

Experimental report

26/04/2023

Proposal: CRG-2955

Council: 10/2022

Title: Coupling strength dependence on temperature and Fe layer thickness in Fe/MgO superlattices

Research area: Physics

This proposal is a new proposal

Main proposer: Anna Lena RAVENSBURG

Experimental team: Anna Lena RAVENSBURG

Local contacts: Alexei VOROBIEV

Samples: MgO/10x [Fe/MgO]/Pt thin film

Instrument	Requested days	Allocated days	From	To
SUPERADAM	11	7	03/04/2023	10/04/2023

Abstract:

We investigate the effect of Fe layer thickness on the interlayer exchange coupling in Fe/MgO superlattices depending on temperature. It has been shown previously that the thickness of the MgO spacer layer and the number of bilayer repetitions influence the coupling strength and magnetic order across the superlattice layers. In order to fully explain these experimental observations, beyond nearest neighbor interactions need to be included, even though these are not expected from the models currently available to describe tunneling mediated interlayer exchange coupling. While also the Fe layer thickness would influence the total extension of the superlattice and, hence, the long-range interactions, its influence has not been investigated yet. But within this study a linear dependence of the coupling strength on the Fe layer thickness has been observed. Using a combination of magneto-optical Kerr effect measurements, and polarized neutron reflectometry, the direction of magnetization in each Fe layer at different applied magnetic fields is investigated at different temperatures, which might allow for investigating the origin of these long range interactions in Fe/MgO superlattices.

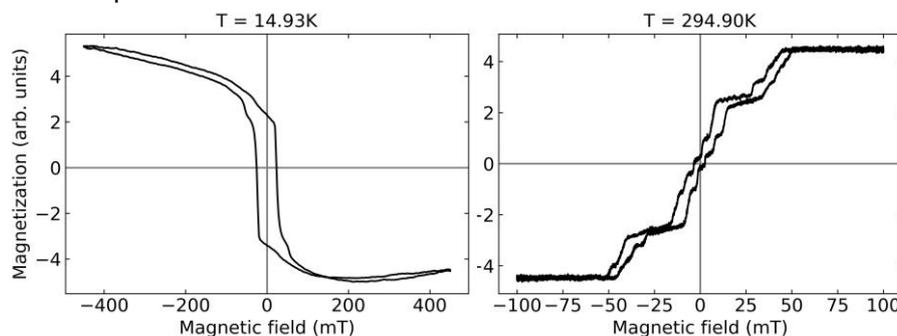
Temperature dependent polarized neutron reflectometry measurements of Fe/MgO superlattices (CRG 2955)

Anna L. Ravensburg, Department of Physics and Astronomy, Uppsala University, Sweden

1. Introduction

Fe/MgO superlattices are artificially manufactured single-crystalline thin films of alternating Fe and MgO layers [1, 2]. Fe/MgO superlattices are interesting because they exhibit large tunnel magnetoresistance and antiferromagnetic interlayer exchange coupling (IEC) [3, 4, 5, 6] between the Fe layers through the non-magnetic MgO spacer layer. When an external magnetic field is applied, layer-by-layer switching is observed as discrete steps in magnetic hysteresis loops for a magnetic field applied along the magnetic Fe easy axis. To explain this sequential switching, including beyond nearest neighbor interactions is suggested [7], despite the tunneling mediated IEC. To explain this, Fe/MgO superlattices can be described as coupled quantum wells created by the Fe layers, potentially forming collective electronic states responsible for the long-range nature of the IEC. Previous studies have investigated the influence of the MgO layer thickness [8] and bilayer repetitions N [7] on the coupling and Fe layer switching. These relate to the barrier width and number of quantum wells, respectively. Currently, we further examine the effect of the quantum well extension, in terms of the number of bilayer repetitions and Fe thickness, on the overall magnetic properties of the superlattices.

Figure 1: Magnetic hysteresis loops of an Fe/MgO superlattice with 10 bilayer repetitions and 20 and 17 Å thick Fe and MgO layers, respectively. The measurements were conducted at 15 K (left) and 295 K (right).



Within this study, longitudinal magneto-optical Kerr effect (L-MOKE) measurements were conducted between 10 and 300 K. Examples are shown in fig. 1. The results show a temperature dependence of the saturation field (300 mT at 15 K, 40 mT at 295 K), the coercivity (20 - 50 mT at 15 K, 5 mT at 295 K), the layer-by-layer switching, and the remanent state (90 degrees relative alignment of magnetic moments at 15 K, antiferromagnetic alignment at 295 K) measured for these samples.

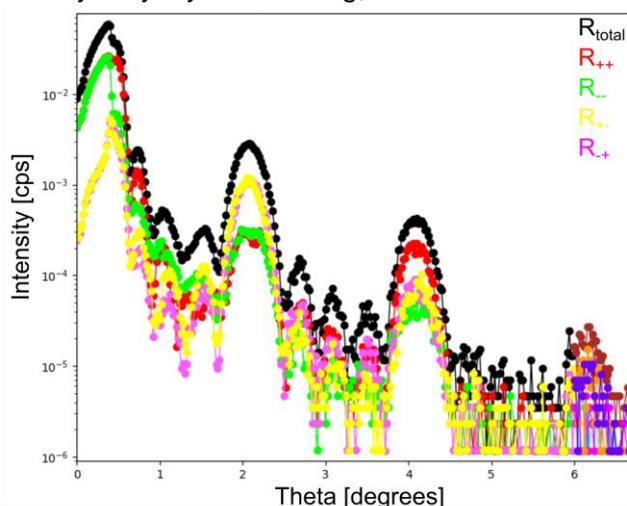


Figure 2: PNR measurements of an Fe/MgO superlattice with 10 bilayer repetitions and 20 and 17 Å thick Fe and MgO layers, respectively. The measurement was conducted at 10 K and remanence. Different curves relate to measurements of different (non-)spin -flip channels.

The changes in magnetic properties of the Fe/MgO superlattices with temperature were found to be dependent on the extension of the superlattice, i.e. on the Fe layer thickness and number of bilayer repetitions. As all of these magnetic properties can be related to the coupling strength, temperature studies of the coupling mechanism in Fe/MgO superlattices with different extension might allow for understanding which mechanisms are responsible for the tunneling mediated coupling in Fe/MgO superlattices.

2. Experiment

During the beamtime at ILL we measured polarized neutron reflectivity (PNR) from Fe/MgO superlattice thin films with different number of bilayer repetitions at selected magnetic fields

applied along the Fe easy axis. We conducted the measurements at different temperatures. The purpose of the experiments was to identify where the magnetization in each Fe layer points at different applied magnetic fields and how it changes with temperature. The results enable us to understand the switching behavior in Fe/MgO superlattices depending on the total extension of the superlattice. The study was completing previous measurements conducted at Paul-Scherrer Institut (PSI) in Switzerland and J-PARC in Japan.

In total, we conducted measurements on samples with 2, 8, and 10 bilayer repetitions. All samples had constant Fe and MgO layer thicknesses of 20 and 17 Å, respectively. Measurements were conducted at 10 K, 300 K, and at around 243 K, which was selected based on the results we obtained from L-MOKE measurements conducted prior to the PNR study.

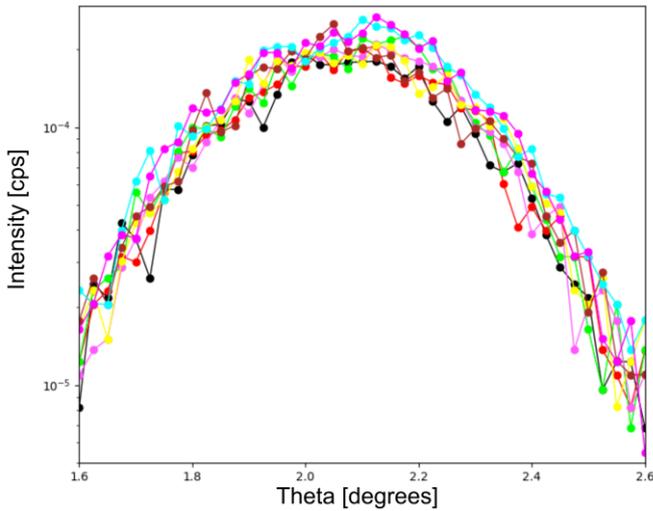


Figure 3: PNR measurements around the Q1/2 Bragg peak of an Fe/MgO superlattice with 8 bilayer repetitions and 20 and 17 Å thick Fe and MgO layers, respectively. The different curves relate to measurements conducted at different temperatures: 10, 100, 150, 200, 250 and 300 K at remanence. Only the intensities of the spin-flip channel are displayed.

3. Results

With the relatively high neutron flux instrument and resolution at ILL we were able to measure PNR up to the 2nd Bragg peak in reflectivity with pronounced Kiessig fringes. Based on the fitting of the measurements, a similar switching behavior for samples with different number of bilayer repetitions is observed. In contrast to the expected antiferromagnetic alignment at remanence, the alignment seems to be locked in a 90 degrees configuration without field for all measured samples. The alignment may originate from a competition between the antiferromagnetic coupling and the four-fold magneto crystalline anisotropy in the single crystalline Fe layers. These observations are interesting because in the previously measured hysteresis loops within an L-MOKE setup, the remanent state of the samples with 8 and 10 bilayer repetitions related to an antiferromagnetic alignment for the sample with 20 Å Fe layer thickness. Based on PNR, the 90 degrees alignment at remanence seems to be more pronounced for samples with 10 compared to 8 bilayer repetitions. The origin of this difference has not been found yet. As PNR measurements illuminate the whole sample area (20 mm x 20 mm) and L-MOKE measurements are probing a smaller area (1 mm x 1 mm), averaging effects from different sample regions have been suggested as a possible cause. Locally resolved L-MOKE measurements within a Kerr microscope are planned in order to confirm or falsify this hypothesis.

Furthermore, PNR measurements around the Q1/2 Bragg peak revealed that the observed 90 degrees alignment at remanence at 300 K does not change with decreasing temperature as the peak intensity is

constant between 10 and 300 K for both, the samples with 8 and with 10 bilayer repetitions. Nevertheless, additional measurements at applied external magnetic fields (10 and 40 mT) and different temperatures confirmed a change in switching behavior with temperature, which can be directly related to the L-MOKE hysteresis loops.

4. Conclusions

The PNR measurements at SuperAdam at ILL complete our study on the dependence of the IEC in Fe/MgO superlattices on the extension of the superlattices. Together with the complete x-ray scattering study on layering and crystal structure of the samples as well as the conducted L-MOKE and ferromagnetic resonance measurements, we are now able to combine all the acquired information to a big picture. The results might shed more light on the physics behind the tunneling mediated coupling in Fe/MgO superlattices, highlighting how coupled quantum well states in artificial magnetic structures can affect their mesoscopic magnetic properties.

5. References

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