Investigating the Magnetic Exchange Coupling Between Semiconducting EuS and Metallic Co Magnetic Layers

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Abstract: This study explores the magnetic coupling between two magnetic ultra thin layers of metallic Cobalt (Co) and semiconducting Europium Sulfide (EuS), aiming to enable efficient switching of EuS through its exchange coupling with Co. This will be beneficial in creating advanced quantum devices.

Introduction

The goal of this project was to analyze the exchange coupling between the magnetic semiconductor EuS and magnetic metal Co, and therefore identify the possibility of electrically switching EuS through Co.

Magnetic Coupling

- **Ferromagnetic Coupling**: Magnetic moments align parallel
- **Antiferromagnetic Coupling**: Magnetic moments align antiparallel

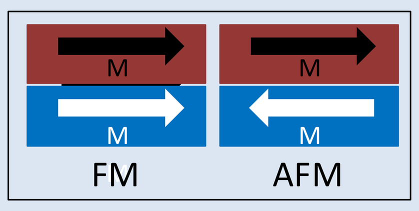


Figure 1: Two examples of magnetic coupling with moments (M) between two materials, illustrating ferromagnetic (FM) (Left) and antiferromagnetic (AFM) alignments (right).

- **Crystal Lattice Structures** of Europium Sulfide (EuS) and Cobalt (Co)

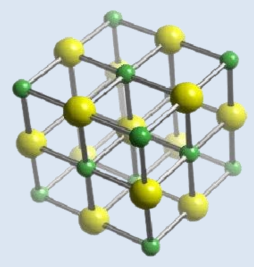


Figure 2: Crystal structure of Europium Sulfide[1] (EuS) with a face-centered cubic (FCC) lattice and a bulk Curie temperature (T_c) of 16.6 K (17 K). (Sharma et al)

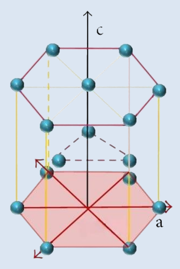


Figure 3: Crystal structure of Cobalt[2] (Co) with a hexagonal close-packed (HCP) lattice and a bulk Curie temperature (T_c) of 1400 K. (Deng et al)

Exchange Coupling Proximity Effect

Exchange Coupling is a quantum interaction where the magnetic moments of adjacent layers influence each other, leading to either parallel (FM) or opposite (AFM) spin alignment. The strength of this coupling depends on the materials and the atomic distance between them and is thus extremely sensitive.

The magnetic proximity effect (MPE) occurs when a ferromagnetic material induces a magnetic moment in an adjacent non-magnetic or weakly magnetic material. Here we explore this phenomenon by keeping Co magnetic while EuS changes from the paramagnetic (nonmagnetic) state to its ferromagnetic state when cooled from room temperature below its Curie temperature of 17 K.

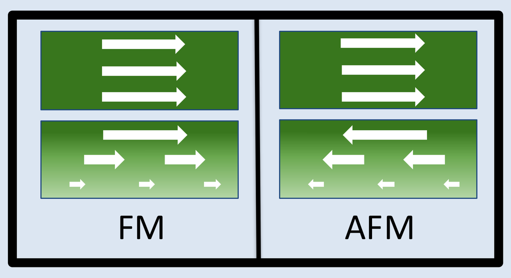


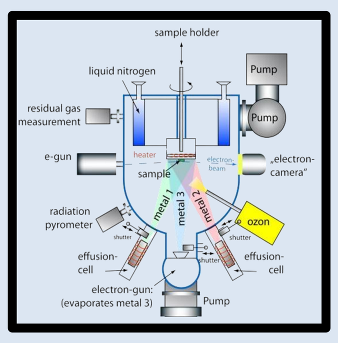
Figure 4: Schematic illustrating how the Cobalt layer (upper block) induces polarization (longer arrow and darker color) in the EuS layer (lower block). The color gradient represents the intensity of magnetization (M).

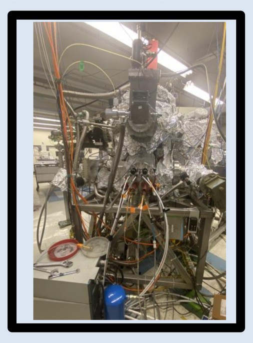
Hypothesis:
The proximity effect could cause magnetic coupling between EuS and Co due to the strong ferromagnetic ordering of Co influencing the magnetic state of adjacent EuS, keeping in mind that this could be significantly pronounced upon cooling when EuS magnetically orders.

Methods

1. Growing Ultra-Thin Film Bilayers of EuS|Co

- Molecular Beam Epitaxy (MBE) - A technique used to grow ultra clean and controlled epitaxial crystal films.



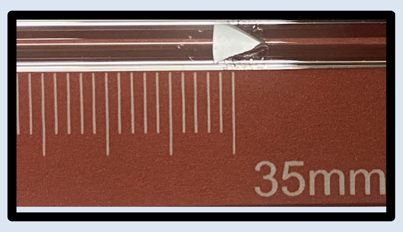


Figures 5 and 6: Molecular Beam Epitaxy (MBE) used for the precise deposition of thin films, including EuS and Co layers. Figure 5 (left) details on the tools available within the MBE[3]. Figure 6 (right) is a picture of the MBE system used.

2. Preparation of the Film

- After fabrication, the films were divided into smaller pieces for further experimentation.

Figure 7: A bilayer of 2 nm EuS / 2 nm Co sample grown on sapphire placed onto VSM sample holder (white triangle) for magnetic measurements



3. Magnetic Field Exposure in VSM PPMS

- The Vibrating Sample Magnetometer (VSM) in the Physical Property Measurement System (PPMS) was used to measure the magnetic properties of the thin film bilayers.

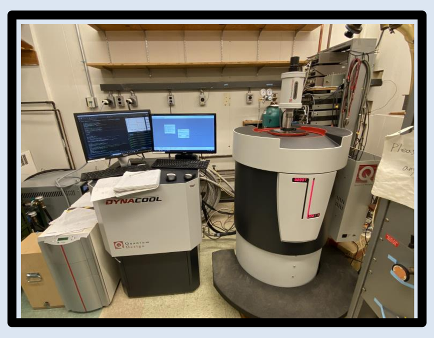
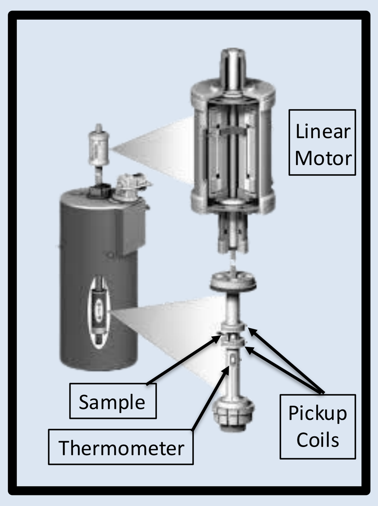


Figure 8: Physical Property Measurement System (PPMS) used for measuring sample magnetization at various magnetic fields and temperatures.

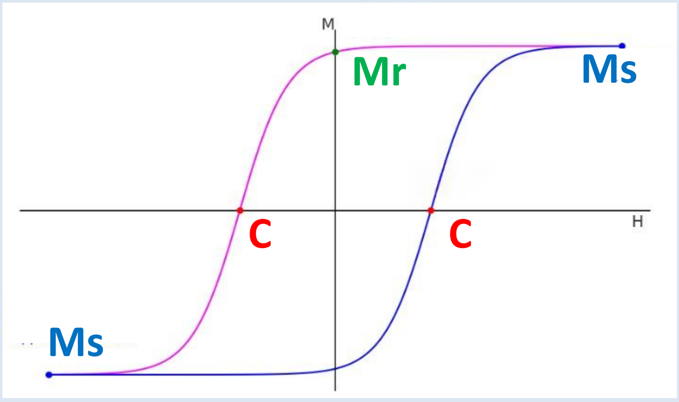
Figure 9: Vibrating Sample Magnetometer (VSM) apparatus[4] used to measure the magnetic moment of samples by detecting the induced voltage in pickup coils as the sample vibrates in an applied magnetic field.



Results

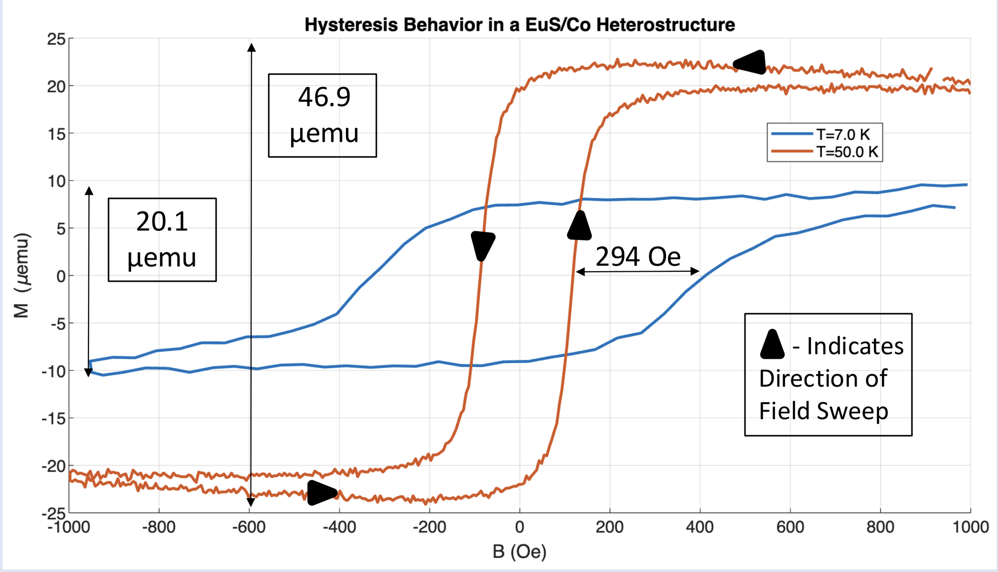
Field-Dependent Magnetization

Signature of a magnetic material - magnetic response to an applied magnetic field called Magnetic Hysteresis

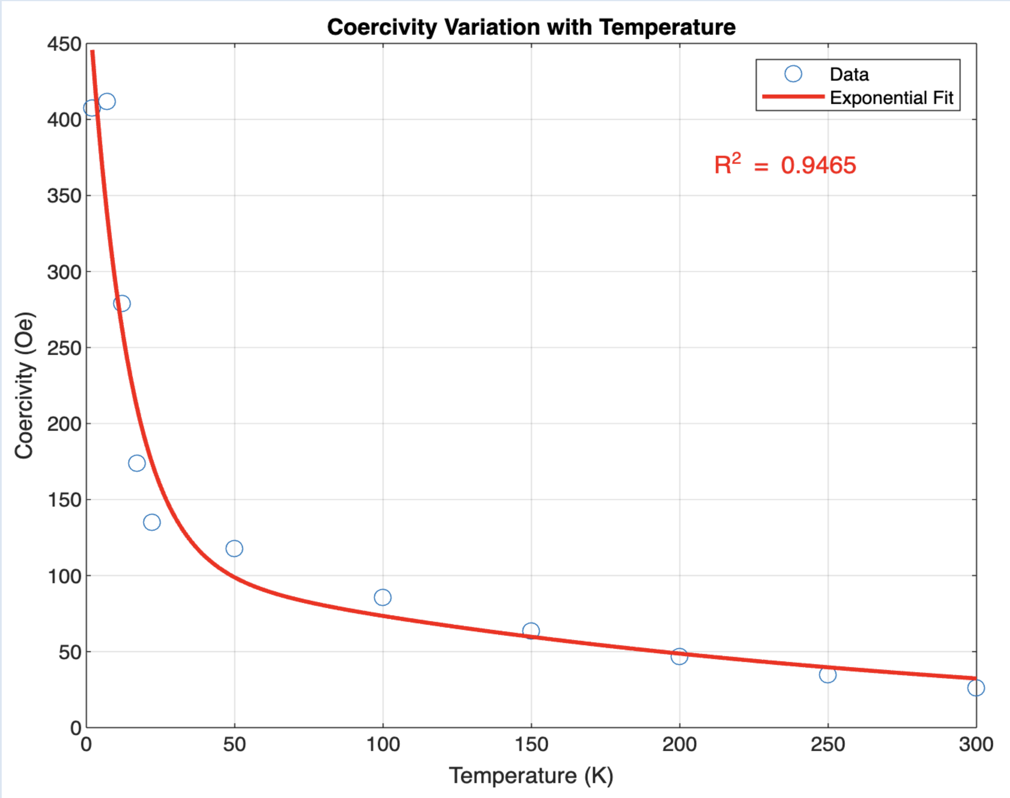


- **Remanence (Mr)** - Magnetization left after the external field is removed.
- **Coercivity (C)** - Field needed to switch or reverse the magnetization direction.
- **Saturation Magnetization (Ms)** - Maximum possible magnetization.

EuS/Co bilayer, each film 2 nm thick



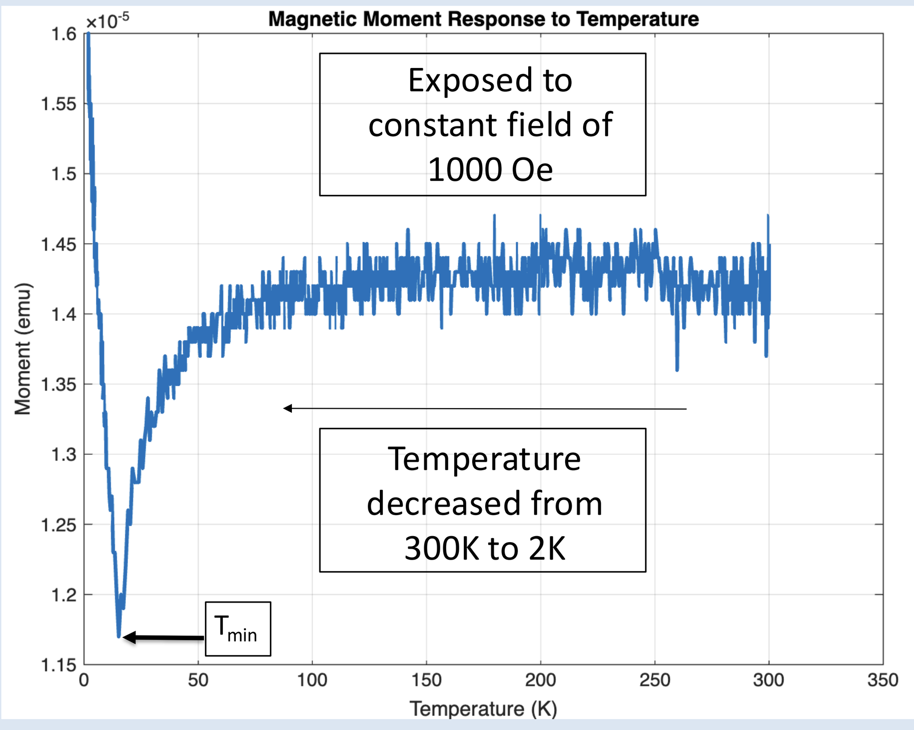
- Evidence of coupling between materials as indicated by **Hysteresis Loops**
- Height of loop increases as temperature increases, **non-consistent with ferromagnetic coupling**.
- Width of loop decreases as temperature increases, relates to materials **coercivity.**



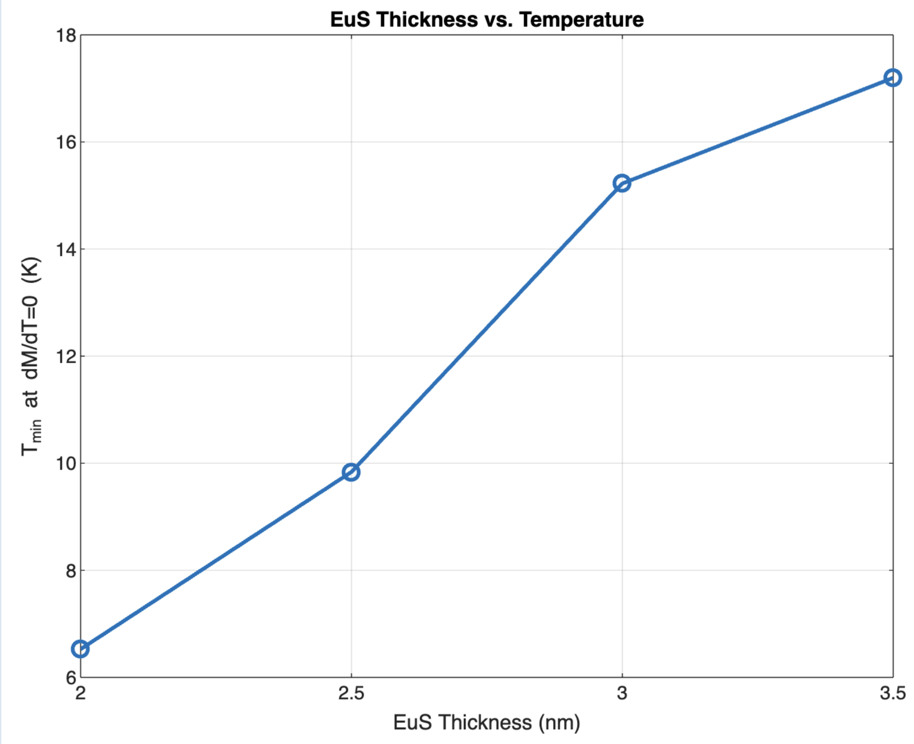
- The observed coercivity decreases exponentially with increasing temperature
- This trend suggests that the material's resistance to demagnetization weakens as temperature rises.
- The weakening of coercivity is consistent with thermal agitation overcoming the material's magnetic anisotropy.

Temperature-Dependent Magnetization

EuS/Co bilayer, EuS 3 nm thick, Co 2 nm thick



- At temperatures (T) above 17 K, only Co is ferromagnetic and EuS is paramagnetic.
- The curve starts to decrease at 100 K and more **significantly** at 50 K until the minimum at **T = 15.2 K**.
- This behavior could be indicative of anti-ferromagnetic coupling due to net M decreasing as EuS becomes ferromagnetic.



- T_{min} is the temperature seen as the minimum on the Moment-Temperature plot
- At T_{min}, EuS magnetization compensates the Co magnetization.
- Non-constant, yet significant, increase in T as EuS thickness increases. Indicating M is reversing at higher temperatures with a more substantial presence of EuS.

****Notes: Films All films were tested at multiple temperatures; necessary data has been displayed for understanding and viewing purposes. Films of x nm EuS, 2 nm Co with x:{1,2,2.5,3,3.5} were created.*

Analysis and Discussion

From room temperature down to the magnetic ordering temperature (T_c) of EuS, samples show a steady decrease in magnetization (while any magnetic material would show an increase). This is consistent with antiparallel alignment typical of **antiferromagnetic coupling**. *This is an important finding of this project.*

Initially, the overall magnetization shows that EuS aligns antiparallel to the Co layer, causing a decrease in the net magnetization (due to antiferromagnetic coupling). As the temperature further decreases, the system reaches a partial compensation point where the opposing magnetizations lead to a decreased overall value by cancelling each other, resulting in a minimum magnetization. (For future reference, this temperature will be referred to as T_{min}.) Below this temperature the intrinsic magnetization of EuS continues to increase and thus dominates the bilayer net magnetization, leading to an overall increase in magnetization. This effect is more pronounced in thicker EuS samples, as expected. This is because the magnetic influence of thicker EuS layer is stronger, while thinner samples expectedly have lower influence due to less magnetization.

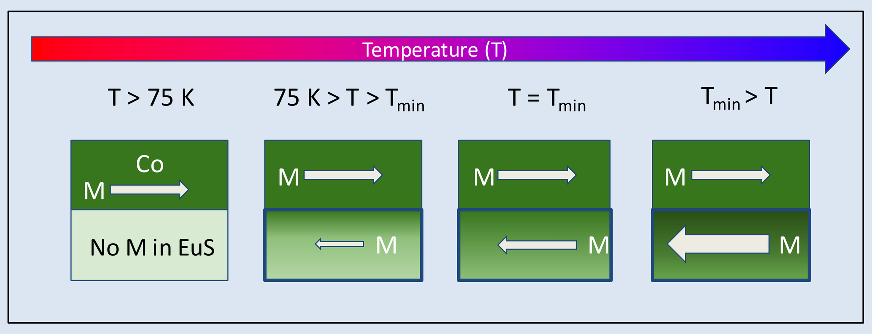


Figure 10: M indicates that the material is magnetic. Net magnetization in EuS|Co bilayer showing temperature-dependent antiferromagnetic coupling, where EuS dominates at lower temperatures, leading to increased magnetization below Tmin.

The observed antiferromagnetic alignment shows the atomic level coupling and interaction of magnetic moments at the interface advancing our understanding of the magnetic interactions between EuS and Co for spintronic applications. The ability to switch the magnetization of EuS by leveraging its coupling with Co could be pivotal in magnetic memory devices, especially in cryogenic environments where less energy consuming control is essential.

Main Outcome

***The coupling between EuS and Co layers is antiferromagnetic.* The magnetic ordering temperature in EuS was found to be enhanced. This discovery has the potential to tune the performance of future quantum devices.**

Future Directions

- Explore Other Magnetic Materials
- Integrate with Nanostructures

References

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[3]*Oxide MBE Lab*. Oxide MBE Lab. www.fkf.mpg.de. https://www.fkf.mpg.de/273938/30_Oxide_MBE_Lab.

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