Spin-Torque Switching with the Giant Spin Hall Effect of Tantalum

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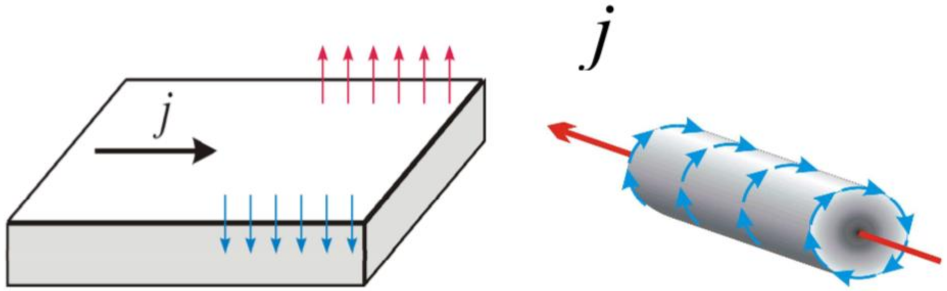
Geometry of spin current and charge current (1)

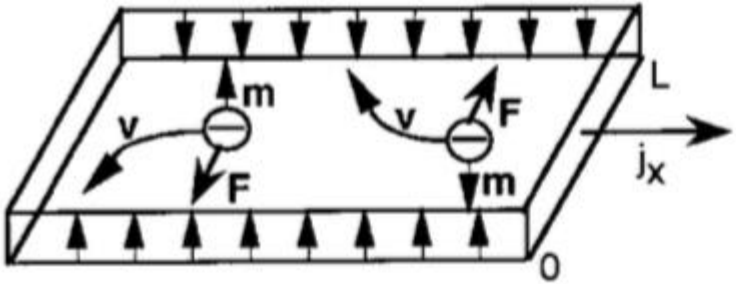
- The geometry of the charge current can be described as the path electrons are traveling due to applied conventional current carrying holes and electrons.
- Polarization of the spin current is along the axis of the spins and is orthogonal to the charge current applied.



[Dyakonov & Perel, JETP 1971]

What is Spin Orbit Coupling (SOC)?

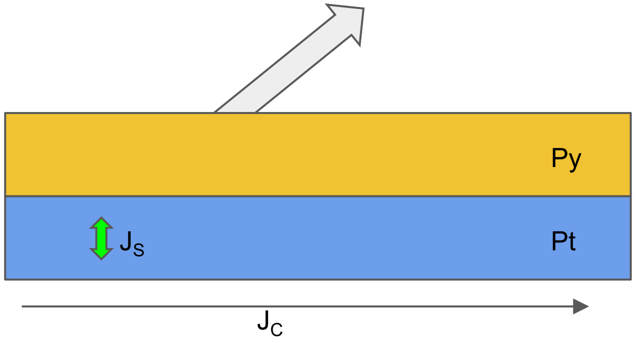
- Spin orbit coupling is the interaction of the magnetic moments of an electron's spin and its orbital motion under the influence of an electrostatic field caused by an electron as it orbits around the nucleus.
- When a current is applied to a NM metal, spin accumulation at the boundaries of the metal happens. This can be called Spin Hall Effect.

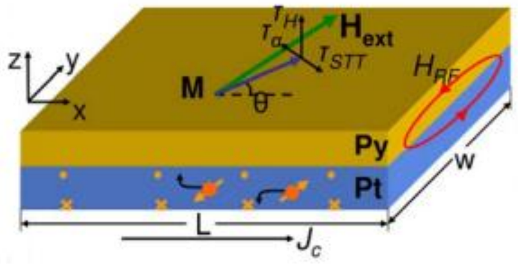


[Dyakonov & Perel, JETP 1971]

Spin-Hall Effect (2)

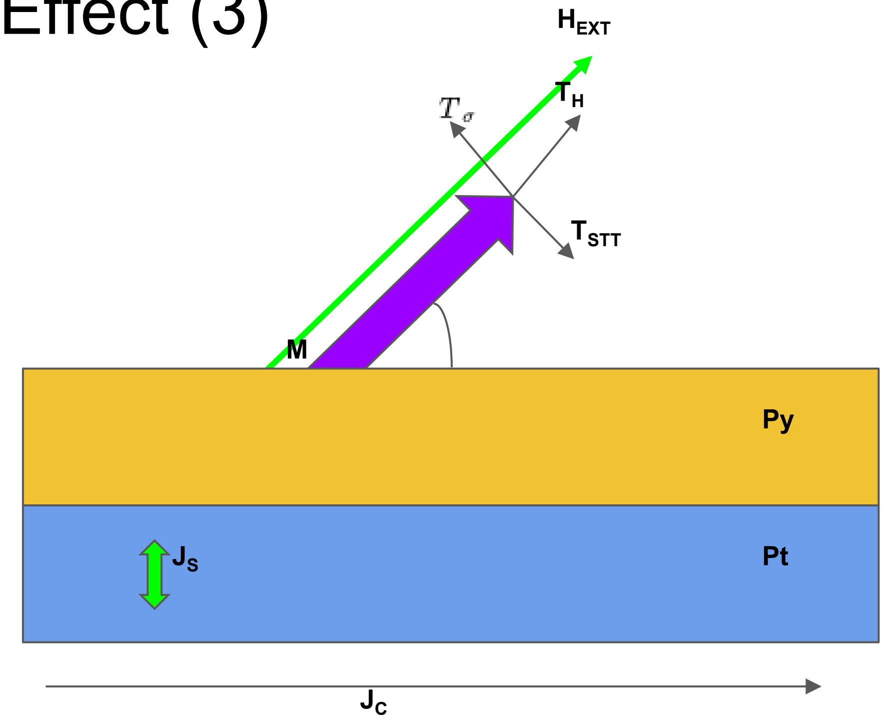
- $\theta_{\text{Spin Hall}} = (J_{\text{Spin}})/(J_{\text{Charge}})$,is the magnitude of SHE which is calculated by the ratio of the spin current and the charge current applied.





[Liu, Moriyama, et al,"Spin-torque ferromagnetic resonance induced by the spin Hall effect" ,2011]

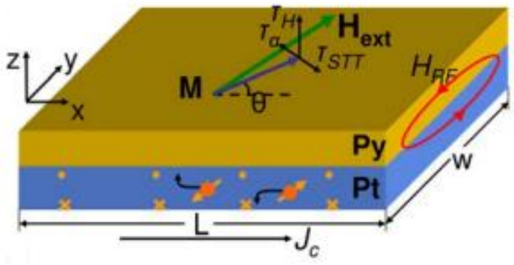
Spin-Hall Effect (3)



[Liu, Moriyama, et al,"Spin-torque ferromagnetic resonance induced by the spin Hall effect" ,2011]

Measurement of SHE efficiency in Platinum (ST-FMR)

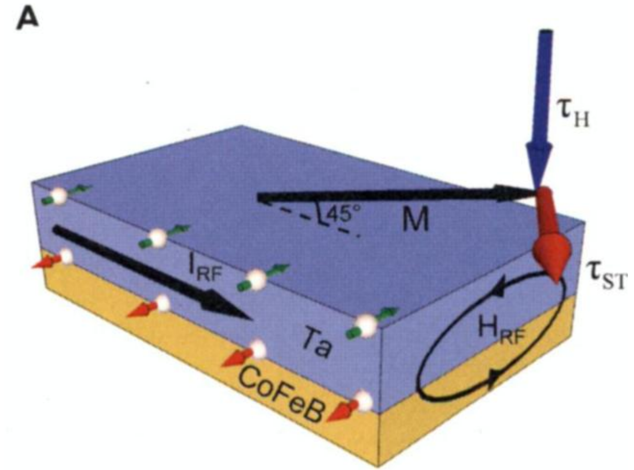
- The authors demonstrate precursor to the Tantalum approach with FMR measurement from STT due to SHE in Platinum.
- Charge current flowing along the x-axis of Pt creates a STT on Py which oscillates the magnetic moments in the Py.
- H_{RF}: Oscillating Oersted field generated from the charge current.



[Liu, Moriyama, et al,"Spin-torque ferromagnetic resonance induced by the spin Hall effect" ,2011]

Measurement of SHE efficiency in Tantalum (1) (ST-FMR)

- Before switching experiments, the authors first quantify the Spin Hall Effect in ß-Ta, the resistivity approximately 190 micro-ohm*cm.
- The CoFeB resistivity was approximately 170 micro-ohm*cm.



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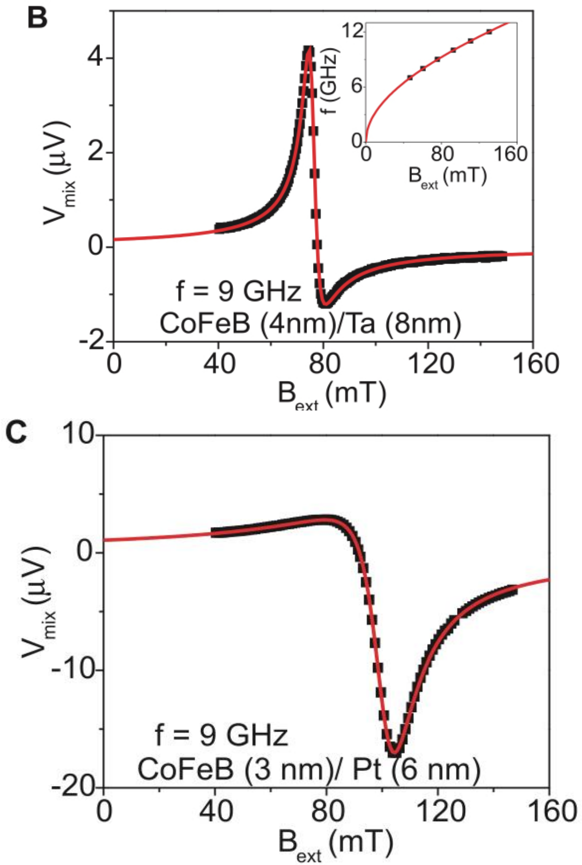
Measurement of SHE efficiency in Tantalum (2) (ST-FMR)

- Figure B shows the resonance signal for CoFeB/T as $V_{mix}(B_{ext})$

$$V_{mix} = -\frac{1}{4}\frac{dR}{d\theta}\frac{\gamma I_{RF}\cos\theta}{\delta 2\pi\left(\frac{df}{dH}\right)}\left[SF_S\left(H_{ext}\right) + AF_A\left(H_{ext}\right)\right]$$

$$\theta_{SH} = \frac{J_{S,RF}}{J_{C,RF}} = \frac{S}{A}\frac{e\mu M_S t d}{\hbar}\left[1 + \left(\frac{4\pi M_{eff}}{H_{ext}}\right)\right]^{\frac{1}{2}}$$

- Figure C shows the resonance signal for CoFeB/Pt as $V_{mix}(B_{ext})$



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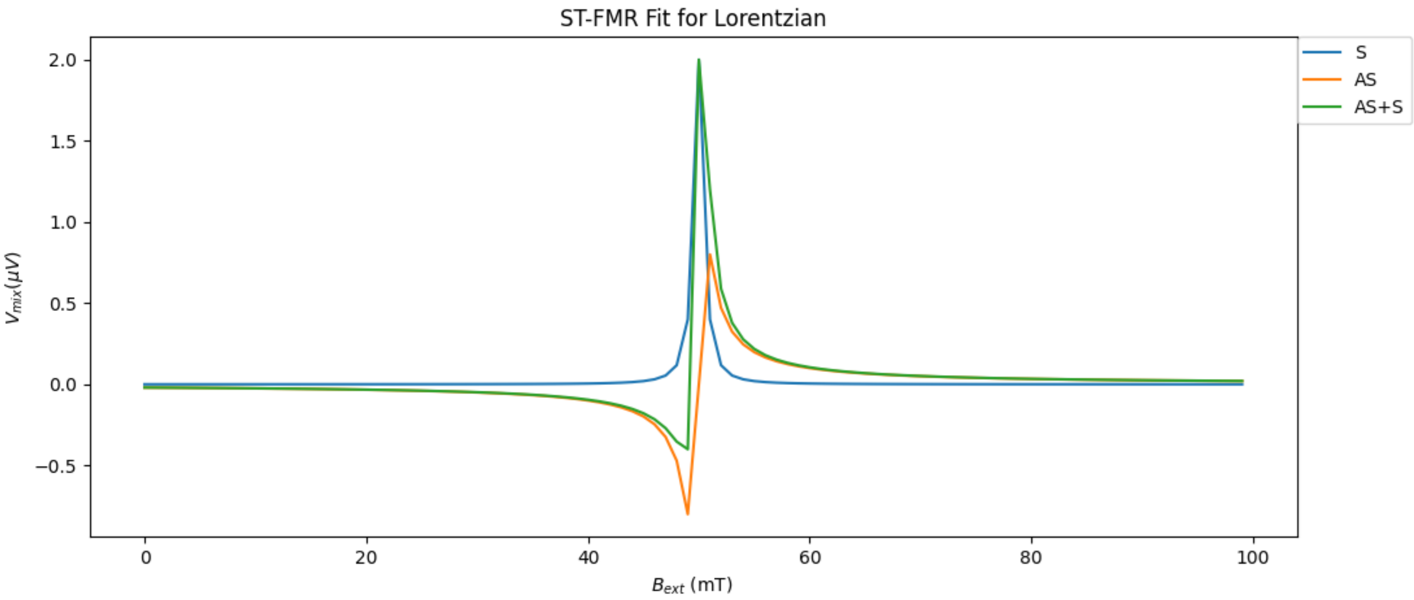
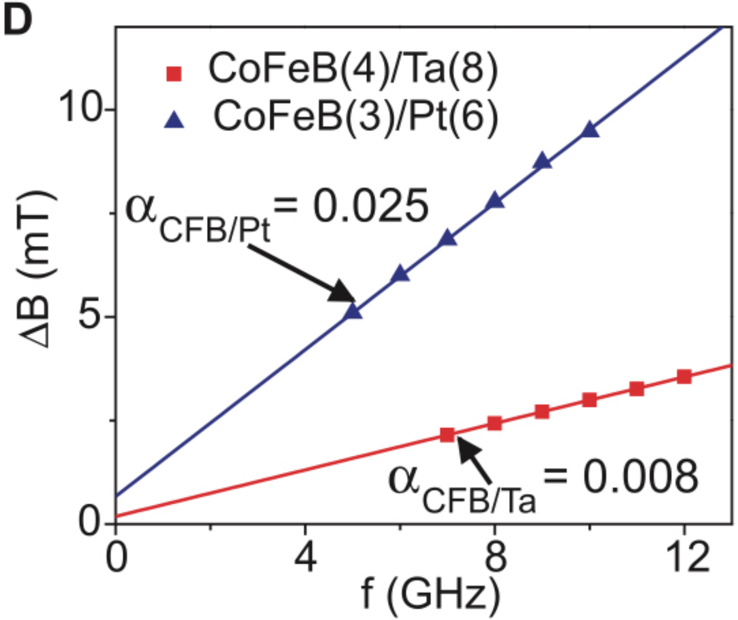
Measurement of SHE efficiency in Tantalum (4) (ST-FMR)

- Visualization of Symmetric and Antisymmetric Lorentzian of Voltage-Magnetic Field.



Measurement of SHE efficiency in Tantalum (3) (ST-FMR)

- Gilbert damping α for different external MF for CoFeB/Ta and CoFeB/Pt.



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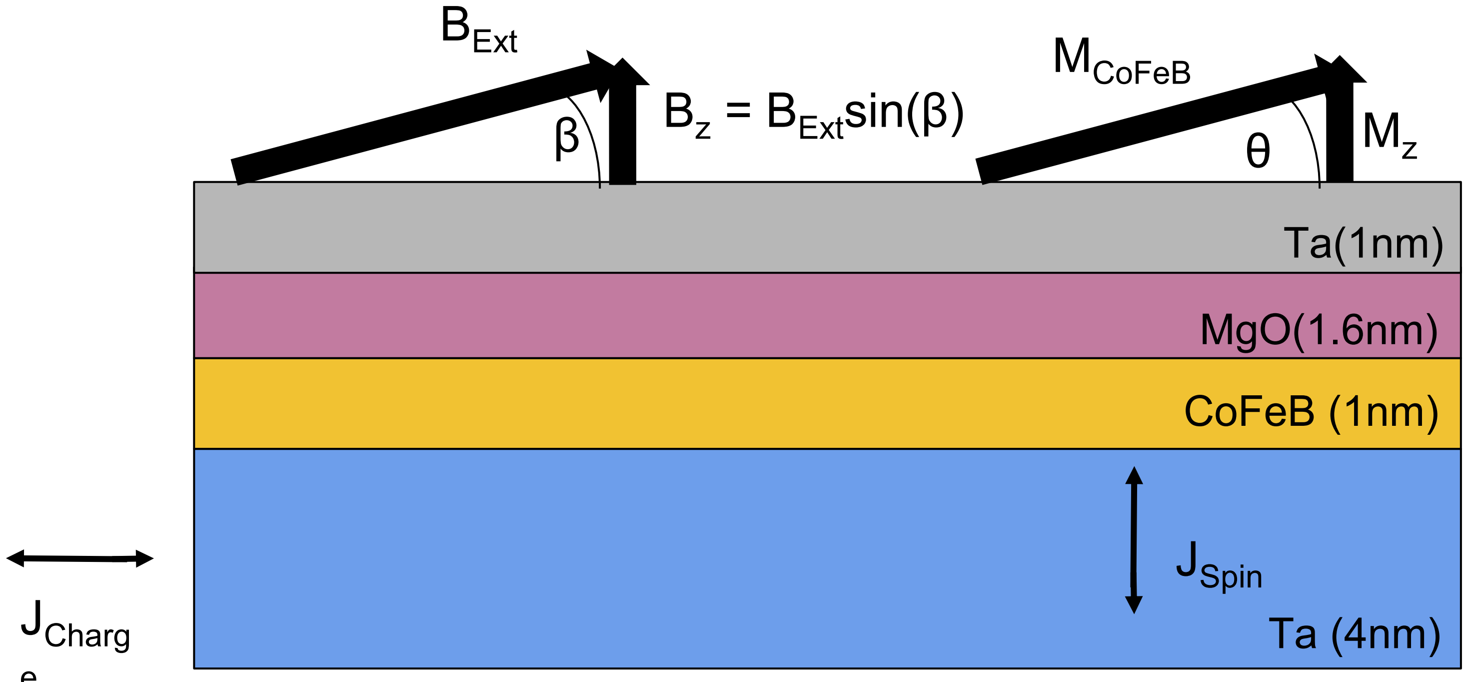
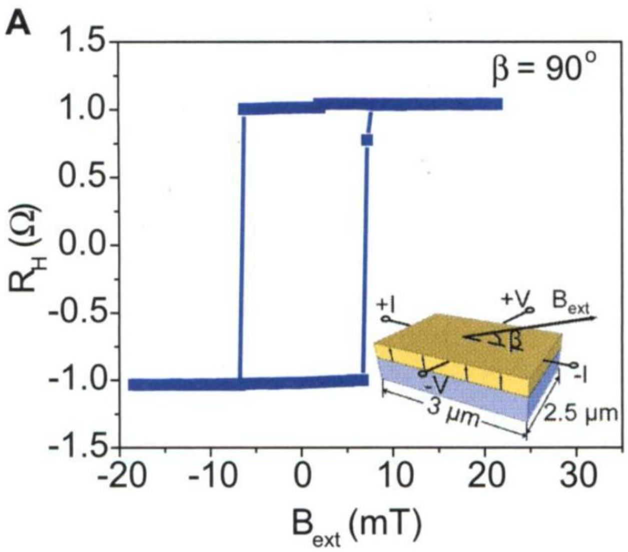
Perpendicular Switching (1)

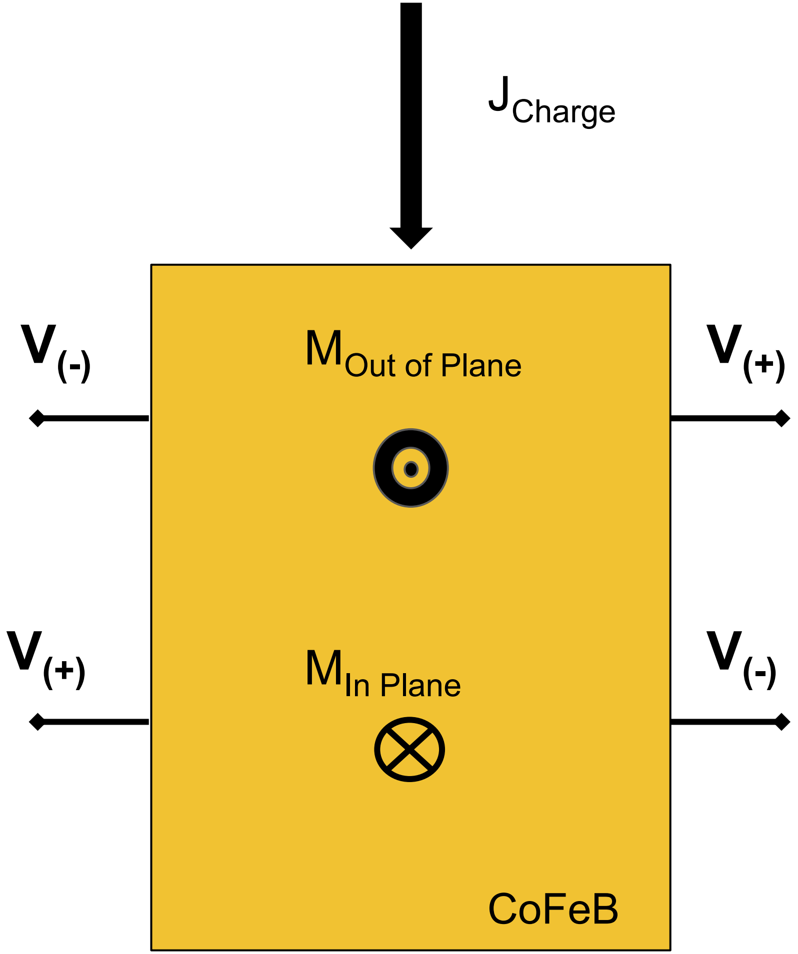
- Device geometry for this experiment
- Combination of very thin CoFeB layer and MgO capping layer creates a strong out-of-plane magnetic anisotropy
    - Magnetic moments of CoFeB have a component that points out of plane



Perpendicular Switching (2)

- The authors measure the anomalous hall resistance, R_H that develops transverse of a current passing through an out-of-plane magnetized sample





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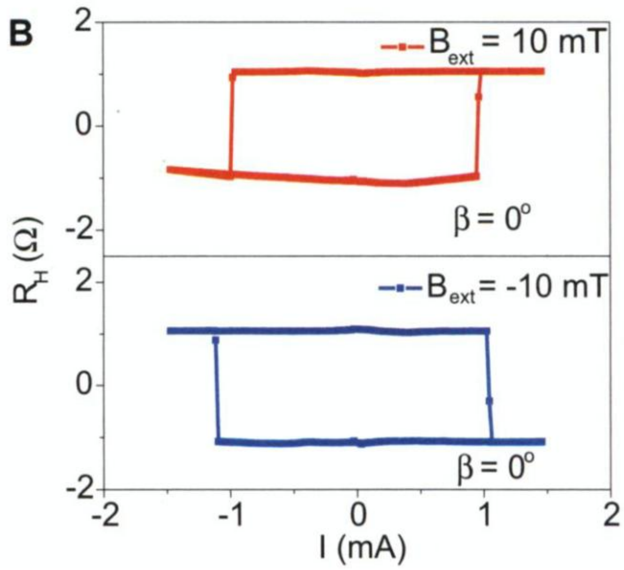
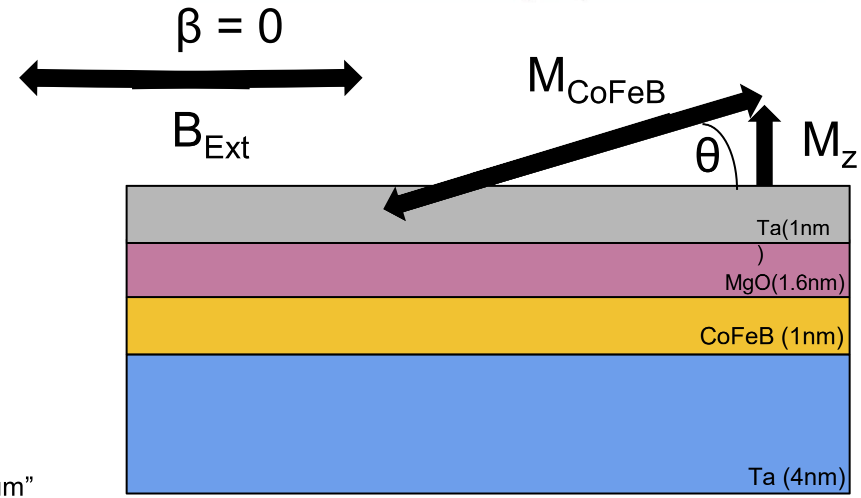
Perpendicular Switching (3)

- Magnetic field applied in-plane
- Magnetization of CoFeB has a non-zero out-of-plane magnetization due to the magnetic anisotropy
- As current (and thus SHE) is varied, there is a clear switching in CoFeB magnetization direction
- Results in varying M_Z components, which affects polarity of R_H
- Confirms perpendicular switching





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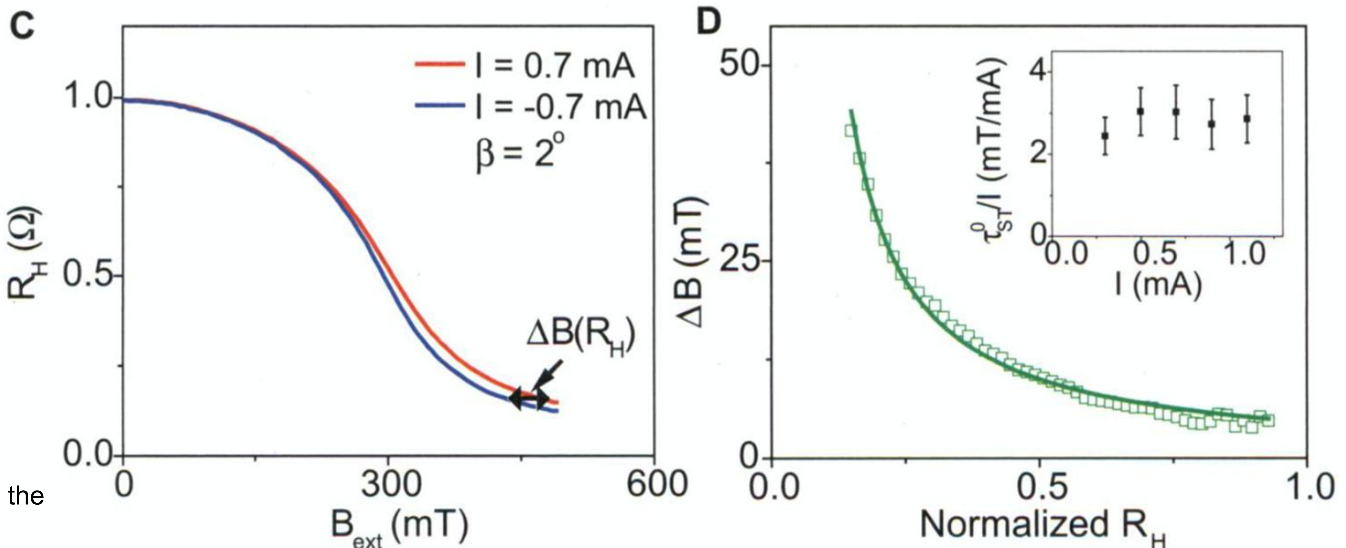
Perpendicular Switching (4)

- Use the formula (from a previous paper):
  - $\Delta B[R_H(\theta)] = B_+(\theta) - B_-(\theta) = (2\tau^0_{ST})/\sin(\theta-\beta)$
- Now B applied at $\beta = 2°$ to the in-plane current direction
- In graph (D) the squares are experimental data, while the green line is the fit from the equation above. Using this they can determine values for τ^0_{ST} at different current values
- $J_S = (2eM_S t\tau^0_{ST})/\hbar$ allows determination of θ_{SH}
- For this device they determine $\theta_{SH} = .12 \pm .03$



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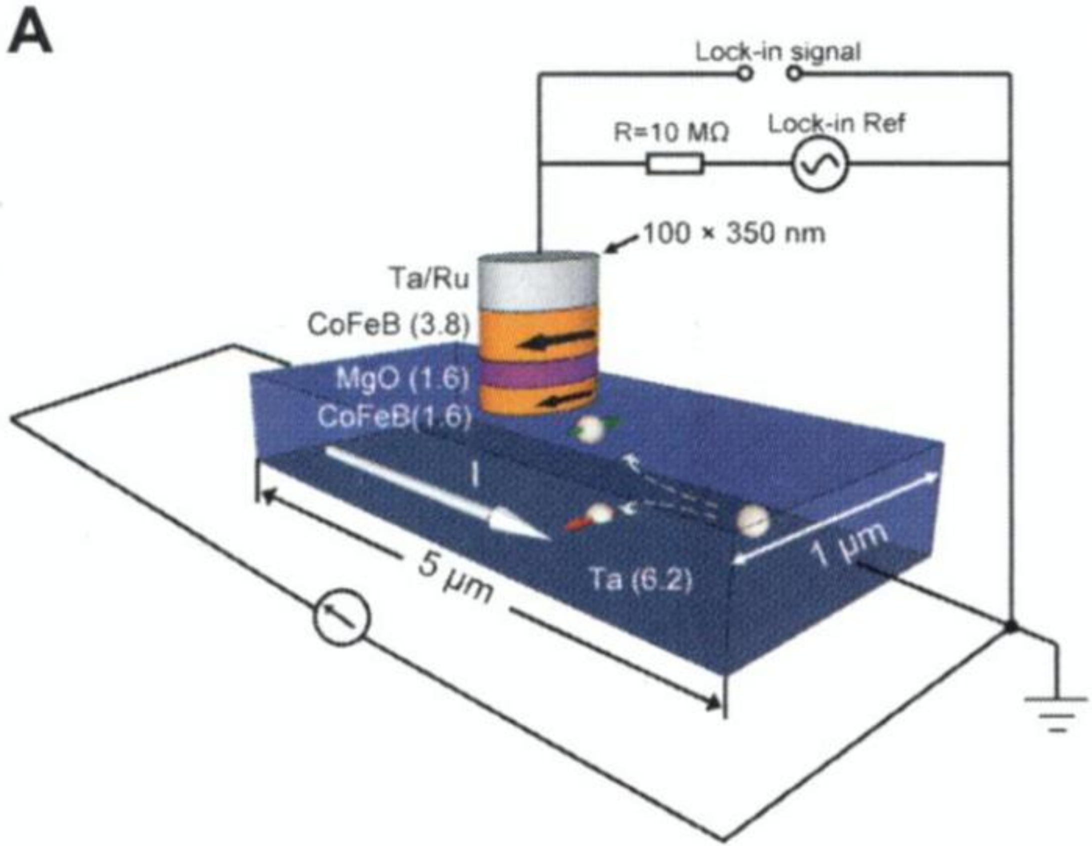
3-Terminal Switching (1)

- The final aim of the paper is to demonstrate SHE switching in a new form-factor: The 3-Terminal Junction
- Prior to SHE switching, MTJs relied on a 2-Terminal (field free) STT switching mechanism, but this came with a couple of downsides:
  - Using the same path for write and read operators leads to a small, but nonzero chance of undesirable switching
  - Currents required to switch from P → AP and AP → P are asymmetric
  - The large write currents passing through the tunneling barrier can cause accelerated wear-and-tear and a reduced device lifespan
- 3-Terminal switching either eliminates or drastically reduces these concerns at the expense of an overall larger device footprint

3-Terminal Switching (2)



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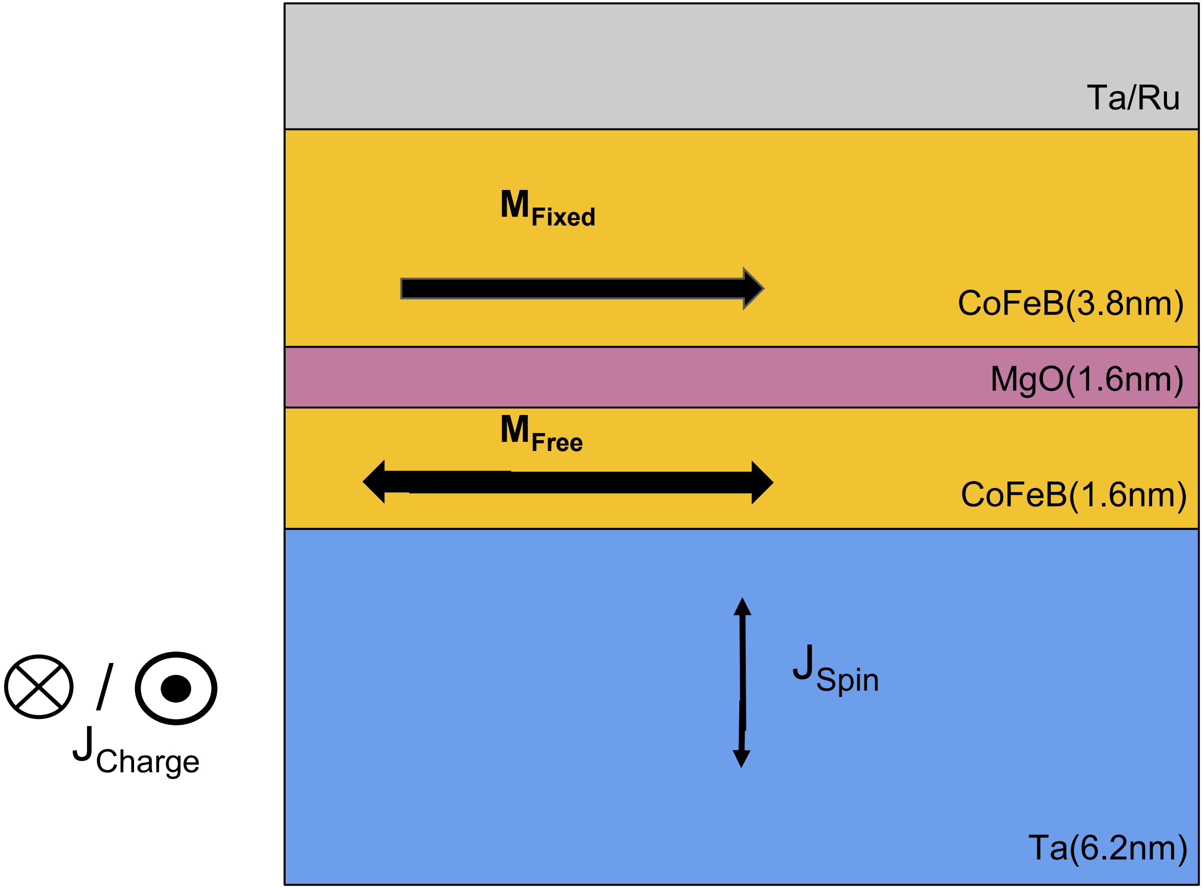
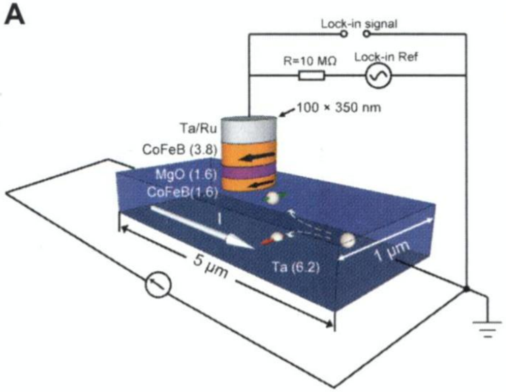
3-Terminal Switching (3)





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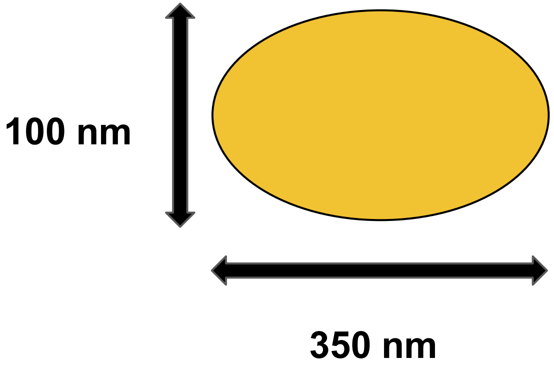
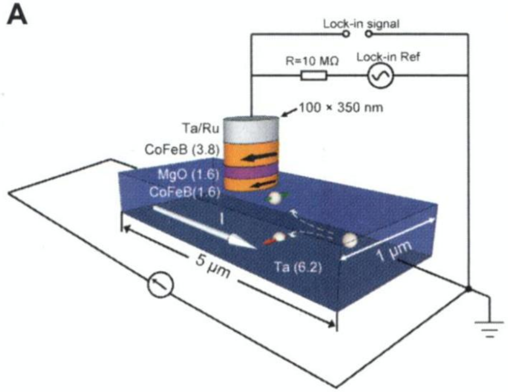
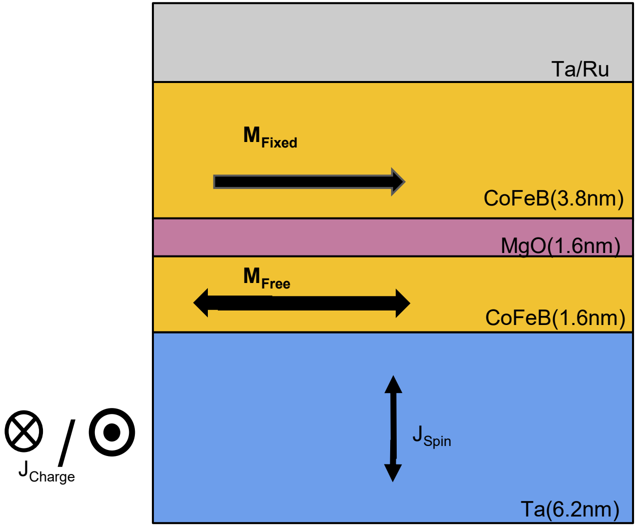
3-Terminal Switching (4)





- In-plane ellipsoidal shape for MTJ stack
- Creates a shape anisotropy and easy axis along the long axis (350 nm) of the FM electrodes
- Polarization of spin current is along the easy-axis direction



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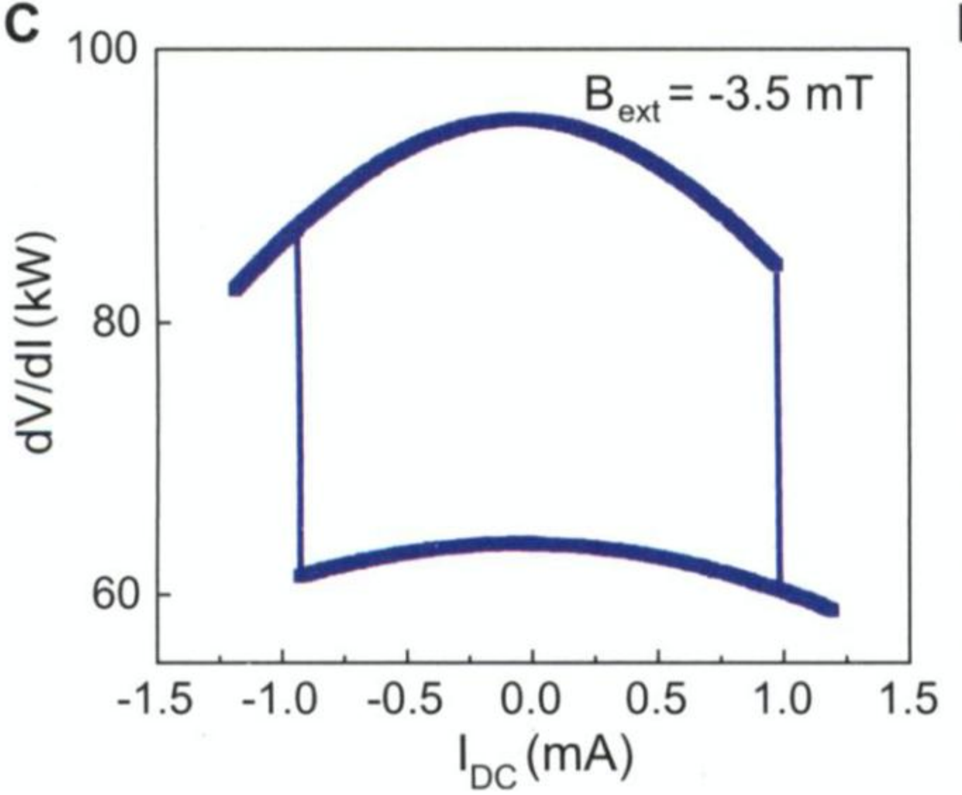
3-Terminal Switching (5)

- Graph of resistance vs applied DC current with a constant applied external field along the easy-axis
- External field is to cancel out dipole effects from the fixed layer on the free layer (which adds an H_{eff} antiparallel to fixed layer **M)**
- Roughly corresponds to a TMR ratio of ~50%



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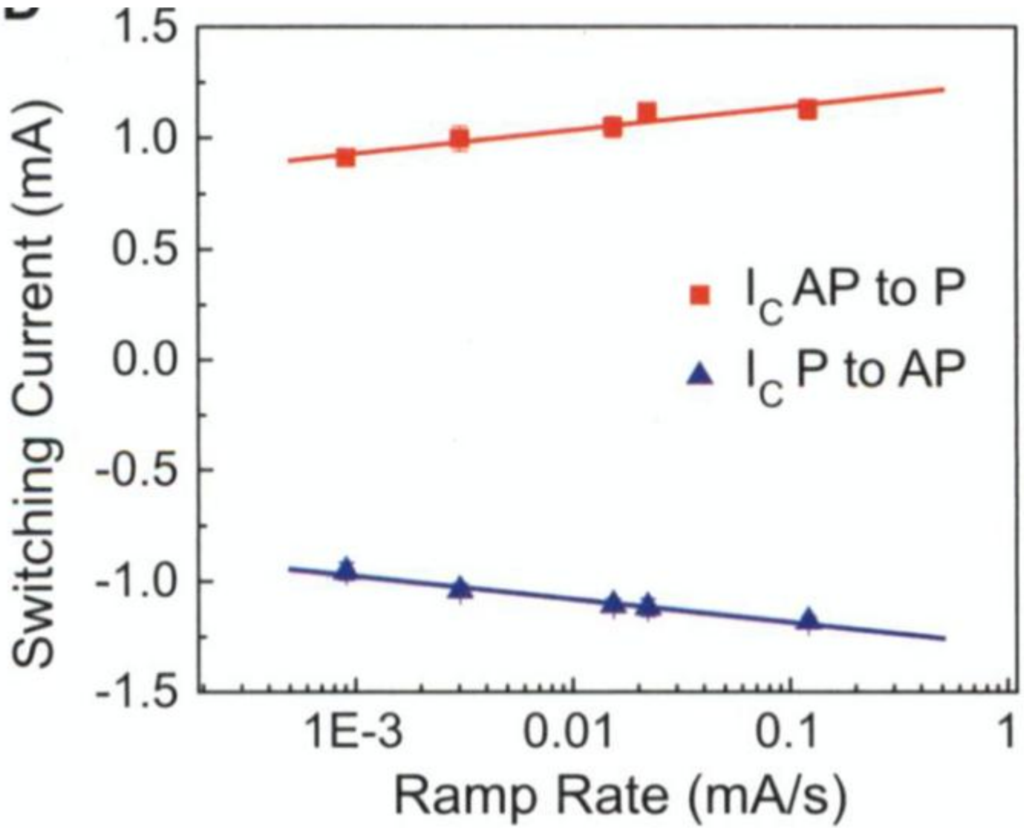
3-Terminal Switching (6)

- Currents required to switch the MTJ from AP → P and P → AP
- Clear symmetry for writing currents regardless of AP/P direction



- For this device they measure θ_{SH} = .12 ± .04, in agreement with the rest of the paper

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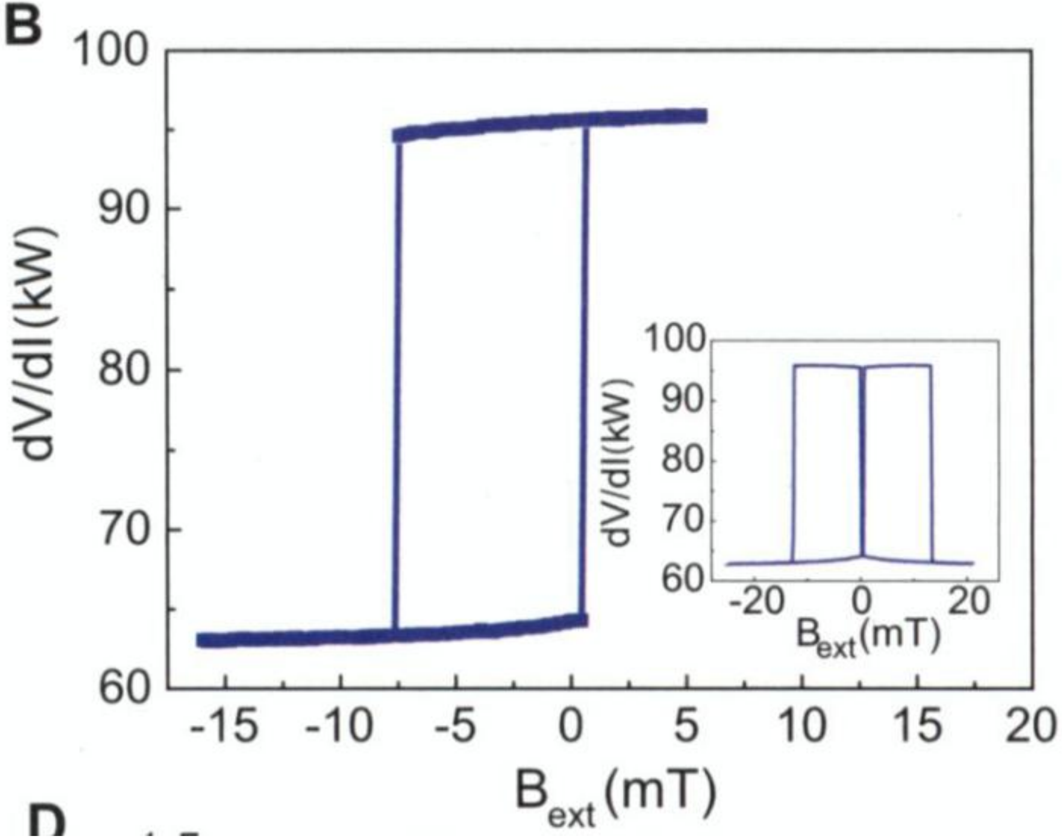
Thank you! Questions?

Additional Slides: 3-Terminal Resistance vs H_{Ext}

- With no external field, the free layer wants to anti-align with the fixed layer to minimize dipole energy; high resistance state
- An external field is required to counteract this effective field - In the paper they determine that to be ~-3.5 mT which is in the center of this TMR loop



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Order of Slide Topics

1. What is the Spin Hall Effect? - **Giovanni**
    a. Geometry of charge current / spin current conversion
    b. Brief mentioning about Spin Orbit Coupling (SOC) which leads into…
    c. Why Tantalum was chosen
2. What experiments / structures were investigated in this paper?
    a. Quantification of SHE in Tantalum - **Giovanni**
        i. Discuss ST-FMR technique
        ii. Visualization of ST-FMR (Python)
    b. Switching of a single perpendicularly magnetized layer with SHE - **Eric**
        i. Show a picture of the geometry
        ii. Graph showing switching
        iii. Talk about the physics of the experiment - why they would expect to see switching
    c. 3-Terminal Structure and switching of the in-plane field -> TMR - **Eric**
        i. Graph showing the switching / discussion of the geometry of the setup alongside a picture of the setup
        ii. Comparison to this 3-terminal geometry to the (at the time) conventional 2-terminal geometry
        iii. Benefits of this 3-terminal geometry → leading into how this was paradigm shifting in terms of the structure / switching mechanism of MTJs