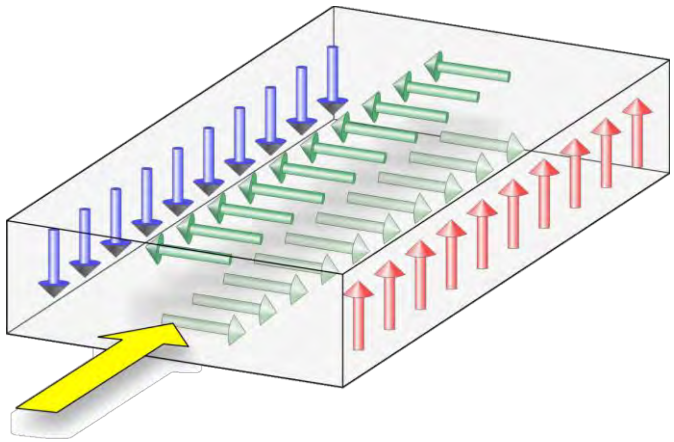
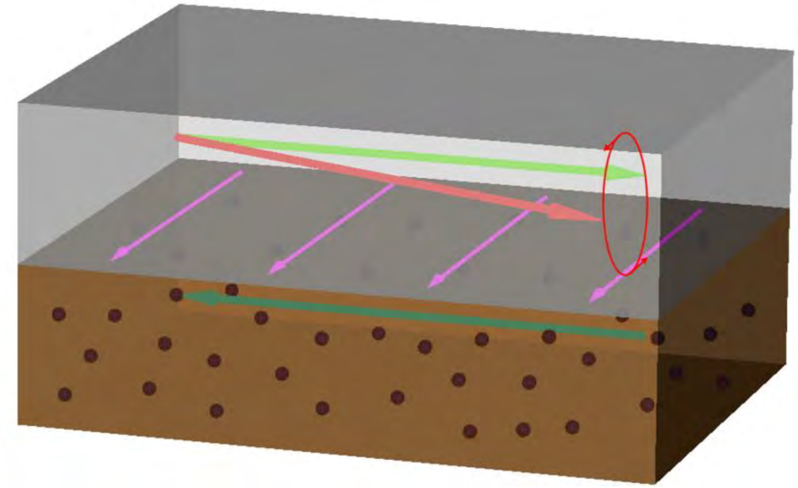
Enhanced spin orbit torques by oxygen incorporation in tungsten films





Timothy Phung

IBM Almaden Research Center, San Jose, California, USA

Motivation: Memory devices based on spin currents

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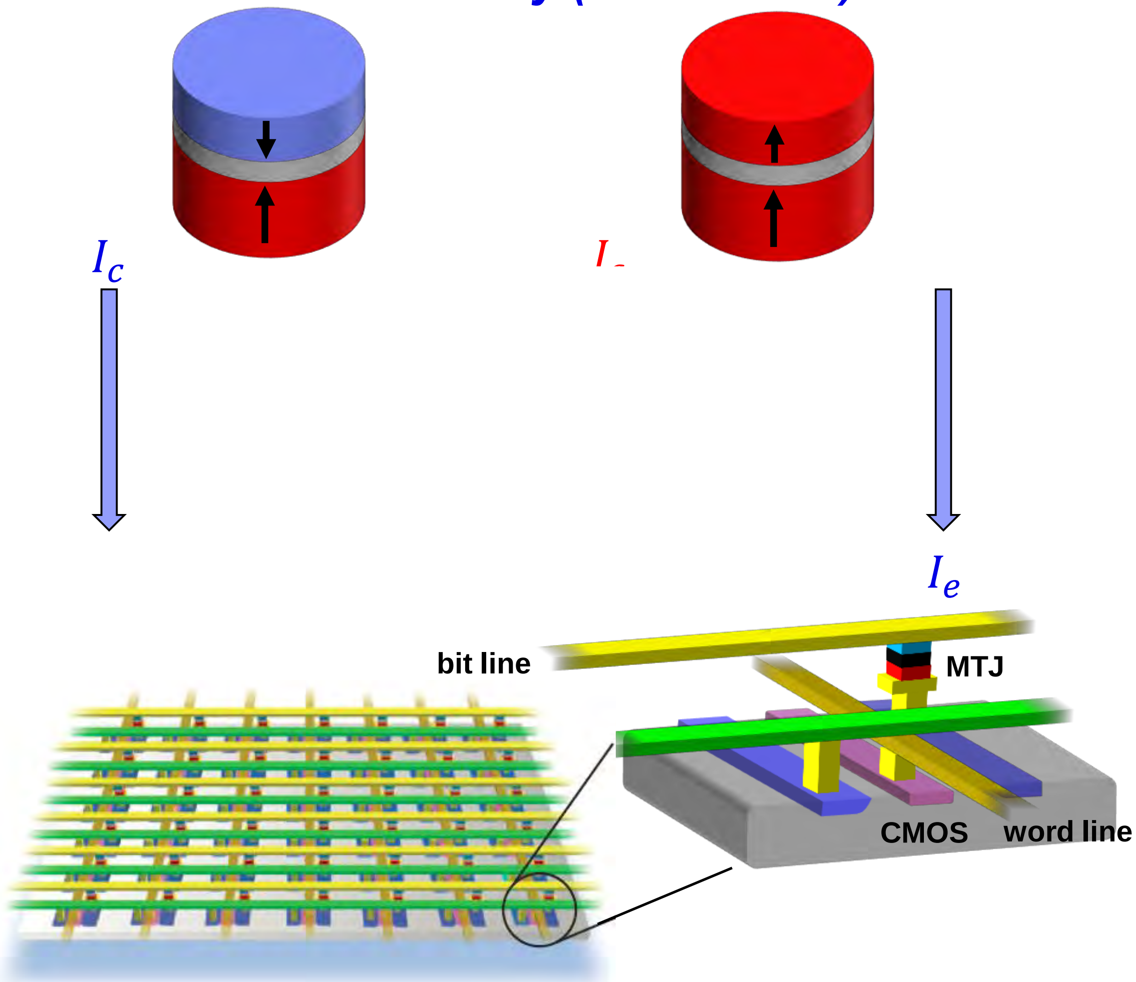
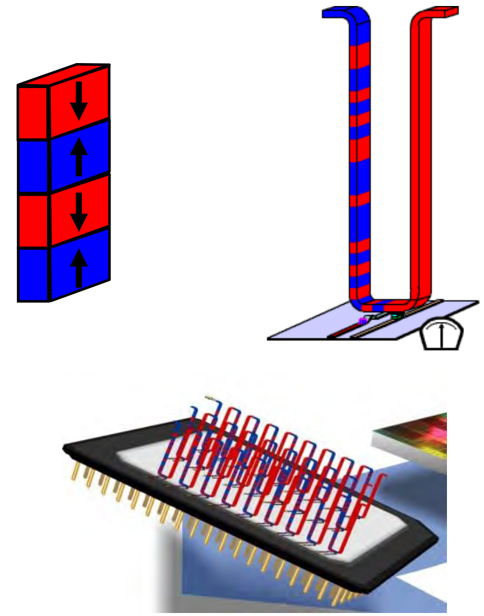
Spin Transfer Torque Magnetic Random Access Memory (STT-MRAM)



Racetrack Memory

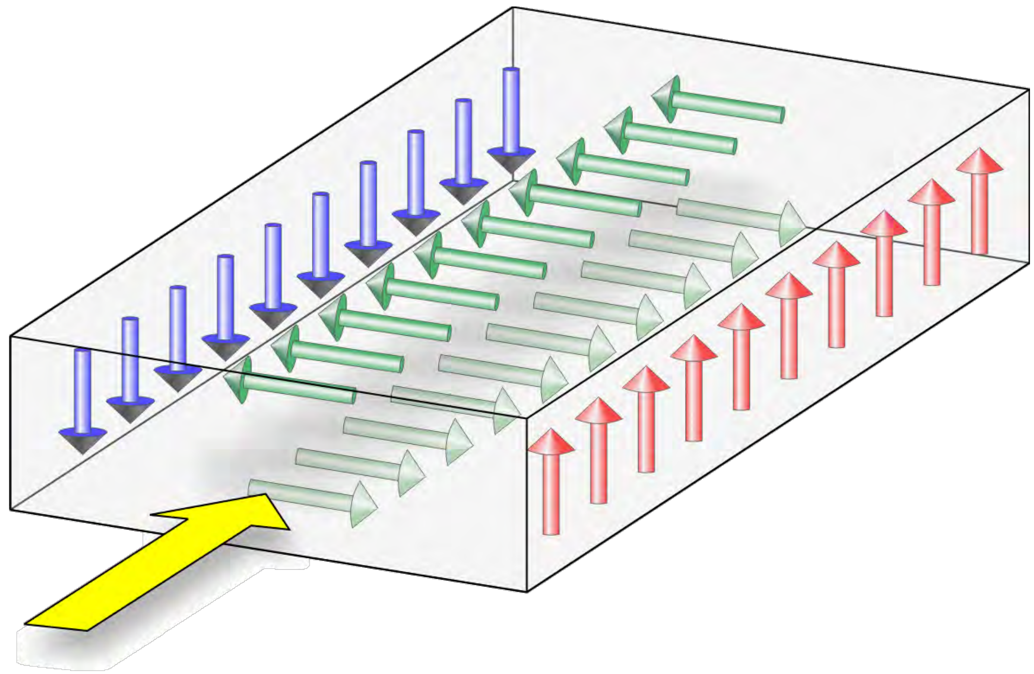


Chiral Spin Transfer torque

Ryu et al., Nat. Nano (2013)

Spin currents are key to switching the magnetic moments in STT MRAM and moving domain walls in racetrack memory

Spin Hall effect



- The spin Hall effect describes the conversion of charge to spin current, ***and existing theoretical explanations of the effect ascribe it to volumetric scattering within the bulk of the film***, similar to the side jump and skew scattering mechanisms, as well as intrinsic mechanism used to explain the anomalous Hall effect
- Understanding microscopic mechanisms responsible for these effects are key to enhancing its magnitude
- One goal is to understand the role of materials micro-structure on the spin-Hall angle

Determining the oxygen concentration inside of tungsten films

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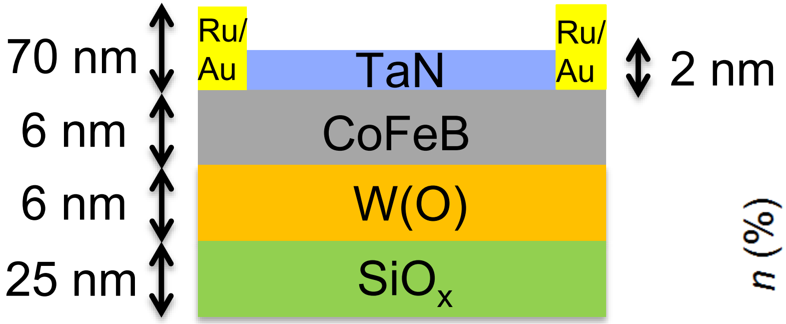
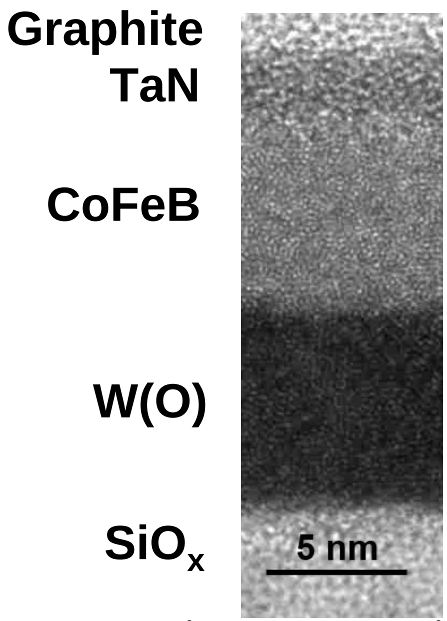
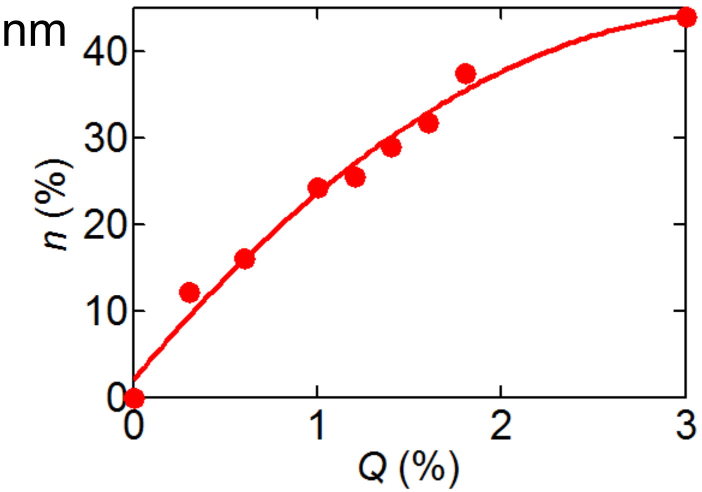
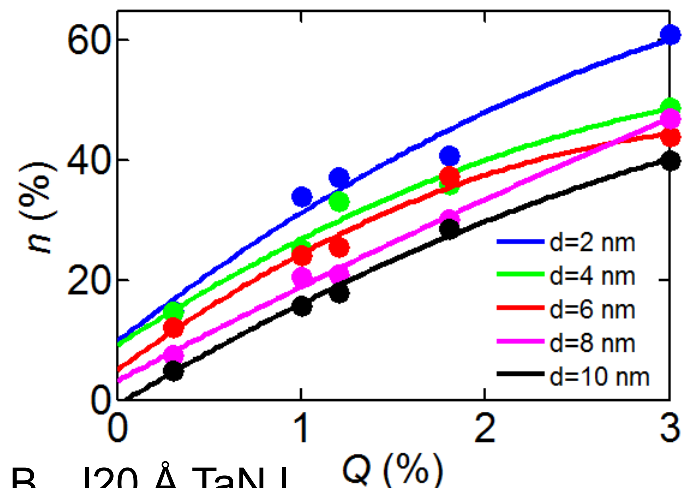


$n = 12.1\ \%$

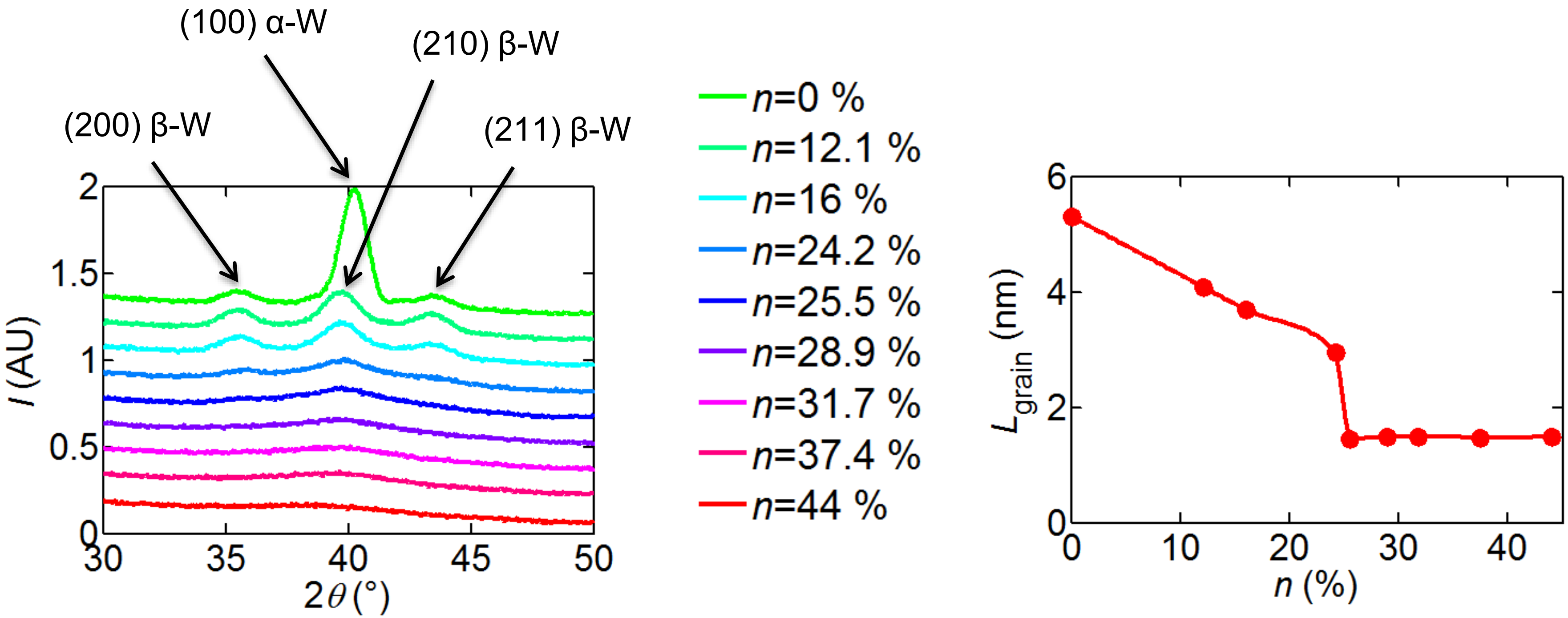




Q: Relative amount of Oxygen Gas flow (%)



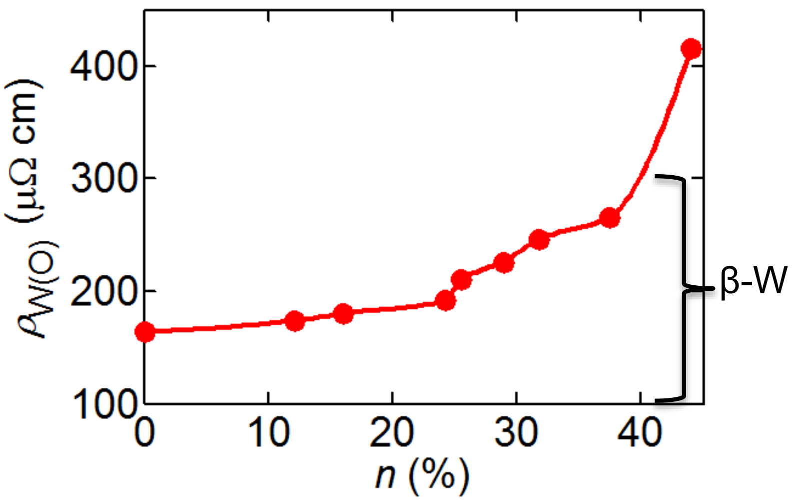
- Graphite | 60 Å W(O) | 60 Å $Co_{40}Fe_{40}B_{20}$ |20 Å TaN |
- We use Rutherford Backscattering Spectrometry (RBS) to determine the oxygen content in our films
- As the thickness of our films increase, the oxygen content that is incorporated actually gets reduced due to the increased compressive stress in the films

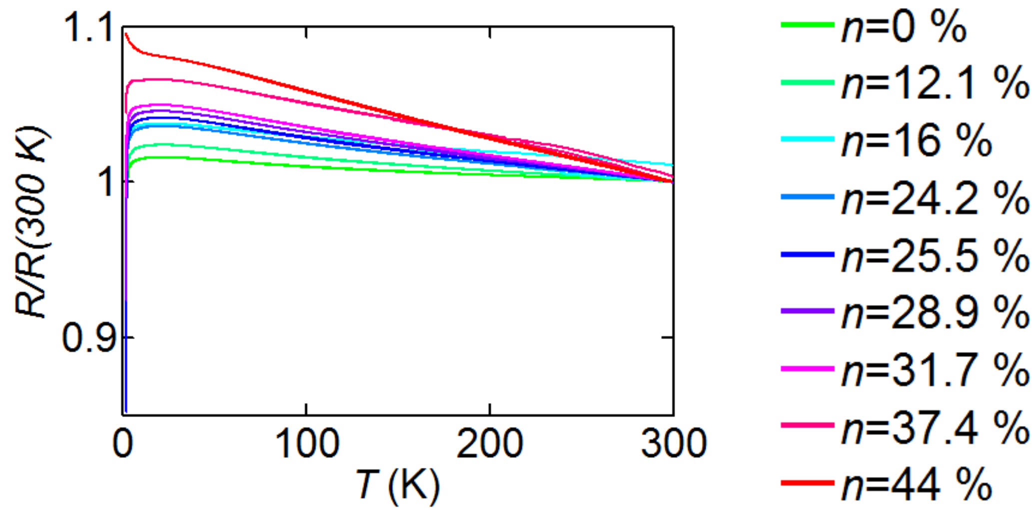


- Stabilization of the beta phase is observed with modest amount of oxygen incorporation as shown by XRD.
- The beta phase co-exists with the alpha phase with no oxygen flow (there the thickness determines the equilibrium phase).
- At large oxygen gas flow, nano-crystallization lead to a reduced grain size

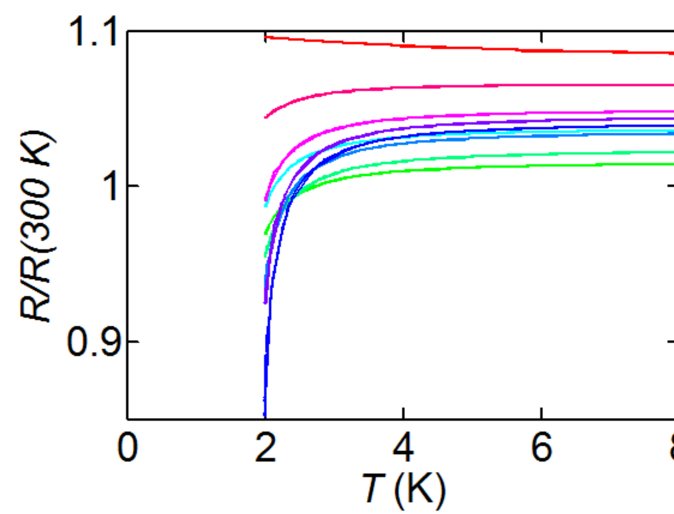
Electrical transport properties as a function of oxygen content

IBM

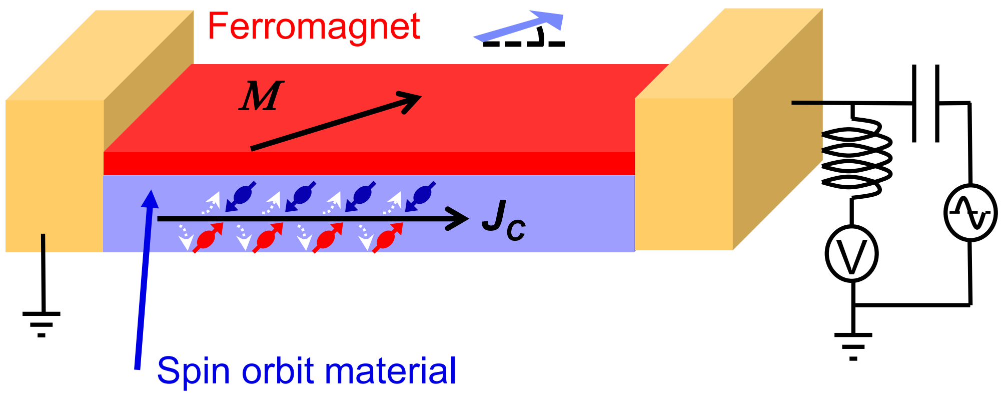


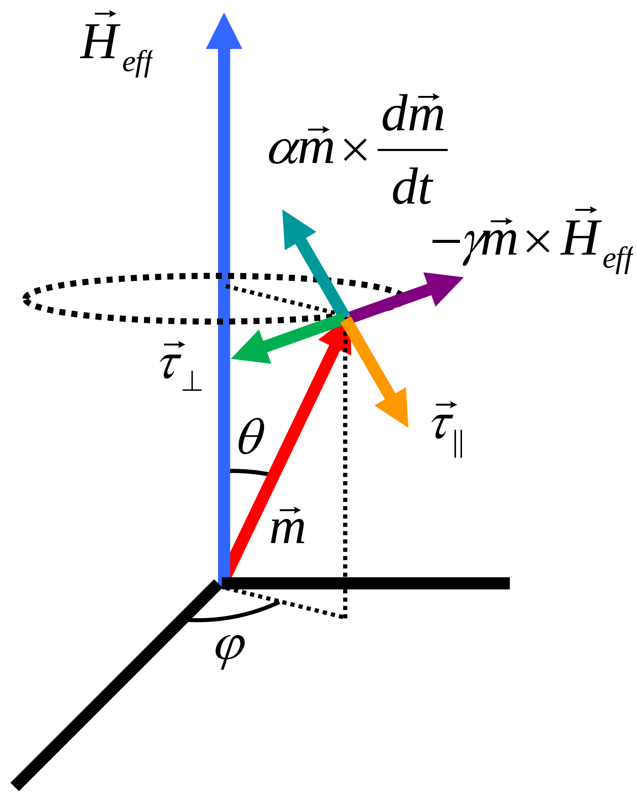


- SiO_x | 60 Å WO_x | 60 Å $Co_{40}Fe_{40}B_{20}$ |20 Å TaN |
- Temperature dependent resistivity measurements reveal a semi-conductor (disordered) like behavior in our films.
- Films where the beta phase is observed show signs of superconductivity, consistent with the increased superconducting temperature of the beta phase of tungsten.
- The films overall show a continuous change in their resistance vs. temperature characteristics with increased oxygen concentration, and continuous resistivity increase as well



STFMR equations of motion





$$\frac{d\hat{m}}{dt} = -\gamma\hat{m}\times\vec{H}_{eff}$$ → Effective field (composed of internal and externally applied fields)

$$+\alpha\hat{m}\times\frac{d\hat{m}}{dt}$$ → damping

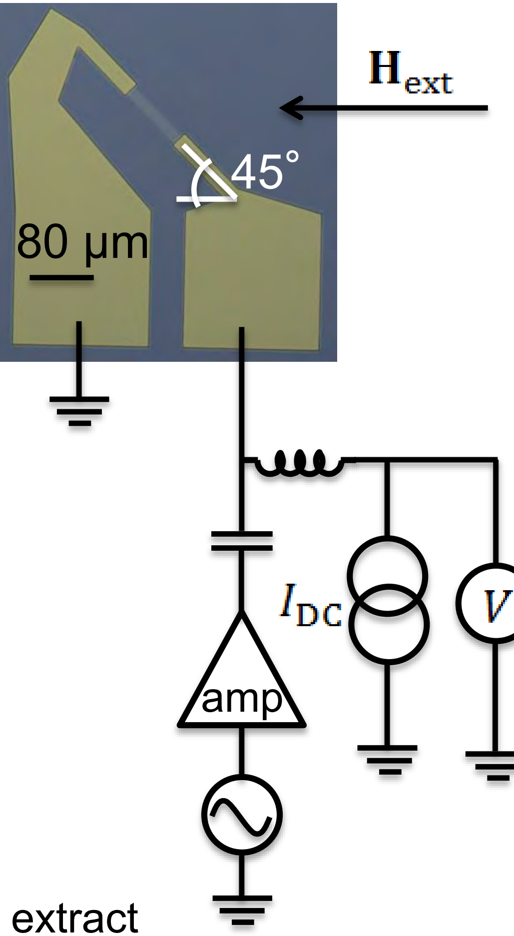
$$+\vec{\tau}_{\parallel}$$ → Damping like contribution of STT

$$+\vec{\tau}_{\perp}$$ → Field like contribution of STT and Oersted field

$\gamma = \frac{ge}{2m_e c}$ is the gyromagnetic ratio

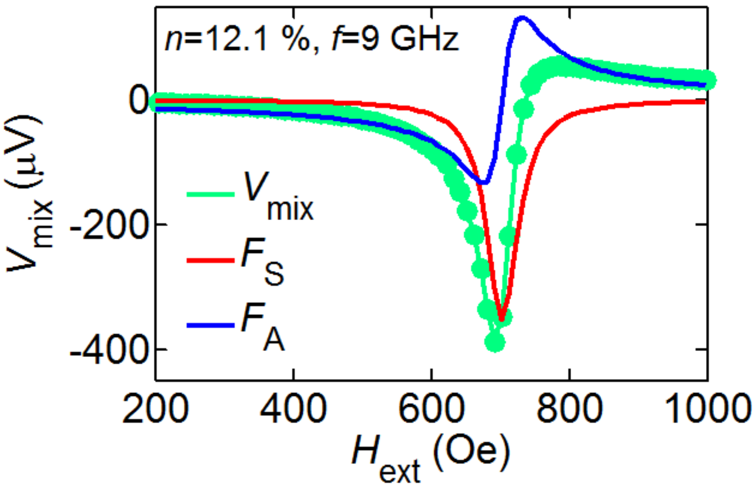
Film structure

Measurement Circuit



$$V(t) = I(t)R(t)$$
$$\propto I_{RF}\cos(\omega t)\Delta R\cos(\omega t + \delta)$$
$$= \frac{1}{2} I_{RF}\Delta R[\cos(\delta) + \cos(2\omega t + \delta)]$$
$$V_{mix} \propto \frac{1}{2} I_{RF}\Delta R\cos(\delta)$$

We use spin torque ferromagnetic resonance (STFMR) to extract the spin-orbit torques and quantify it as a spin Hall angle



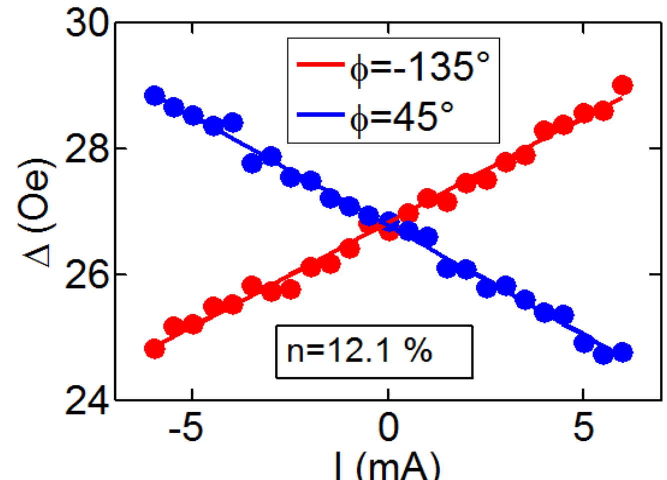
- ***Caveats of taking the ratio of symmetric and asymmetric are assuming that the symmetric component has no spin pumping contribution and the asymmetric component arises completely from the Oersted field***
- ***Alternatively, the change in the line-width and resonant field with a superimposed DC current can be used to obtain the magnitude of the spin orbit torques***

$$V_{mix} = V_0\left(SF_s\left(H_{ext}\right) + AF_A\left(H_{ext}\right)\right)$$

$$V_0 = -\frac{1}{4}\frac{dR}{d\varphi}\frac{\gamma\mu_0 I_{rf,tot}\cos\varphi}{\Delta 2\pi\left(df/dH_{ext}\right)\big|_{H_{ext}=H_0}}$$

$$F_s\left(H_{ext}\right) = \frac{\Delta^2}{\Delta^2 + \left(H_{ext} - H_0\right)^2}$$

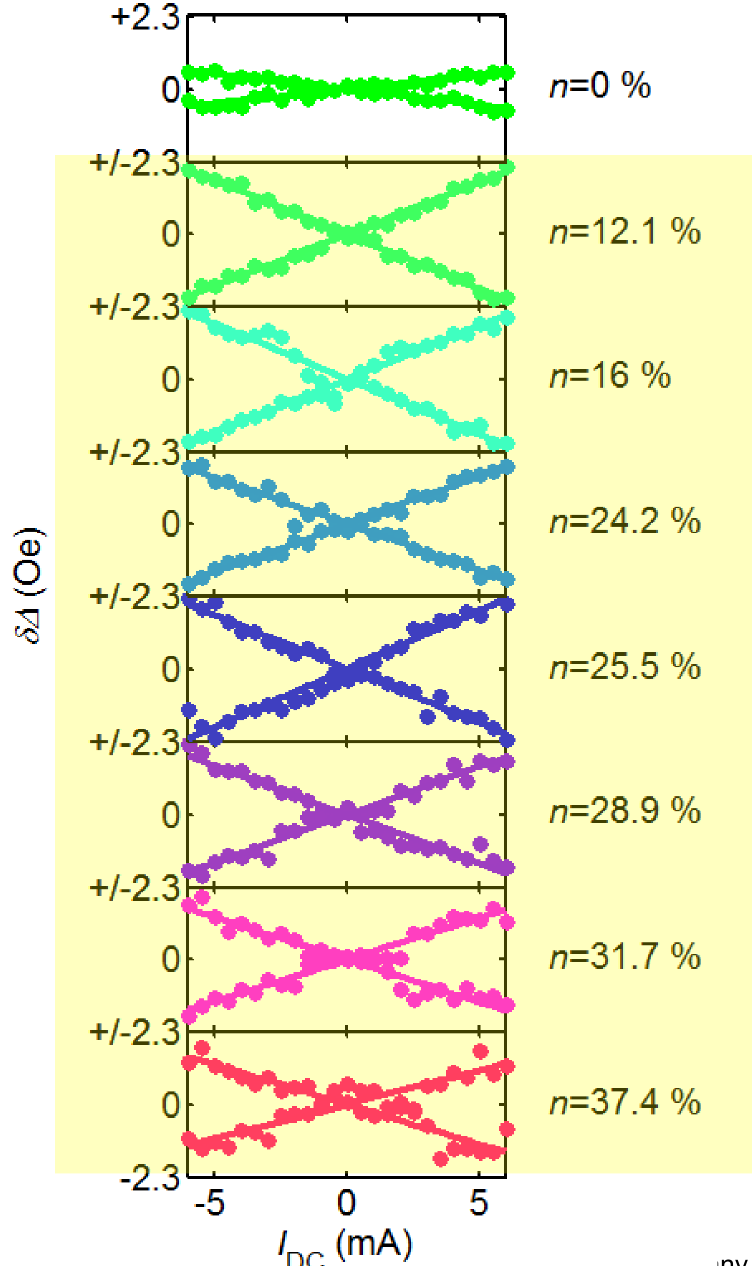
$$F_A\left(H_{ext}\right) = F_S\left(H_{ext}\right)\frac{\left(H_{ext} - H_0\right)}{\Delta}$$



torque)

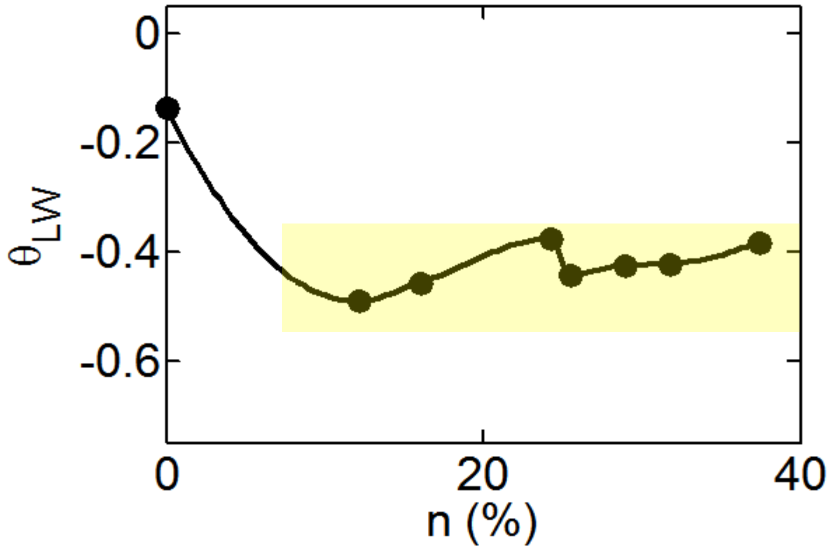
Ando et al, PRL (2008)
Liu et al., PRL (2011)

Dependence of line-width modulation on oxygen concentration



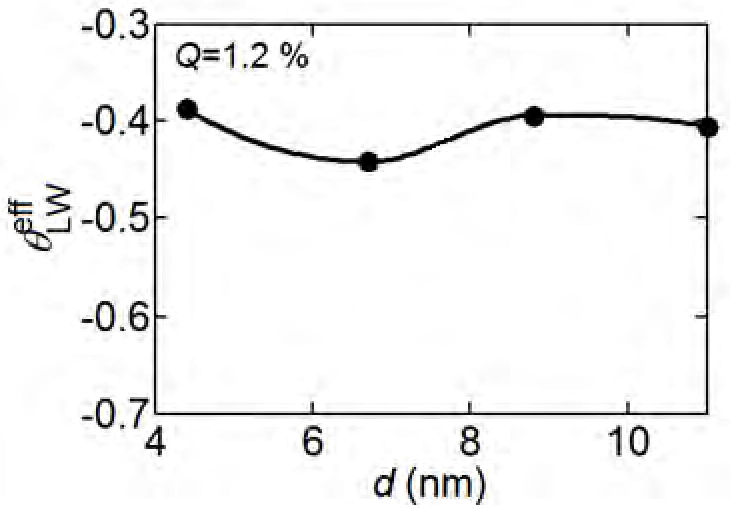
- The slope (change in linewidth with DC current), effectively change in damping, can be used to determine the spin Hall angle.
- The slope is quite independent of the oxygen concentration

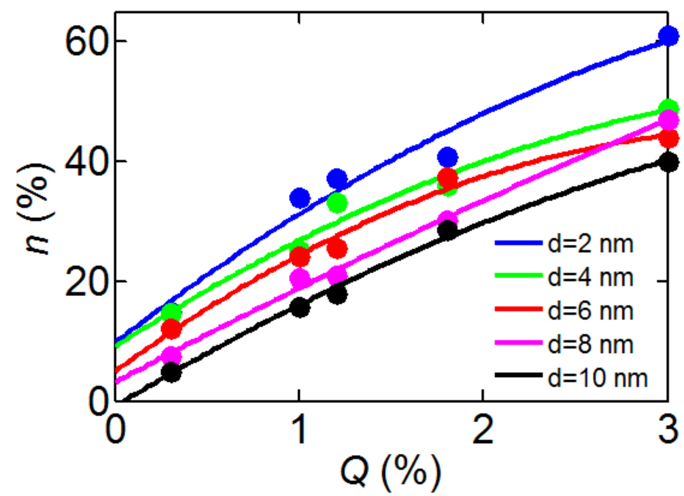
Using the linewidth to determine the Spin orbit torque

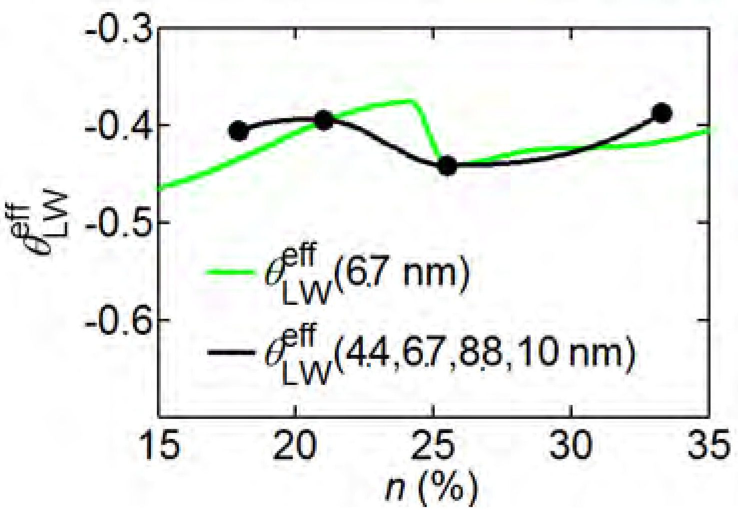


- After extracting the spin Hall angle, we see that it is independent of oxygen content and remains rather flat. ***The value obtained is the highest to be reported in a conventional metals based system (~-50%).***
- ***Our results thus suggest that the mechanisms behind the spin Hall angle are independent of the bulk volumetric properties of the W(O) films, and may potentially stem from the interface instead.***

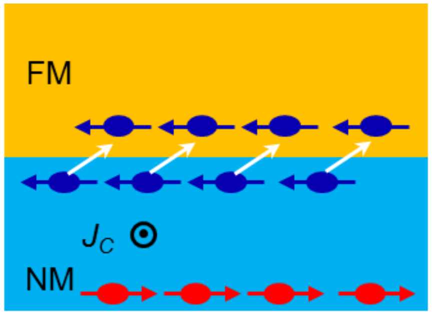
Thickness dependence of the effective spin Hall angle

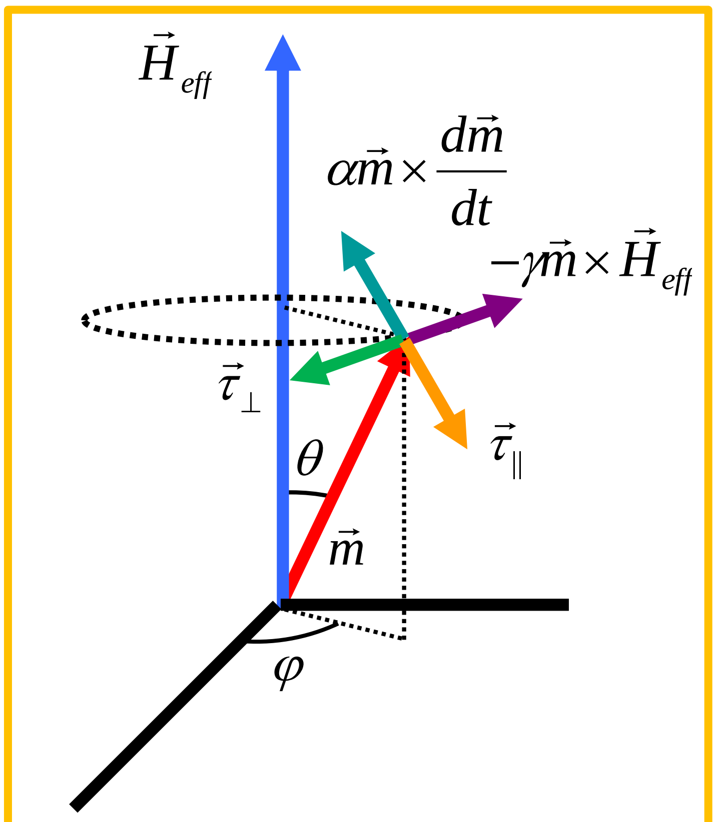




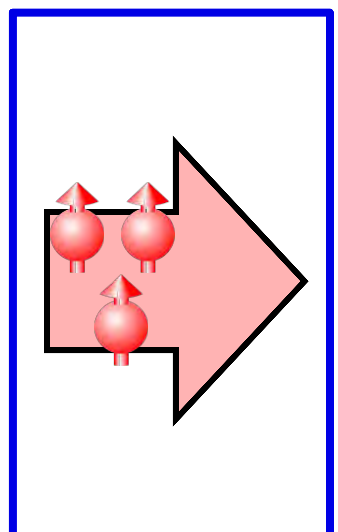


- The effective spin Hall angle can be compared as a function of the thickness where we observe that is quite independent of thickness beyond 4 nm.
- ***However, the amount of oxygen incorporated also changes, so when comparing the thickness dependent data to films of the same composition at our nominal thickness, we also see that the is not thickness dependent → the spin diffusion length is very small or the spin-orbit torque is interfacial in origin.***





- The spin Hall angle assumes that all the spins generated in the non-magnetic layer are completely transferred to the ferromagnet and exert spin transfer torque on it.
- The transparency of the spins is an important consideration
- Spins can be transferred to the non-magnetic layer and thus form another loss channel for the spin relaxation

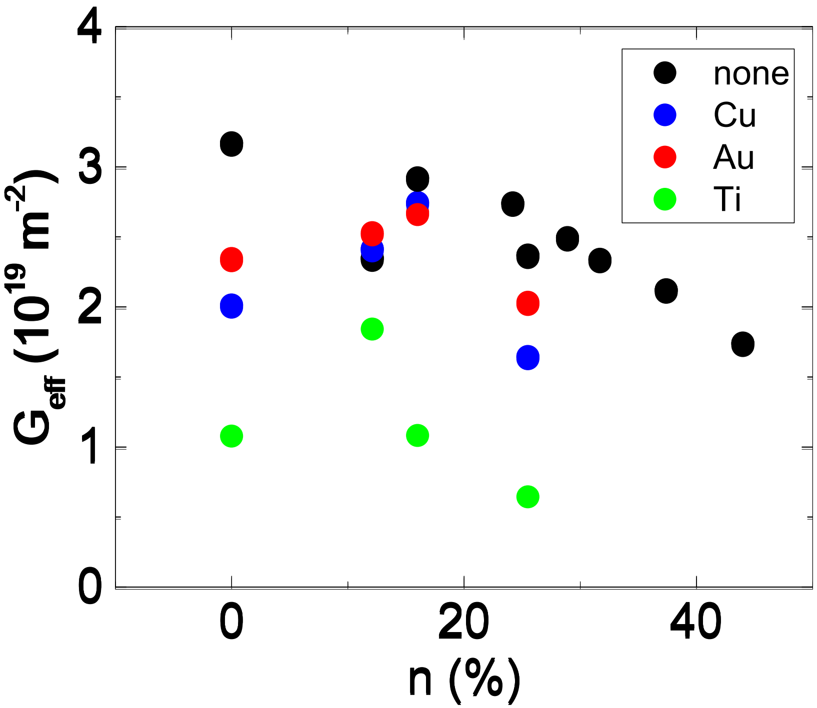


$$G_{eff} = \frac{4\pi M_s t}{g\mu_b}(\alpha - \alpha_0)$$

Effective spin mixing conductance includes the back flow contribution

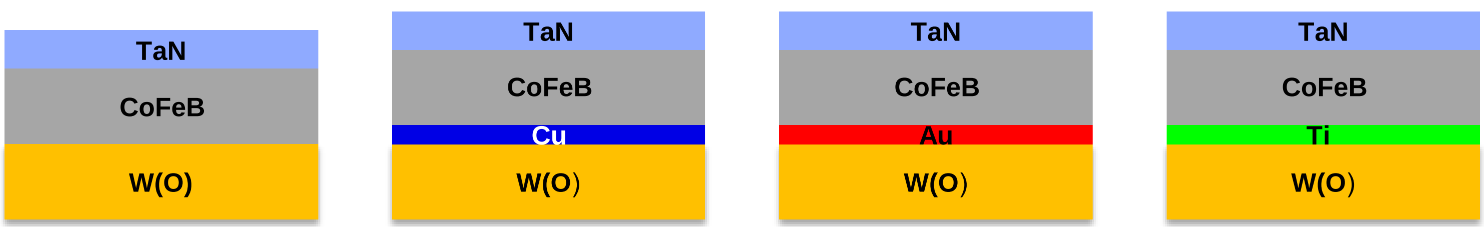
Tserkovnyak Y *et al.* PRL **88**, 117601 (2002)
Mosendz, O. et al. PRL 104, 046601 (2010)

Effective spin mixing conductance

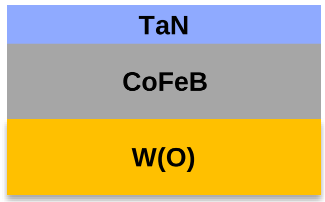


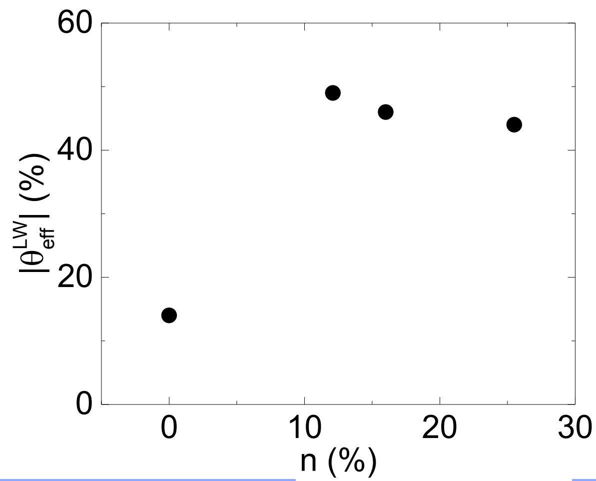
$$\theta_{Lw}^{eff} = \frac{2G_{eff}}{\sigma_{W(O)}/\lambda_{W(O)}}\theta_{SH}^{int} = T\theta_{SH}^{int}$$

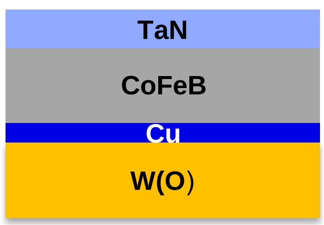
$$G_{eff} = \frac{4\pi M_s t}{g\mu_b}(\alpha - \alpha_0)$$

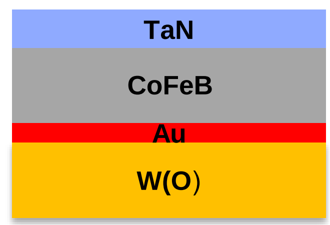


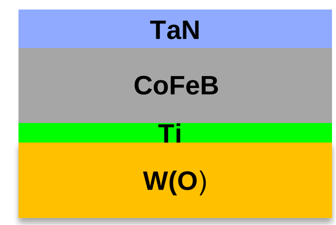
Influence of Insertion Layer

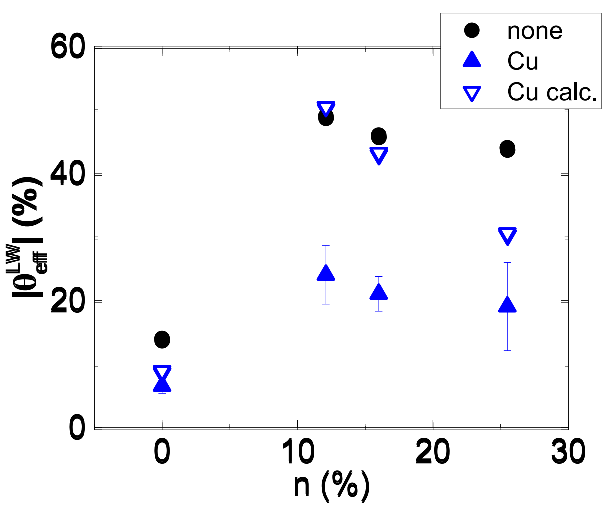


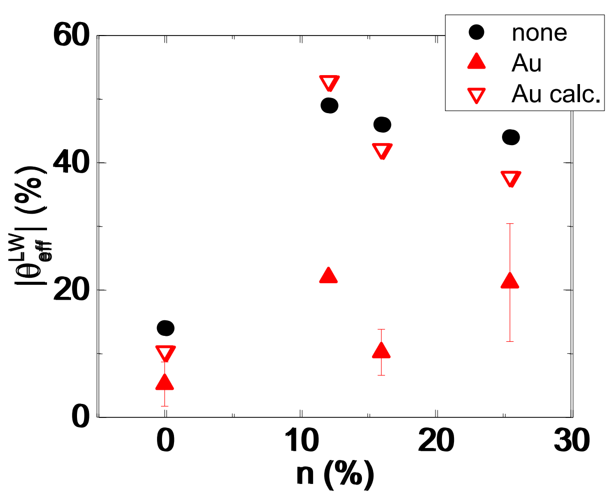


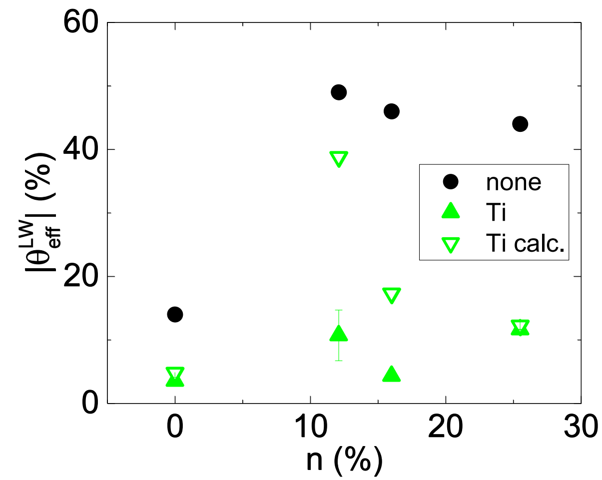




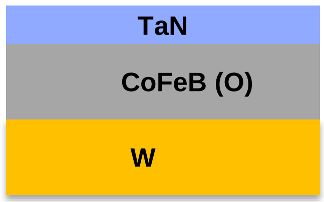


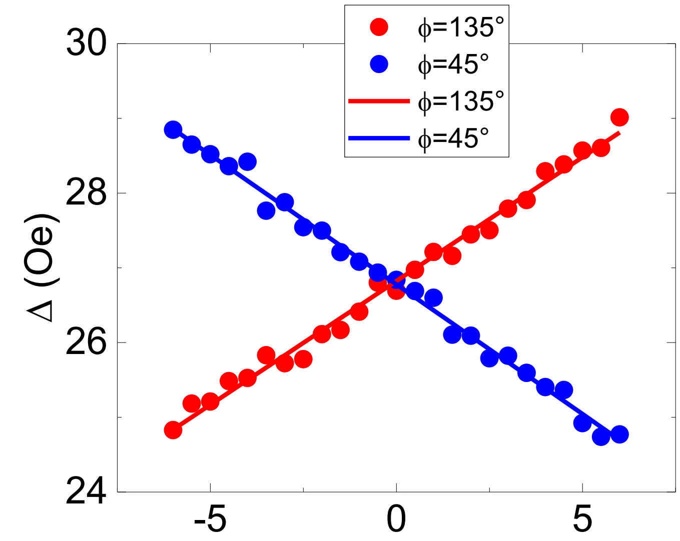


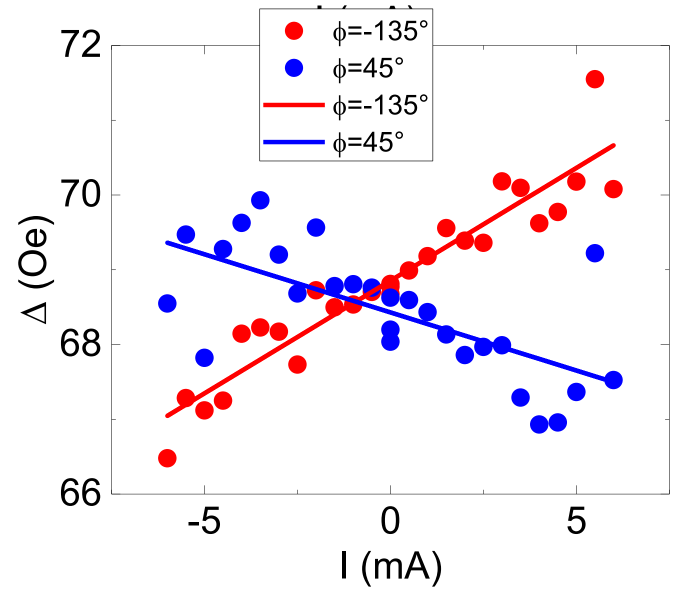




Effect of oxygen in CoFeB layer



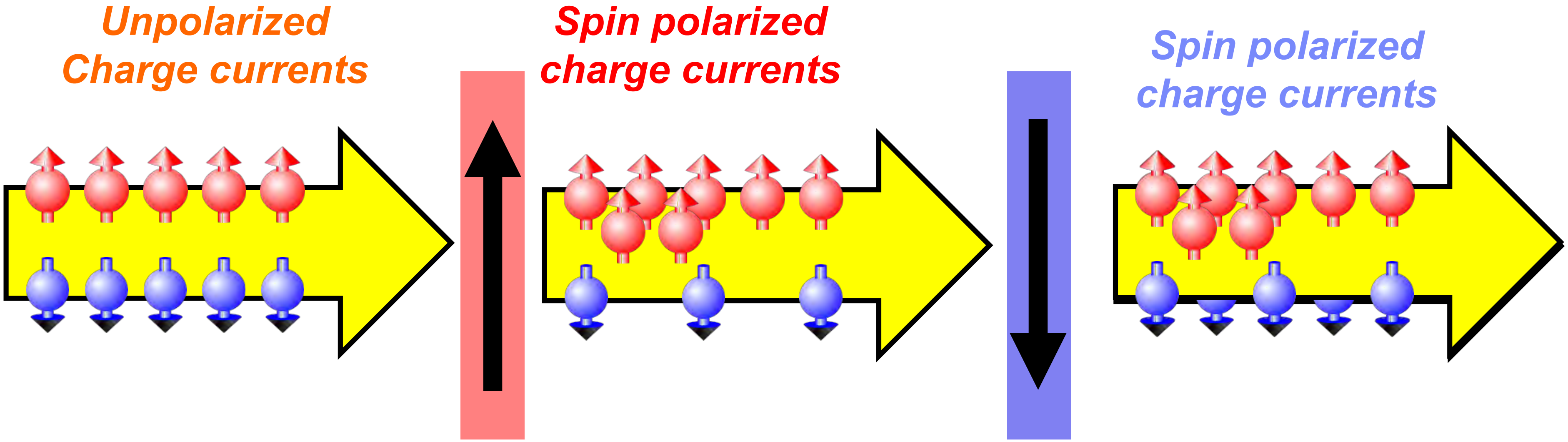




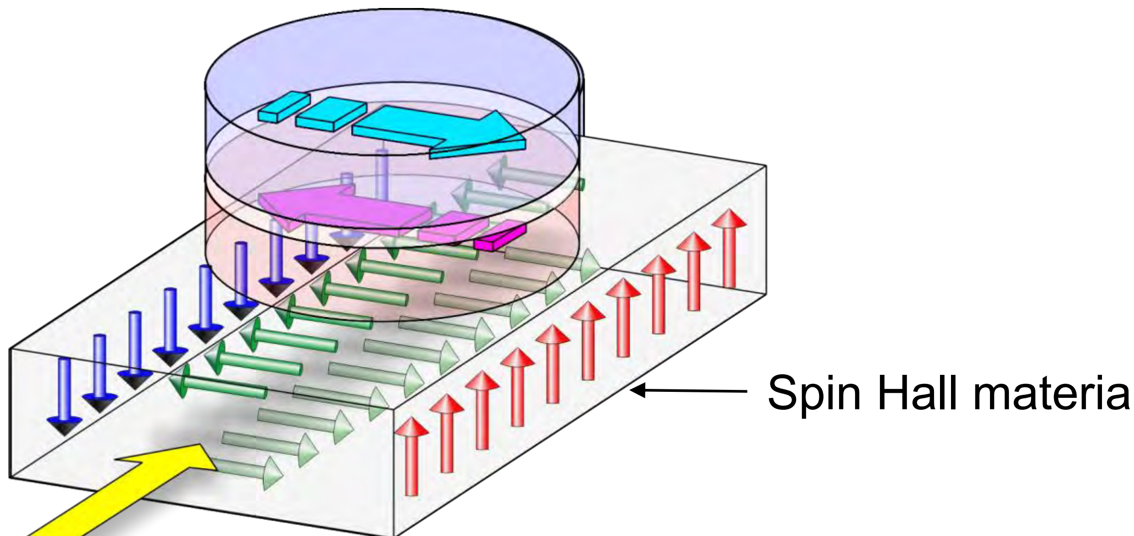
By intentionally oxidizing the oxygen, we observed that the linewidth dramatically increased, past what we experimentally measure in the W(O) case → it is unlikely then that the oxygen that could migrate away from the W(O) layer into the CoFeB could be driving the effect we observe

The spin Hall angle in this case is ~10.23% (slightly smaller than what we typically measure for pure tungsten

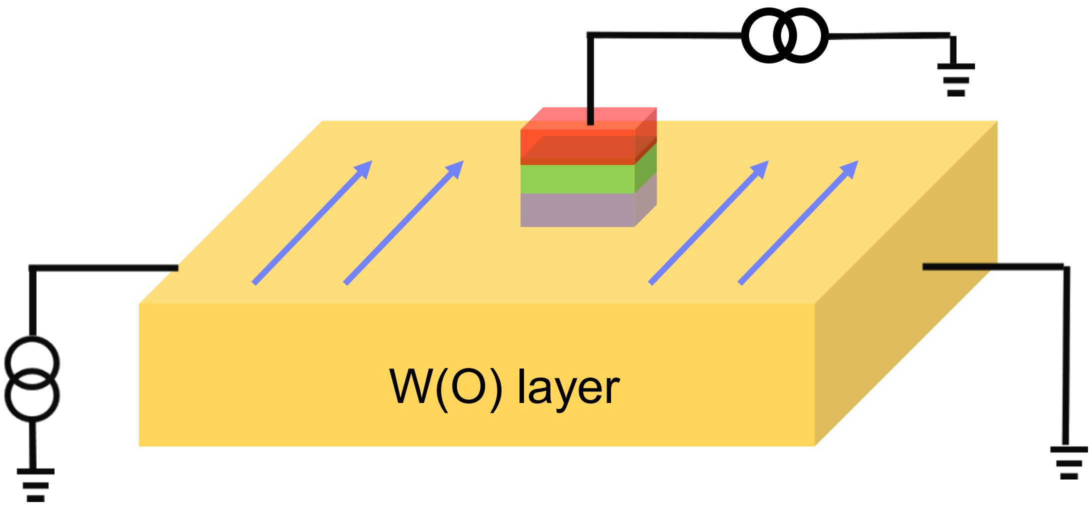
Switching Using Spin Filtering of Ferromagnets



Switching using the Spin Transfer Torque from the Spin Hall effect



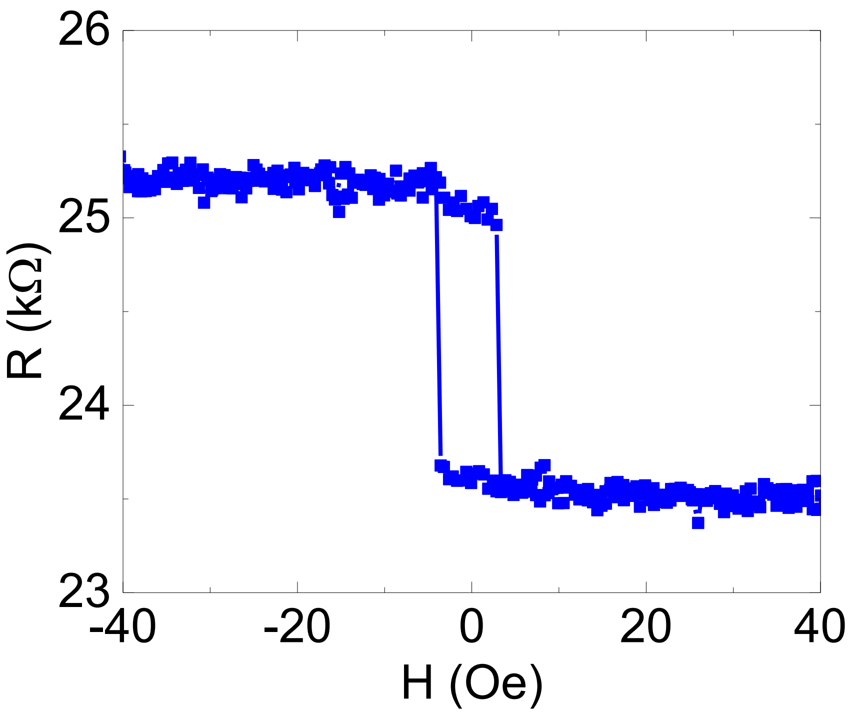
Three terminal spin orbit switching device geometry



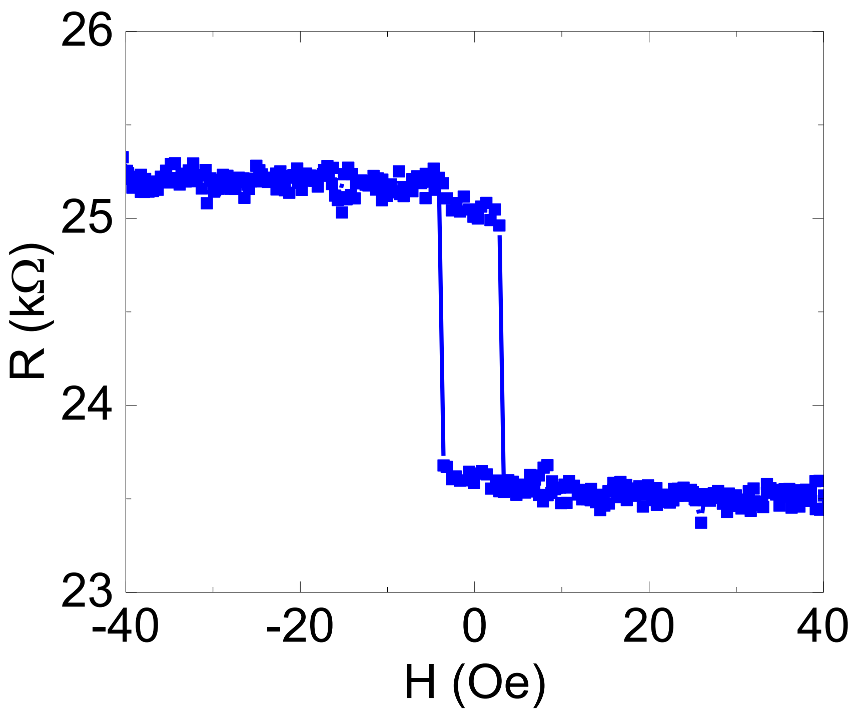
Si | Si(ox) | 60 W in (98.80 Ar/1.20 O2) | 20 $Co_{40}Fe_{40}B_{20}$ | 0.50 $Co_{70}Fe_{30}$ | 8 Mg + 20 MgO | 20 $Co_{70}Fe_{30}$ | 5 Ru | 25 $Co_{70}Fe_{30}$ | 50 Ta | 50 Ru |

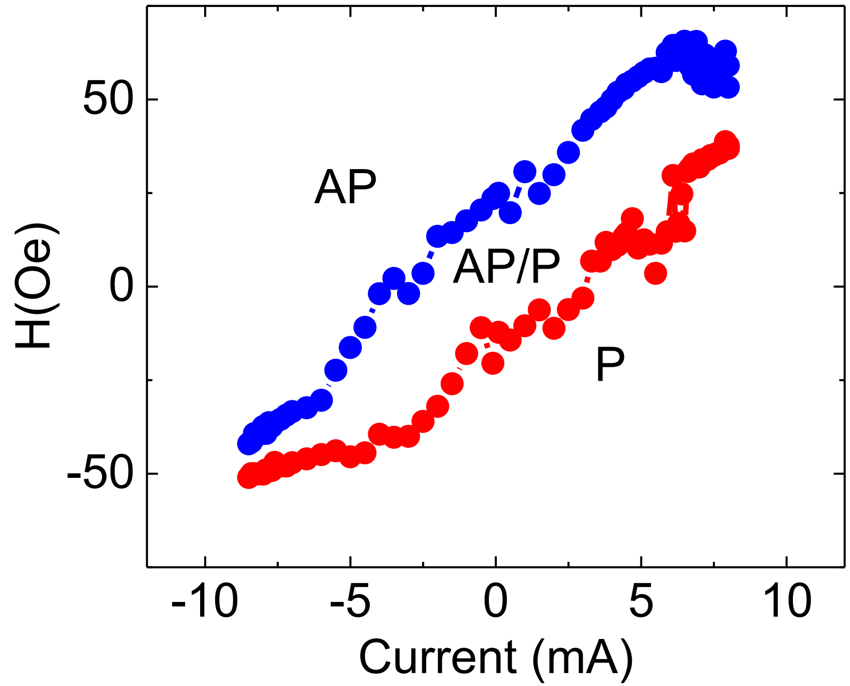
Designed to be 105 nm x 55 nm

25.5 % incorporated oxygen in the tungsten



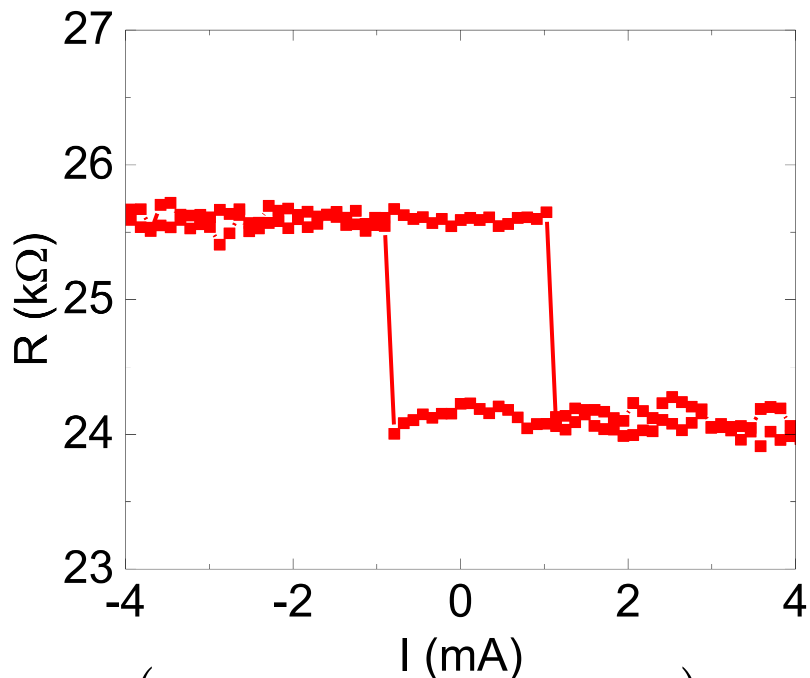
- Fabricated three-terminal spin Hall MTJ switching devices
- Low TMR (7.2%) since films have not been annealed (can result in higher switching fields as well as larger TMR), such studies are being planned for a future report
- Offset field ~ -0.3 Oe.

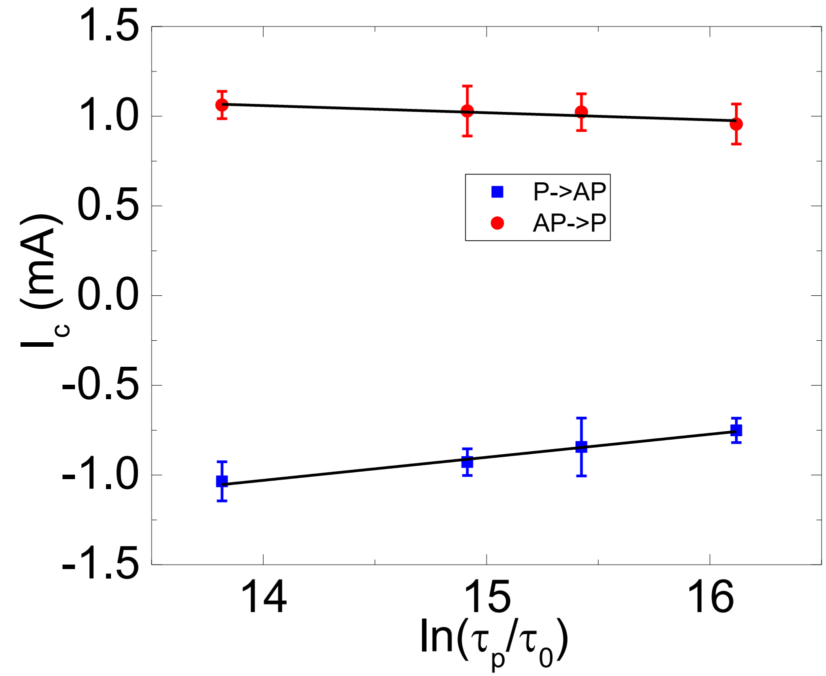




- Quasistatic switching phase diagram measured through measurements of the switching field as a function of DC current applied in the spin Hall layer
- Strong change in switching field seen → evidence of the anti-damping torque from the spin Hall effect

Three terminal spin orbit switching



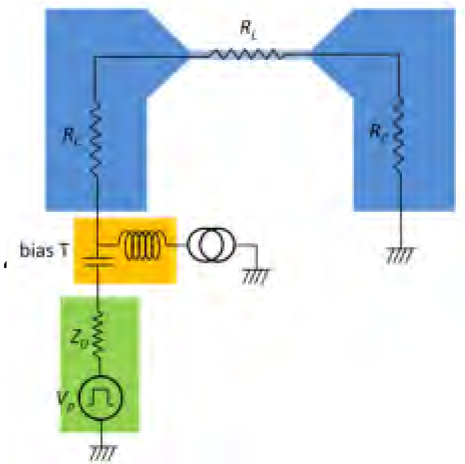


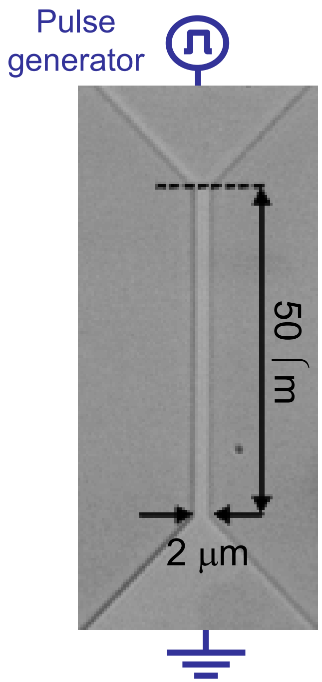
$$I_c = I_{c0}\left(1-(k_B T / E_j)\ln(\tau_P / \tau_0)\right)$$

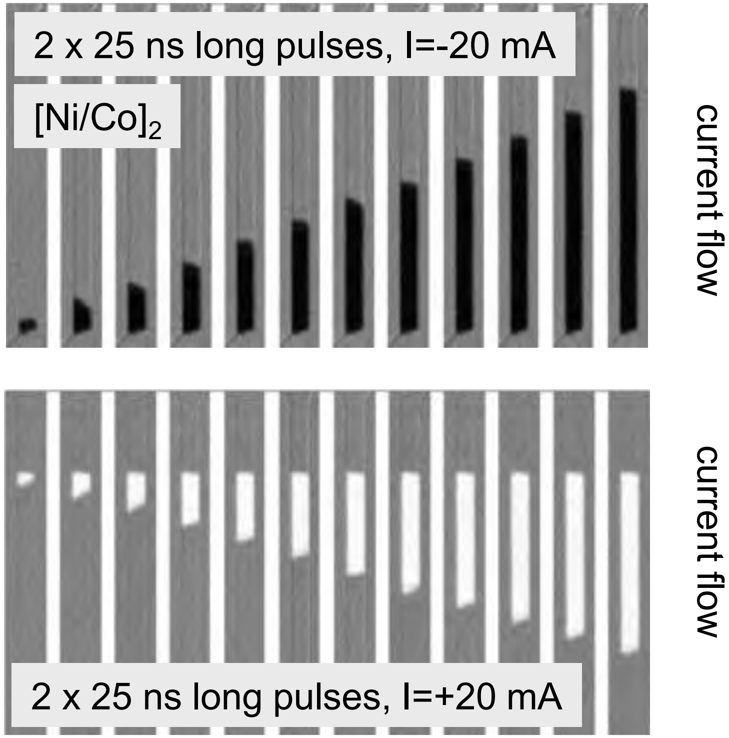
- Switching achieved with no externally applied field (10 ms pulses), thermally activated switching
- I_{c0} =2.2 ± 0.22 mA
- E_b/k_bT = 31.3 + 5.7
- Spin Hall layer ~ 824 ohms (6.05 µm long x 4 µm wide) → 6.6 nm spin Hall layer
- Resistivity of 210.27 µΩ*cm
- J_{c0} = 0.83e11 A/m^2, significantly less than that for β-W films where a current density of 1.8e11 A/m^2 is required (consistent with the larger spin Hall angle observed in W(O) films).

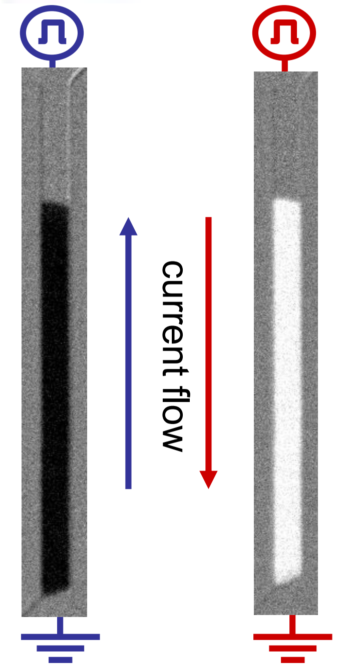
Current driven domain wall motion in PMA racetracks on Pt layer

- Kerr microscopy (Evico) in differential mode
  (25 to 50 μm long, 0.1 to 10 μm wide)
- Co/Ni multilayers with perpendicular anisotropy:
  20TaN / 15Pt / 3Co [7Ni /1.5Co]$_x$ /50 TaN x=1,2,3,4

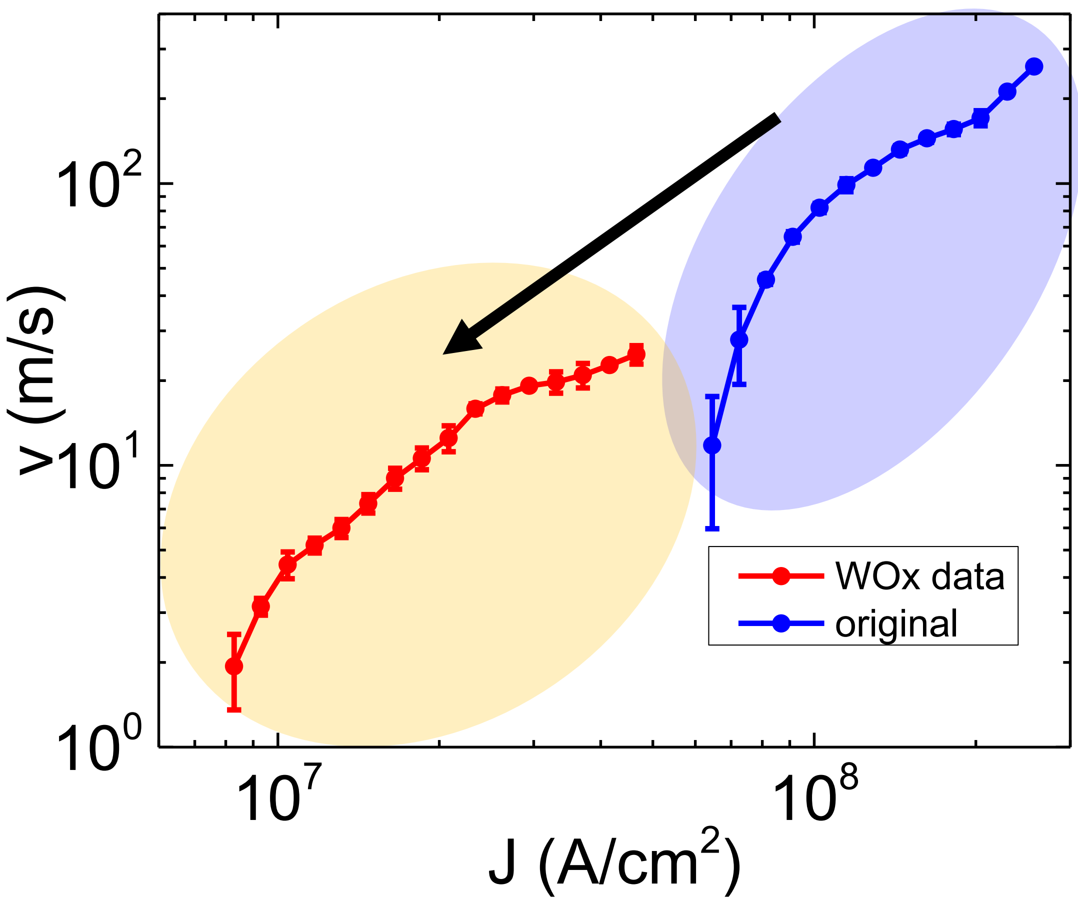






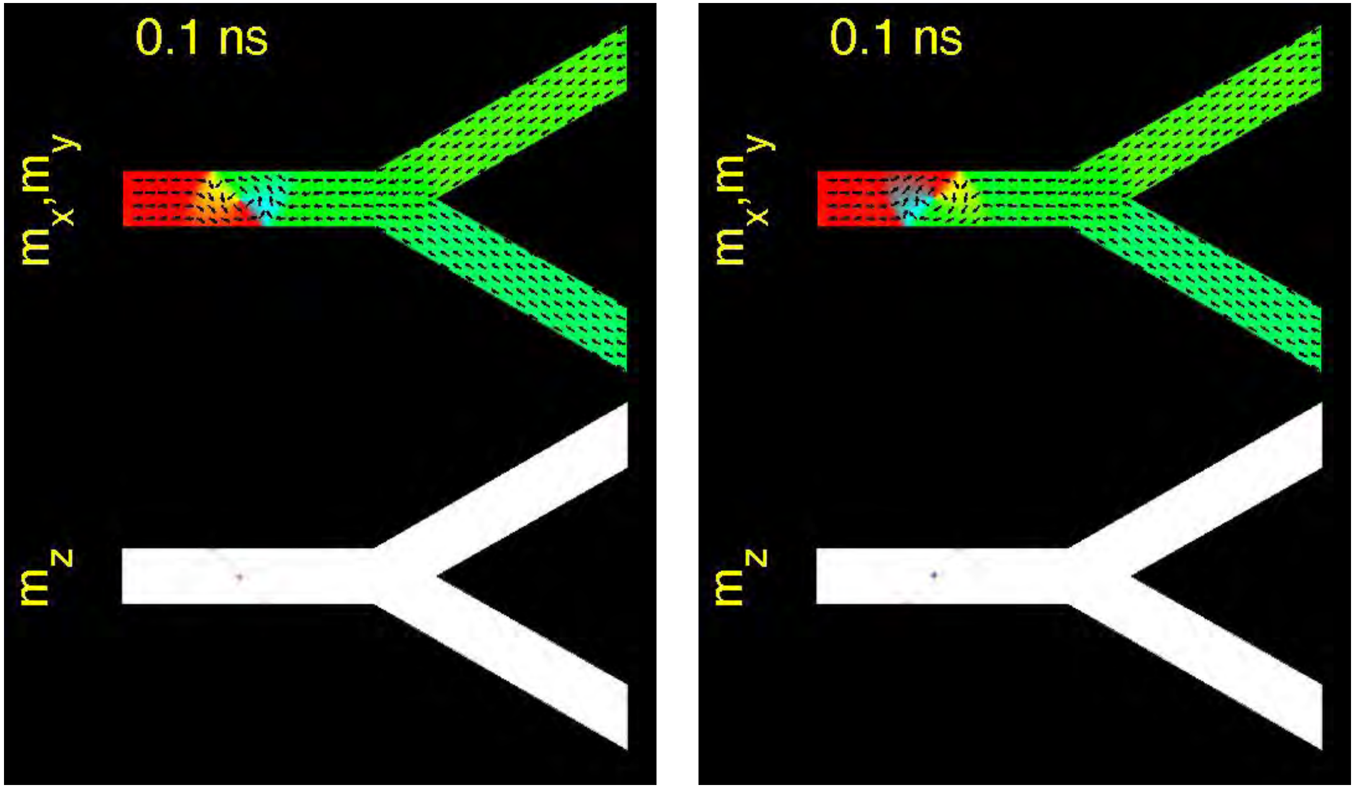


Enabling Domain Wall motion at ultra-low current densities



- ***DW motion is enabled at much lower current densities than before*** (one order of magnitude smaller) (although velocities are reduced, this can be suitably increased)
- SiO_x | 60 Å WO_x (Q = 1.2 %) | 7 Å $Co_{40}Fe_{40}B_{20}$ | 21 Å AlO_x |

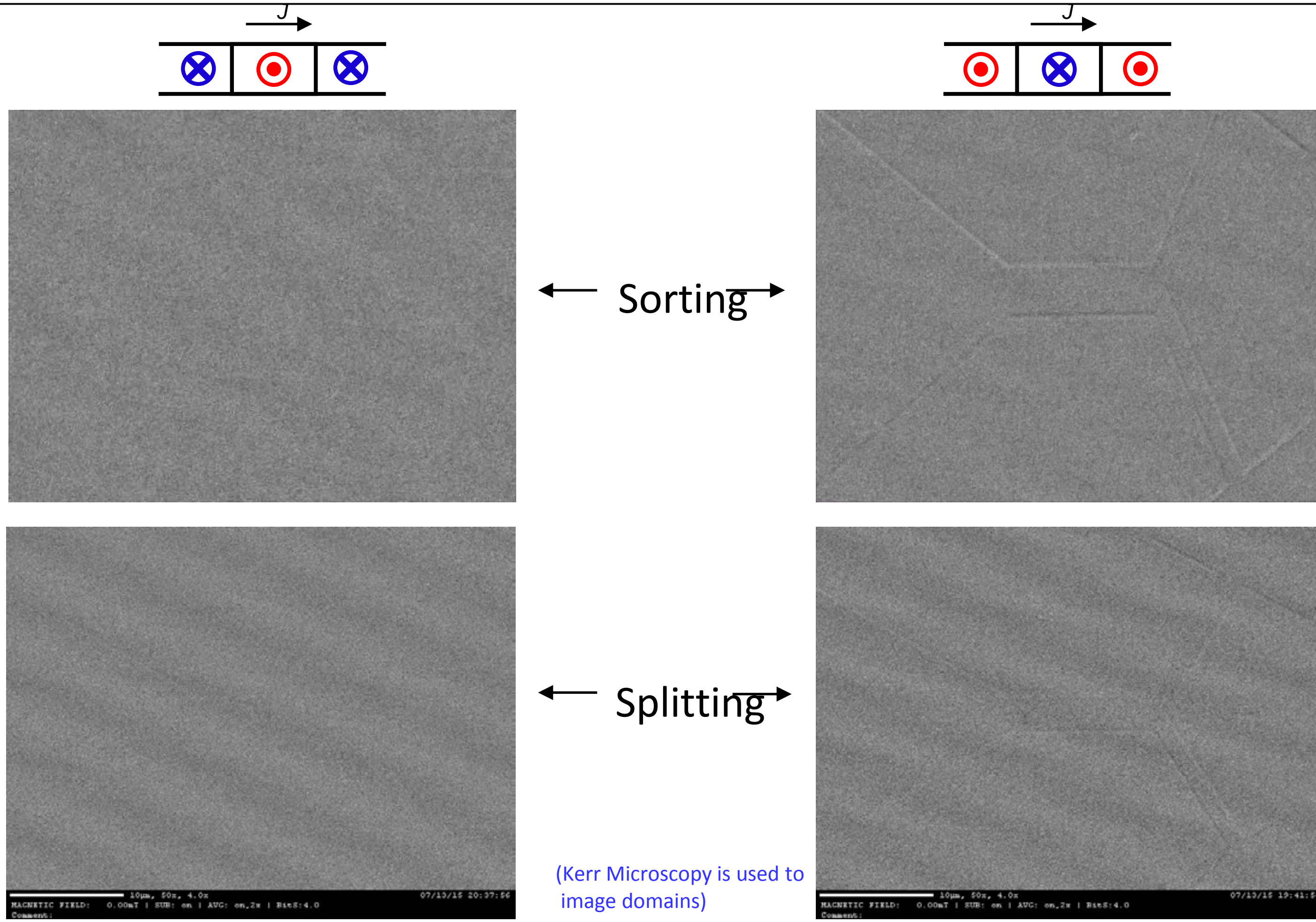
DW sorting in in-plane Y-shaped demultiplexer



Magnetic Field Direction 50 Oe

Pushp, Phung *et al.*, *Nature Phys.* (2013)

Domain sorting/splitting in PMA Y-shaped demultiplexer

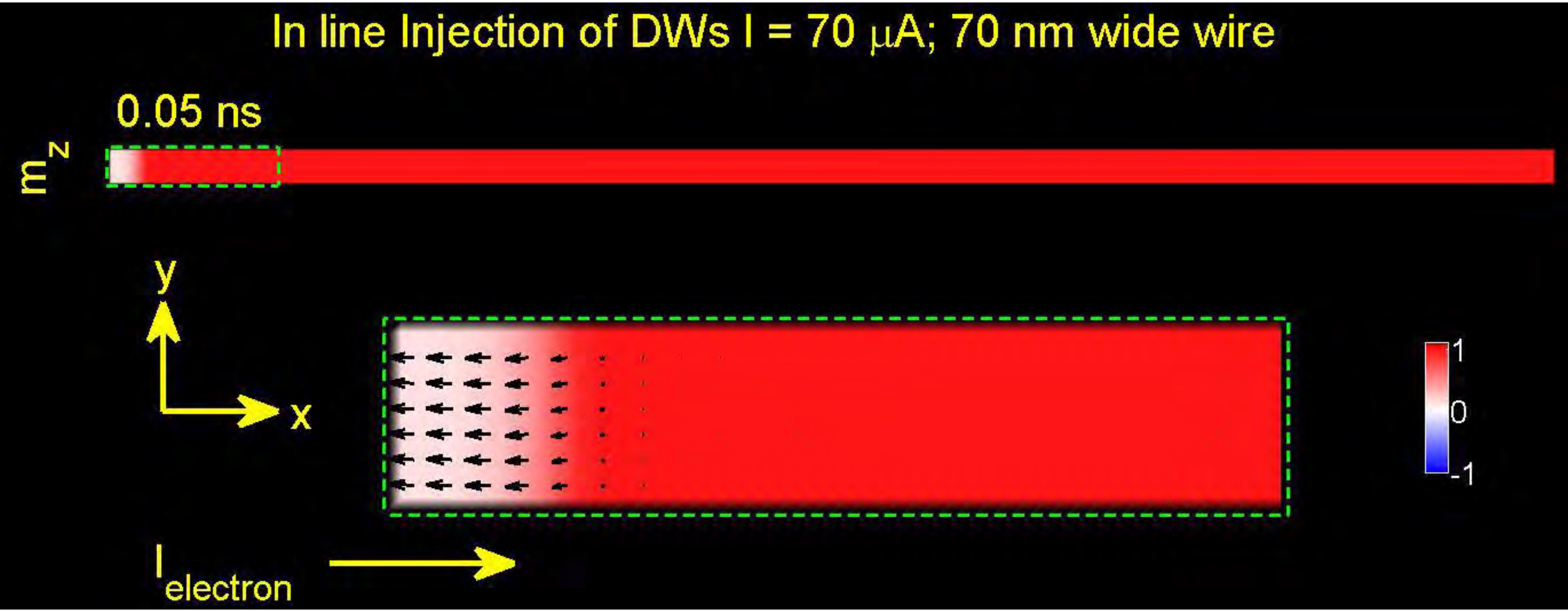


(Kerr Microscopy is used to image domains)

- Magnetic stack: 10 AlOx | 2 TaN | 1.5 Pt | 0.3 Co | 0.7 Ni | 0.15 Co | 5 TaN |
- (the numbers indicate the respective film thickness in nm)
- Photolithography (etching with a mask with an undercut) → Smooth edges
- Each branch is 20µm long
- ***Width, w, of branch A (5µm) is twice that of branches B and C (2.5µm) → Constant current density***

Micromagnetic simulation of In-Line Injection

IBM



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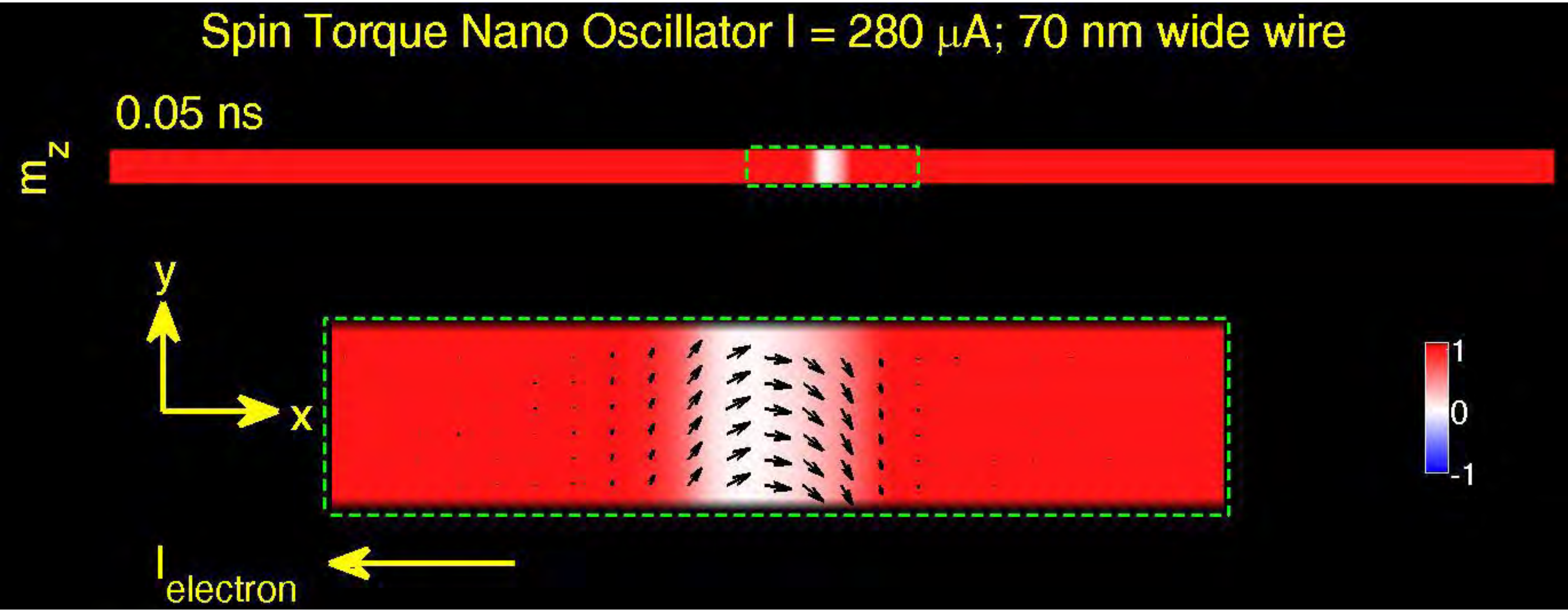
T. Phung, A. Pushp et al., Nano Letters 2015

In-line Spin Torque Nano-oscillators



•Can form spin torque oscillators based on similar concepts.

R. Van Mourik, T. Phung, S.S. P Parkin, and B. Koopmans PRB 2016

Conclusions

- ***Measured spin-orbit torques that when quantified as a spin hall angle of are up to -50%. This is the largest to be observed in a conventional metal based systems.***
- The spin-orbit torques are rather insensitive to the oxygen concentration and suggest that an interfacial mechanism is responsible for the torques.
- Moreover, the spin-orbit torques do not scale with bulk and volumetric properties of the films.
- These large spin-orbit torques can play an important role for future spintronic devices, such assisting MTJ switching as well as in racetrack memory devices.

Demasius, Phung, et al., *Nature Communications (*2016).

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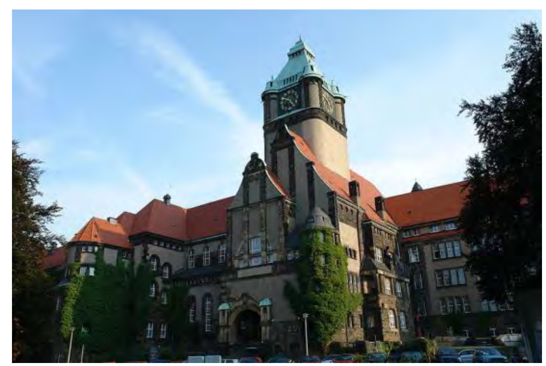
Kai-Uwe Demasius[1,2], Brian Hughes[1], See-Hun Yang[1], Andy Kellock[1], Jie Zhang[1], Charles Rettner[1], Aakash Pushp[1], Chirag Garg[1,3], R.A. Van Mourik, Wei Han[1], and Stuart S.P. Parkin[1,3]

[1]IBM Almaden Research Center, San Jose, California, USA
[2]Dresden University of Technology, Dresden, Germany
[3]Max Planck Institute for Microstructure Physics, Halle (Saale), Germany



Thank you for your attention!