Measuring Interface and Bulk Spin Diffusion in Platinum with Spin Rotation

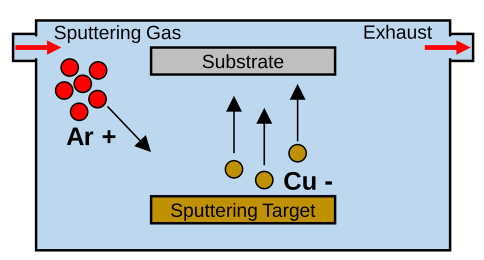
Shane Allen, Xin Fan

Research Goal:

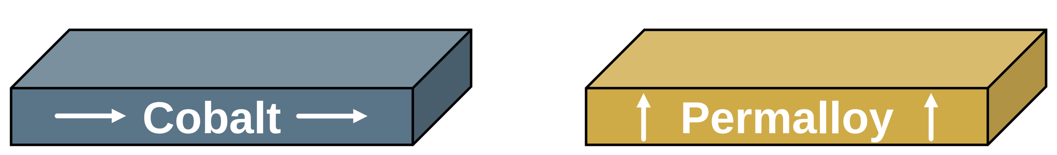
- In order to improve information available to nano-materials engineers, we aim to rectify the accepted figures for λ_{SR} (Spin Diffusion Length) in Platinum.
- Spintronics devices rely heavily on transmitting spin information through materials by diffusion, so properly understanding the λ_{SR} of common materials is critical.
- Our measurement technique is relatively novel, and yields results which are an order of magnitude more accurate (±1% vs. ±10%). Hopefully by publishing my data others will begin to use our method for other experimentation.

Sample Fabrication:

- Our laboratory uses a form of Plasma Vapor Deposition (PVD) known as magnetron sputtering to make metallic films with layers that are only a few atoms thick.
- We deposit onto wafers of silicon which have an oxidized top layer, in order to increase surface smoothness and reduce the interaction between the wafer and the sample.



- This exact procedure (and a very similar machine) is used by electronics manufacturers like Intel and AMD to make their high end computer processor chips.
- For this experiment, we used Cobalt for layers with in-plane magnetization, and an Iron-Nickel alloy called Permalloy for layers with normal magnetization:



Understanding Magnetism and Spin Diffusion:

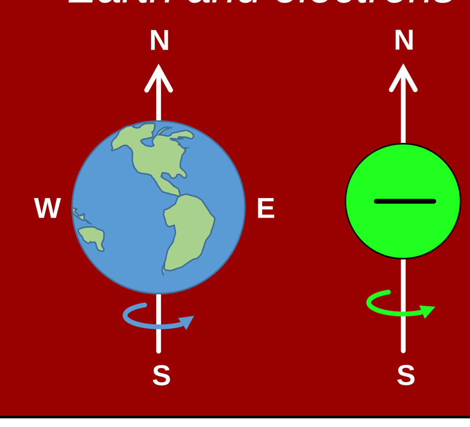
Magnetic Field and Electron Spin:

- Magnetic Fields arise from spinning charges.
- The Earth contains a lot of charges, and it's rotating, which is why it has a magnetic field!
- Electrons inside matter also rotate about an axis, and behave like tiny magnets.
- Most materials have no average alignment, but "ferromagnets" have a magnetic field because most of their electrons share the same axial alignment.

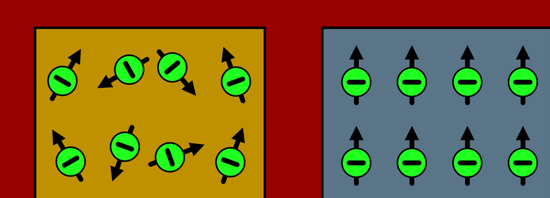
Spin Diffusion and Damping:

- When a conductive ferromagnet and an ordinary metal are adjacent, the FM's spin information can be diffused into the metal.
- The spin information from the FM can only travel a limited distance through another metal before it's completely randomized.
- This distance is known as λ_{SR} (Spin Diffusion Length), and it depends heavily on the properties of the adjacent metal.

Magnetic Fields: *Earth and electrons*



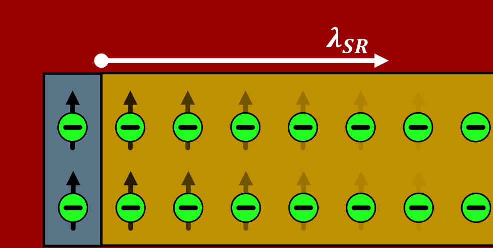
Electrons in Metals: *Standard vs. Ferromagnetic*



Most metals have no spin alignment

Ferromagnets have strong alignment

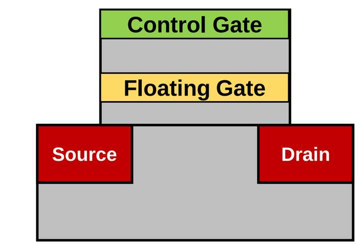
Spin Pumping: *FMR and Spin Diffusion Length*



The traditional means of finding λ_{SR} is by ejecting aligned e-'s with FMR and observing the sample's resultant temperature gain.

Flash Memory vs. MRAM:

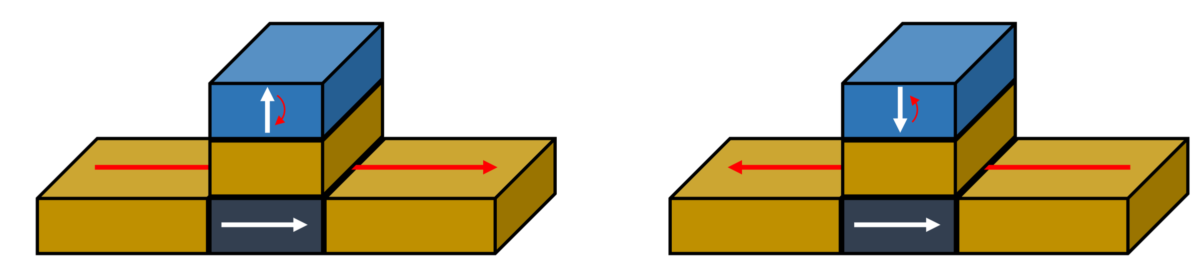
Flash Memory:



- This type of memory relies on a floating gate transistors which fill up with electrons.
- The gate must hold >10^4 electrons when charged, and uses a lot of current for read and write operations.

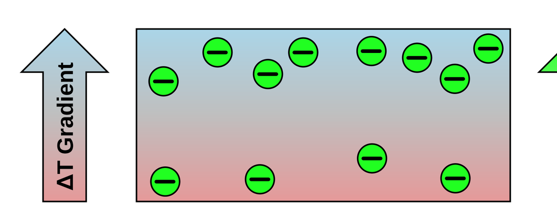
STT - MRAM:

- MRAM relies on the concept of storing data in magnetic bits rather than neutral or charged cells.
- This variety of MRAM relies on Spin Rotation and the Spin Hall effect to manipulate magnetic cells with out of plane magnetization (depicted below).



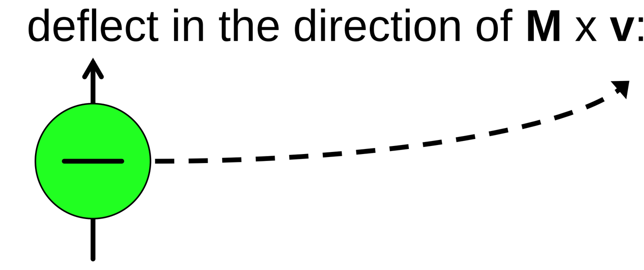
Seebeck Effect (SE):

- In metals, e-'s transmit heat energy through the material.
- Hotter e-'s have higher velocity and demand more space.
- Thus a temperature gradient results in different charge density on either side of the sample – an electric potential (ΔV hot to cold).

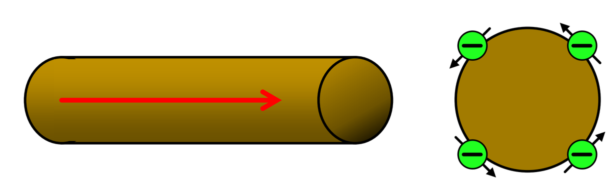


Spin Hall Effect (SHE):

- Similar to a curveball in baseball, e-'s traveling in a straight line will deflect in the direction of **M** x **v**:

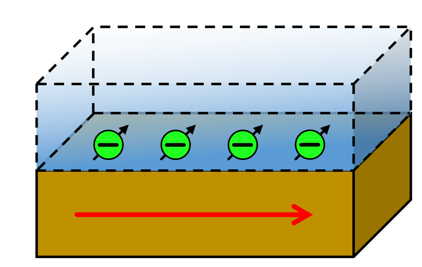


- Thus a current leads to the accumulation of e-'s with aligned spins at the edges of the flow:



SHE in Thin Films:

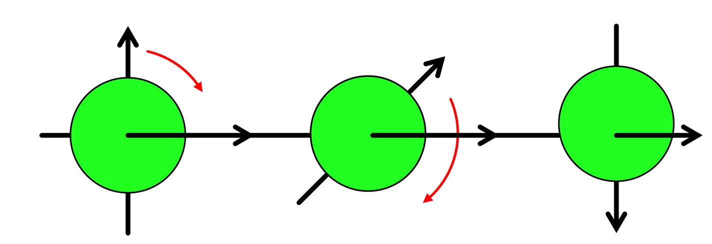
- In conductive thin films, the Spin Hall effect still applies. When a voltage is applied, the top of the sample becomes magnetized:



- This effect has an inverse (ISHE): when aligned e-'s are transmitted vertically through a thin film, an in-plane potential is observed.

Spin Rotation (SR):

- In a magnetic field, e-'s will rotate or precess around the axis of the field:

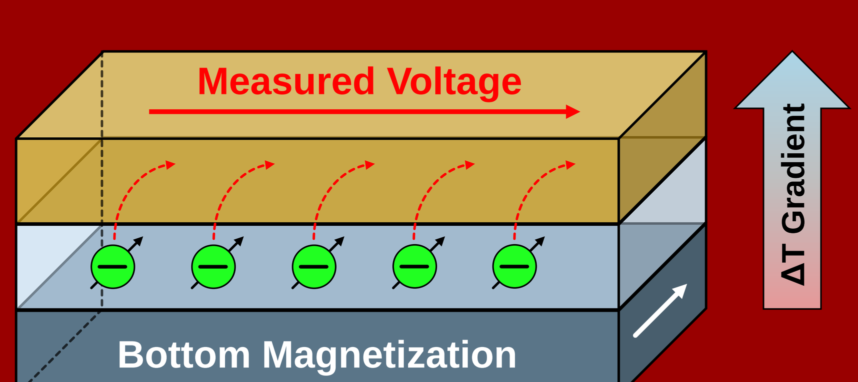


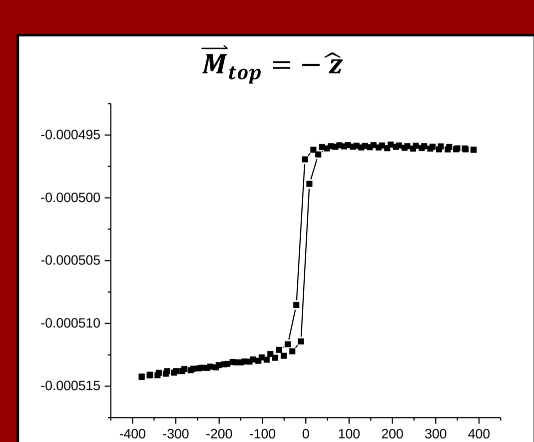
- This behavior can be explained by Quantum Mechanics principle known as spin-transfer torque.
- As this precession occurs, the e-eventually aligns with the axis of the magnetic field.

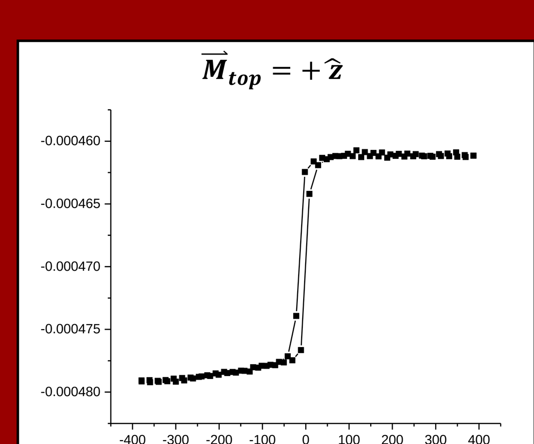
First Measurement – Nernst Effect:

$$\vec{M}_{bot} = \pm\hat{y}\,;\vec{M}_{top} = \pm\hat{z}\,;\vec{I}_{measured} = \pm\hat{x}$$

- Tri-layer samples with orthogonal magnetic layers encasing Platinum (below) are pressed between a heat source and sink, between the poles of an electromagnet.
- Aligned e-'s from the bottom layer are ejected into the Platinum (Seebeck effect).
- These e-'s generate voltage in the indicated direction (inverse Spin Hall effect).
- In this orientation, all ejected e-'s are measurable. This is the control dataset.



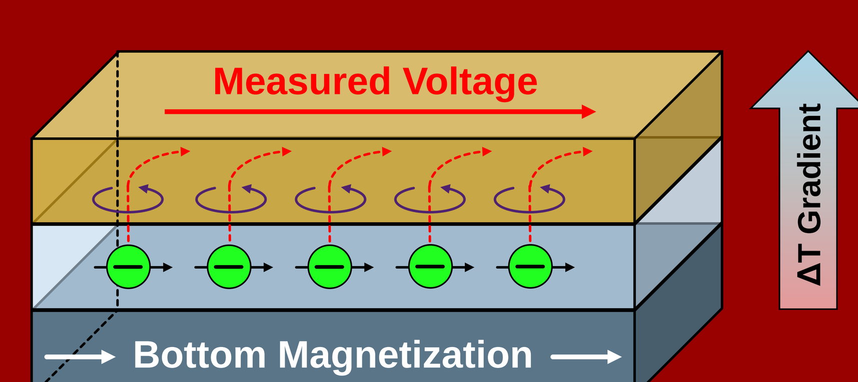


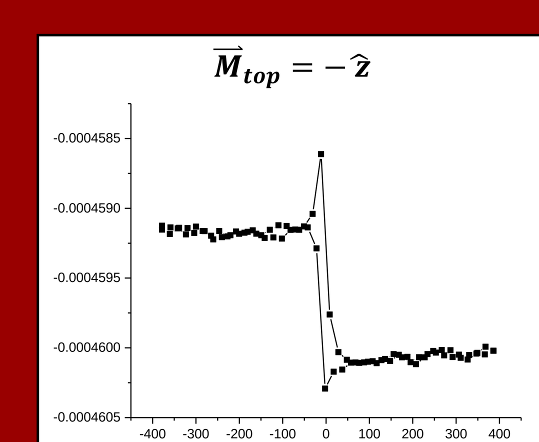


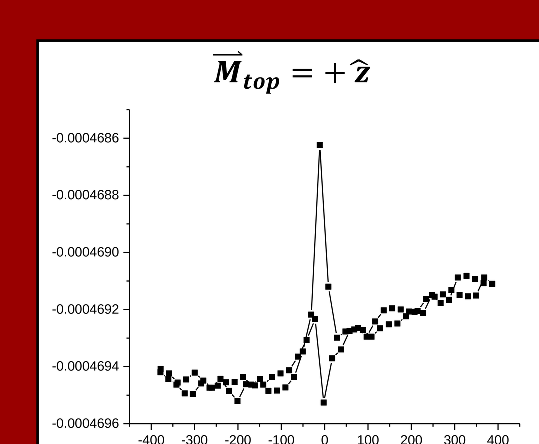
Second Measurement – Spin Rotation:

$$\vec{M}_{bot} = \pm\hat{x}\,;\vec{M}_{top} = \pm\hat{z}\,;\vec{I}_{measured} = \pm\hat{x}$$

- The magnetization of the bottom layer is rotated by 90° (the electromagnet is rotated).
- The previous potential is now orthogonal to the leads, so it is not detected.
- The e-'s which transmit through the Platinum layer without losing their spin alignment are *spin rotated* by the top layer, at which point they can generate voltage (ISHE again).
- Only ejected e-'s which haven't had their spin diffused can be measured this way.



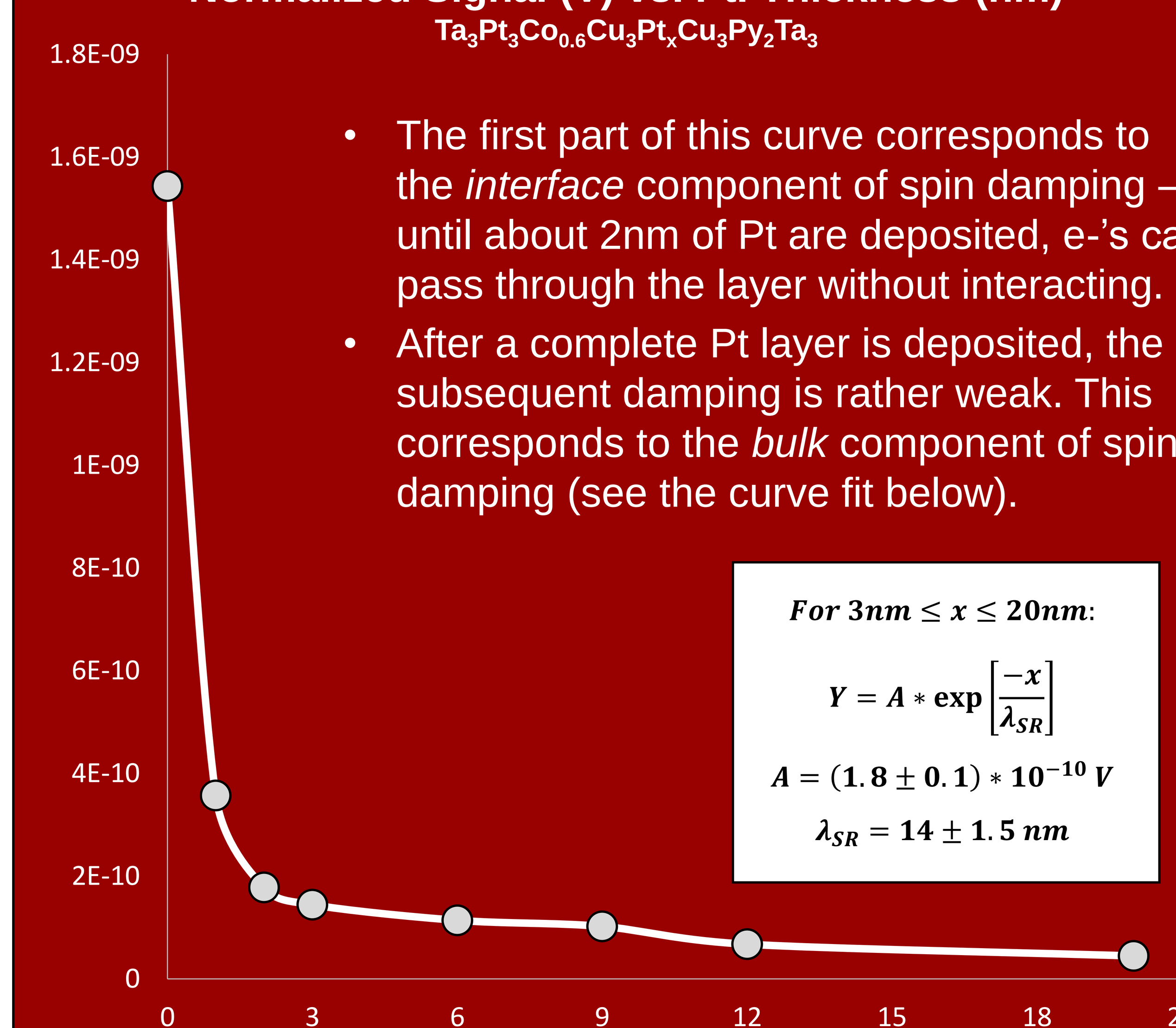




λ_{SR} from Spin Rotation:

Normalized Signal (V) vs. Pt. Thickness (nm)

$Ta_3Pt_3Co_{0.6}Cu_3Pt_xCu_3Py_2Ta_3$



- The first part of this curve corresponds to the *interface* component of spin damping – until about 2nm of Pt are deposited, e-'s can pass through the layer without interacting.
- After a complete Pt layer is deposited, the subsequent damping is rather weak. This corresponds to the *bulk* component of spin damping (see the curve fit below).

For $3nm \le x \le 20nm$:

$$Y = A * \exp\left[\frac{-x}{\lambda_{SR}}\right]$$

$$A = (1.8 \pm 0.1) * 10^{-10}\ V$$

$$\lambda_{SR} = 14 \pm 1.5\ nm$$

References and Acknowledgements:

I would like to thank DU's Partners in Scholarship program for financing my research this summer