<table>
<tr><td>ESRF</td><td>Experiment title:
Investigation of bandgap dependent magnetic coupling strength probed by x-ray resonant magnetic reflectivity</td><td>Experiment number:
HC-2097</td></tr>
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Report:

Recently, static magnetic proximity effects (MPEs) in terms of an induced spin polarization in a non-magnetic metal (NM) adjacent to a ferro(i)magnetic material (FM) are receiving a lot of attention, due to their potential interference with pure spin current effects investigated in spincaloric and spintronic experiments. In particular, a wide range of experiments in the field of spin caloritronics have been subject to controversial discussion, as many of the studied spin current phenomena depend on the application of Pt films in contact to a FM as a spin detector via the inverse spin Hall effect. Pt is well known to be a strongly Stoner enhanced Pauli paramagnet and, thus, is likely to exhibit an MPE in the vicinity to a FM. The resulting interface spin polarization can generate spurious effects obscuring the experimental results [1]. Therefore, a thorough observation of the interface between Pt and a FM is imperative in order to investigate spin caloritronic effects unequivocally.

In general, it is well understood that the MPE is mainly governed by band hybridization of NM and FM interface states and by exchange interactions across the interface. Both of these mechanisms critically depend on the electronic structure of the contributing materials, specifically on the presence of electronic states around the Fermi level. However, since in many spin caloritronic experiments ferro(i)magnetic insulators (FMIs) are utilized, an experimental validation of this mechanism would be a highly valuable result for this field of research.

In order to investigate and evaluate these questions we measured a series of different sputter deposited Pt/FM bilayers with different FM compositions. In particular, we varyied the oxygen content in different ferro(i)magnetic $NiFe_2O_x$ compounds from metallic to insulating and measured the Pt interface spin polarization using x-ray resonant magnetic reflectivity (XRMR) at the Pt L_3 absorption edge. Thus, we monitored the induced MPE in Pt in contact to different FMs with strongly varying electronic properties.

The method XRMR provides element specific information on the magnetic properties of thin film materials, in particular the spatial distribution of magnetic moments in multilayer systems [2]. Thus, XRMR represents an excellent technique in order to probe the interface spin polarization in our hybrid structures. All measurements were performed in a diffractometer at beamline BM28, which provides excellent conditions for the resonant scattering experiments regarding photon energies, beam polarization, detection capabilities, and switchable magnetic fields.

Prior to our experiments at the ESRF we tested the electronic properties of each FM by temperature dependent conductivity measurements and evaluated the transport properties and the electronic activation energy with respect to the different degrees of oxidation. The best suited samples were investigated at the beamline. We studied four different Pt(~3nm)/$NiFe_2O_x$(~50nm) bilayers for MPEs using XRMR at the L_3 edge of Pt, including a purely metallic $NiFe_2$ sample and an insulating $NiFe_2O_4$ film, as well as two samples with intermediate oxygen contents and corresponding electrical characteristics, i.e., semiconducting properties.

The XRMR measurements on the hybrid structure with metallic $NiFe_2$ reveal a pronounced MPE in Pt, while the Pt/$NiFe_2O_x$ bilayers with finite oxygen content do not show any evidence for an induced spin polarization in the Pt layer within the detection limits. Thus, even a small bandgap in the FM generated by the oxidization seems to suppress a coupling between the interface states and prevents an MPE. Complementary spin caloritronic experiments on the Pt/$NiFe_2O_x$ samples are currently carried out in order to gain a copious picture.

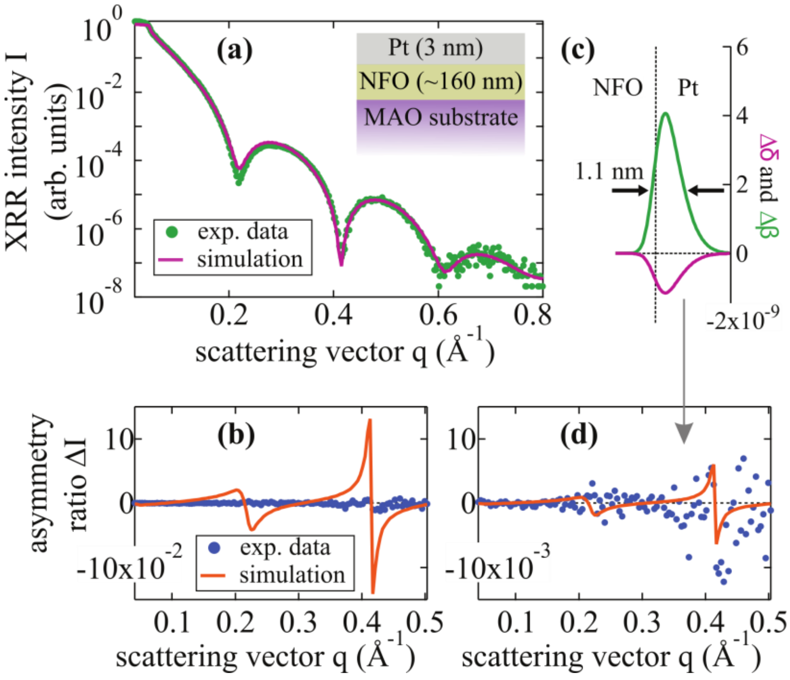

Figure 1: Resonant non-magnetic x-ray reflectivity (XRR) (a) and XRMR ((b), (d)) along with corresponding magnetooptical profile (c) of the Pt/$NiFe_2O_4$ bilayer.

The Pt/$NiFe_2O_4$ heterostructure is evaluated in more detail, since this system is particularly interesting for spin caloritronic studies and has already been applied in different investigations of the longitudinal spin Seebeck effect [3,4]

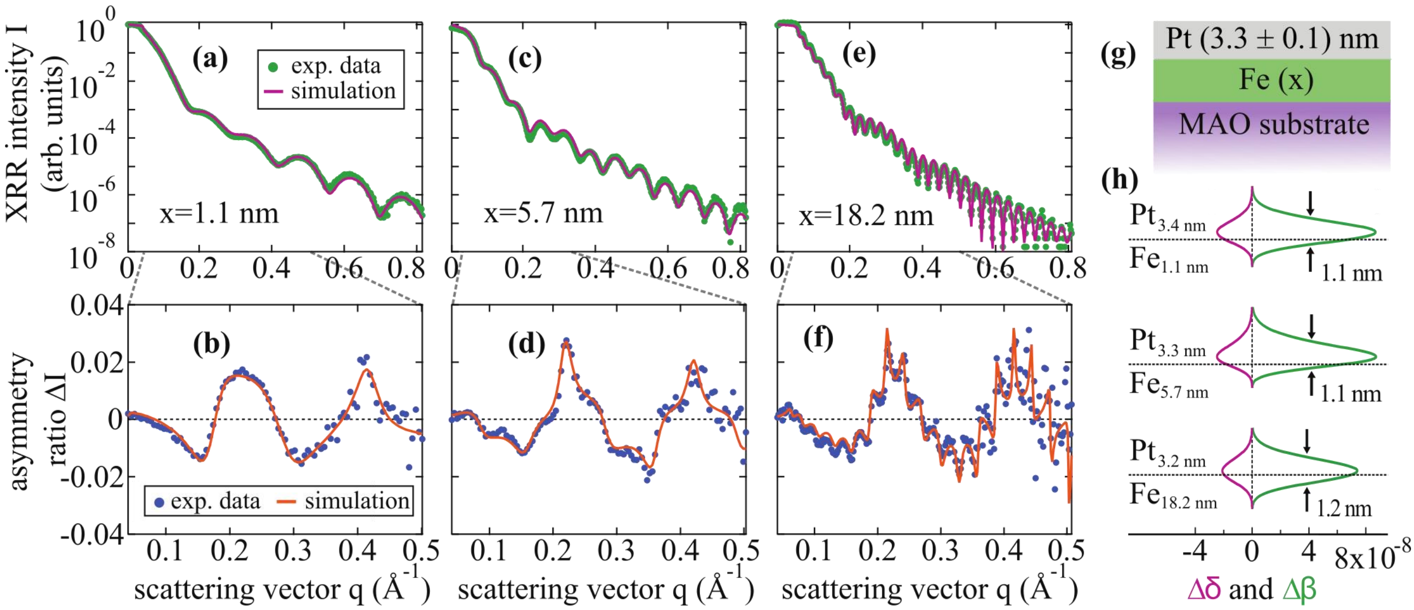

Figure 2: Resonant non-magnetic XRR ((a), (c), and (e)) and XRMR ((b), (d), and (f)) along with the corresponding magnetooptical profiles (h) of the different Pt/Fe samples.

and the spin Hall magnetoresistance [5]. A precise analysis based on simulations for different magnetization profiles allows us to estimate an upper limit for the induced magnetic moment of 0.04 μ_B/atom in an effective spin polarized Pt interface layer. The corresponding measurements and the magnetooptical profile is shown in Figure 1.

Additionally, we measured a series of Pt(~3.3nm)/Fe(x nm) heterostructures with different Fe thicknesses (x=1.1–18.2 nm) as a reference. Figure 2 shows the results from the XRMR measurements on the different Pt/Fe bilayers. The induced spin polarization is around 0.5 μ_B/Pt atom in all three hybrids, thus, the MPE shows no Fe thickness dependence down to a film thickness of 1.1 nm. This is a strong evidence that the MPE is a pure interface effect and is generated by only a few monolayers of the FM.

The results of the beamtime HC-2097 at BM28 are published in Ref. [6], which is currently in press. They are in good agreement with our previous work [7] and complement these studies to a comprehensive overview on the MPE in different Pt/$NiFe_2O_4$ bilayers and on the dependence of the MPE on the NM and the FM thickness.

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