Switching Performance of Mo-based pMTJ and DS-MTJ

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Outline

Introduction

- MRAM
- Micromagnetic Model
- MTJ and DS-MTJ

Methodology

- Mo-based MTJ
- Mo-based DS-MTJ
- Switching Performance

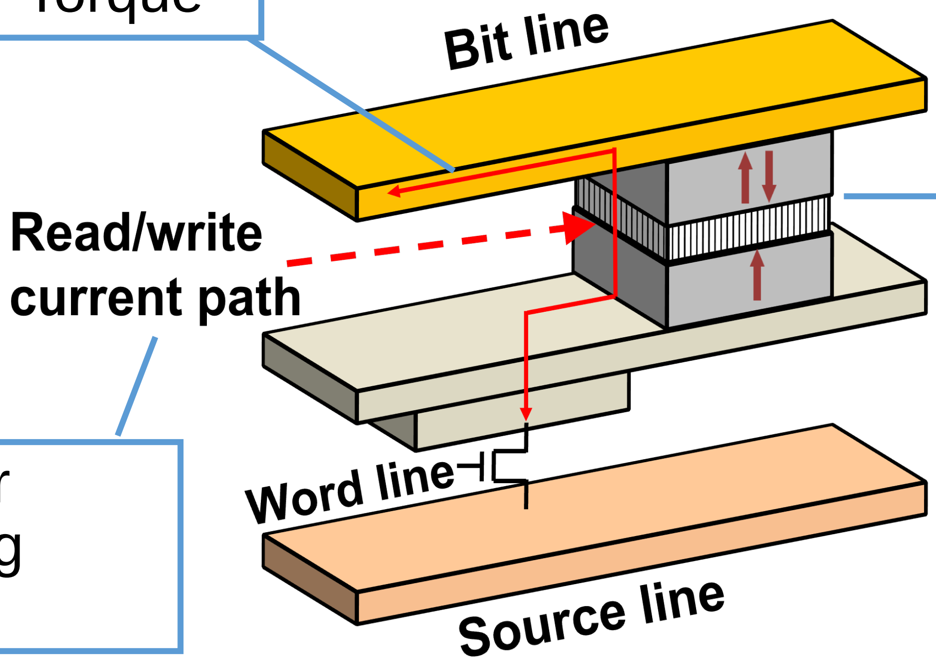
Conclusion

MRAM

Polarized current flow causes switching via Spin-Transfer Torque

Perpendicular magnetization leads to lower critical current for switching

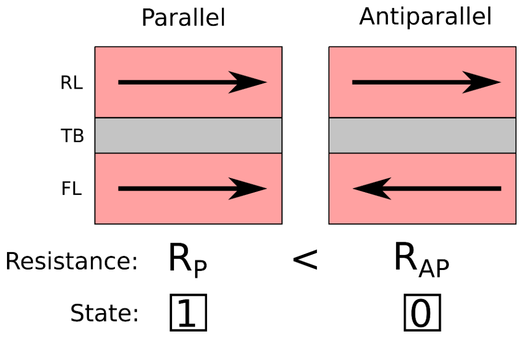
Same path for reading/writing operations



MRAM

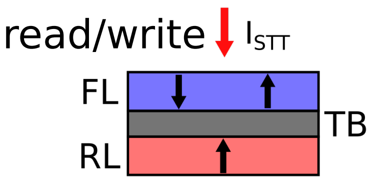
Magnetic tunnel junction (MTJ):

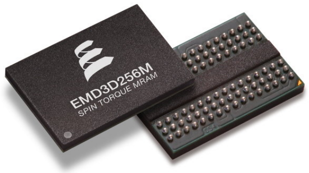
- Reference layer (RL)
- Tunnel barrier (TB)
- Free layer (FL)
- Reading: tunnel magnetoresistance
- Writing: external field, spin-polarized current
- Non-volatile



Spin Transfer Torque (STT) MRAM:

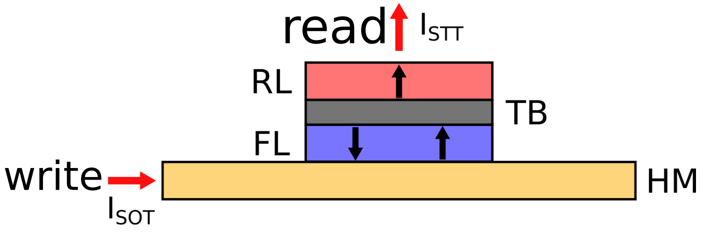
- Fast (~ns)
- High endurance (>10^{12})
- Long retention
- CMOS compatible

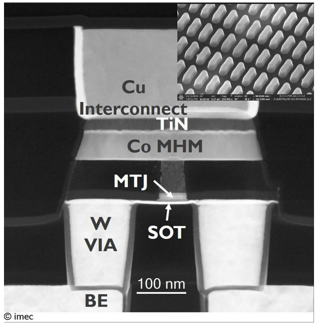




Spin-Orbit Torque (SOT) MRAM:

- Faster (< ns)
- Higher endurance
- Bigger foot print (3 terminal)
- Potential SRAM replacement





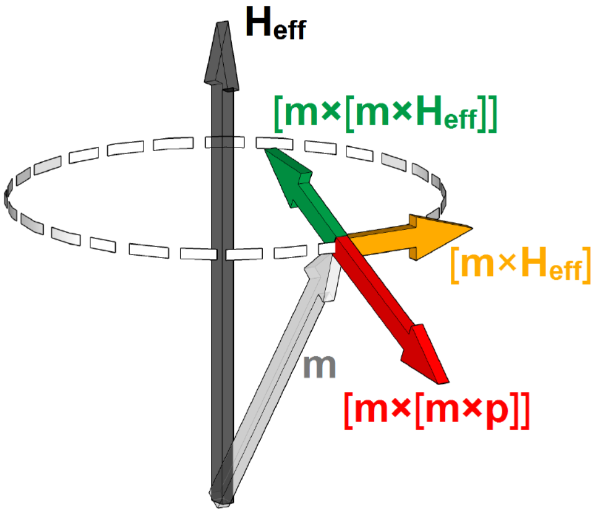
Q. Shao *et al*., *IEEE Trans. Magn.* 57, 7 (2021)
https://www.everspin.com/spin-transfer-torque-ddr-products
https://www.eeweb.com/mram-technologies-from-space-applications-to-unified-cache-memory/ (2021)

Micromagnetic Model

- Landau–Lifshitz–Gilbert (LLG) equation:

$$\frac{\partial \mathbf{m}}{\partial t} = -\gamma\mu_0 \mathbf{m} \times \mathbf{H_{eff}} + \alpha \mathbf{m} \times \frac{\partial \mathbf{m}}{\partial t} + \frac{1}{M_S}\mathbf{T_S}$$

$$\mathbf{H_{eff}} = \mathbf{H_{aniso}} + \mathbf{H_d} + \mathbf{H_{exch}} + \mathbf{H_{bDMI}} + \mathbf{H_{ext}}$$



- Coupled spin-charge drift-diffusion equations:

$$\frac{\partial \mathbf{S}}{\partial t} = 0 = -\nabla \cdot \overline{\mathbf{J_S}} - D_e\left(\frac{\mathbf{S}}{\lambda_{sf}^2} + \frac{\mathbf{S}\times\mathbf{m}}{\lambda_J^2} + \frac{\mathbf{m}\times(\mathbf{S}\times\mathbf{m})}{\lambda_\varphi^2}\right)$$

$$\overline{\mathbf{J_S}} = -\frac{\mu_B}{e}\beta_\sigma \mathbf{m} \otimes \left(\mathbf{J_C} - \beta_D D_e \frac{e}{\mu_B}\left[(\nabla \mathbf{S})^{\mathbf{T}}\mathbf{m}\right]\right) - D_e \nabla \mathbf{S} - \theta_{SHA}\frac{\mu_B}{e}\varepsilon \mathbf{J_C}$$

$$\mathbf{J_C} = -\sigma \nabla V$$

  – TB treated as poor conductor dependent on relative magnetization orientation of FL & RL

  – External boundaries: $\boldsymbol{Jc \cdot n} = 0$, $\boldsymbol{Js \cdot n} = \boldsymbol{0}$.

  – Solve for a steady state

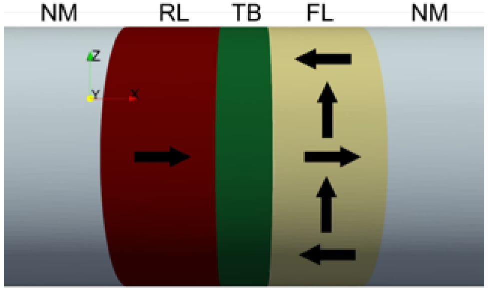
C. Abert et al., Scientific Reports 5, 14855 (2015)
S. Lepadatu, Scientific Reports 7, 12937 (2017)
S. Fiorentini et al., Micromachines 14, 898 (2023)
G. Hrkac et al., Adv. Comput. Math. 45, 3 (2019)

Tunnel Barrier

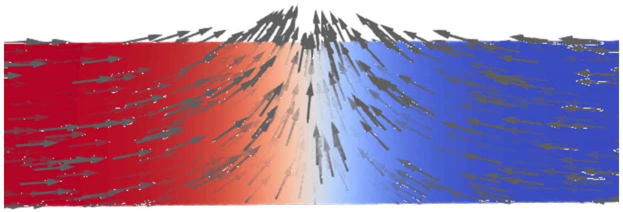
Charge current

- Tunnel barrier modeled as poor conductor
- Conductance depends on angle between $\mathbf{m_{RL}}$ and $\mathbf{m_{FL}}$ (TMR)

$$J_C^{TB} = J_0(V)\,(1 + P_{RL}\,P_{FL}\,\cos\theta)$$



- Magnetization in free layer during switching



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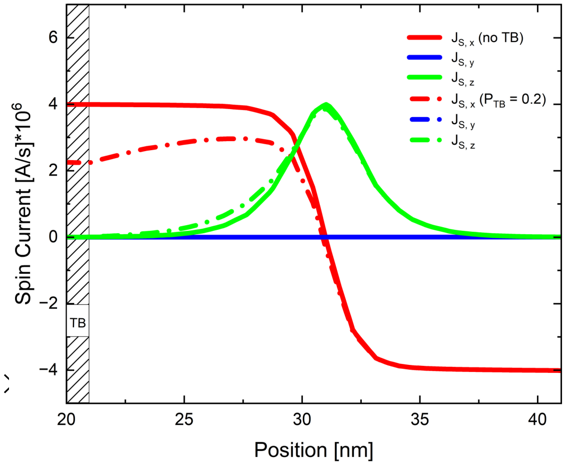

Spin Current

- Boundary condition at TB interfaces

$$\boldsymbol{J_s} = -\frac{\mu_B}{e}\,\frac{\boldsymbol{J_C}\cdot\boldsymbol{n}}{1 + P_{RL}P_{FL}\cos\theta}\left(\alpha_{RL}P_{RL}\,\boldsymbol{m_{RL}} + \alpha_{FL}P_{FL}\,\boldsymbol{m_{FL}} + 1/2\left(P_{RL}P_{RL}^{\eta} - P_{FL}P_{FL}^{\eta}\right)\boldsymbol{m_{RL}} \times$$

Increasing STT-Switching Performance

Mo-based perpendicular MTJ

- Up to sub-ns switching performance
- strong PMA and thermal tolerance

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Sub-ns Switching and Cryogenic-Temperature Performance of Mo-Based Perpendicular Magnetic Tunnel Junctions

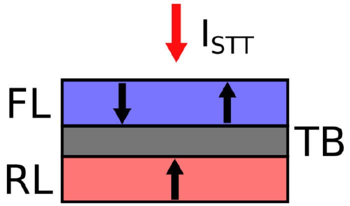
Deyuan Lyu, *Graduate Student Member, IEEE*, Pravin Khanal, Yang Lv, Bowei Zhou, Hwanhui Yun, Qi Jia, *Graduate Student Member, IEEE*, Brandon R. Zink, Yihong Fan, K. Andre Mkhoyan, Weigang Wang, *Member, IEEE*, and Jian-Ping Wang, *Fellow, IEEE*

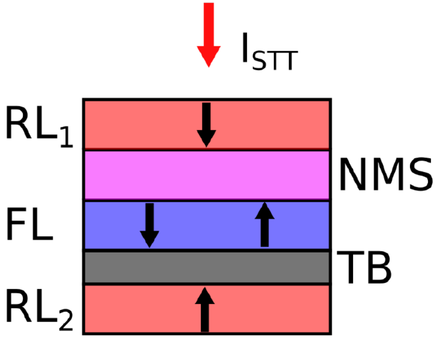
Double spin-torque magnetic tunnel junction (DS-MTJ)

- Second ferromagnetic reference layer (RL) on top
- Separated from free layer (FL) by non-magnetic spacer (NMS)
- 2 RLs with antiparallel magnetization
- Additional torque coming from 2nd RL acting in FL (“double” spin-torque)

Double spin-torque magnetic tunnel junction devices for last-level cache applications

G. Hu, C. Safranski, J. Z. Sun, P. Hashemi, S. L. Brown, J. Bruley, L. Buzi, C. P. D’Emic, E. Galligan, M. G. Gottwald, O. Gunawan, J. Lee, S. Karimeddiny, P. L. Trouilloud, and D. C. Worledge
IBM-Samsung MRAM Alliance, IBM TJ Watson Research Center, Yorktown Heights, New York, email: hug@us.ibm.com



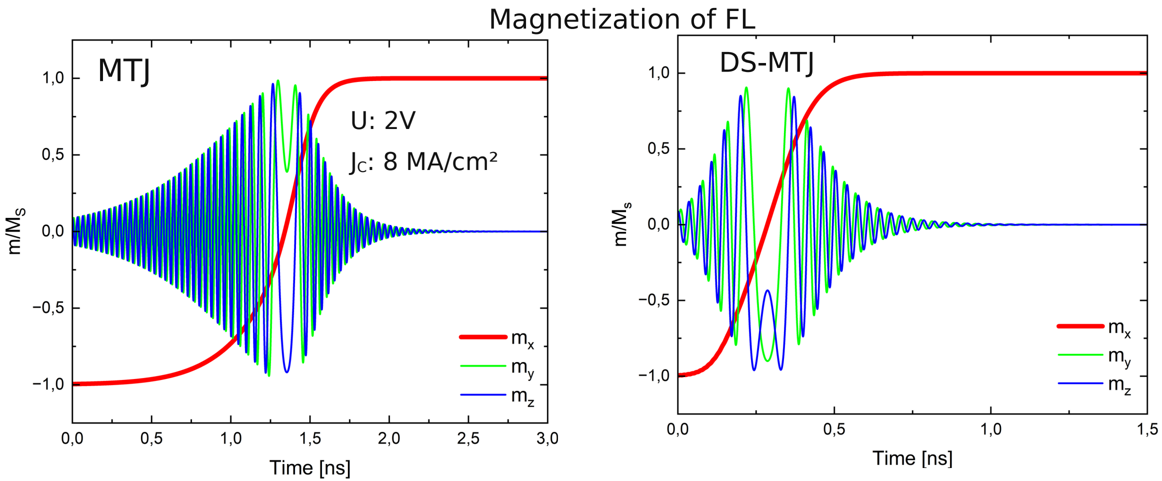


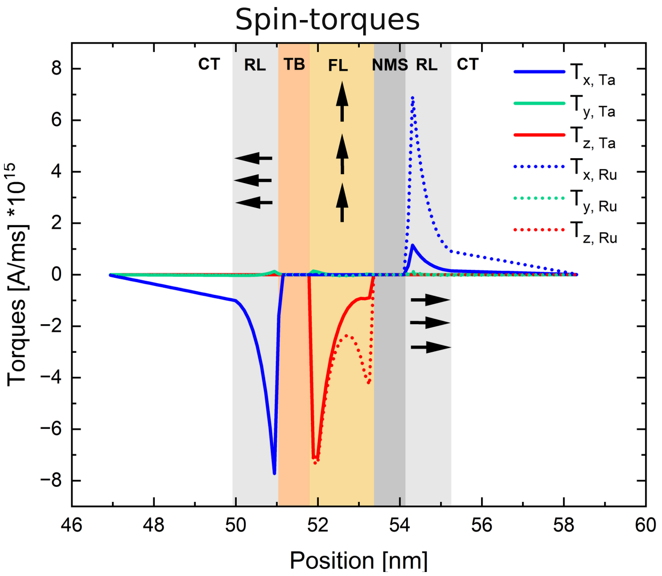
D. Lyu at al., IEEE Electron Device Letters, 43, 8, 1215-1218, (2022)
G. Hu et al., 2022 International Electron Devices Meeting (IEDM), pp. 10.2.1-10.2.4, (2022)

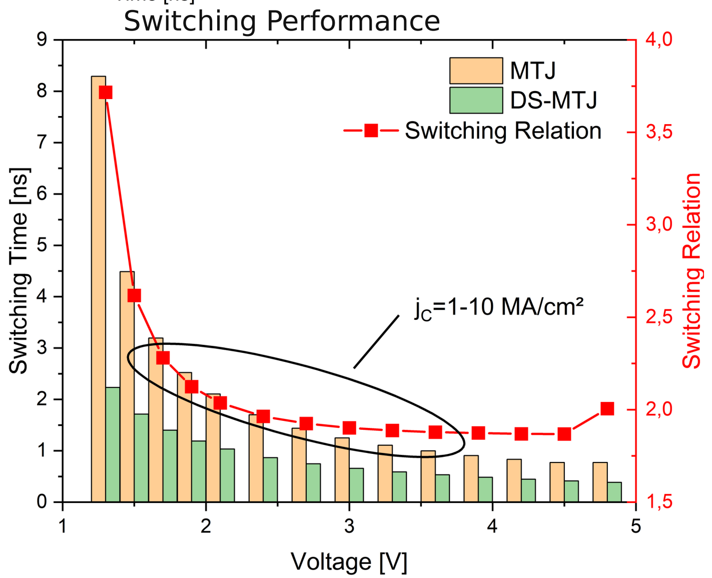
Switching Performance of MTJ and DS-MTJ

Switching Simulations

- Adding second RL
- Additional spin-torque in FL dependent on NMS





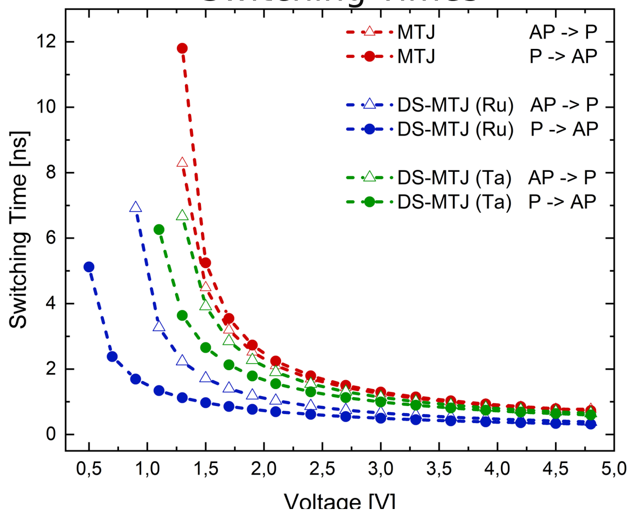


DS-MTJ – Influence of non-magnetic spacer

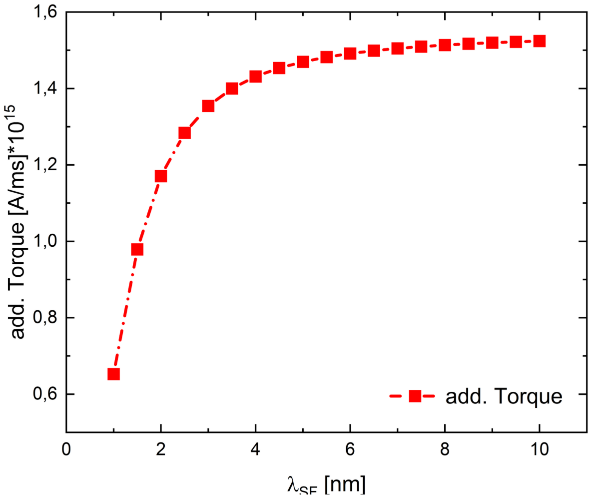
- Switching perfomance strongly dependent on NMS-material
- Spin-flip length λ_{SF} determines additional torque in FL
- λ_{SF} governs decay of longitudinal components of the spin current

Tantalum (Ta): λ_{SF} = 1.9 nm, Ruthenium (Ru): λ_{SF} = 4 nm

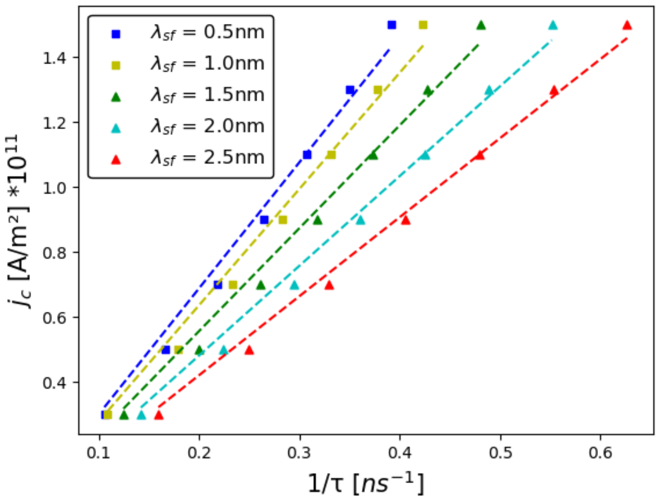
Switching Times

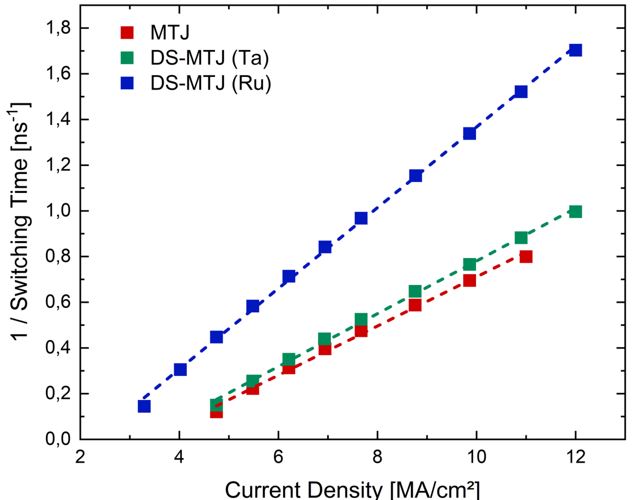


Add. spin-torque



Switching Perf. For different λ_{SF}





Conclusion

- Double Spin-Torque Magnetic Tunnel Junctions (DS-MTJ) show 2x faster switching than regular MTJ

- Application of the DS-MTJ structure to promising Mo-based MTJ

- DS-MTJ structure shows increased switching performance (Sub-ns switching)

- strongly dependent on material of non-magnetic spacer

- Spin-flip length λ_{SF} influences additional spin-torque in free layer

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