Compact Modeling of STT-MTJ for SPICE Simulation

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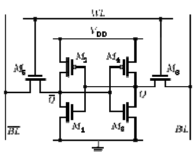
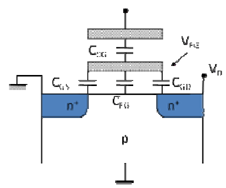
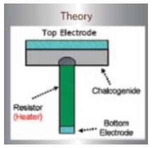
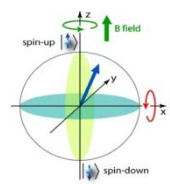
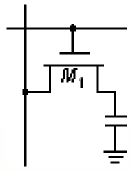
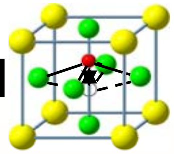
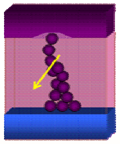
Trend of Technology Scaling

Bulk/SOI MOSFET | Strained MOSFET | HKMG MOSFET | MG MOSFET

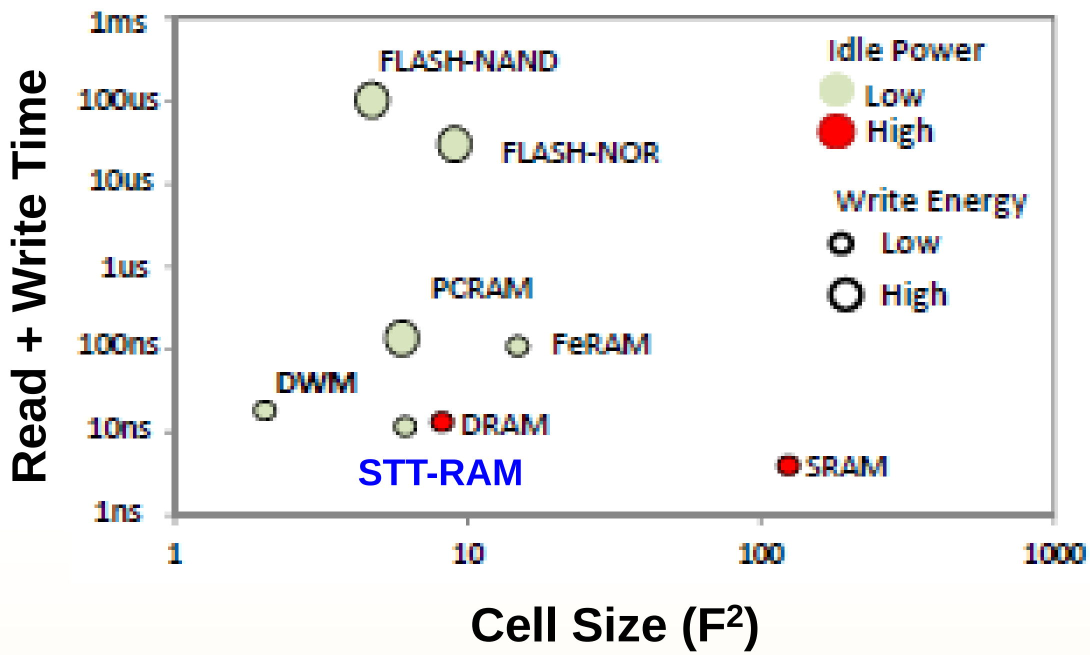
SRAM  Flash  PCM  STT 

DRAM  FRAM  RRAM 

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

Tremendous Diversity

- Performance

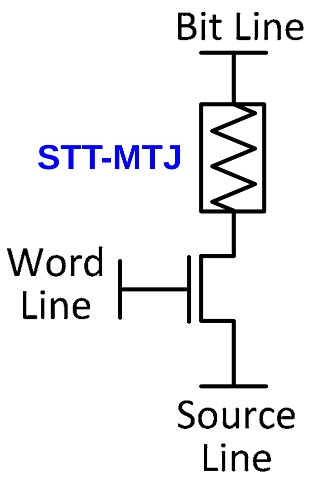


[R. Venkatesan, ISLPED 2012]

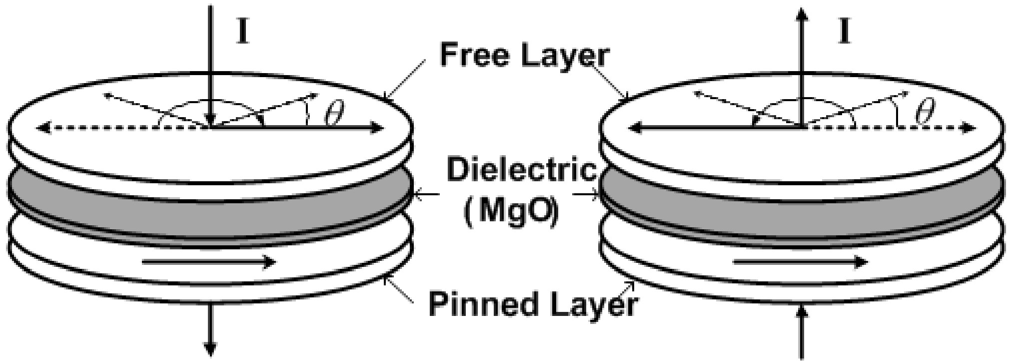
- STT-RAM Advantages:
  - Access time comparable to SRAM
  - Density comparable to DRAM
  - Low standby power
  - High endurance (>10^{16})
  - Good scalability

STT-MTJ Fundamentals

Memory Cell



Spin-Transfer-Torque
Magnetic Tunnel Junction



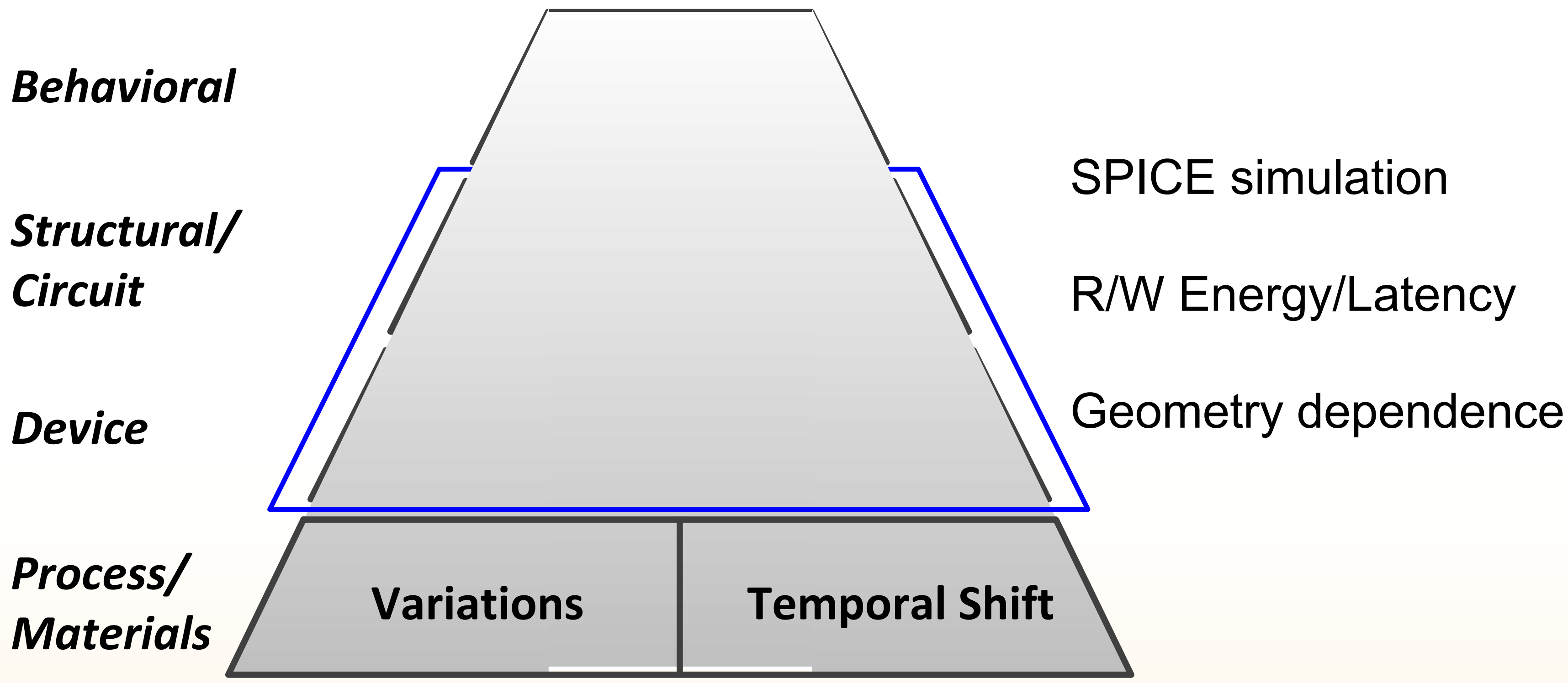
Parallel
Low R => bit ‘0’

Anti-Parallel
High R => bit ‘1’

- Direction of the magnetization angle in the free layer controls the resistance of magnetic-tunnel-junction (MTJ)
- Parallel state (P) corresponds to bit ‘0’ being stored and anti-parallel state (AP) corresponds to bit ‘1’.

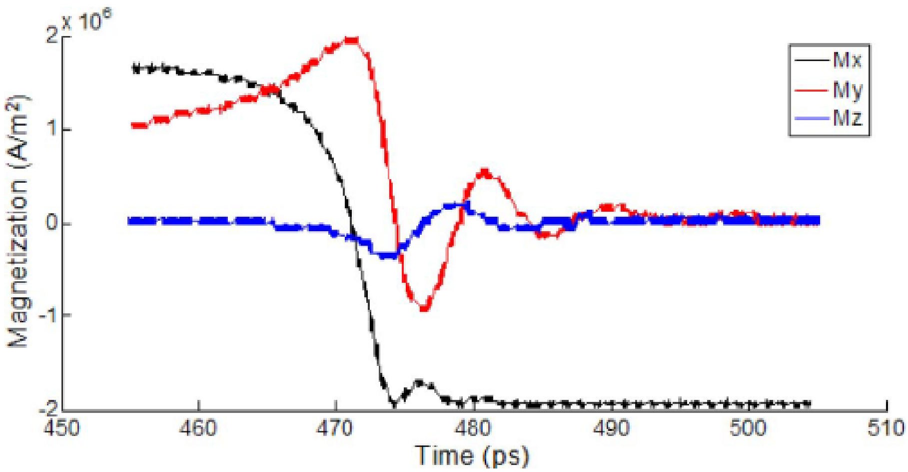
Hierarchical Memory Device Model

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



Approach 1: Numerical Method

- Numerically solve 3D LLG differential equation
- **Pros**: Capture both static and transient behavior, and the dependence on geometry, etc.
- **Cons**: Incompatible with IC design infrastructure, and low computation efficiency



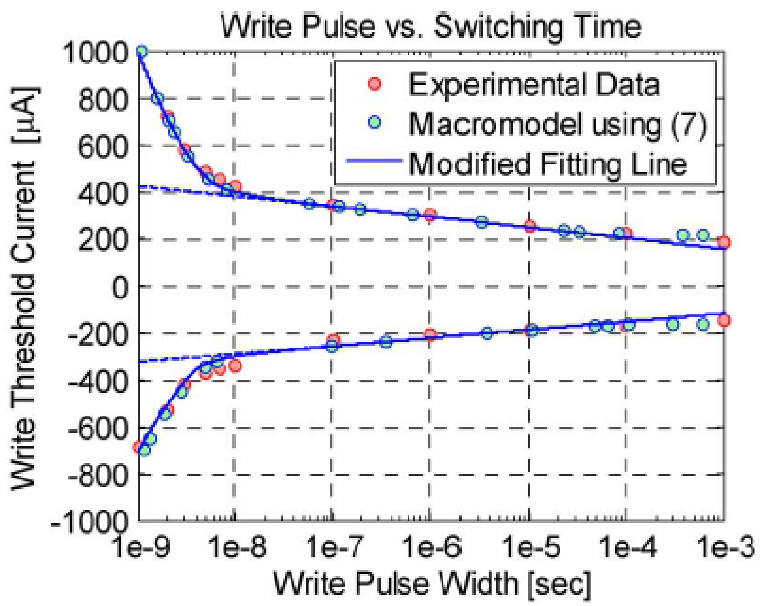
[J. B. Kammerer, TED 2010]

Approach 2: Macro Modeling

- Compact models of cell performance metrics

- **Pros**: Capture the relationship between programming input and the performance

- **Cons**: Lacking sufficient details and flexibility for optimization and exploration with CMOS



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

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

[J. D. Harms, TED 2010]

Compact Model of STT-MTJ

- Fundamental physics in STT-MTJ
  - 3D LLG equation
  - Simplified 1D LLG equation
  - Critical points in switching
- Structural / Circuit model
- Device model
- Validation

3D LLG Equation

$$\frac{d\vec{M}}{dt} = -\gamma\mu_0\vec{M}\times\vec{H}_{eff} - \gamma\frac{2K}{M_s^2}\left(\vec{M}\cdot\vec{u}_{ea}\right)\cdot\left(\vec{M}\times\vec{u}_{ea}\right) + \frac{\alpha}{M_s}\vec{M}\times\frac{d\vec{M}}{dt} + \eta\frac{\mu_B I}{eV}$$

Zeeman **Anisotropic** **Damping** **Spin-transfer torque**

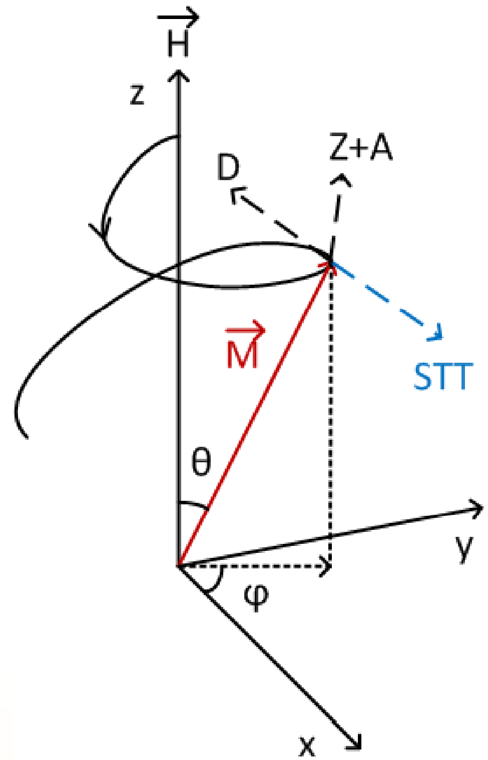
- Zeeman energy: aligns the magnetization field with the applied field
- Anisotropic: self-alignment of magnetization along easy axis $\vec{u}_{ea}$
- Damping: energy loss of the precession of magnetization
- **Spin-transfer torque**: the interaction with the spin of electrons
- Constants:
  - $\gamma \approx 1.76 \times 10^{11}\ rad \cdot s^{-1} \cdot T^{-1}$ gyromagnetic ratio
  - $\mu_0 = 4\pi \times 10^{-7}\ N \cdot A^{-2}$ permeability constant
  - K is anisotropy constant dependent on material
  - $\alpha \approx 0.02$ damping constant

1D LLG Equation

- Decompose 3D LLG into two perpendicular directions

Rotation: $$M_s \frac{d\varphi}{dt} = -\gamma\mu_0 M_s H \sin\theta - 2\gamma K \sin\theta \cos\theta$$

Switching: $$M_s \frac{d\theta}{dt} = \alpha M_s \frac{d\varphi}{dt} + \eta \frac{\mu_B I}{eV}$$



- Simplified 1D Equation:

$$M_s \frac{d\theta}{dt} = -\alpha\gamma\left(\mu_0 M_s H \sin\theta + 2K \sin\theta \cos\theta\right) + \eta \frac{\mu_B I}{eV}$$

- Assumption: The damping of θ switching is negligible since α is small enough.

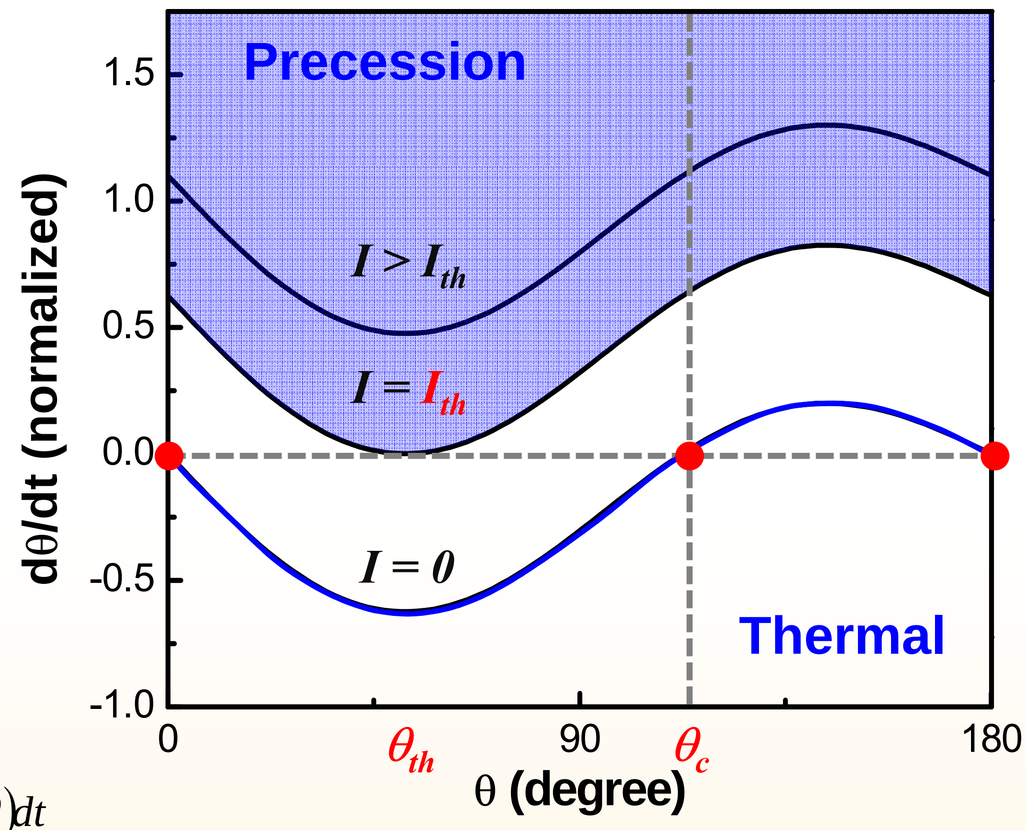
Critical Points in Switching

$$M_s \frac{d\theta}{dt} = -\alpha\gamma\left(\mu_0 M_s H \sin\theta + 2K \sin\theta\cos\theta\right) + \eta \frac{\mu_B I}{eV}$$

- $I > I_{th}$: active switching
  - θ_{th} is associated
- At the end of I pulse,

  $\theta > \theta_c$ to complete the switching
  - Minimum current I_c is defined, given τ

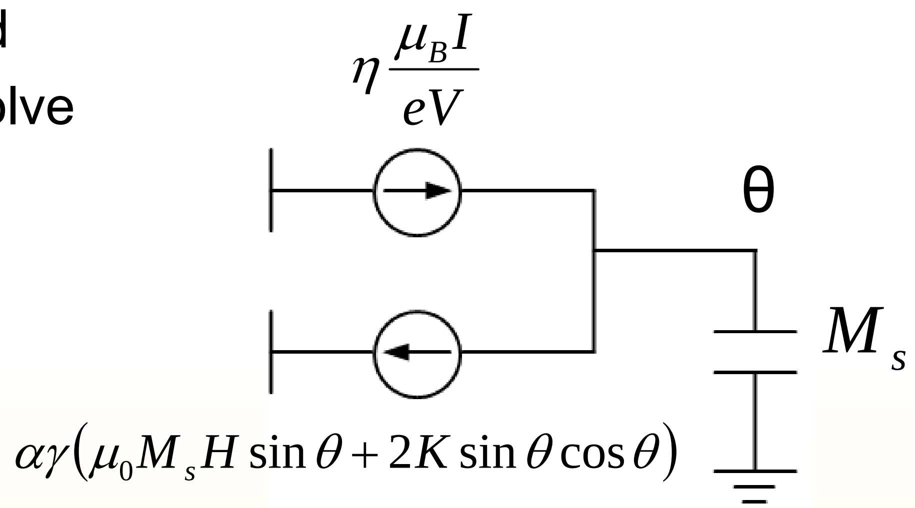
$$M_s\theta_c = \eta \frac{\mu_B I_c}{eV}\tau + \int_0^\tau -\alpha\gamma\left(\mu_0 M_s H \sin\theta + 2K\sin\theta\cos\theta\right)dt$$



Structural / Circuit

$$M_s \frac{d\theta}{dt} = -\alpha\gamma\left(\mu_0 M_s H \sin\theta + 2K \sin\theta \cos\theta\right) + \eta \frac{\mu_B I}{eV}$$

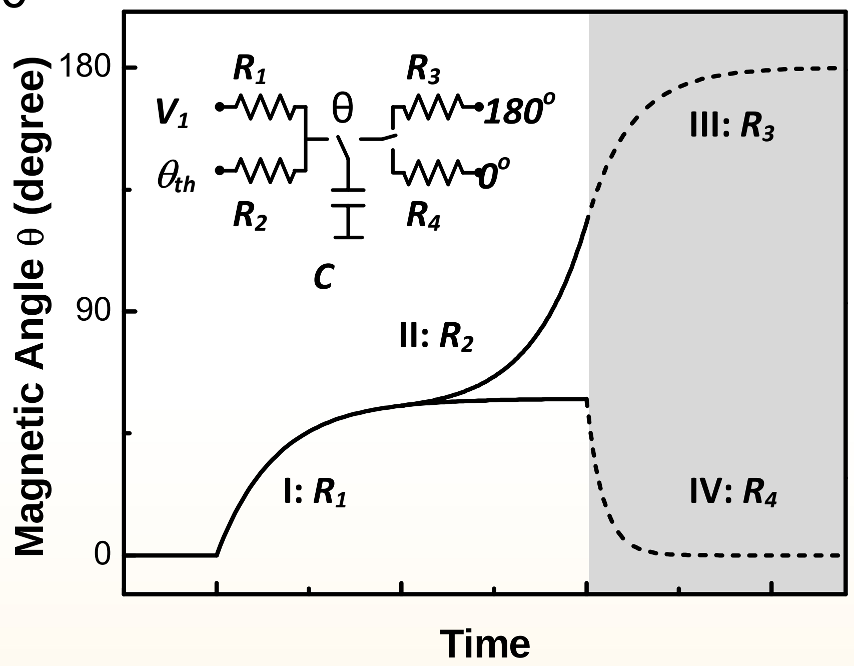
- $\theta \rightarrow$ V
- A straightforward way: Numerical
  - Use current sources and capacitor in SPICE to solve the differential equation
  - Accurate
  - Iteration involved



A more compact approach

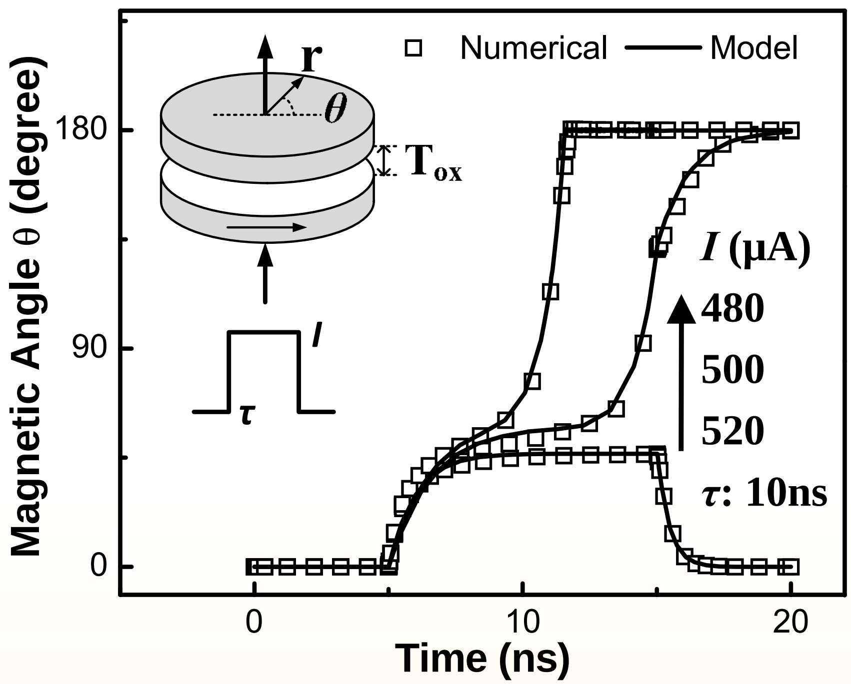
$$M_s \frac{d\theta}{dt} = -\alpha\gamma\left(\mu_0 M_s H \sin\theta + 2K \sin\theta \cos\theta\right) + \eta \frac{\mu_B I}{eV}$$

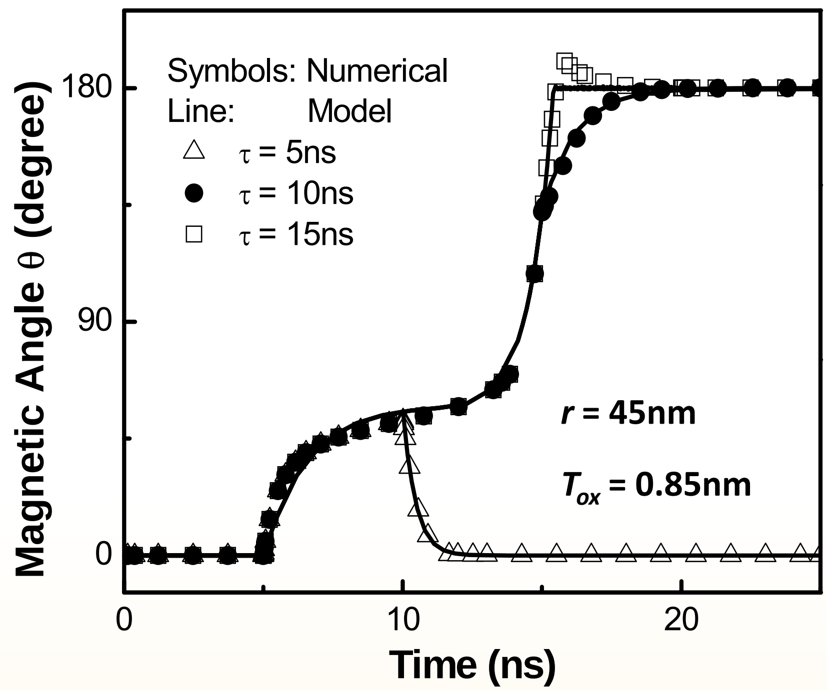
- Region based RC circuit
  - θ approximation near 0°, 90°, 180°
  - Pre-solve differential equation
  - All elements do not depend on θ
  - No iteration
  - Faster in large scale simulation



Comparison

- Numerical: accurate, iterative
- Compact: fast, easy for designers





Device

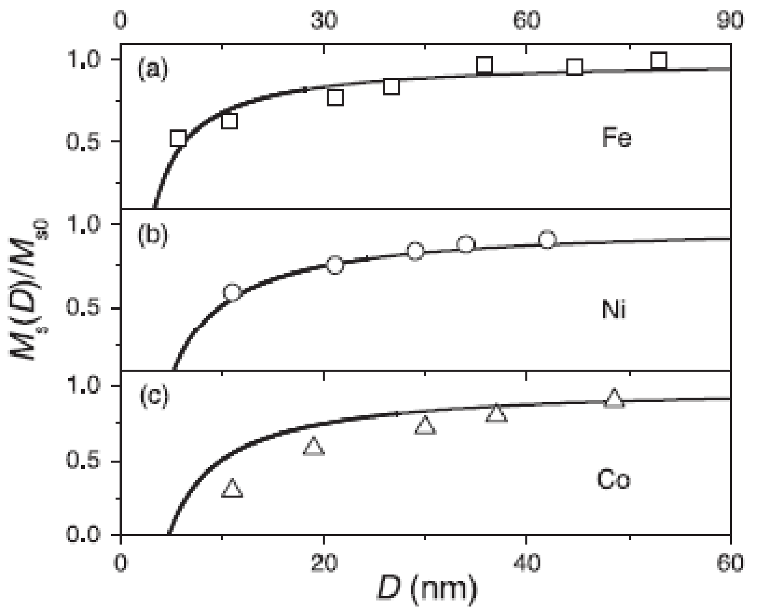
- Magnetic Angle to Resistance

$$R(\theta) = 2R_P\left(\frac{1+TMR}{2+TMR+TMR\cdot\cos\theta}\right)$$

$$TMR = \frac{R_{AP} - R_P}{R_P}$$

- Saturation Magnetization (M_s)

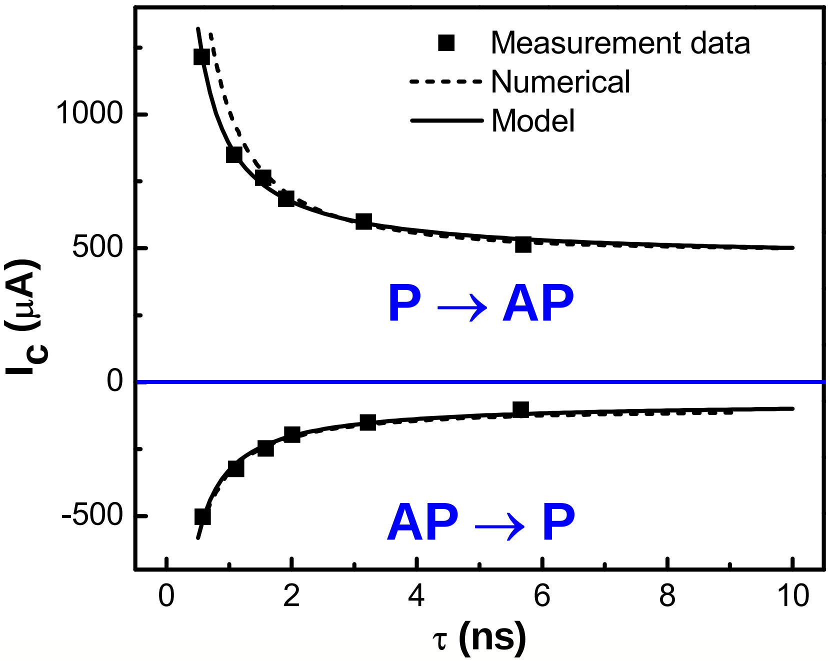
$$\frac{M_s(D)}{M_{s0}} = 4\left[1 - \frac{1}{\frac{2D}{ch} - 1}\right] \cdot exp\left[-\frac{2S_b}{3R}\frac{1}{\frac{2D}{ch} - 1}\right] - 3$$



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

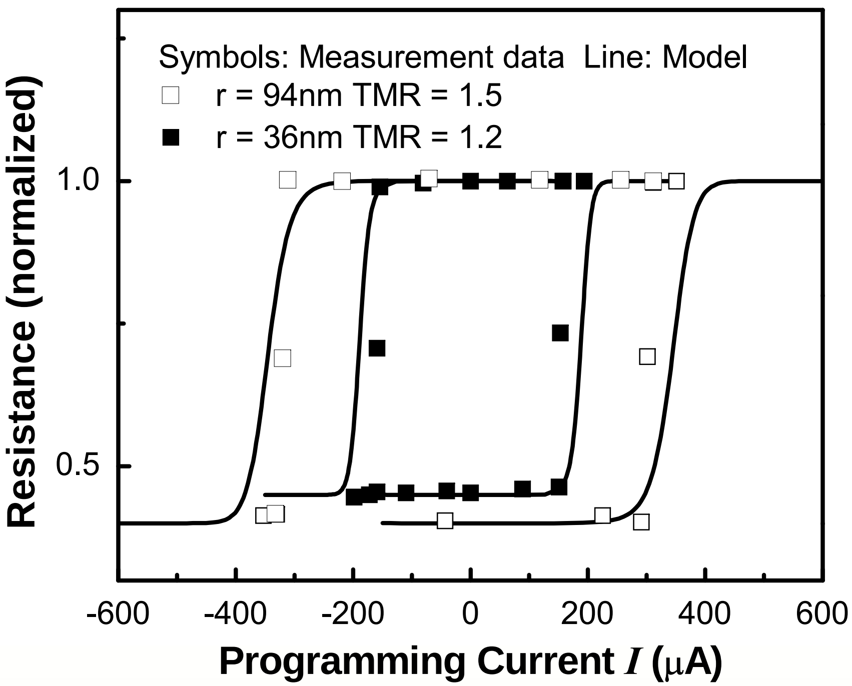
Model Validation

- Programming current



[K. C. Chun, JSSC 2013]

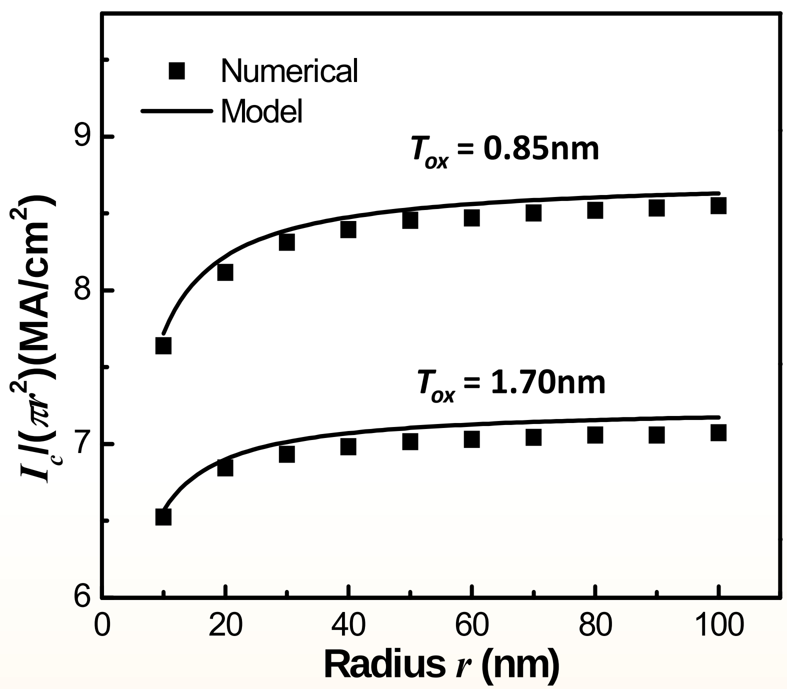
- Hysteresis characteristics

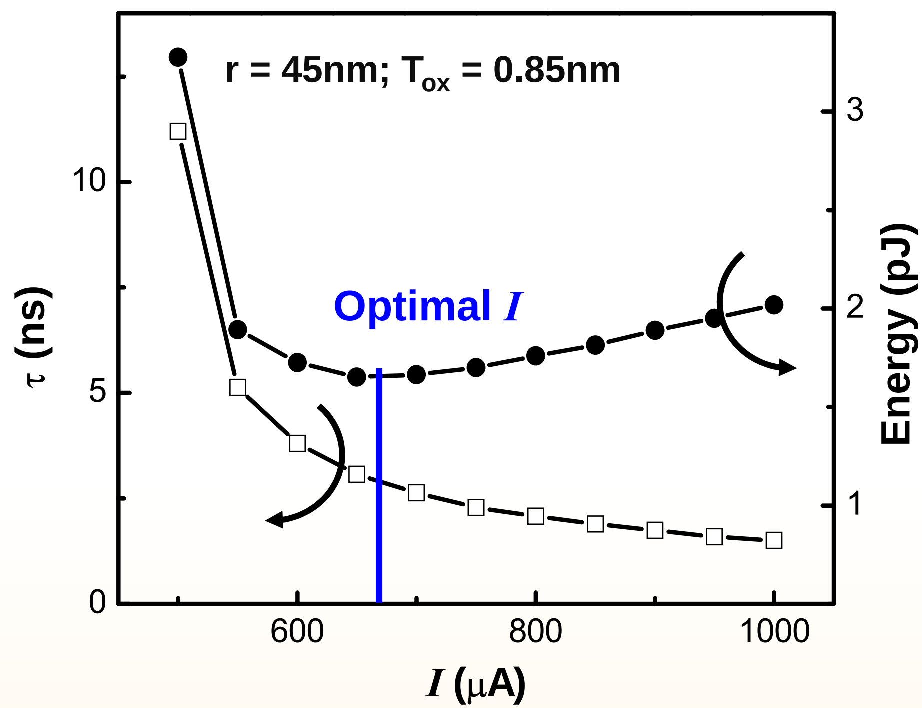


[Z. Diao, J. Phys. 2007, C. J. Lin, IEDM 2009]

Results

- Geometry dependence
  - r impacts switching current density through M_s
- Write energy and latency
  - Optimal I achieves minimum programming energy





Summary and Future Work

- Compact model of STT-MTJ in a hierarchical framework
  - Simplified LLG equation
  - Region based RC circuit model
  - Geometry dependence of model parameters