Experimental report

31/10/2022

Proposal: **5-54-373** **Council:** 4/2021

Title: Magnetic proximity in Superconducting Semiconductor

Research area: Physics

This proposal is a continuation of 5-54-298

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Samples: InAs/EuS/Pb/AlOx
InAs/EuS/InAs/Pb/AlOx

Instrument	Requested days	Allocated days	From	To
D17	4	3	24/09/2021	27/09/2021

Abstract:

Topological materials are promising platforms for implementing quantum information unit by processing the quasiparticle excitations at the material boundaries. The key elements for topological quantum computation are the Majorana bound states (MBS) representing the zero energy state of superconducting particle-hole superposition, which is invariant under charge conjugation. In these systems, the Zeeman energy required to enter the topological phase is provided by an external magnetic field. However, the requirement of a strong external magnetic field imposes additional restrictions on the device fabrication layout and components. Therefore, it is of interest to integrate materials that are intrinsically topological. Composite tri-crystals using ferromagnetic insulators (FMI) in close proximity to the SE-SU structure have been proposed as a solution. Recently, we performed a polarized neutron reflectometry (PNR) experiment at D17 to investigate the magnetic proximity effect in a sample composed by InAs (substrate)/EuS/Pb. Here, we propose to continue characterization of this sample and the other sample of InAs (substrate)/EuS/InAs/Pb which has a superconducting semiconductor layer.

Magnetic proximity in superconducting semiconductor

Scientific Background and Experimental Objectives:

Topological materials are promising platforms for implementing quantum information unit by processing the quasiparticle excitations at the material boundaries [1,2]. The key elements for topological quantum computation are the Majorana bound states (MBS) representing the zero energy state of superconducting particle-hole superposition, which is invariant under charge conjugation. Recently, strong indications of MBS have been predicted in one-dimensional semiconductor (SE) nanowire coupled to a superconductor (SU) in presence of a strong Zeeman field [3,4]. In these experimental reports, the Zeeman energy required to enter the topological phase is provided by an external magnetic field. However, the requirement of a strong external magnetic field imposes additional restrictions on the device fabrication layout and components. Therefore, it is of interest to integrate materials that are intrinsically topological. This possibility can be realized by integrating a ferromagnetic insulator (FMI) in the existing design of the SE-SU hybrid structure, where the Zeeman splitting could be induced by an exchange coupling to the FMI. Recently, tri-crystal InAs (SE)/Al(SU)/EuS(FMI) nanowires have been studied using tunnel spectroscopy measurements which indicated the presence of finite exchange magnetic fields [5,6].

Our experimental objective is to quantify the strength of magnetic proximity and its spatial extension with respect to interface in the SU-FMI and SU-SE-FMI hybrid structures. With this motive, earlier, we performed a polarized neutron reflectometry (PNR) experiment at D17 (experimental report 5-54-298) to investigate the magnetic proximity effect and interfacial magnetic coupling in InAs(SE)/EuS(FMI)/Pb(SU)/AlOx hetrostructure grown by molecular beam epitaxy. In the next experiment at D17, we planned to further extend this study in two ways: First, we continued the previous work of investigating the magnetic proximity at the EuS/Pb interface by measuring the PNR profiles at temperature values close to the characteristic transition temperatures of Pb and EuS in the presence of distinct values of the applied magnetic field. Secondly, we further planned to understand the evolution of magnetic proximity effect in a more complex structure: InAs (Substrate)/EuS/InAs/Pb/AlO_x, where both SE-SU and SE-FMI interfaces are present. Importantly, this tri-layer structure is closer to our nanowire system which is designed to observe the signatures of MBS.

Results and Discussions:

We performed a polarized neutron reflectometry (PNR) experiment at D17 to investigate the magnetic proximity effect in two samples: S_1- InAs (Substrate)/ EuS(4nm)/ Pb (60nm)/AlOx(2nm) and S_2- InAs(Substrate)/EuS(12nm)/InAs(5nm)/Pb(20nm)/AlOx(2nm). In bulk-magnetometric measurements of these hetro-structures, we have observed that the superconducting ordering temperature of Pb is ~ 7 K (T_s), whereas the ferromagnetic ordering temperature of EuS is ~16 K (T_c). The wavelengths from 4 Å to 20 Å were used for the measurements. For each measurement, the detector was placed at three different angles - 0.5°, 1.2°, and 2° relative to the sample surface. Each measurement took around 6 hours.

Firstly, we continued the previous investigation of the sample S_1 to obtain more details about the impact of the superconducting transition over the magnetic properties of the EuS/Pb interface. We collected the PNR data in the presence of 0.1 T magnetic field at temperature values T= 6 K, 7 K and 8K which lie in the close vicinity of superconducting transition. In order to distinguish the role of defect states at superconducting Pb layer in the origin of the interfacial magnetic coupling and to observe how the competing magnetic orderings evolve with the magnetic field, we also performed PNR measurements at 2K in presence of different applied magnetic field values: 0.01T, 0.25T and 1T. All of these measurements were performed in the zero field cooled mode.

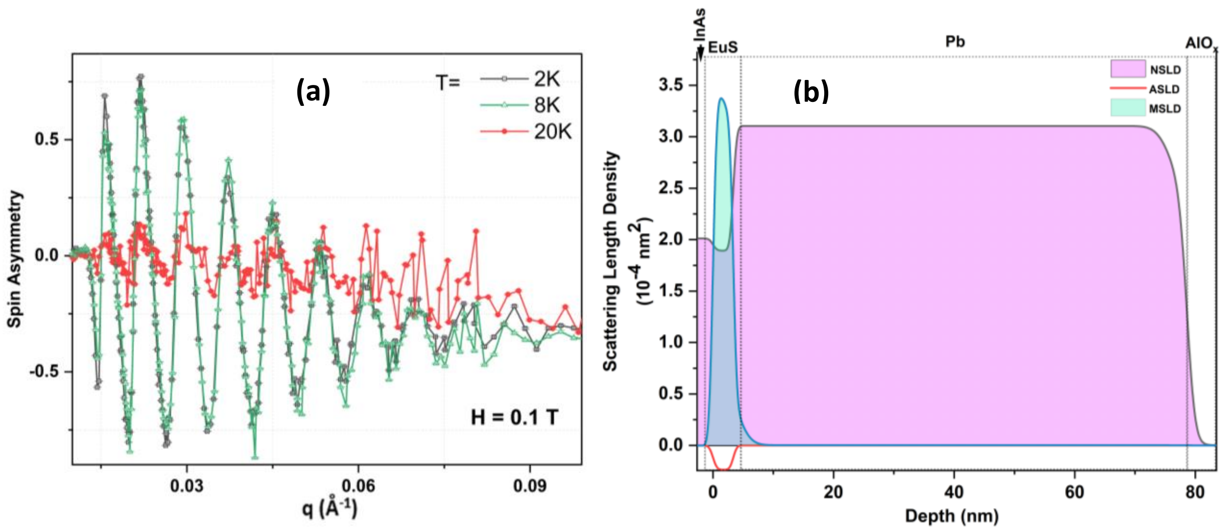

Figure 1. (a): Spin asymmetry profiles of sample S1 across superconducting transition of Pb and ferromagnetic transition of EuS. (b) Scattering length density profiles generated from the refined model simulations of PNR profiles.

Fig.1 (a) shows the measured spin asymmetry profiles for temperature values across T_s and T_c. The change in the spin-asymmetry across T_s is reflected by comparing the measured profiles at 2K and 8K. The difference is small and more prominent for high q values, which suggest that the induced magnetization due to superconductivity is mostly localized near the interfaces. The recorded PNR data sets for temperature values above T_s are analyzed with a model with layer stacking similar to the structural profile. We have further assumed that the magnetic phase in the EuS layer below T_c is homogeneous with respect to the layer thickness. However, we noticed that, a good agreement between the fitting curves and the experimental data set at 2 K in high q-range could be achieved only when we considered the presence of an additional magnetic layer in Pb at the Pb-EuS interface. Based on our simulations, we have generated the nuclear, magnetic and absorption scattering length density profiles at T= 2 K, as shown in Fig.1 (b). These results show the presence of small induced magnetization in Pb layer till 4.5 (2) nm. As the width of the

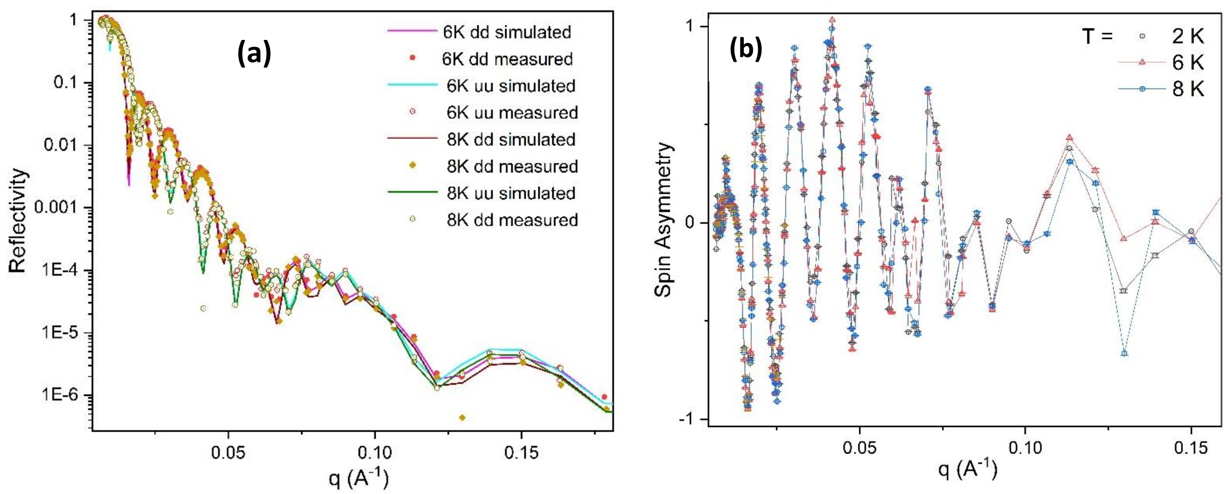

Figure 2. (a): PNR profiles of sample S_2 in the close vicinity of superconducting transition of Pb along with the model simulated profiles (b) Spin asymmetry data recorded for S_2 at temperature values above and below superconducting transition temperature.

magnetic layer in superconducting Pb is quite small, we cannot neglect the possibility of trapped magnetization at the interfacial defect states of superconducting Pb layer.

Secondly, we recorded PNR data for tri-crystal structure sample S_2 at temperature values T = 2K, 6K, 8K, 20K and 50K in presence of 0.1T applied magnetic field. We also measured PNR profiles at 2K in presence of 4T applied magnetic field which is above the critical magnetic field of superconducting Pb. Figure 2.(a) shows the experimental data for sample configuration S_2 measured at 6K and 8K in presence of 0.1T magnetic field, along with a preliminary fit that we performed using GenX. The spin asymmetry data (as shown in Fig.1 (b)), reveal a slight peak shift which indicates to the change in magnetic thickness of different layers. We are currently refining our fits so that we can extract more conclusive information from the data. 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.

References:

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