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Magnetization Switching Using Spin Orbit Torques from Sputtered Conductive WTe_x

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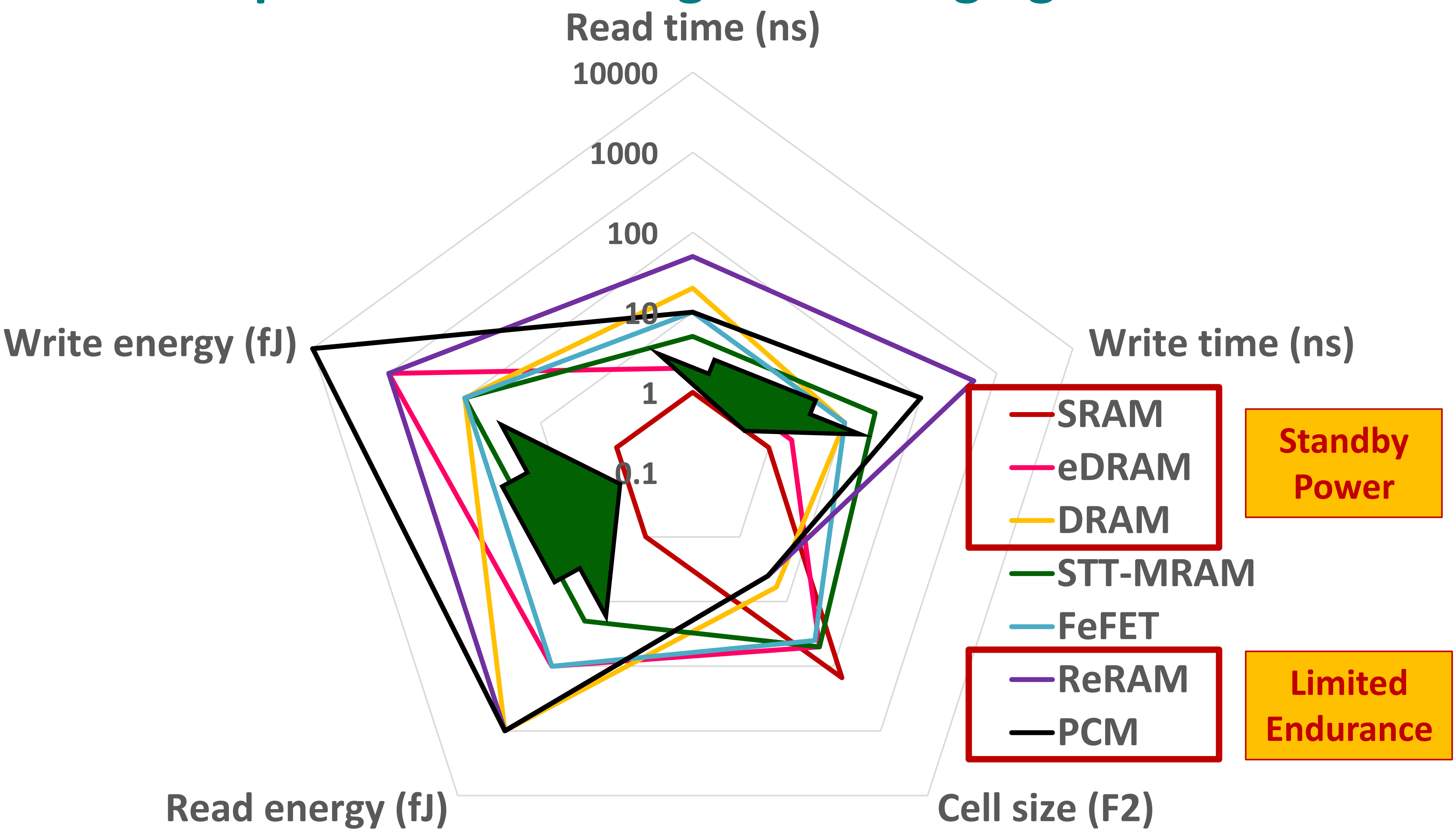
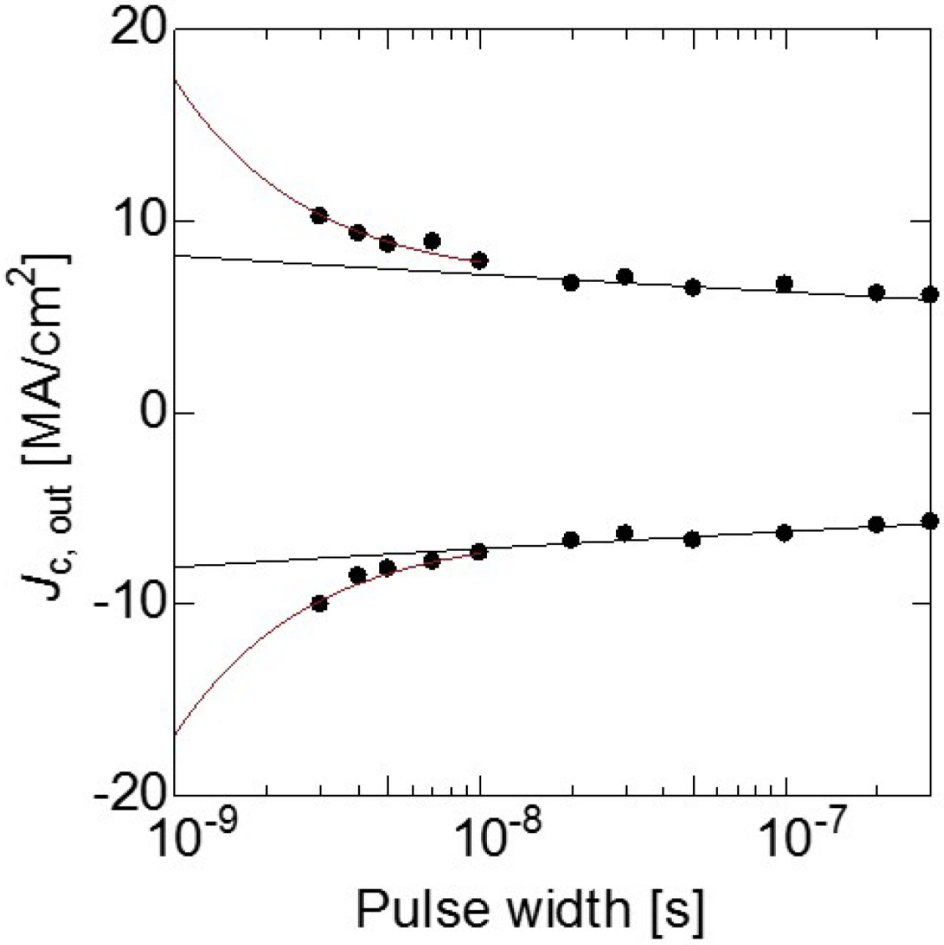
Comparison of Existing and Emerging Memories



Xiang Li, Kang L. Wang, et al., *MRS Bulletin*, vol. 43, pp. 970-977, 2018.
S. Salahuddin, K. Ni, and S. Datta, Nature Electronics, vol. 1, pp. 442-450, 2018.

SOT-MRAM Towards SRAM Performance



Bit switching energy estimates:

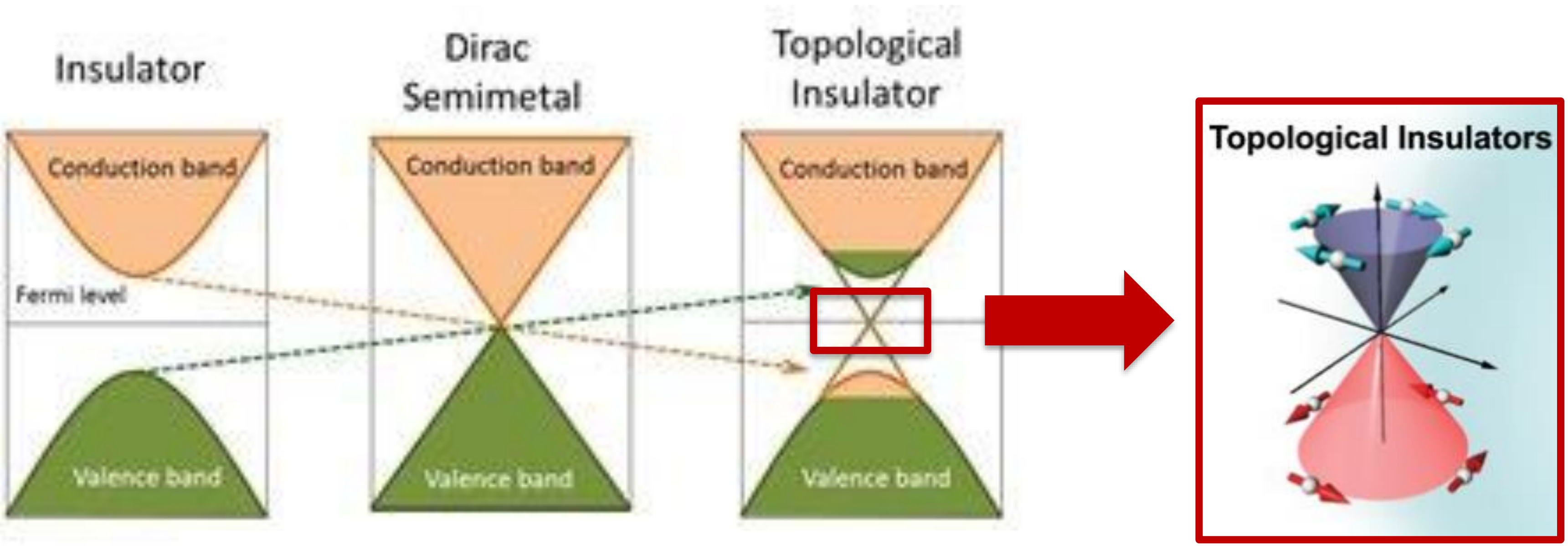
~250 fJ @ 110 nm

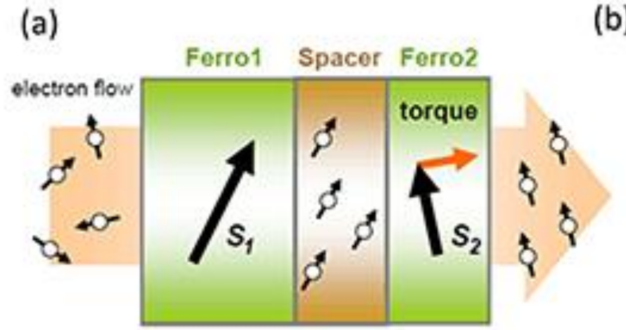
Scaling down possibility:

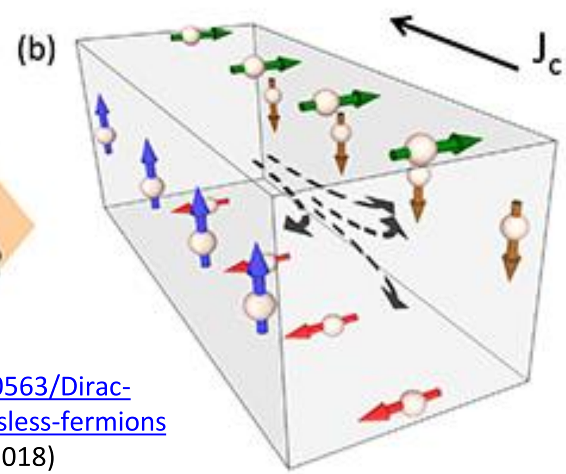
~10 fJ @ 22 nm
~0.5 fJ @ 5 nm

Sato, Wang, et al., Nature Electronics, 1(9), 508, 2018

Leverage New Physics for More Efficient Write

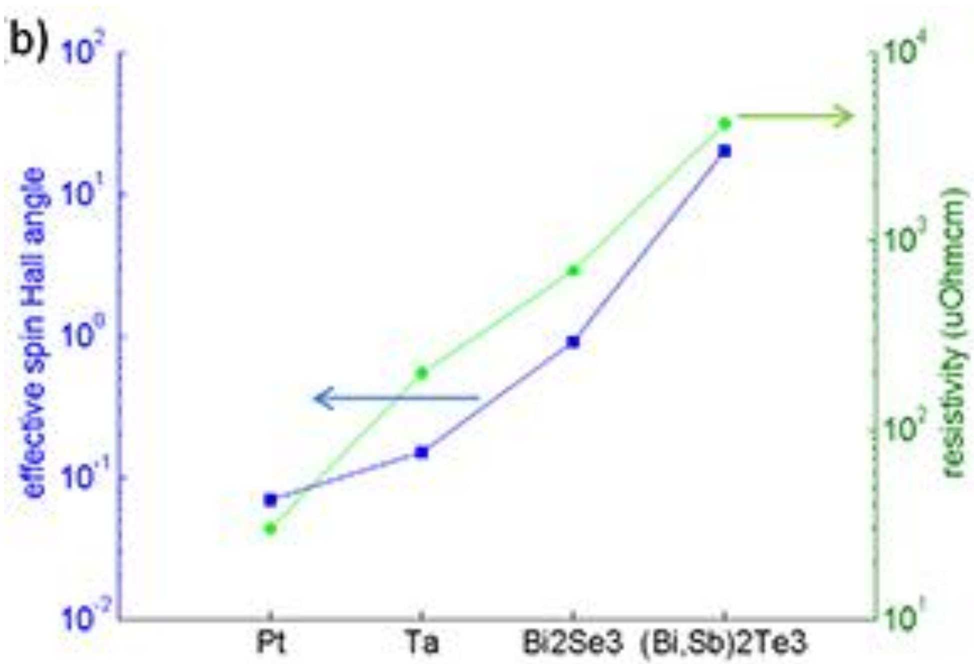






http://www.cpfs.mpg.de/2520563/Dirac-semimetal_-Transport-by-massless-fermions
J. Phys. Soc. Jpn. 87, 041002 (2018)
https://www.eecs.mit.edu/node/6509

Topological Insulator and Weyl Semimetals



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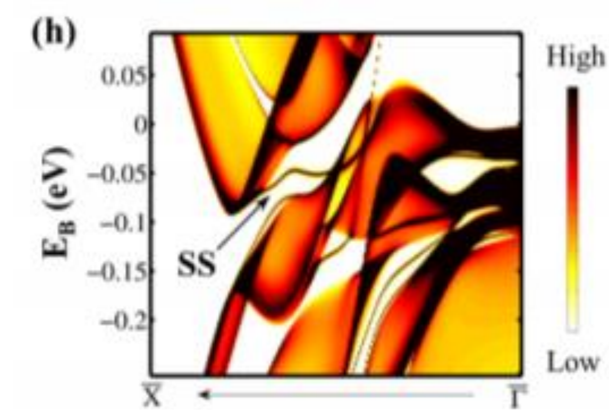
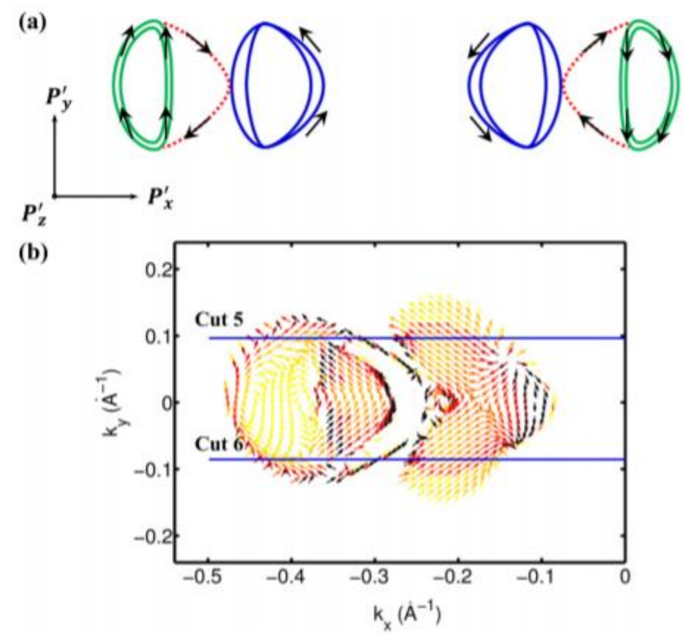
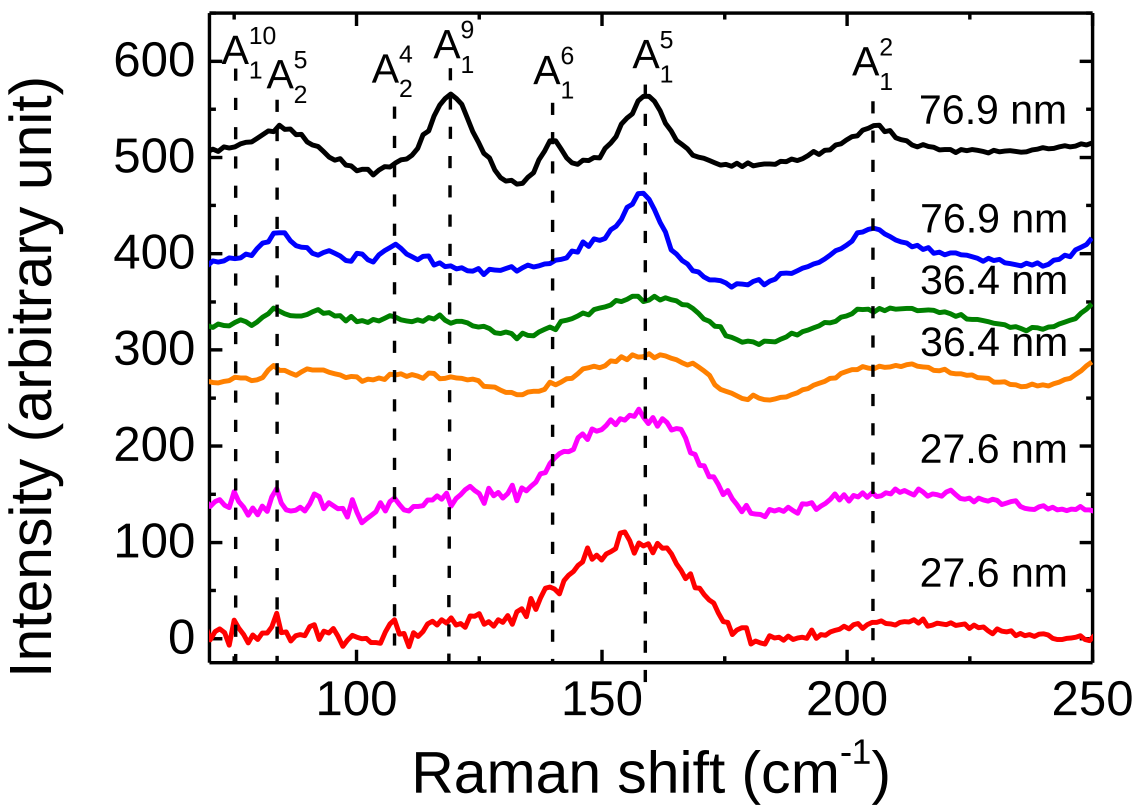


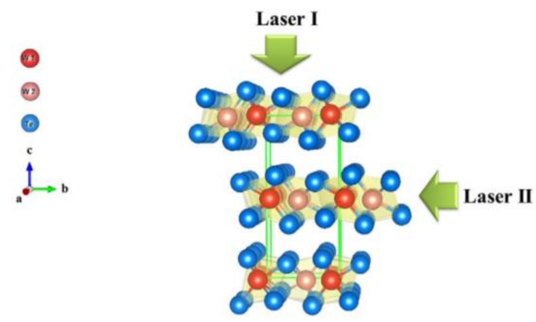


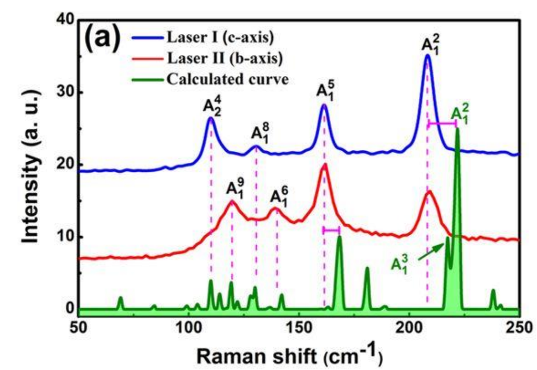
- **High resistivity** of topological insulators lowers overall on/off ratio (over 4000 $\mu\Omega$ cm for 5 nm films)
- **Weyl semimetals** are promising candidates, for example WTe_2

K. Kuroda, *et al.*, *Physical Review B*, vol. 94, Nov 18 2016.

Sputtered Weyl Semimetal WTe_x





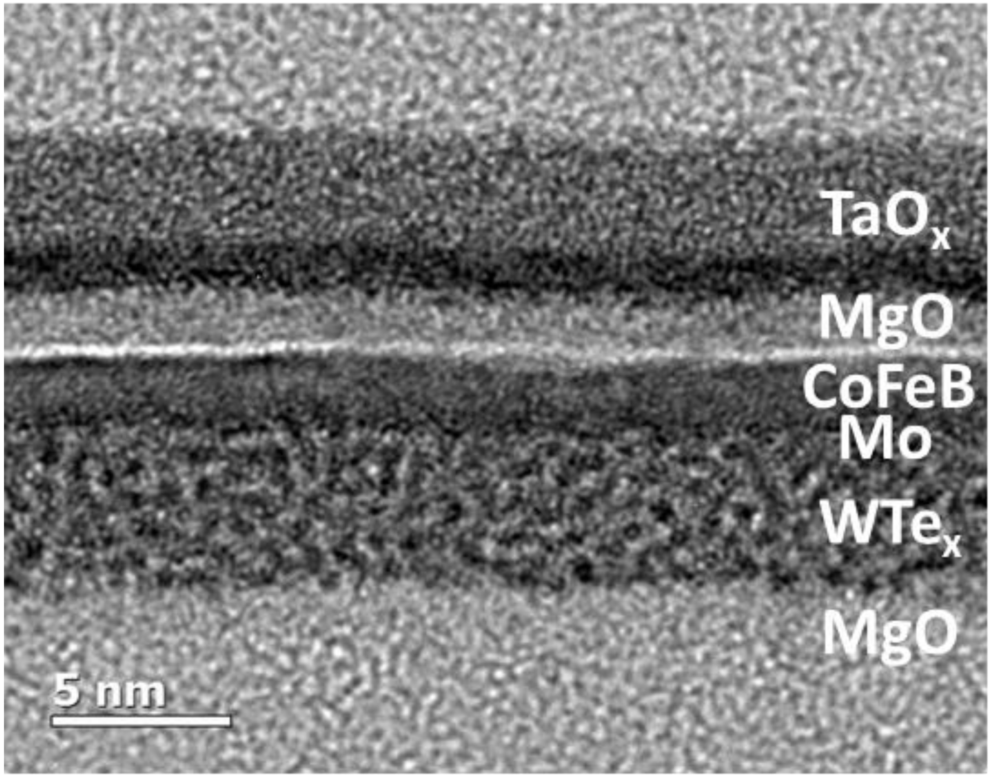


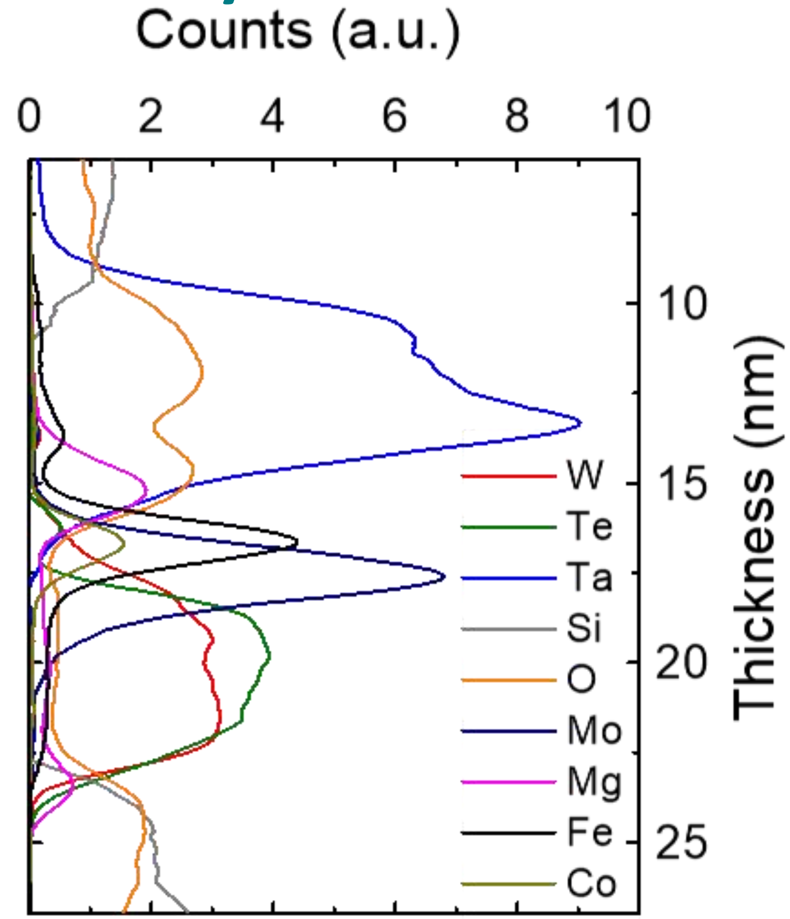
- **Sputter deposition** desired for industry adoption
- Signature **Raman peaks** of sputtered WTe_2

Y. C. Jiang, J. Gao, and L. Wang, *Scientific Reports*, vol. 6, p. 19624, 01/22/online 2016.

Xiang Li, Shan Wang, et al., in preparation

High Resolution TEM Analysis

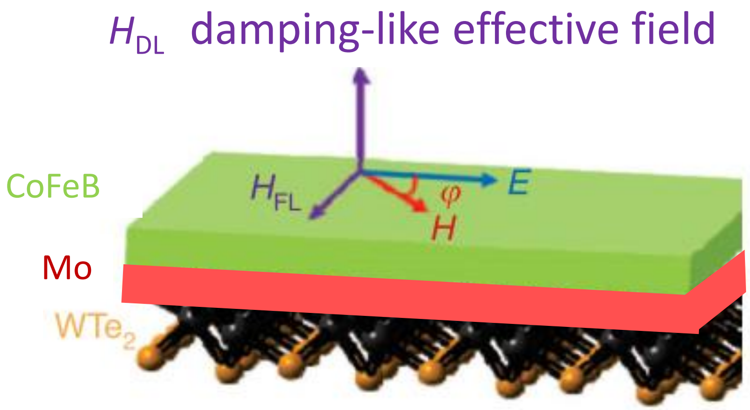


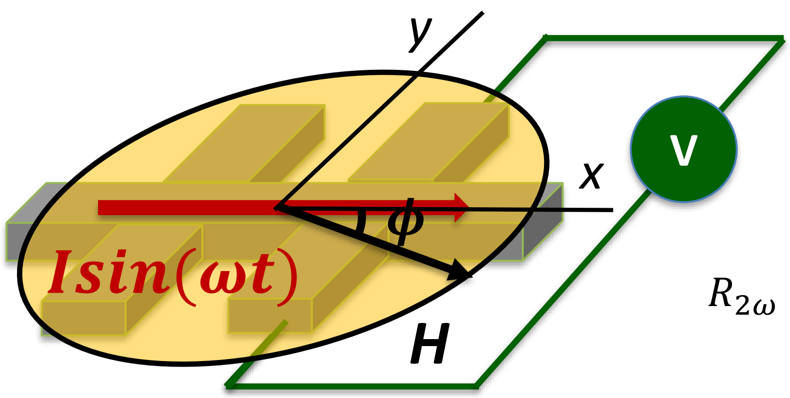


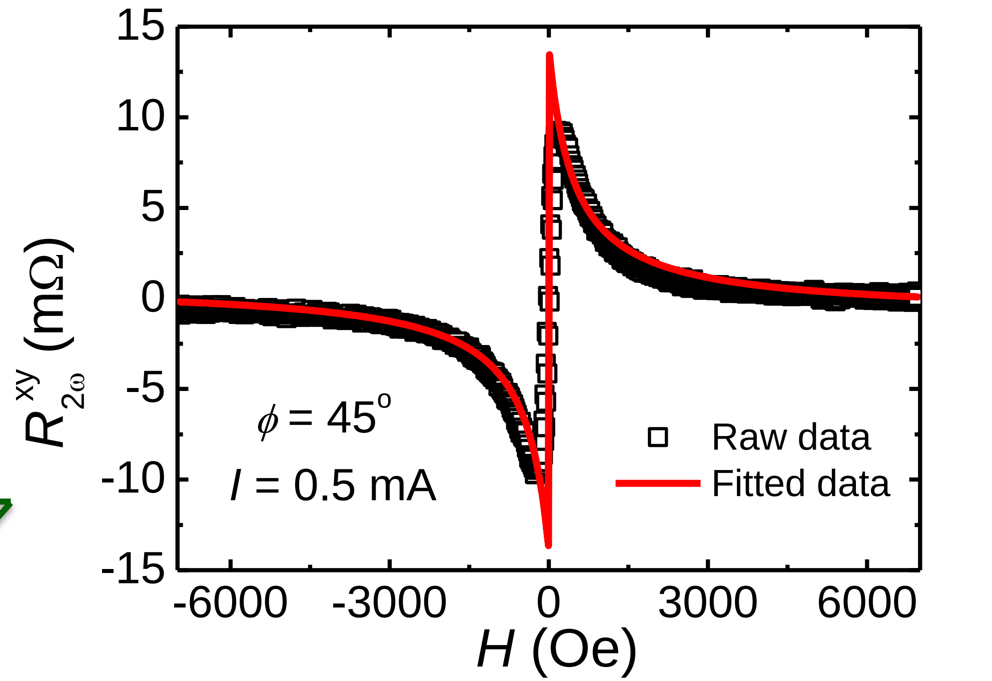
- TEM shows **W:Te ratio of 1:1.34** with visible WTe$_x$ grains/clusters

Xiang Li, Shan Wang, et al., in preparation

Low Frequency Current Induced Resistance Change







$$R_{2\omega} = R_P \frac{H_{FL}}{|H_{ext}|} cos2\phi cos\phi + \left(\frac{R_A}{2}\frac{H_{DL}}{|H_{ext}| - H_K} + R_{th}\right) cos\phi$$

Q Shao, Kang Wang et al., 2018 IEDM

- **Charge-to-spin conversion efficiency** characterized using harmonic current induced magnetization oscillation
- H_{DL} is the **damping-like effective field** that drives switching

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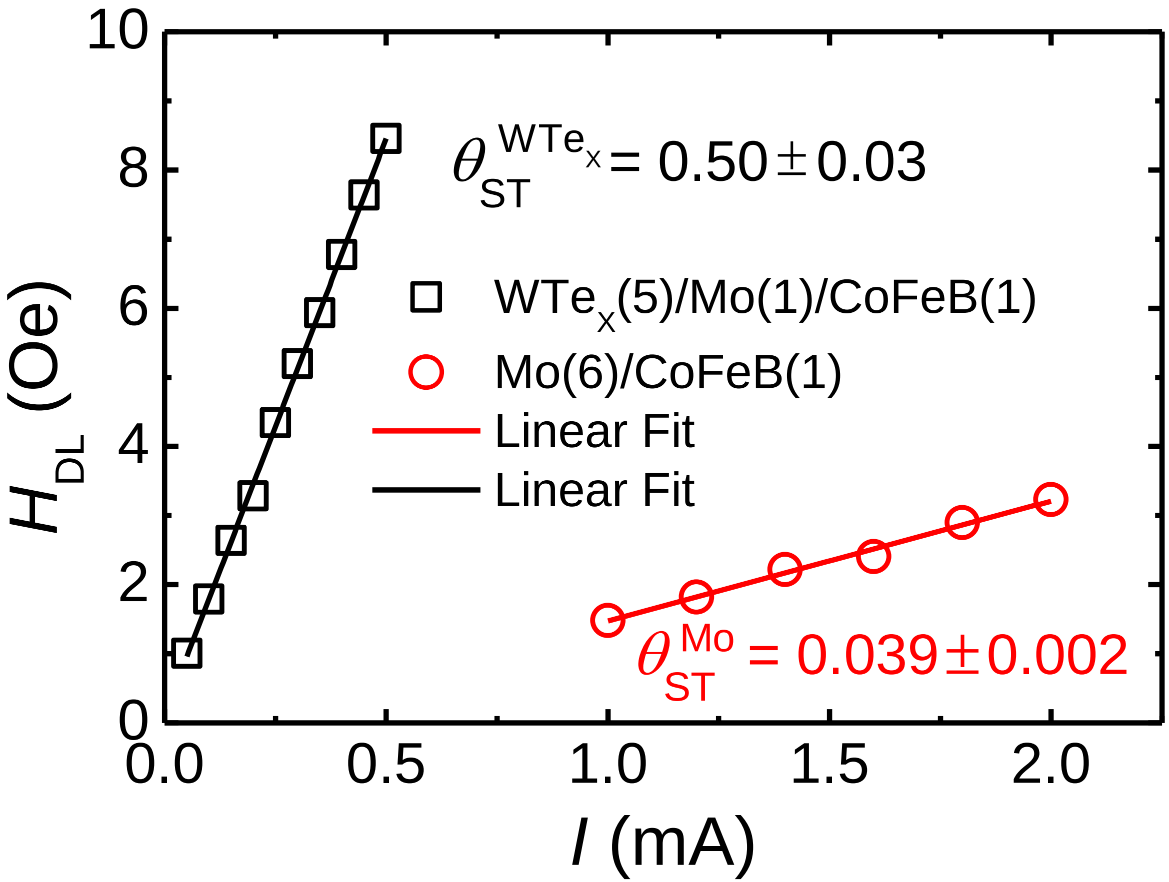
Charge-to-Spin Conversion Efficiency

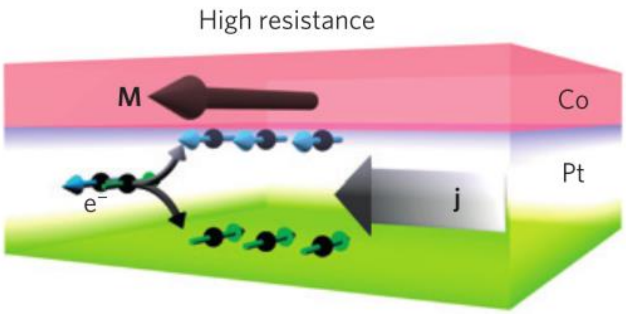


- Mo between WTe_2 and CoFeB partially absorb spin-polarized electrons
- Real ξ_{ST} value of WTe_2 should be larger

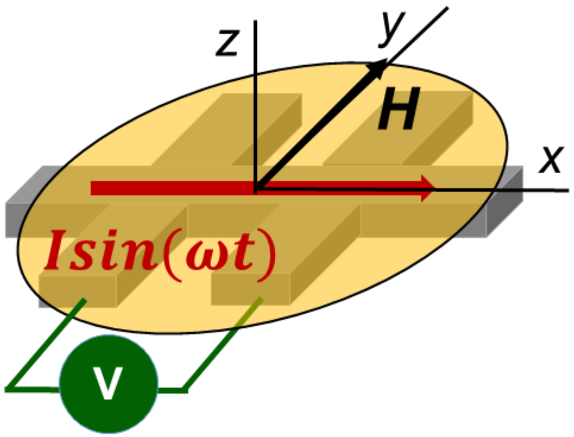
$$\xi_{ST} = \frac{2eM_S t_{CoFeB}}{\hbar} \frac{H_{DL}}{J_{WTe2}}$$

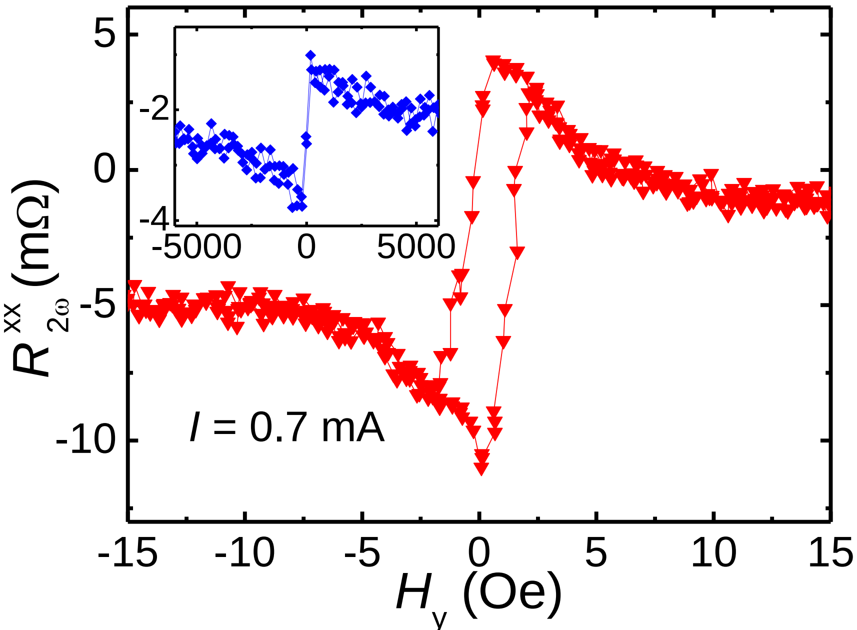
Xiang Li, Shan Wang, et al., in preparation

Unidirectional Spin Hall Magnetoresistance (USMR)



C. O. Avci et al., Nature Physics, vol. 11, p. 570, 2015.





- Spin currents interaction with magnetization affects **interface scattering**, thus changes **longitudinal resistance**

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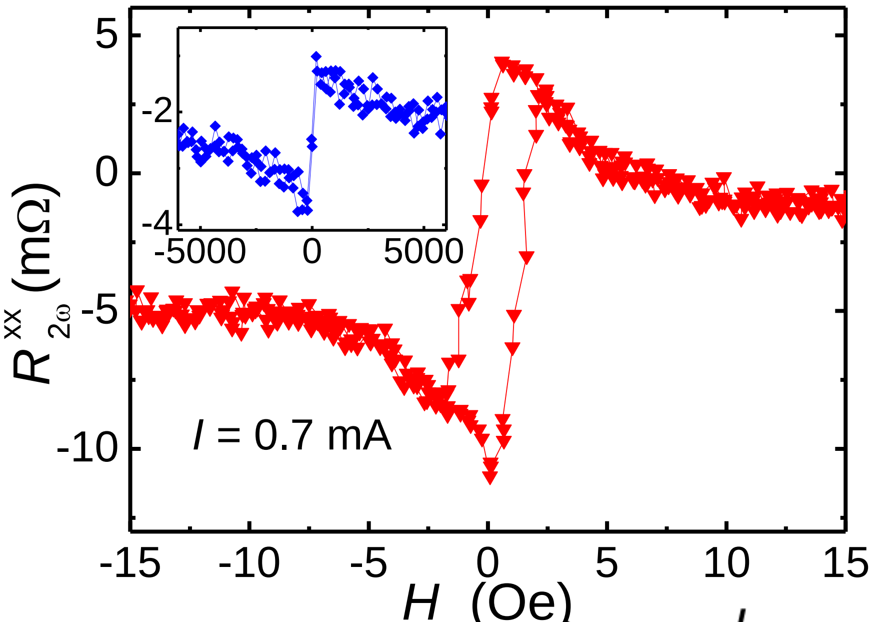
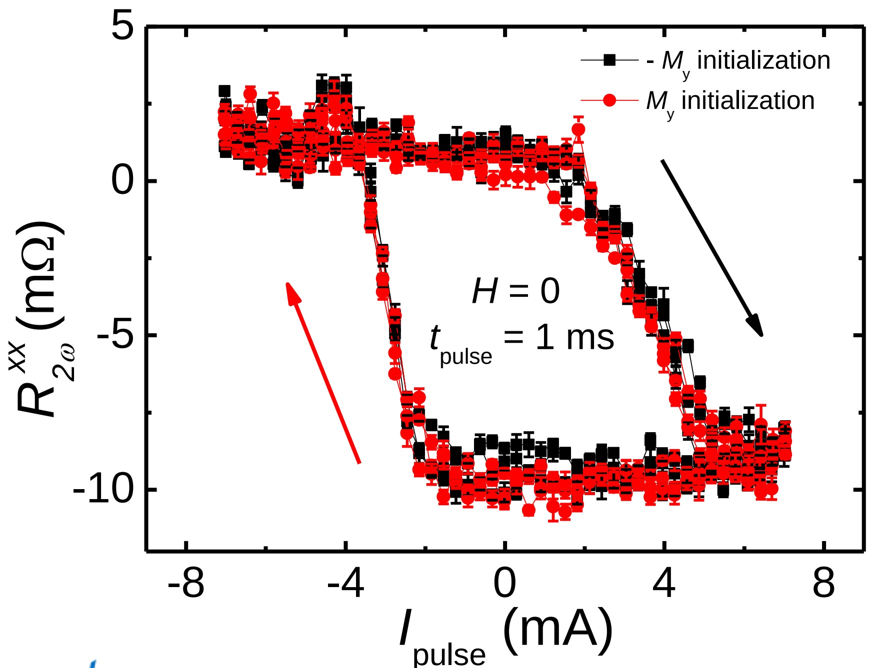
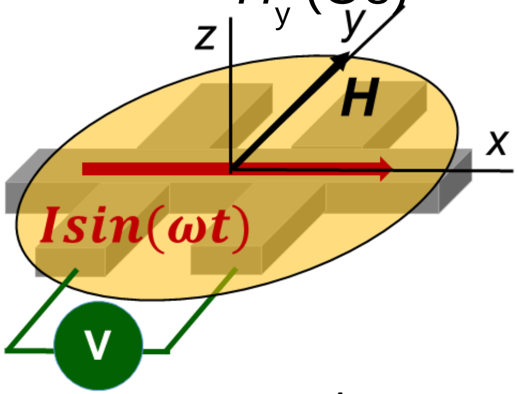
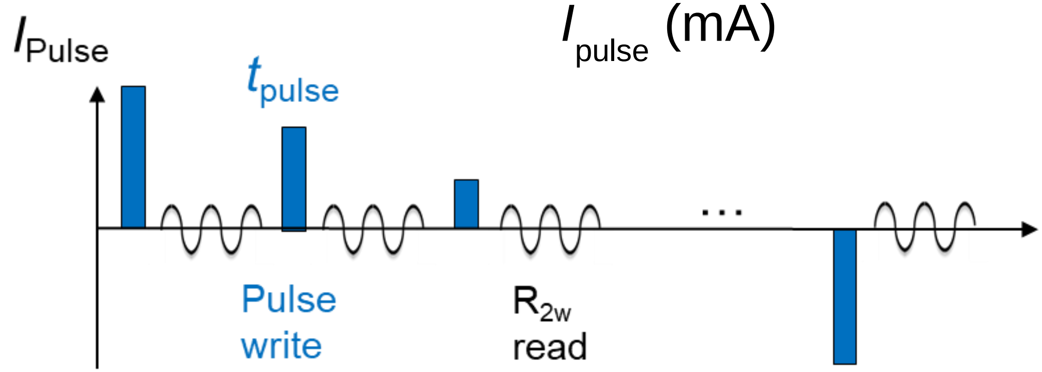
Current-Induced Field-Free Switching









- Switching current density in WTe_x **0.77-1.41 MA/cm²**

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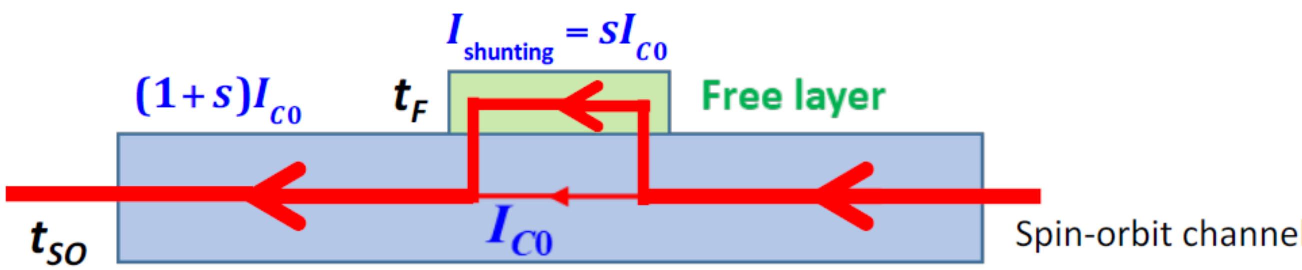
Benchmark: Power Efficiency of SOT-MTJ Cell



$$s \equiv \frac{I_{shunt}}{I_{C0}} = \frac{\rho_{SO}}{t_{SO}} \frac{t_F}{\rho_F}$$
≈ 0.2 for Pt

≈ 1 for W

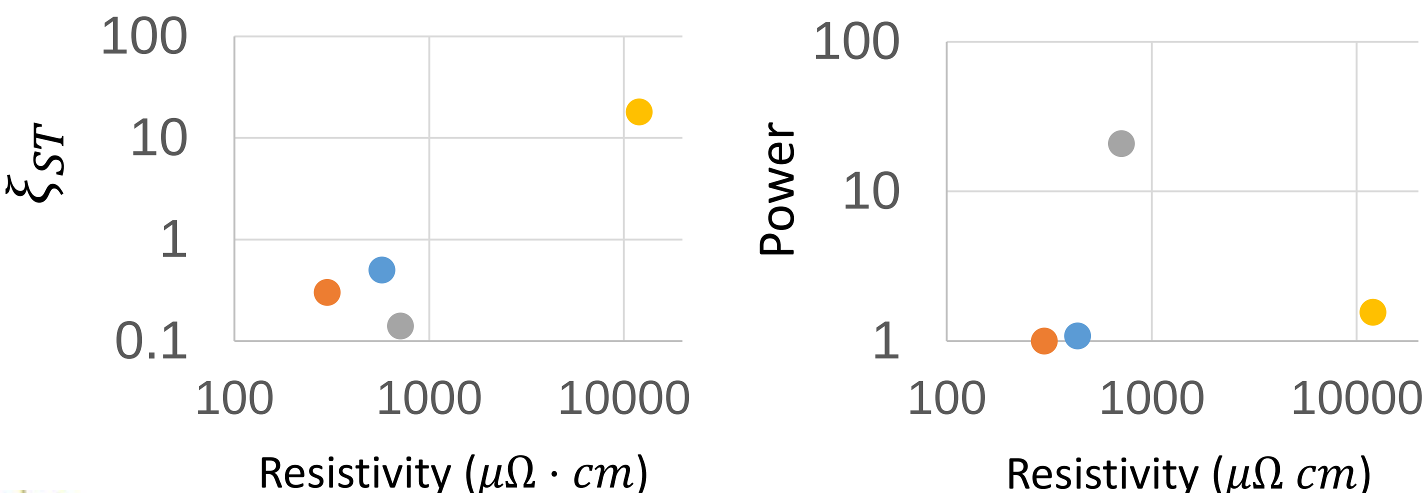
≈ 50 for Bi_2Se_3

with FeCoB

$$I_{tot} \propto \frac{s+1}{\theta_{SH}} \qquad Power \text{ (approx)} \propto \rho_{SO} I_{tot}^2 \propto \frac{\rho_{SO}(s+1)^2}{\theta_{SH}^2}$$

Physical Review Applied, vol. 10, Sep 6 2018.

Assumes 6 nm SOT write line under 1 nm in-plane CoFeB.

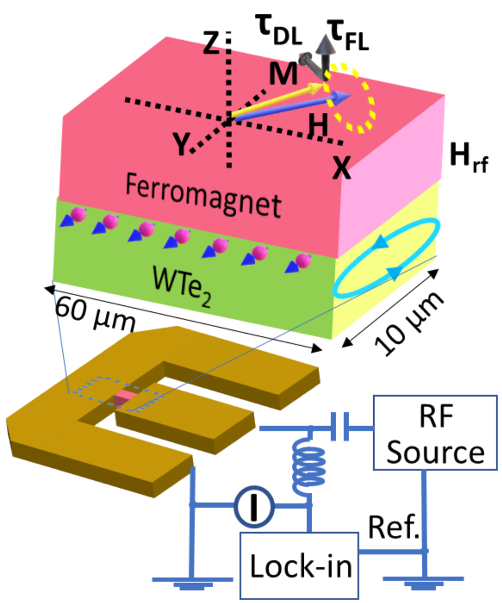


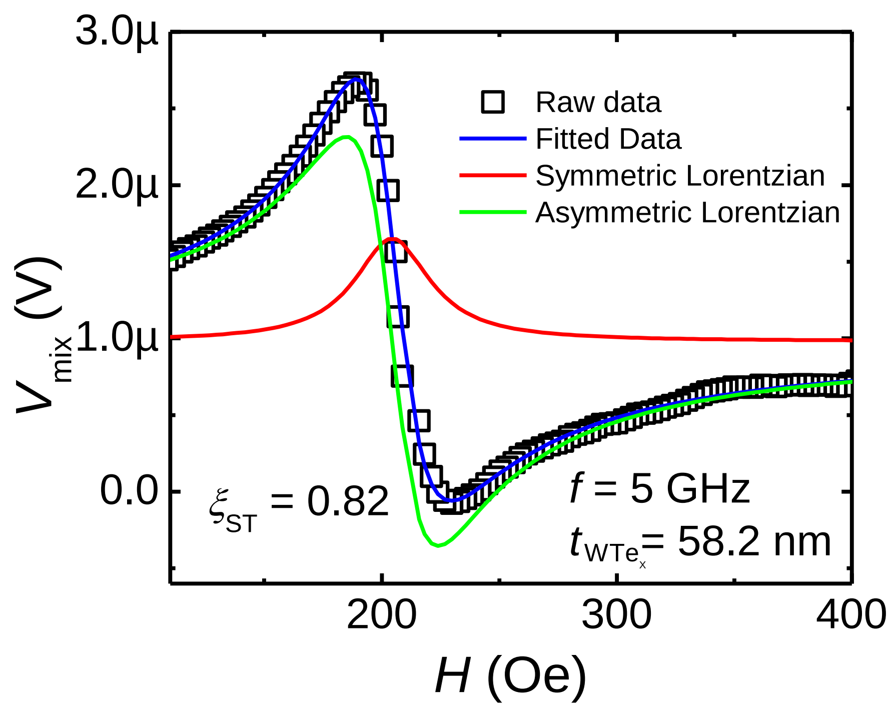
- Sputtered WTe_x
- Sputtered W
- Exfoliated WTe_2*
- Sputtered $BiSe_x$**

*Yang et al., *Nature Nano*, 2019.
**Wang et al., *Nature Materials*, 2018.

Xiang Li, Shan Wang, et al., in preparation

High Frequency Current Induced Magnetic Resonance





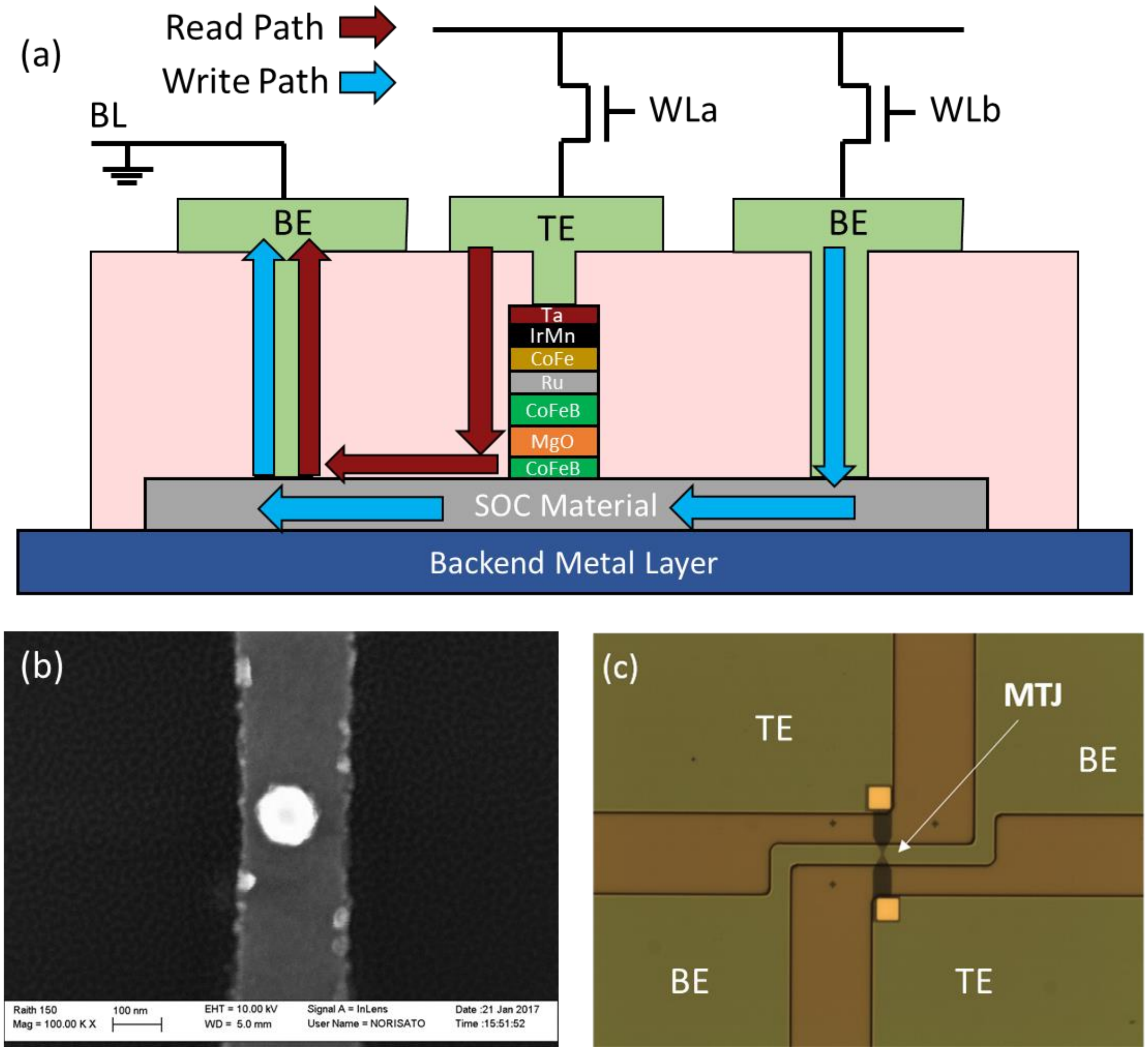
$$V_{\text{mix}} = -\frac{1}{4}\frac{dR}{d\theta}\frac{\gamma I_{\text{rf}}\cos\theta}{\Delta 2\pi (df/dH)|_{H_{\text{ext}}=H_0}}[SF_S(H_{\text{ext}}) + AF_A(H_{\text{ext}})], \qquad \theta = \frac{J_{S,\text{rf}}}{J_{C,\text{rf}}} = \frac{S}{A}\frac{e\mu_0 M_S t d}{\hbar}[1 + (4\pi M_{\text{eff}}/H_{\text{ext}})]^{1/2}.$$

Luqiao Liu, et al., PRL 106, 036601 (2011)

- Fitted resonance peak with symmetric and asymmetric Lorentzian line shapes

Xiang Li, Shan Wang, et al., in preparation

SOT-MTJ Integration and Test



Conclusions

- MRAM holds great promise to **replace or complement SRAM** for data-centric applications as **high-density on-chip memory**
- Unique topological band structure gives rise to highly spin polarized electrons in **Weyl semimetal WTe_2**
  - Sputtered 5 nm WTe_x at room temperature shows attractive charge-to-spin conversion efficiency (**0.5**), low switching current density (**1 MA/cm²**), and low thin film resistivity (**570 $\mu\Omega\cdot cm$**)
  - Greatly improved energy/delay performance compared with other topological materials such as BiSe or exfoliated WTe_2
  - Even larger charge-to-spin conversion efficiency up to **0.8**

Acknowledgements

tsmc

SystemX ALLIANCE
Stanford University

E3S
Center for Energy Efficient Electronics Science

NMTRI
Non-volatile Memory Technology Research Initiative