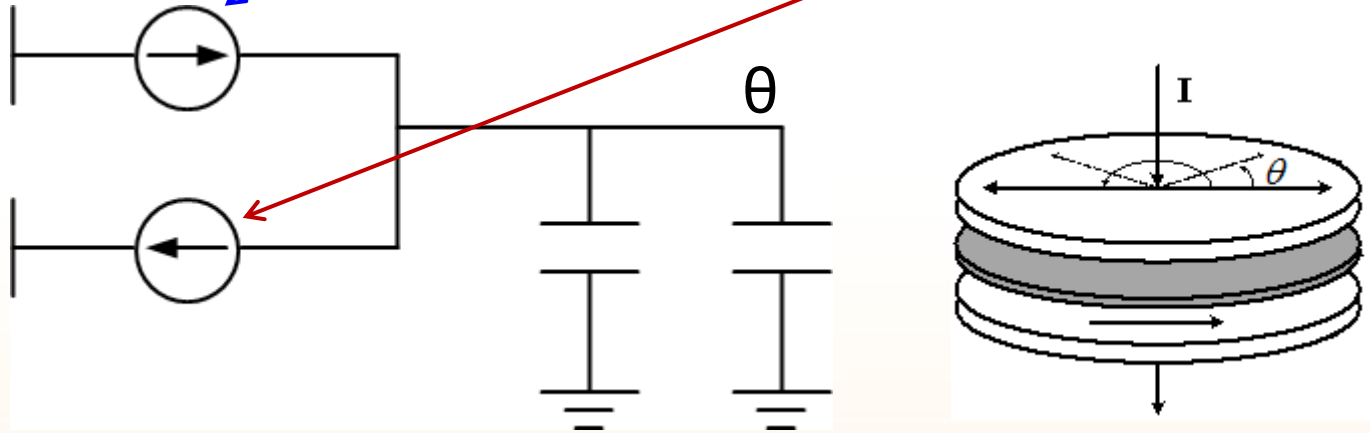


# SPICE Model

3D 
$$\frac{d\vec{M}}{dt} = -\gamma\mu_0 \cdot \vec{M} \times \vec{H} + \frac{\alpha}{M_s} \cdot \vec{M} \times \frac{d\vec{M}}{dt} + \gamma \frac{K}{M_s^2} \cdot (\vec{M} \cdot \vec{u}_{ea}) \cdot (\vec{M} \times \vec{u}_{ea})$$

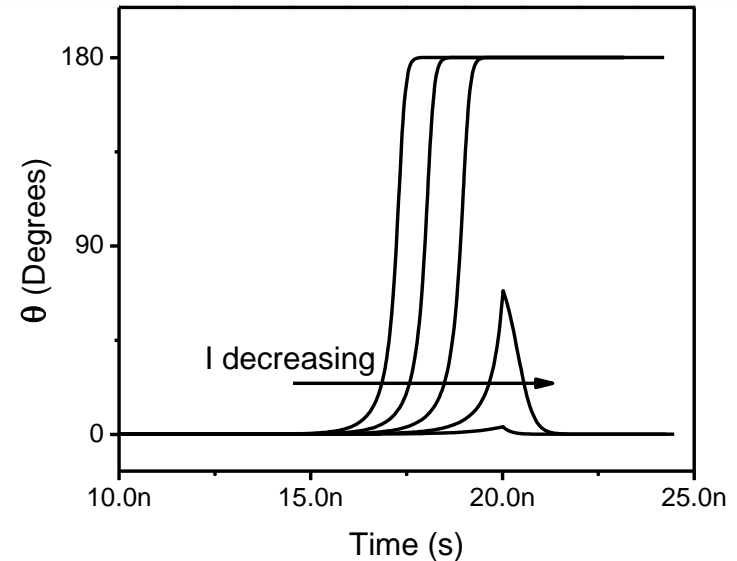
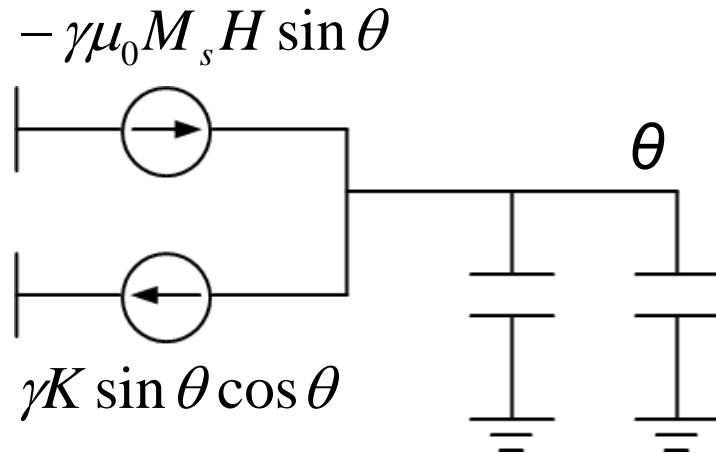


1D 
$$M_s \frac{d\theta}{dt} = \underbrace{-\gamma \cdot \mu_0 \cdot M_s \cdot H \cdot \sin \theta}_{\text{blue box}} + \alpha M_s \cdot \frac{d\theta}{dt} + \underbrace{\gamma \cdot K \sin \theta \cos \theta}_{\text{red box}}$$



Equivalent Circuit

# Equivalent Circuit Model



- Be able to simulate transient behavior
- Easy implementation with SPICE components and Verilog-A models
- Differential equation is solved by SPICE simulator reducing computation time

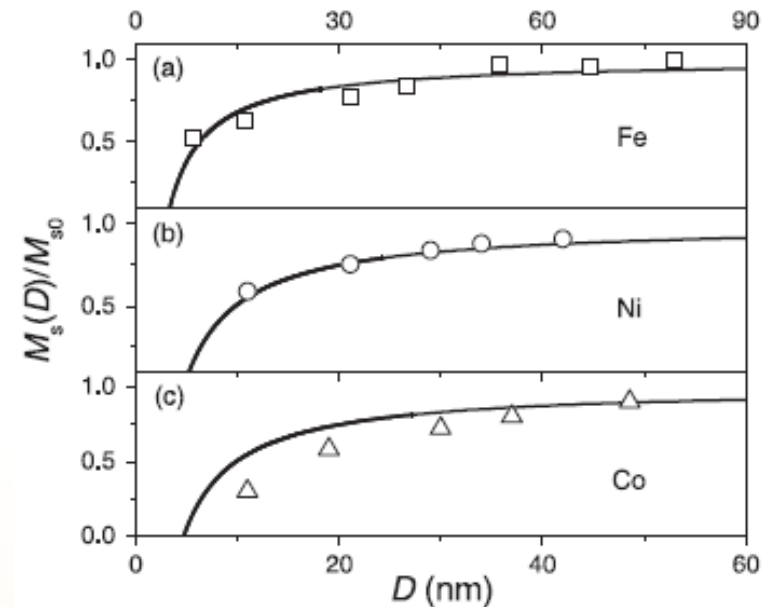
# Saturation Magnetization ( $M_s$ )

$$M_s \frac{d\theta}{dt} = -\gamma \cdot \mu_0 \cdot M_s \cdot H \cdot \sin \theta + \alpha M_s \frac{d\theta}{dt} + \gamma \cdot K \sin \theta \cos \theta$$

- Material and geometry dependent

$$\frac{M_s(D)}{M_{s0}} = 4 \left[ 1 - \frac{1}{\frac{2D}{ch} - 1} \right] \cdot \exp \left[ -\frac{2S_b}{3R} \frac{1}{\frac{2D}{ch} - 1} \right] - 3$$

- D: diameter of MTJ layer
- $M_{s0}$ :  $M_s$  of bulk ferromagnetic material
- c: a constant ( $0 < c \leq 1$ ) depends on the interface
- h: atomic diameter
- $S_b$ : bulk solid-vapour transition entropy
- R: ideal gas constant



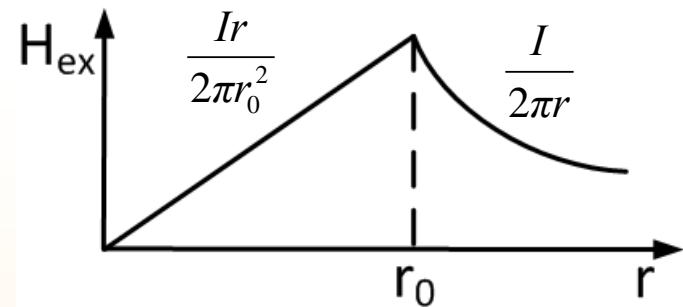
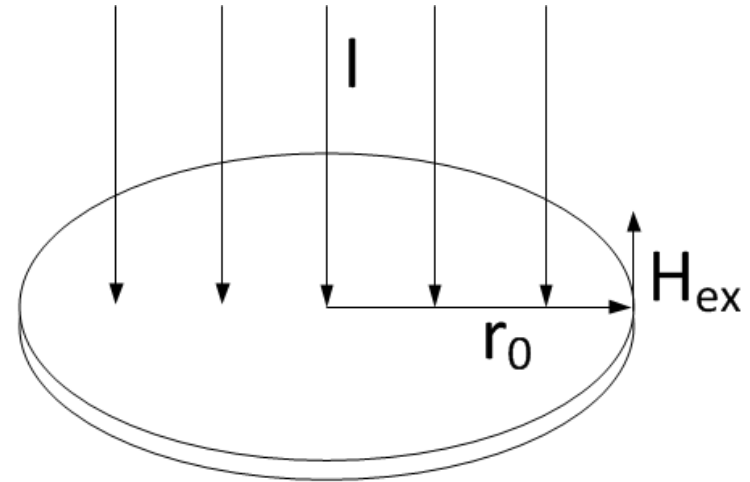
[H. M. Lu, J. Phys. D 2007]

# Magnetic Field (H)

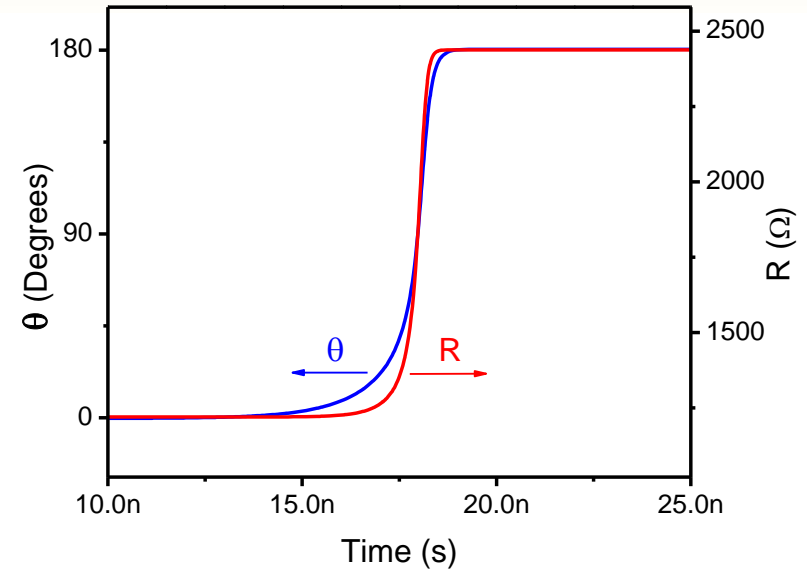
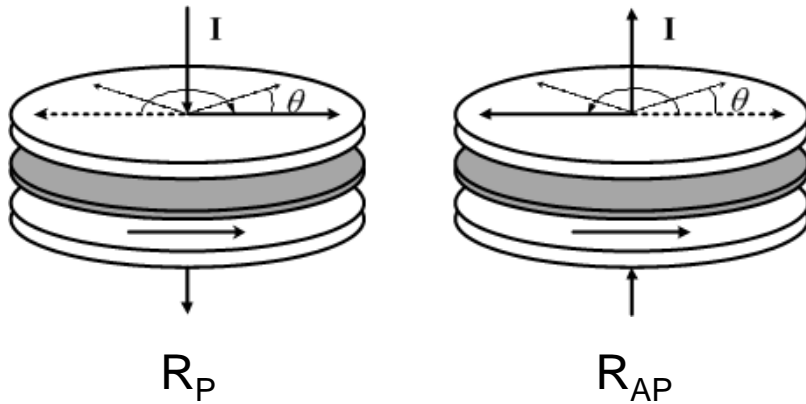
$$M_s \frac{d\theta}{dt} = -\gamma \cdot \mu_0 \cdot M_s \cdot \mathbf{H} \cdot \sin \theta + \alpha M_s \frac{d\theta}{dt} + \gamma \cdot K \sin \theta \cos \theta$$

- $H = H_{ex} + H_0$
- $H_{ex}$  is the external magnetic field generated by input current
- $H_0$  captures the asymmetric switching threshold

$$H_{ex} = \begin{cases} \frac{Ir}{2\pi r_0^2} & (r \leq r_0) \\ \frac{I}{2\pi r} & (r > r_0) \end{cases}$$



# Magnetic Angle to Resistance



- $R = R_P [1 + 0.5TMR(1 - \cos \theta)]$

- $R_P = \frac{t_{ox}}{F\sqrt{\phi}A} \exp(1.025t_{ox}\sqrt{\phi})$

[J. C. Slonczewski, Phys. Rev. B 2005, Y. Zhang, TED 2012]

- As  $\theta$  approaches  $180^\circ$ ,  $R = R_{AP}$

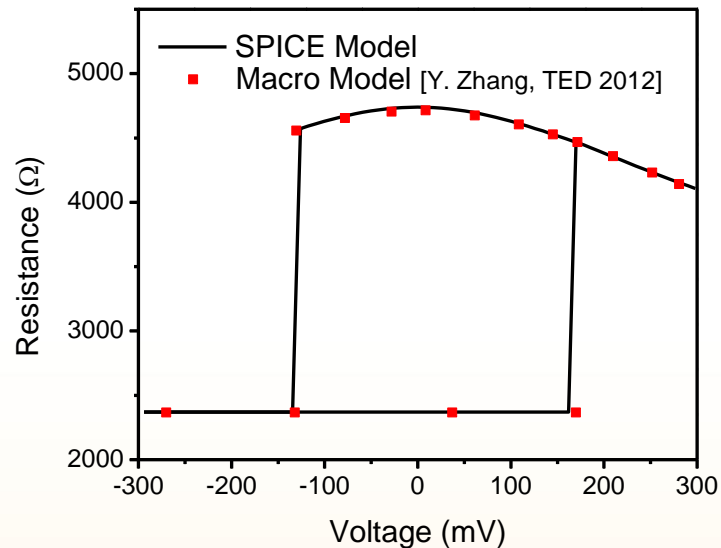
$t_{ox}$	Oxide thickness	0.85 nm
F	Material parameter	332.2
$\phi$	Potential barrier	0.4 eV
A	Area	3318 nm <sup>2</sup>

# Voltage Dependence of TMR

- Tunnel Magnetoresistance (TMR) is the resistance difference ratio of MTJ of the two states.  $TMR = \frac{R_{AP} - R_P}{R_P}$
- TMR depends on the voltage across the MTJ.

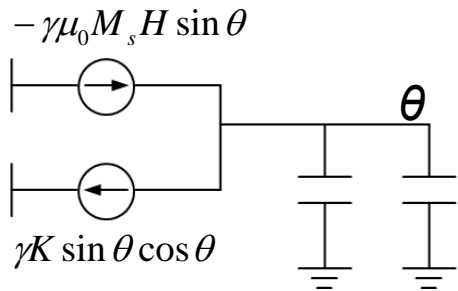
$$TMR = \frac{TMR_0}{1 + V^2 / V_h^2}$$

- $TMR_0$  is the TMR ratio with 0 voltage.
- $V_h$  is the voltage as  $TMR = 0.5 \times TMR_0$ .



# Model Summary

- Equivalent Circuit:



$$M_s \frac{d\theta}{dt} = -\gamma \cdot \mu_0 \cdot M_s \cdot H \cdot \sin \theta + \alpha M_s \frac{d\theta}{dt} + \gamma \cdot K \sin \theta \cos \theta$$

- Device Models and Parameter Values (65nm) :

$$\frac{M_s(D)}{M_{s0}} = 4 \left[ 1 - \frac{1}{\frac{2D}{ch} - 1} \right] \cdot \exp \left[ -\frac{2S_b}{3R} \frac{1}{\frac{2D}{ch} - 1} \right] - 3$$

$$H = \frac{Ir}{2\pi r_0^2} + H_0$$

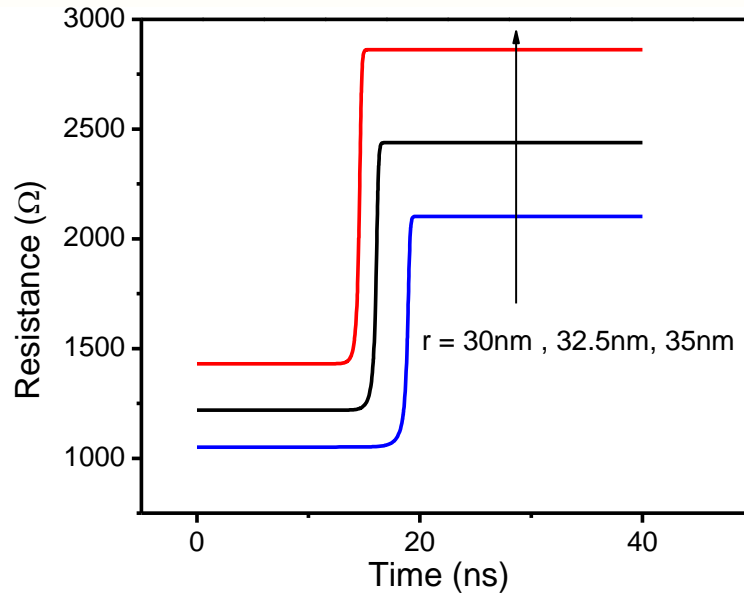
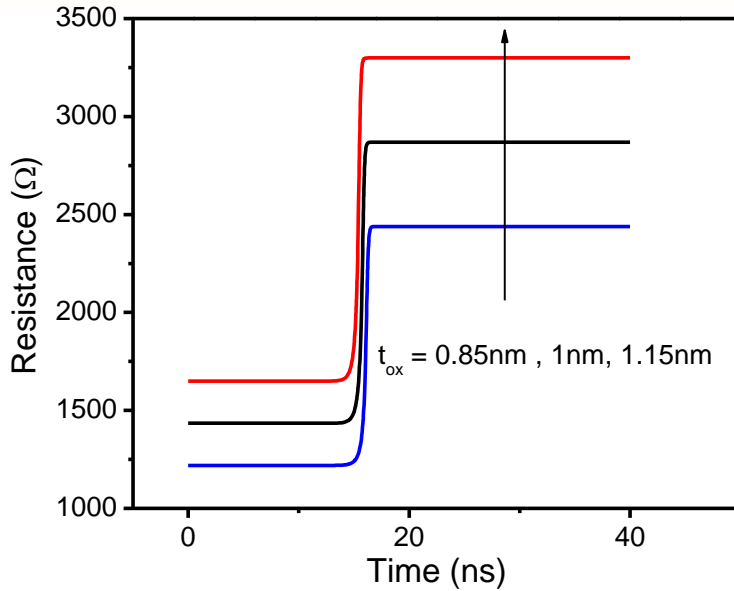
$$R = R_P [1 + 0.5TMR(1 - \cos \theta)]$$

$M_{s0}$	$4.94 \times 10^5$ A/m
D	65 nm
c	1
h	0.24 nm
$S_b/R$	13

$r_0$	32.5 nm
$H_0$	49 A/m

TMR	$\frac{TMR_0}{1 + V^2/V_h^2}$
$TMR_0$	1.2
$V_h$	0.5 V
$R_P$	1.2 k $\Omega$

# Geometry Dependence



- This model captures the transition behavior under process variation.

# Temperature Dependence

## ■ Resistance

- $R(T) = R(0) \frac{\sin(\lambda T)}{\lambda T}$

- $R(0)$  is the resistance at  $T=0K$

- $\lambda = \frac{\pi t_{ox} k}{\hbar} \sqrt{\frac{2m_e}{e}}$

- $t_{ox}$  is oxide thickness,  $k$  is Boltzmann constant,  $\hbar$  is reduced plank constant,  $m_e$  is electron mass.

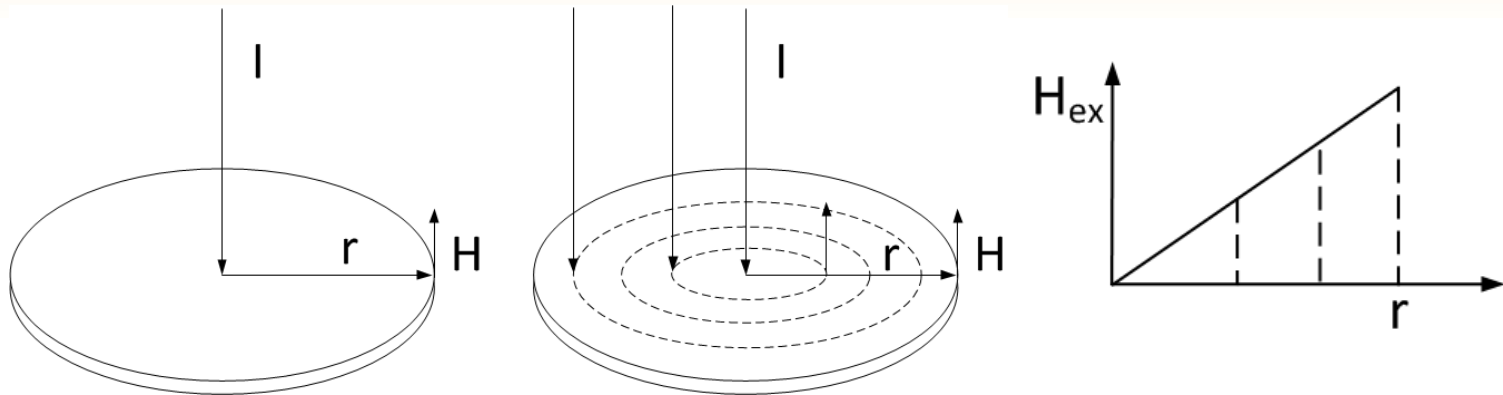
[M. El Baraji, J. Appl. Phys. 2009]

## ■ Magnetic field

- Thermal fluctuating field  $H_{fluc}$

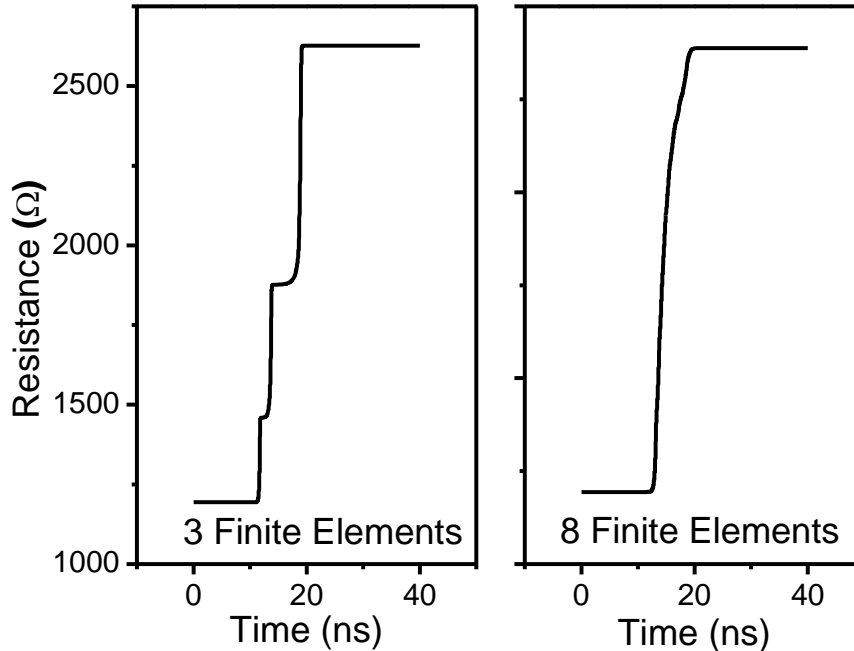
[Y. Zhang, ICCAD 2011]

# Finite Element Method



- Magnetic field being function of radius 'r', the field is non-uniform across MTJ causing different switching of magnetization angle.
- Finite element method helps to capture the non-uniform distribution of magnetic field

# Finite Element Simulations

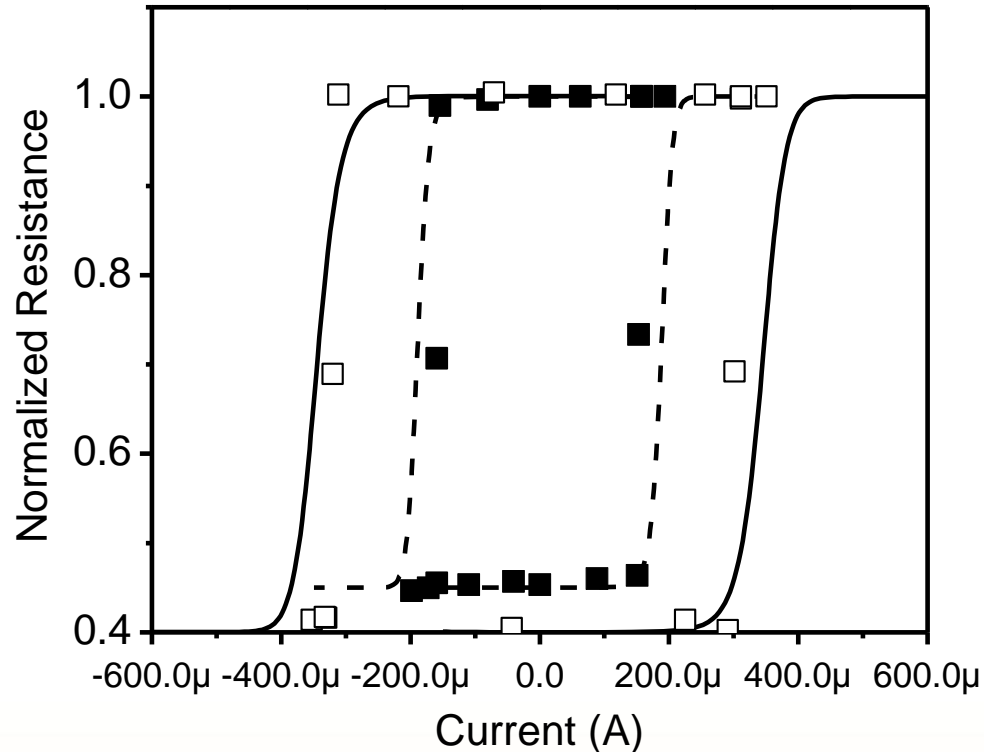


## Simulation time

3 Elements	1.72 s
8 Elements	4.01 s

- For accurate and fast simulation, we choose 8 elements in the simulation.
- Increasing number of finite element for simulation increases simulation time with marginal improvement in accuracy.

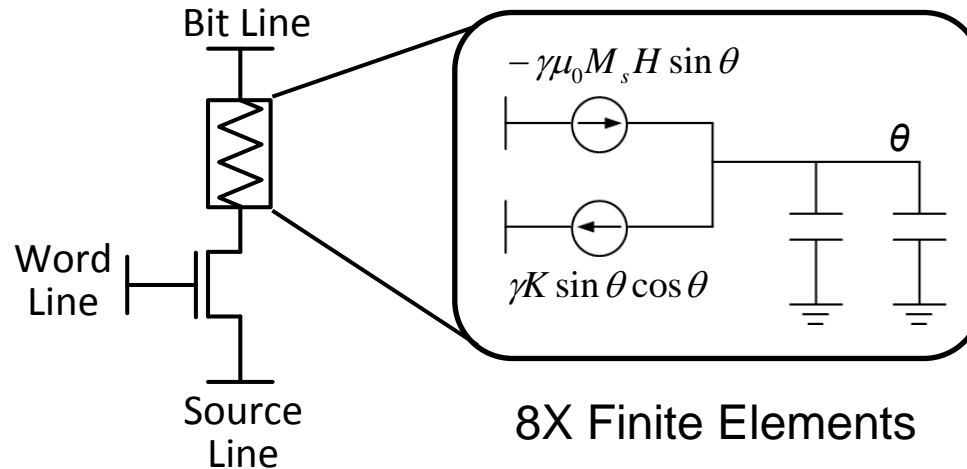
# Model Validation



[Z. Diao, J. Phys. 2007]

- Hysteresis effect predicted by model validated by experimental data for two different MTJs.

# Simulation Setup



- Read operation: current lower than critical value is applied to MTJ to determine its resistance state.
- During write operation, BL and SL are charged to opposite values depending on bit value that is to be stored. For write-0,  $BL = V_{dd}$ ,  $SL = 0V$ ; write-1,  $BL = 0V$  and  $SL = V_{dd}$ .

# Simulation Results

- Evaluation of STT-RAM performance with proposed model using 10ns pulse.
  - Write energy for single cell

0 -> 1	1.48 pJ
1 -> 0	2.09 pJ

- Based on the proposed SPICE model, cell level parameters such as resistance, current and geometry dependent variables can be obtained.
- Using above parameters, a system level memory simulator (CACTI) evaluates memory access time, cycle time, area, leakage, and dynamic power for entire architecture.

# Summary and Future Work

- SPICE model of STT-RAM
  - Hierarchical modeling approach
  - Equivalent circuit model
  - Geometry dependence of model parameters
- Next step:
  - Validation with silicon data
  - Variability and reliability effects
  - Implementation into multi-level memory design tools
  - Adaptive design techniques: R/W, ECC, etc.
  - Integration of heterogeneous memory devices