Experimental report

12/09/2023

Proposal: **5-54-384** **Council:** 10/2022

Title: Detecting magnetic proximity in structurally designed ferromagnetic-superconductor superlattices and ferromagnetic-semiconductor bilayers

Research area: Materials

This proposal is a new proposal

Main proposer: **Kim LEFMANN**

Experimental team: Kamaldeep DALAL

Local contacts: Thomas SAERBECK
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Samples: InAs(Sub)/EuS(5nm)/InAs(5nm)/Al2O3(2nm)
InAs(Sub)/[EuS(5nm)/Pb(10nm)]x10/Al2O3(5nm)
InAs(Sub)/EuS(20nm)/InAs(5nm)/Al2O3(2nm)

Instrument	Requested days	Allocated days	From	To
D17	4	3	13/05/2023	16/05/2023

Abstract:

The integration of ferromagnetic insulators (FMI) with semiconducting-superconducting (SE-SU) structures provides a generic platform for topological quantum computation, since no external field is required in the experimental setup. In these structures, the exchange coupling of FMI with SE-SU materials should provide the essential Zeeman energy to lift up the spin degeneracy. However, in our recent PNR experiments of these tri-layer EuS-InAs-Pb structures (proposal Id: 5-54-373), we have seen that it is difficult to detect the signatures of weak magnetic proximity effect. In this proposal, we have designed the superlattices and bilayer structures containing only one type of interface (either SE-FMI or SU-FMI), in which the sensitivity of the PNR measurement to detect the small magnetic proximity effect could be greatly enhanced by the structural design. The information acquired from these PNR measurements will allow quantification of the magnetic exchange at EuS/Pb and EuS/InAs interfaces, and precise modelling of more complicated tri-layer structures which will ultimately point towards experimental realization of real device structures.

Experimental report: 5-55-384

Title: Investigation of superlattices of FMI/SU and a bilayer structure of FMI/SE for magnetic proximity

Proposers: Kamaldeep Dalal, Dr. Malvika Tripathi, Dr. Yu Liu, Dr. Thomas Saerbeck, Dr. Nina J. Steinke, Prof. Kim Lefmann

Experimentors: Kamaldeep Dalal, Dr. Thomas Saerbeck, Dr. Nina J. Steinke

Date of experiment: 13^{th} - 15^{th} May, 2023

ILL instrument: D17

Scientific background: EuS/Pb and EuS/InAs interfaces form building blocks of a device structure which has been proposed to hold topologically protected surface states, called Majorana bound states (MBS). There exist a few proposals on how one can manipulate these states to store the information with longer coherence time. The material's choice is very limited by certain parameters that need to be fulfilled such as lattice matching, large spin-orbit splitting, high electron mobility, metallic superconductivity, etc. Using MBE, we fabricated the layers on InAs substrates with variable Pb and EuS thicknesses. The existence of proximity effects at EuS/Pb and EuS/InAs interfaces are crucial for the aforementioned states to appear in the proposed device structure. However, since, the difference in transition temperature of ferromagnetic (T_C) and superconducting (T_S) materials is very small, changes in the global magnetization can also correspond to the thermal evolution of the ferromagnetic moment of EuS. For a more adequate quantification of magnetic proximity effect, we designed simplified structures with one type of interface (SU-FMI or SE-FMI), in which the sensitivity of the Polarized neutron reflectometry (PNR) measurements to detect the small magnetic proximity effect could be greatly enhanced by the structure design. With this motivation, we planned to measure the PNR on the samples, where the respective thicknesses are optimized to give the maximum interface sensitivity.

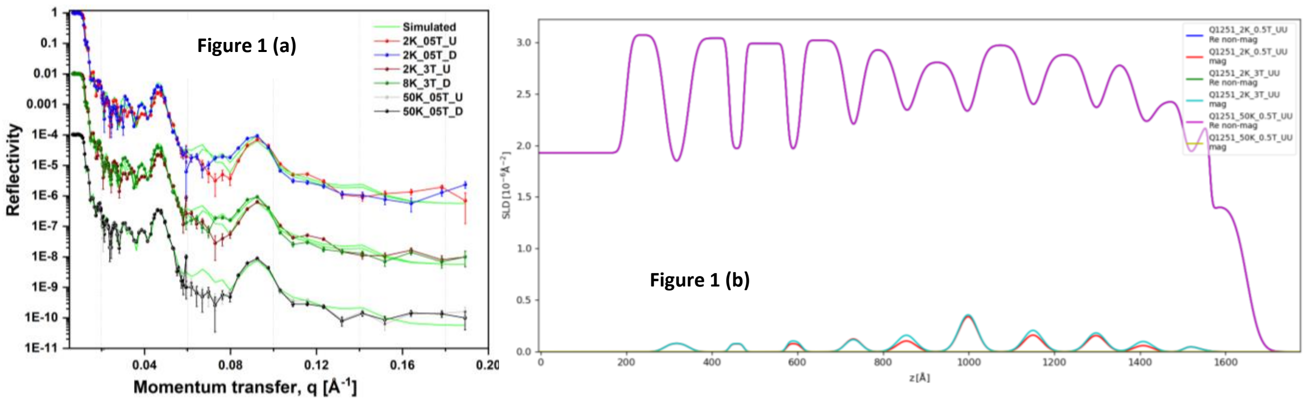
Preliminary results and discussion:

These two samples were measured at D17 instrument during three days beamtime –

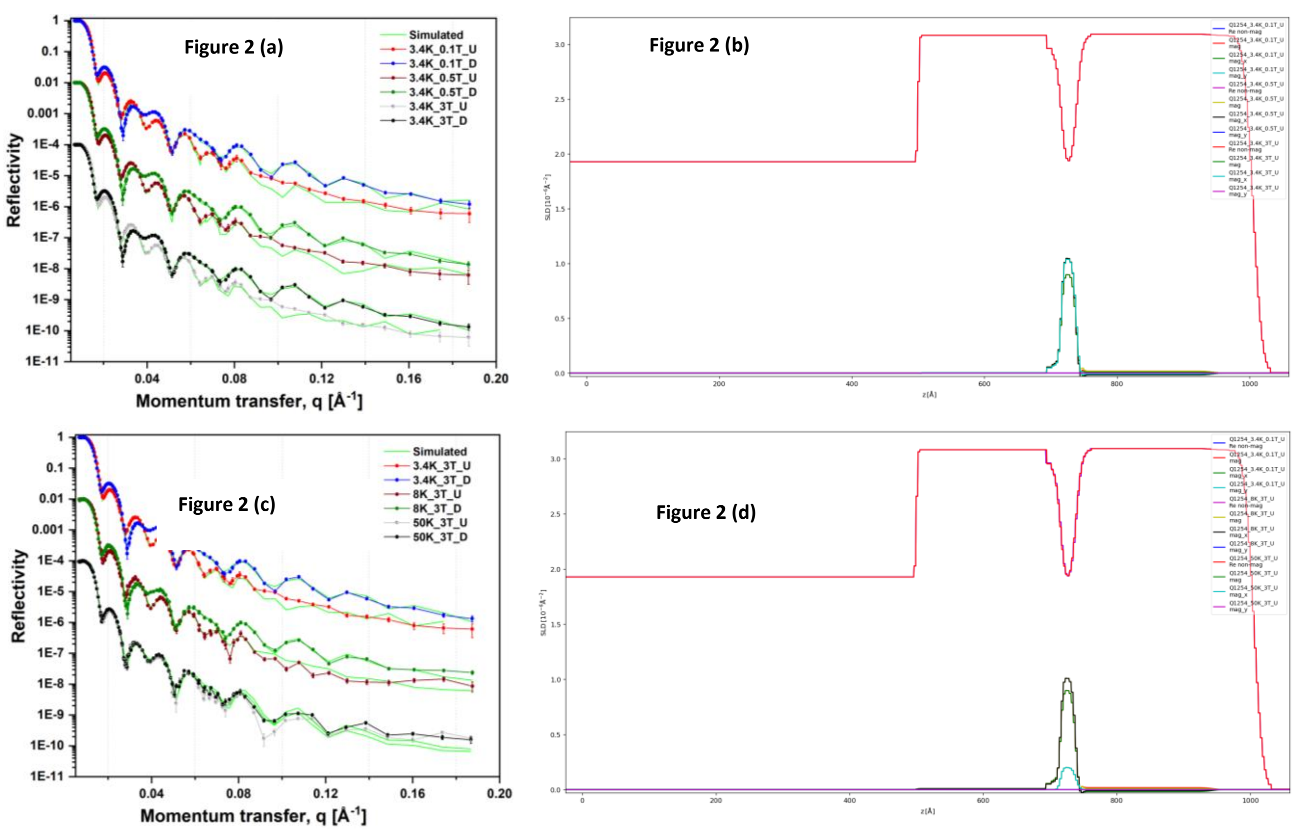
1. Qdev1251 - superlattice of [Pb(10nm)/EuS(5nm)], structure repeated 10 times, on InAs substrate
2. Qdev1254 **-** InAs (Substrate)/ Pb (20nm)/ EuS(2.5nm)/ Pb (20nm)/AlOx(2nm)

We have measured these samples at different temperatures covering both superconducting and ferromagnetic ordering temperature range. We started the experiment by measuring the intensity of the direct beam, which was later used for the normalization of the data. The samples were placed at three fixed angles – 0.6, 1.5 and 3.5 (in degrees) to cover the whole q-range. PNR measurements were recorded in time of flight mode with a wavelength range from 4 to 20Å. Firstly**,** the samples were cooled in zero magnetic field to a temperature well below both superconducting (~7.5K) and ferromagnetic (~17.5K) transitions. Then, we applied an external in-plane magnetic field (guiding field) of 0.5T in order to saturate the ferromagnet while maintaining the superconductivity. In order to decouple the magnetic effects due to the presence of superconductivity and ferromagnetism, we tried to destroy the superconducting at 2K by applying a higher magnetic field of 3T (a field higher than the critical field for Q1251). For acquiring the structural information, a reference measurement was performed, for both the samples, by warming to 50K (a temperature well above both transitions). For these samples, each measurement took around 8hrs. All of these measurements were performed in the zero field cooled mode.

Sample Q1251 – The recorded data along with preliminary fits is shown in figure 1. We have tried to fit the data with simple model with no interfaces. The initial analysis of the data suggest that the interfaces are highly rough and the thicknesses are not consistent in superlattice. Also, the fitted nuclear SLDs [figure 1 (b)] for the upper layers are not in good agreement with the literature values. It was worth trying to study the superlattice but higher interfacial roughness hinders the observation and quantification of interfacial magnetism.



Sample Q1254 - We recorded the PNR data for five measurements on this sample. To explore how competing magnetic ordering evolves with external magnetic field, we performed measurements at 3.4K for three magnetic fields – 0.1T, 0.5T and 3T. The field dependency data is shown in figure 2 (a). Then, we heated the sample to 8K (@3T), a temperature just above the superconducting transition, to see the changes in interfacial magnetism. Figure 2 (c) shows the temperature dependent PNR data for this sample. We have tried to fit the data using two models – simple and with magnetic interfaces at Pb/EuS of around 1.5nm. The fit improves when you have a magnetic interface. The fitted SLDs [figure 2 (b) & (d)] are in good agreement with the literature values.



The preliminary fits to the experimental data also provides the structural information that agrees to a certain limit with the data from other structural characterization techniques. We are currently fitting our PNR profiles with appropriate structural and magnetic models which would lead to further conclusive results.