University of Pittsburgh

Modeling of Biaxial Magnetic Tunneling Junction for Multi-level Cell STT-RAM Realization

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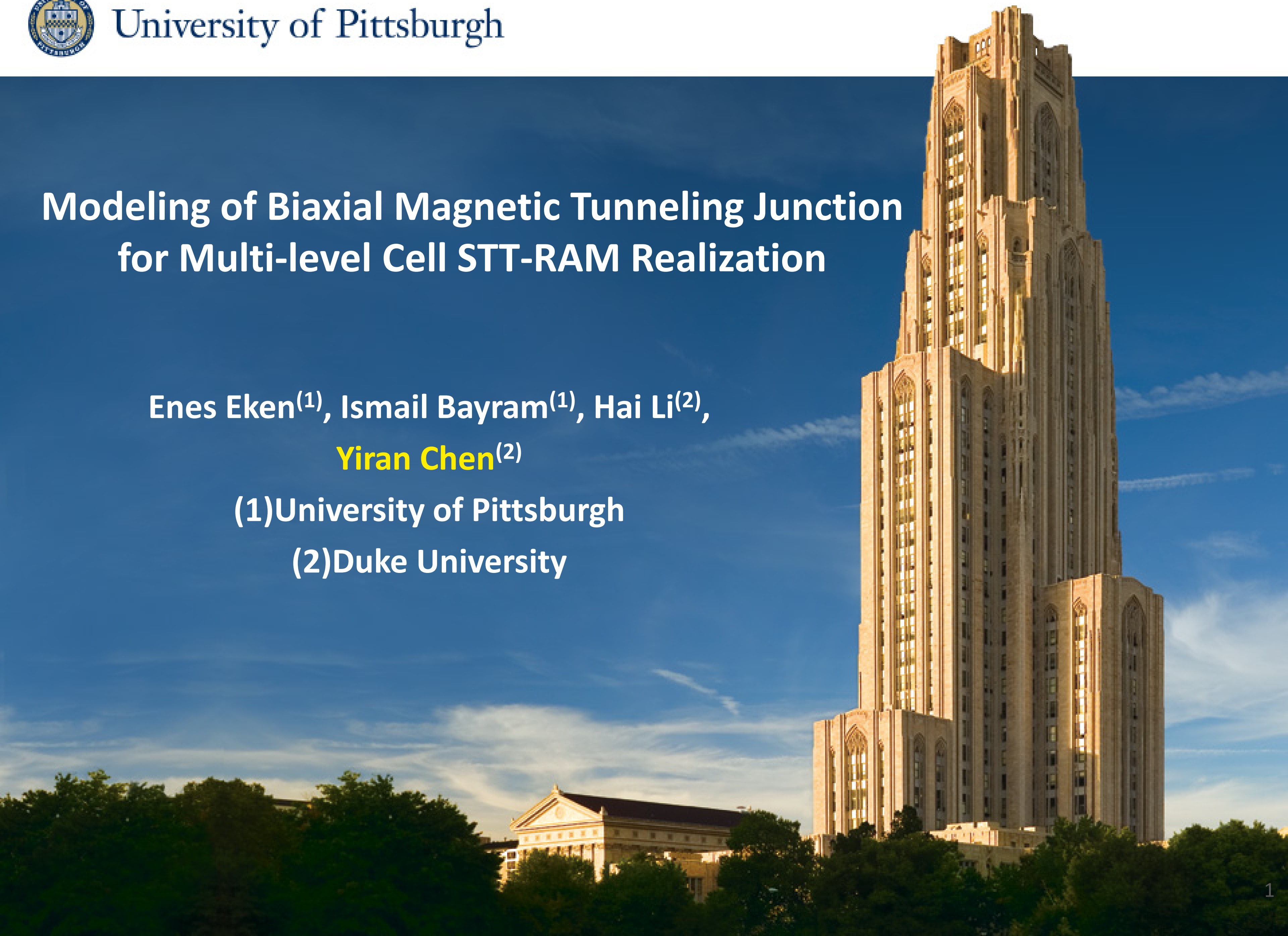

Outline

- **STT-RAM Basics for Uniaxial and Biaxial MTJs**
- **Modeling of Biaxial MTJ**
  - **Model Description of Biaxial MTJ**
  - **Basic Functions of Biaxial MTJ Model**
  - **Some Discussions and Differences of Biaxial MTJ**
- **Model Validation**
- **Reliability Analysis**
- **Conclusion**

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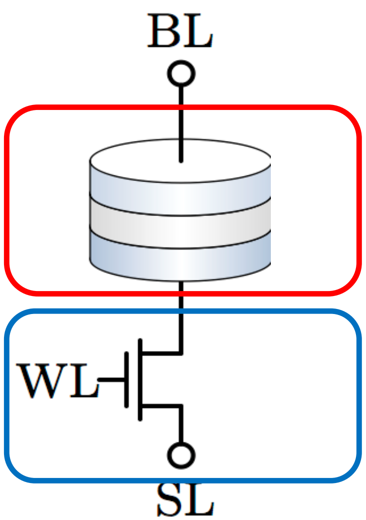
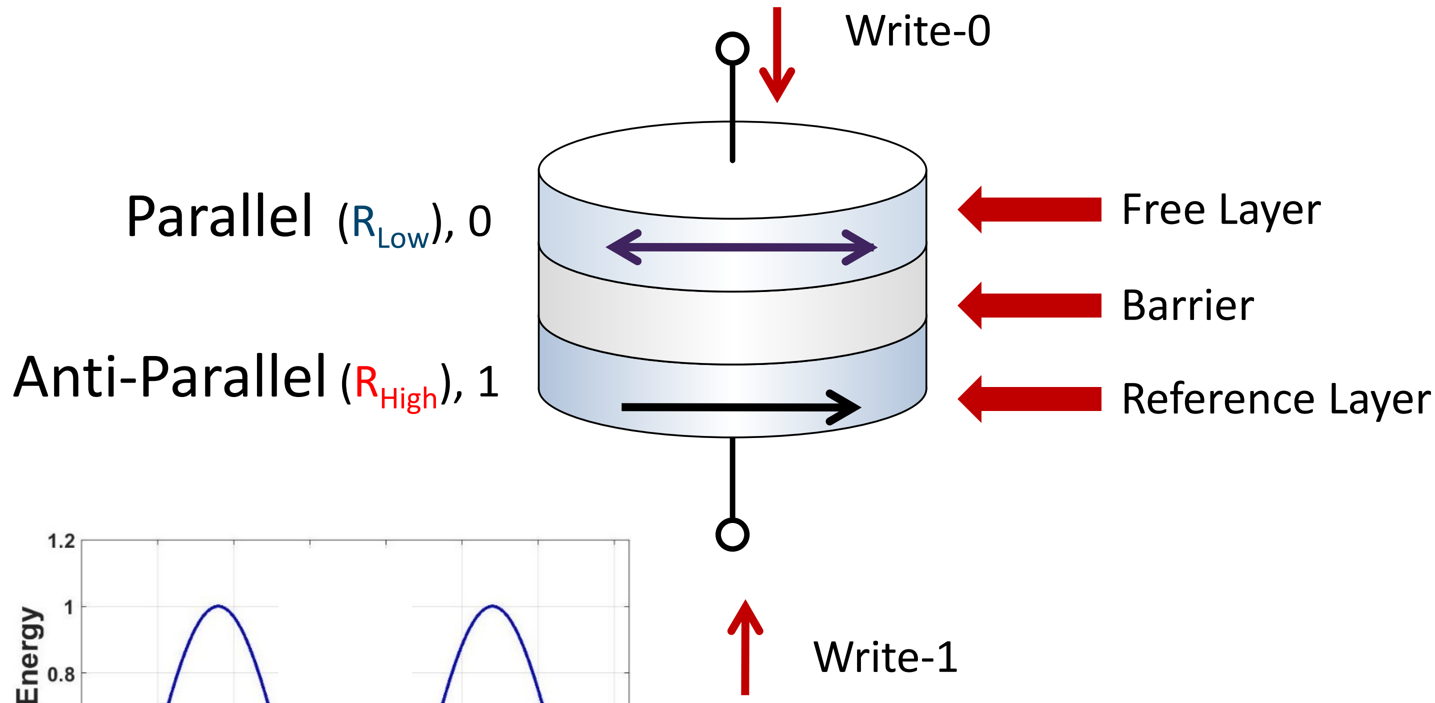
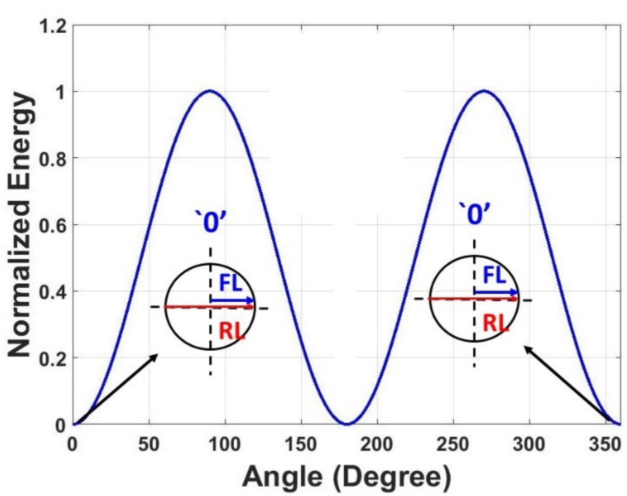
STT-RAM Basics for Uniaxial MTJ

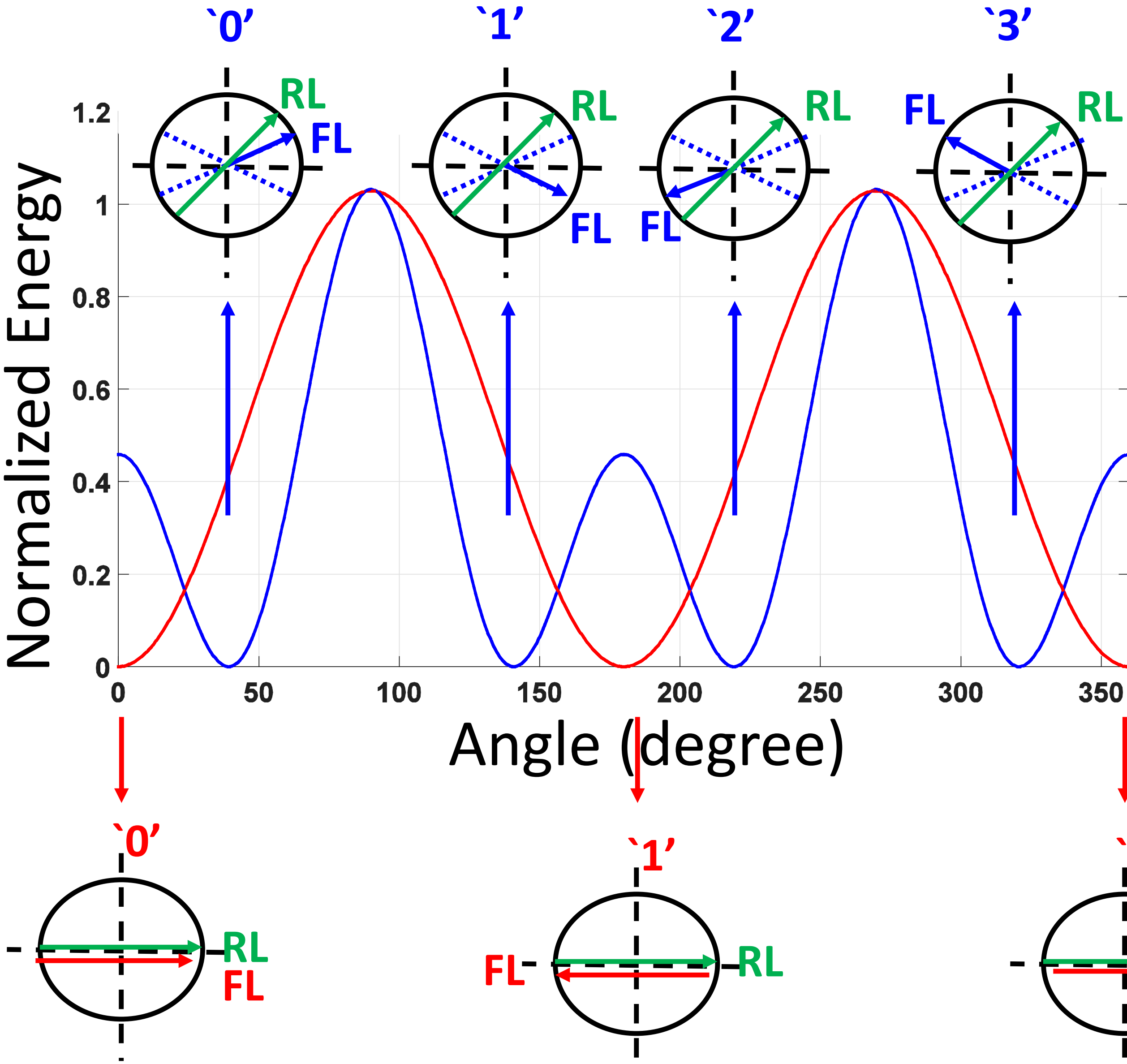
In a conventional STT-RAM, data is stored in a Uniaxial MTJ which has two minimum energy points corresponding to one bit. In contrast, Biaxial MTJ has four minimum energy points corresponding to two bits.





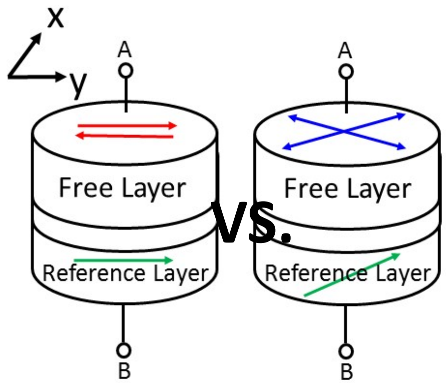


STT-RAM Basics for Biaxial MTJ



Conventional MTJ
Uniaxial Anisotropy

$$E_u = K_u \sin^2\theta$$



Biaxial MTJ
Biaxial Anisotropy

$$E_b = K_u \sin^2\theta + \frac{1}{4} K_b \sin^2 2\theta$$

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Model Description of Biaxial MTJ

Landau-Lifshitz-Gilbert (LLG) equation for magnetization dynamic is give by;

$$\frac{d\theta}{dt} = \frac{\gamma_0}{1+\alpha^2}(H_\varphi + \alpha H_\theta)$$
$$\frac{d\varphi}{dt} = \frac{\gamma_0}{(1+\alpha^2)\sin\theta}(\alpha H_\varphi - H_\theta)$$

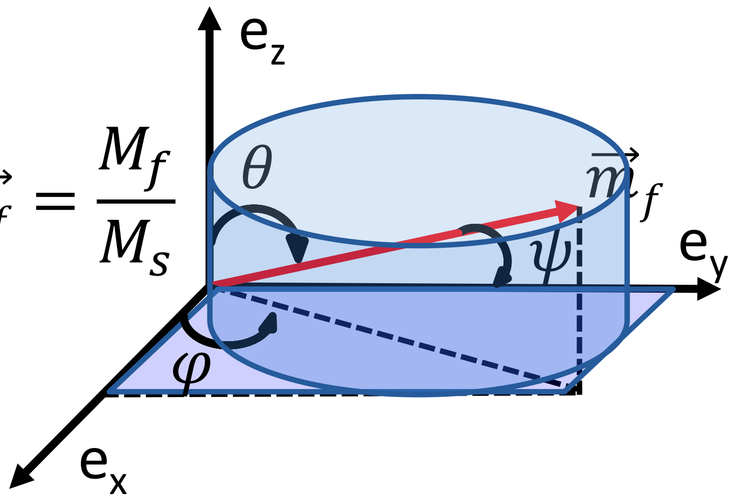
Here H_φ and H_θ are the net effective fields containing easy-plane anisotropy, Langevin random thermal field , STT field, and biaxial anisotropy field, for θ and φ components

$$H_\theta = -\frac{1}{\mu_0 M_s}\frac{\partial E}{\partial \theta}$$
$$H_\varphi = -\frac{1}{\mu_0 M_s \sin\theta}\frac{\partial E}{\partial \varphi}$$

Model Description of Biaxial MTJ

$$\frac{\partial E_b}{\partial \theta} = ? \quad \frac{\partial E_b}{\partial \varphi} = ?$$

$$\overrightarrow{m_f} = \frac{M_f}{M_s}$$



$$E_b = K_u \sin^2(\theta) + \frac{1}{4} K_b \sin^2(2\theta)$$

$$E_b = K_u \sin^2(\psi) + \frac{1}{4} K_1 \sin^2(2\psi)$$

$$cos\psi = \frac{m_f . e}{\|m_f\| . \|e\|}$$

$$m_f = \frac{M_f}{M_s} = (\sin\theta\cos\varphi\hat{\mathbf{x}}, \sin\theta\sin\varphi\hat{\mathbf{y}}, \cos\theta\hat{\mathbf{z}}\Big)$$

$$e = (e_x\hat{\mathbf{x}}, e_y\hat{\mathbf{y}}, e_z\hat{\mathbf{z}}),$$

$$\psi = \cos^{-1}(m_f . e) = \cos^{-1}(v).$$

$$v = m_f . e = e_x \sin\theta\cos\varphi + e_y \sin\theta\sin\varphi + e_z \cos\theta.$$

$$\frac{\partial E_b}{\partial \theta} = \frac{\partial E_b}{\partial \psi} \frac{\partial \psi}{\partial \theta}$$

$$\frac{\partial E_b}{\partial \varphi} = \frac{\partial E_b}{\partial \psi} \frac{\partial \psi}{\partial \varphi}.$$

$$\frac{\partial \psi}{\partial \theta} = \frac{\partial \psi}{\partial v} \frac{\partial v}{\partial \theta}$$

$$\frac{\partial \psi}{\partial \varphi} = \frac{\partial \psi}{\partial v} \frac{\partial v}{\partial \varphi}.$$

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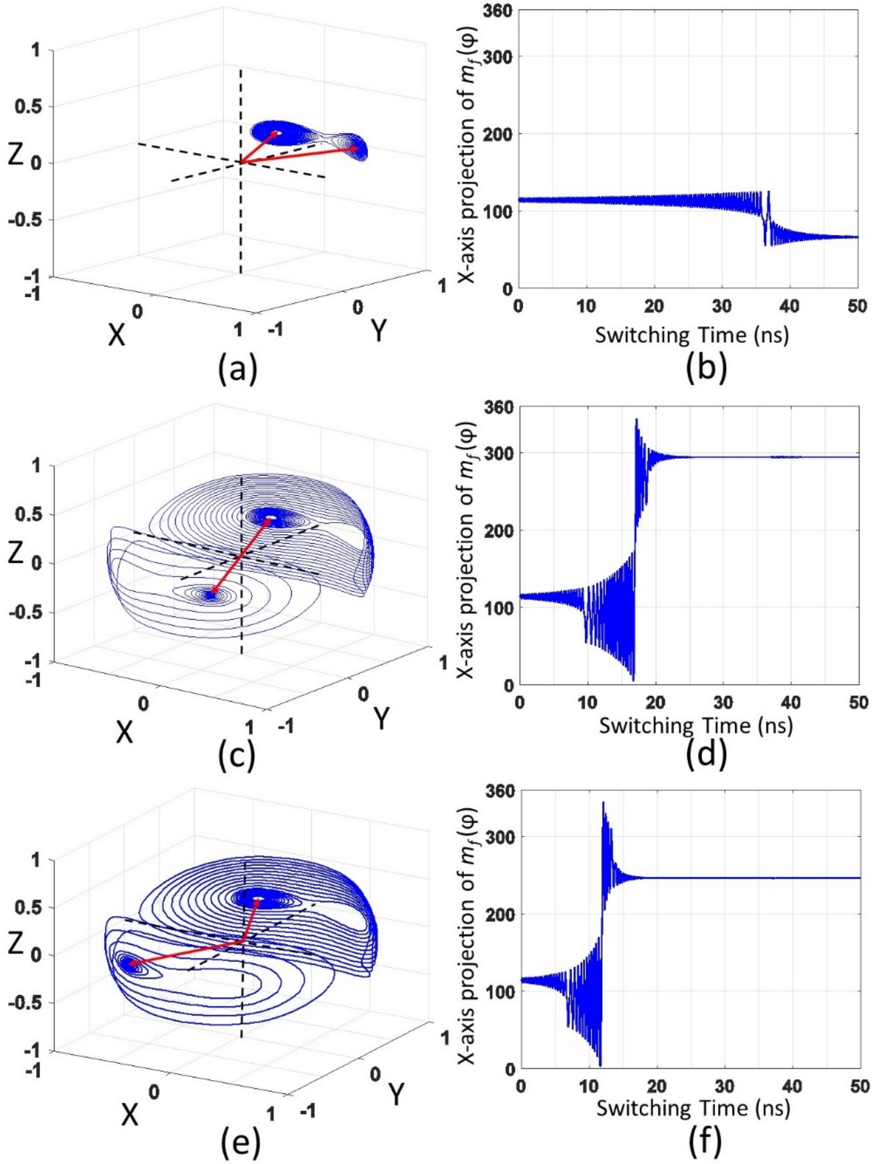
Basic Functions of Biaxial MTJ Model



Change of m_f during the MTJ switching.

a) ‘0’ to ‘1’ switching transience.

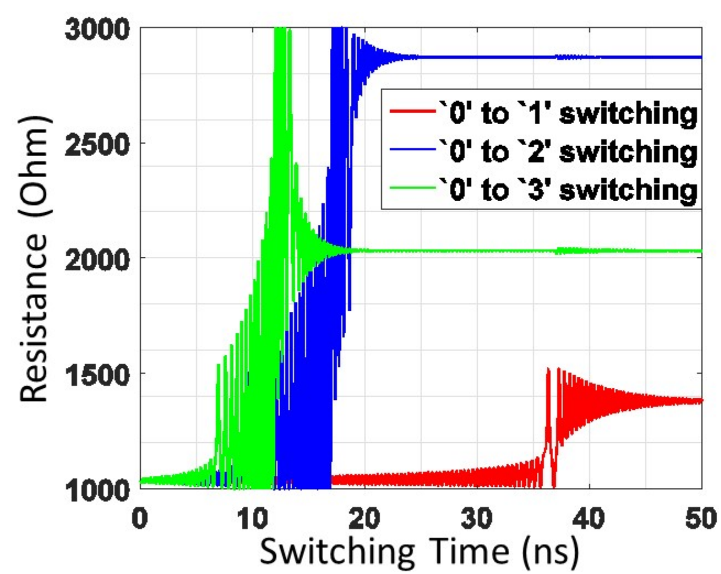
b) ‘0’ to ‘1’ switching time.

c) ‘0’ to ‘2’ switching transience.

d) ‘0’ to ‘2’ switching time.

e) ‘0’ to ‘3’ switching transience.

f) ‘0’ to ‘3’ switching time.



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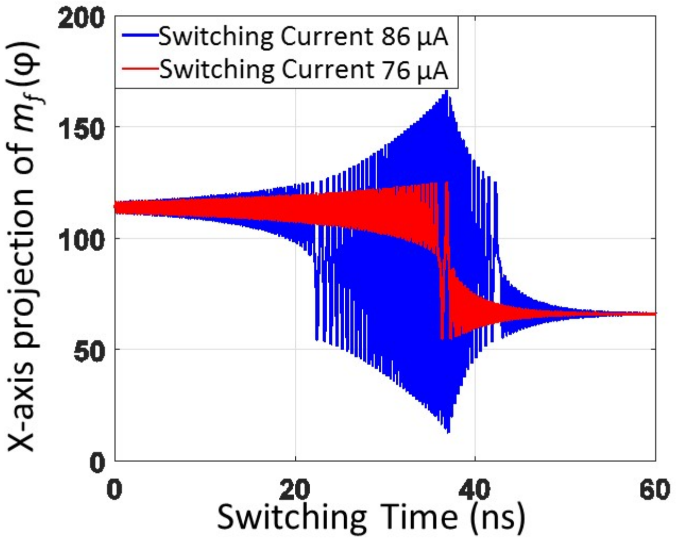

`0' to `1' Switching

- Increasing switching current doesn't result in a faster switching for adjacent states, in contrast to uniaxial MTJ

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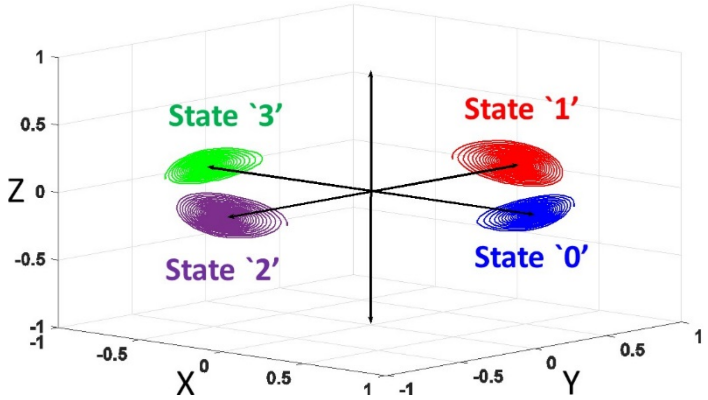
Model Validation

- We validated our developed biaxial MTJ model against to one of the first four-state manufactured[1] MTJ with the following customization
  1. Manufactured MTJ has four in-plane magnetization directions toward 0^o, 90^o, 180^o, and 270^o.
  2. Magnetic field is used for write operation.

[1] T. Uemura, T. Marukame, K.-i. Matsuda, and M. Yamamoto. “Four-state magnetic random access memory and ternary content addressable memory using cofe-based magnetic tunnel junctions.” In 37th International Symposium on Multiple-Valued Logic (ISMVL’07), pages 49–49. IEEE, 2007.

Model Validation



- Free layer settles down toward 0^o, 90^o, 180^o, and 270^o for 4 states following some spin relaxation, as expected .

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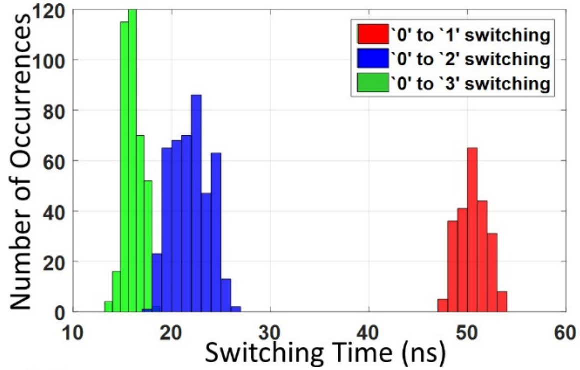
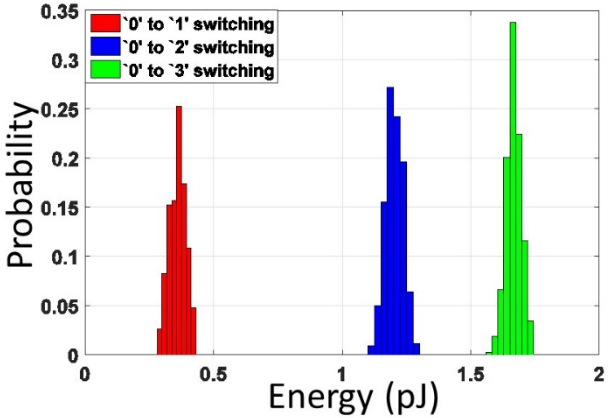
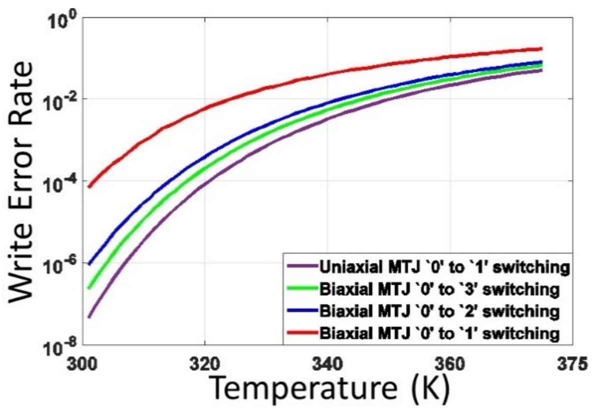
Reliability Analysis







- Faster switching of `0’ to `3’ is a result of using higher current
- Write time is fixed 60ns for all switching
- `0’ to `1’ switching has worst error rate as a result of fixed write time

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Conclusion

- To eliminate the two-step write operations of conventional MLC STT-RAM cells, biaxial MTJ structure is proposed to store more than one bit in one MTJ device.

- In this work, we developed a dynamic biaxial MTJ model that can capture the switching transience between different resistance states of the biaxial MTJ and validated our model against the data measured from real device. Our simulation results show that our model matches the measured data very well.

THANKS FOR LISTENING.
QUESTION?