Electrical Field Switching of Magnetic Devices for Superconducting Electronics

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Abstract- This research examines the relativistic phenomena of Spin Orbit interaction at the atomic level to electrically switch ultra-thin magnetic films. Pt/Co and Pt/EuS bilayers were chosen to evaluate the ability to prove this. The findings could provide insight in the development of cryogenic technology.

Introduction

Spin Orbit Torque

What? A phenomenon where a **charge current** flowing in a heavy metal layer (*i.e.,* elements with high atomic numbers, such as Pt, W, Ta…) generates a transverse spin current which exerts a torque in an adjacent **ferromagnet** layer thereby causing the ferromagnet's magnetization to switch direction.

Importance: Highly valued in the development of super high density, energy efficient and fast non-volatile Magnetic Random Access Memory (MRAM) devices[1] and can be extended to other devices.

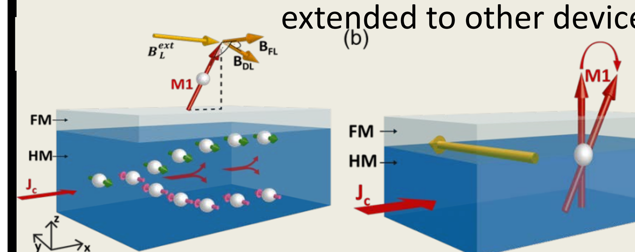


Fig. 1. Schematic of Spin orbit torque magnetization switching in thin film. [2]

Research Focus

- Investigate how Spin Orbit Torque (SOT) affects the magnetic semiconductor EuS.
- Understand how SOT affects different materials
- Optimize the material/layers for large spin currents

Fig. 2. Schematic of thin film multilayer used [*] – grown in Ultra-clean Molecular Beam Epitaxy system

Applicability

SOT is promising in the development of SOT-MRAM for low-power, dense, efficient, and high-speed switching.[3] This project seeks to further the development of superconductive electronic devices for future cryogenic supercomputing.

Goal

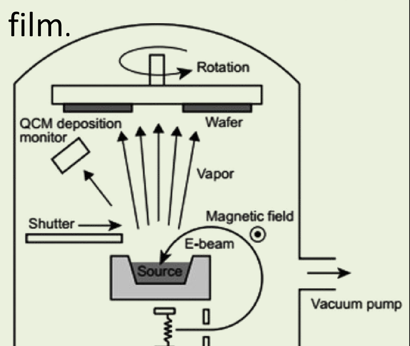
The Goal of this research is to apply spin orbit to switch EuS and compare it to a Pt/Co bilayer.

Methods

1. Growing of ultrathin films of Pt/Co and Pt/EuS:

E-Beam Evaporation- a technique to deposit thin films of Pt/Co/Al_2O_3 and Pt/EuS/Al_2O_3 on a substrate. This was conducted in an ultra high vacuum chamber (called MBE). High energy focused electron beam bombarding a material source evaporates it, the vapor subsequently gets deposited on a clean surface (called a substrate, sapphire in this case) to create a thin film.

Fig. 3. Schematic of E-Beam Evaporation process used for vaporizing target Material to grow thin film. [4]



2. Microfabrication:

Electron-Beam Lithography- a technique to define patterns on the thin films. An electron beam is applied to the sample after e-beam resist is applied and shortens the polymer chains of the exposed areas so that the developer can remove them which creates a nano-sized pattern on the thin film.

a. Thin film after being coated in e-beam resist
b. E-beam resist is exposed to radiation and removed.
c. Thin film section is etched.
d. Final device after e-beam resist is removed

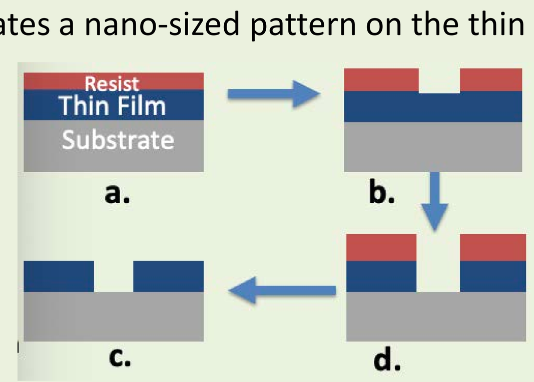


Fig. 4. Schematic of E-Beam Lithography and etching process [*]

Ion Milling- focused ion beam (FIB) milling etched away the exposed areas of the film made by the lithography. This was done by directing argon plasma at the film which removed the remaining e-beam resist and all exposed film.

Wire-bonding- the patterned samples were wire-bonded with a circuit to conduct measurements through the PPMS. This was done by using an ultrasonic wedge bonder that attached copper wires from a circuit to the thin film.

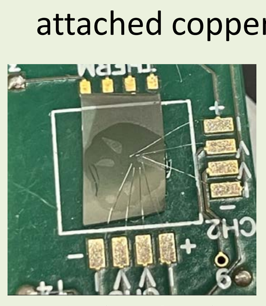


Fig. 5. Wire bonding between the circuit and thin film [*]

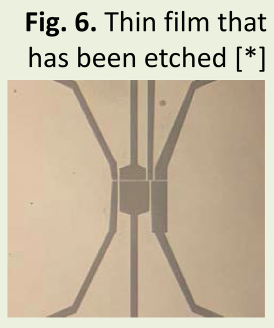


Fig. 6. Thin film that has been etched [*]

3. Measuring transverse resistance

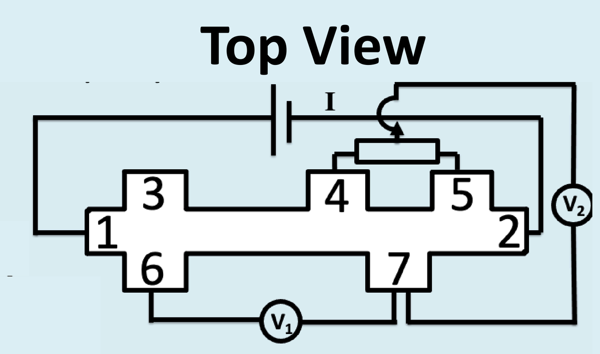
Physical property measuring system (PPMS)

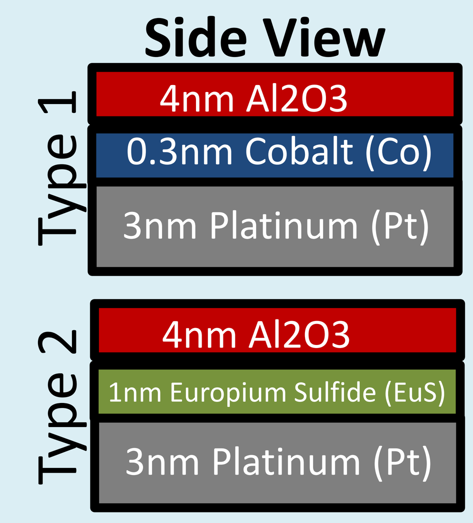
An automated well controlled system that allows the measurement of transverse and longitudinal resistance of the patterned thin film Hall bar structures at various magnetic fields and temperatures.

Results

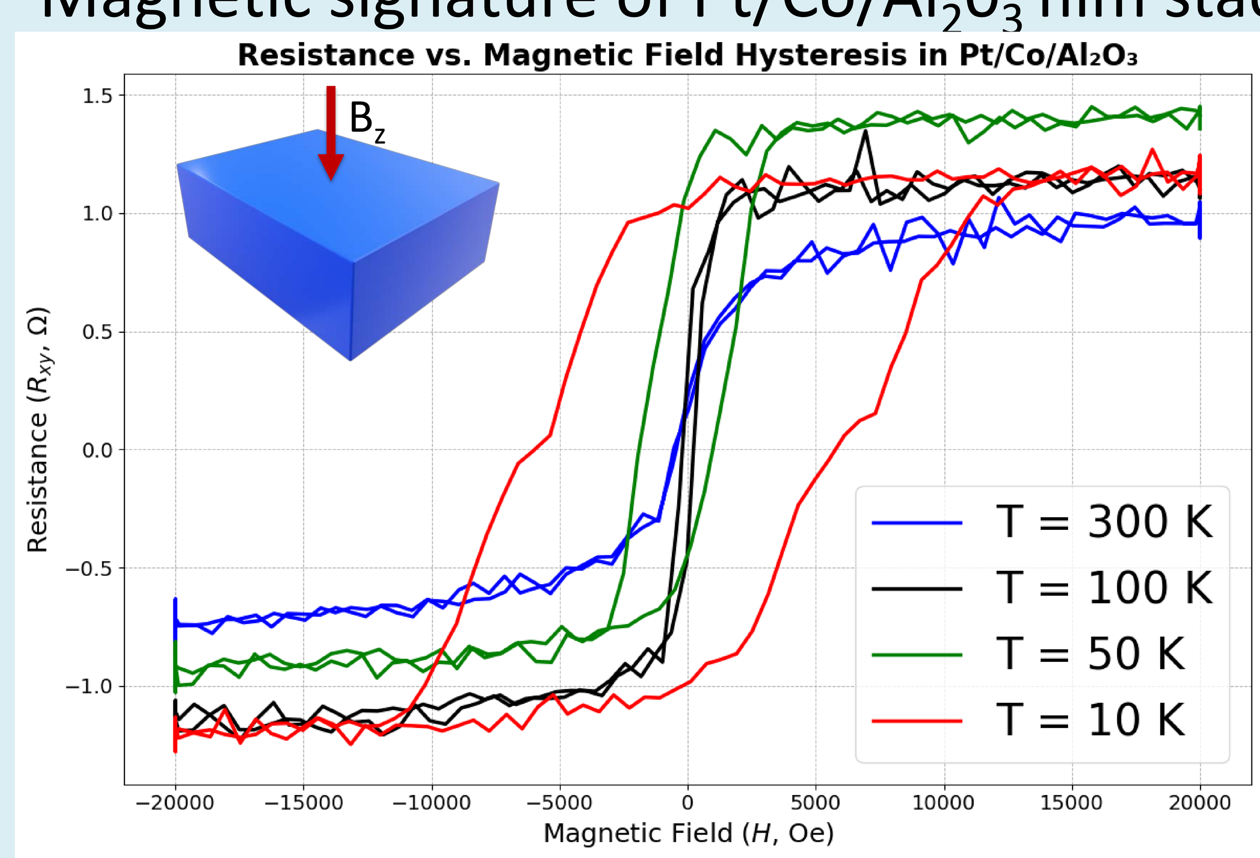
Magnetic field and **transverse resistance** (measured using PPMS) are compared for **Pt/Co/Al_2O_3** and **Pt/EuS/Al_2O_3** bilayer systems.

Fig. 7. Schematic of the **Hall Bar structure** of the film stack (top view). Current flows from 1 to 2. **Longitudinal voltage,** v_1, (resistance R_{xx}) was measured across 6 and 7. **Transverse voltage,** v_2 (resistance R_{xy}) was measured between 4/5 and 7. (*)

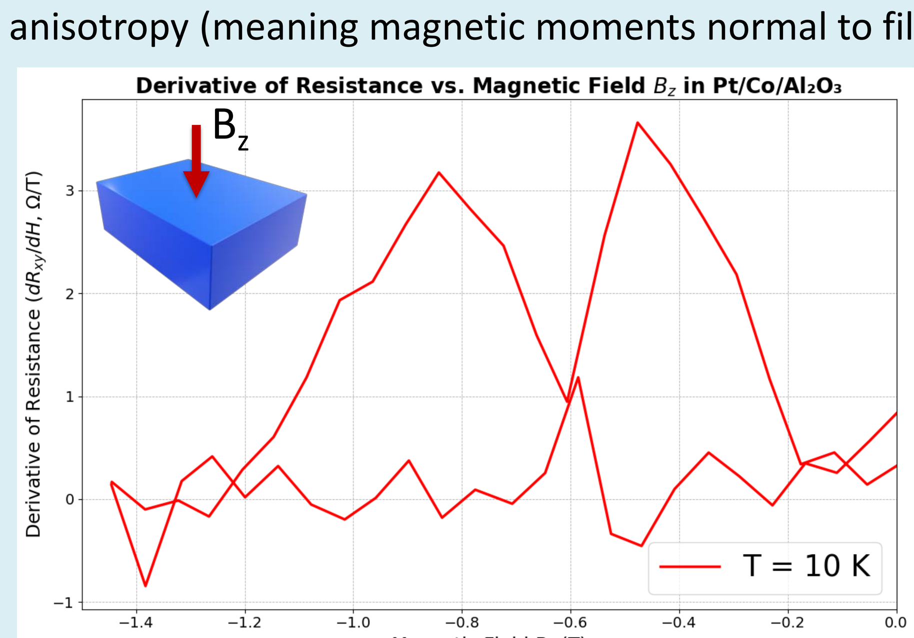




Magnetic signature of Pt/Co/Al_2O_3 film stack

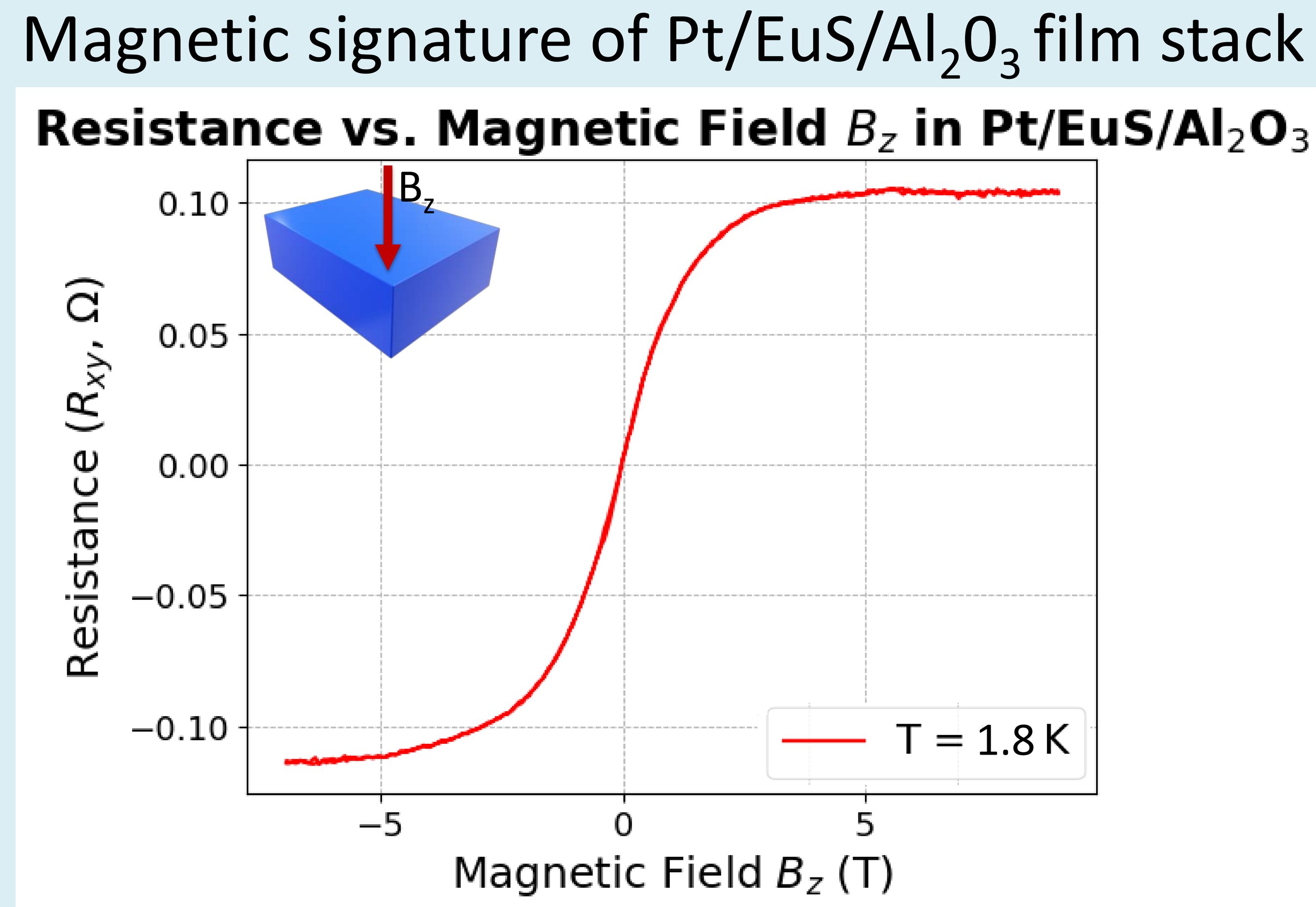


Hall resistance (representing magnetic behavior of the layer stack) show that as the temperature drops, the hysteresis of Pt/CO bilayer, showing perpendicular magnetic anisotropy (meaning magnetic moments normal to film plane), becomes pronounced.

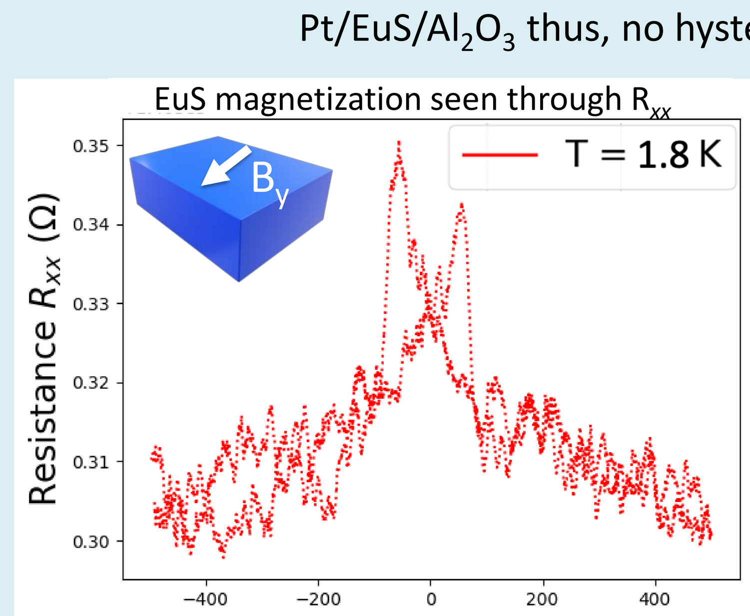


Derivative of R_{xy} vs H data at 10 K shows two well-separated switches in Pt/Co magnetization indicating that Pt layer is magnetized, in proximity to Co layer.

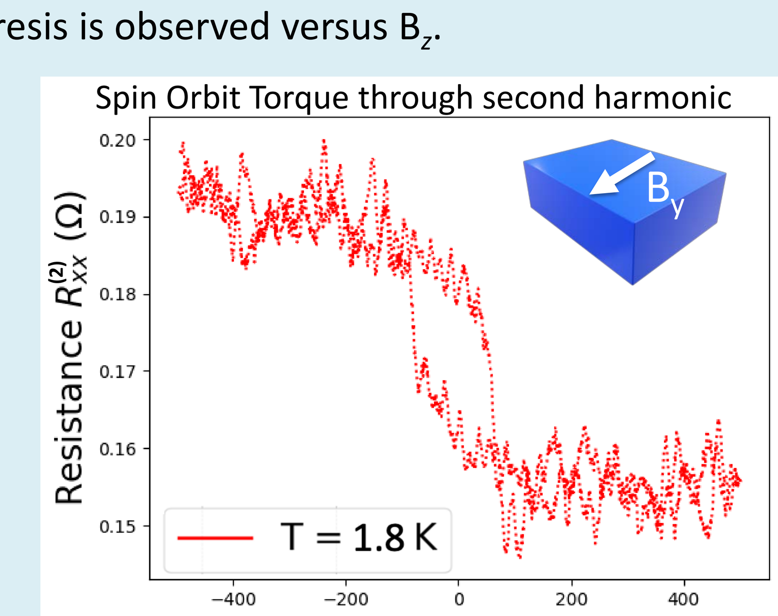
Magnetic signature of Pt/EuS/Al_2O_3 film stack



Hall measurements show the in-plane magnetic anisotropy of Pt/EuS/Al_2O_3 thus, no hysteresis is observed versus B_z.



In-plane magnetic anisotropy of Pt/EuS/Al_2O_3 seen through first harmonic signal in ac measurement



In-plane magnetic anisotropy of Pt/EuS/Al_2O_3 seen through second harmonic signal in ac measurement

Discussion

The experiment found:

- As the temperature decreased, the measured hysteresis of Pt/Co/Al_2O_3 shows perpendicular magnetic anisotropy becoming more pronounced.
- Pt/EuS/Al_2O_3 showed signatures of SOT in the second harmonic data while Pt/Co/Al_2O_3 did not.
- The hysteresis of Pt/Co/Al_2O_3 displayed two-steps in Rxy vs H at low temperature, showing induced magnetization in Pt layer. This is attributed to the Co layer magnetizing the Pt layer, which shows different switching field resulting in the two-step hysteresis as was observed.
- Pt/EuS/Al_2O_3 does not show a hysteresis in R_{xy} vs $B_{||}$. However, R_{xx} showed the magnetization of EuS in the first harmonic when $B_{\perp}$ is applied.

Major Implications

This research is important for advancing non-volatile storage at low temperatures, especially in superconductive electronics when combined with a superconductor. By optimizing SOT, this could potentially revolutionize the field of cryogenic electronics, in particular supercomputing and quantum computing towards the development of highly energy efficient technology.

Future Direction

Optimization of material interface for spin orbit torque efficiency

Increased development of low-power switching materials

EuS could be integrated in STT devices.

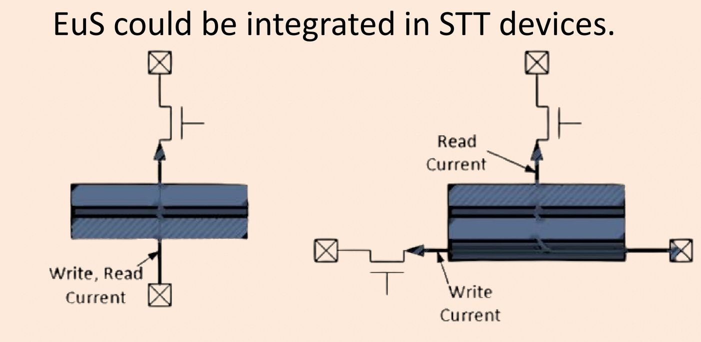


Fig. 8. Difference between Spin Transfer Torque in STT-MRAM and Spin Orbit Torque in SOT-MRAM [5]

Outcome

The results provide promising insight into the possibility to apply spin orbit that would enable efficient switching of thin film magnetic layers. This could lead to highly energy efficient non-volatile cryogenic data storage technology technology.

References

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[5] https://semiengineering.com/sot-mram-to-challenge-sram/

[*] Pictures taken at the Moodera Lab at MIT or schematic made by the author.

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