Static proximity effect in Pt/NiFe$_2$O$_4$ and Pt/Fe bilayers investigated by x-ray resonant magnetic reflectivity

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In spintronics [1] and spin caloritronics [2] a spin current can be generated in ferromagnetic insulators (FMI) e.g. by the spin Seebeck effect (SSE) [3]. These spin currents are typically detected using a normal metal (NM) thin film attached to the FM material. The inverse spin Hall effect (ISHE) [4] converts the spin current into a transverse voltage in the NM which should have high spin-orbit coupling for large spin Hall angles. Here, Pt is typically used, but controversially discussed due to its closeness to the Stoner criterion. A magnetic proximity effect in the NM at the NM/FMI interface has to be taken into account and can lead to the proximity anomalous Nernst effect [5]. Therefore, we investigated the spin polarization of Pt in Pt/NiFe$_2$O$_4$ and Pt/Fe bilayers by x-ray resonant magnetic reflectivity (XRMR) [6] at the resonant scattering beamline P09 [7]. This study follows our temperature- and angle-dependent SSE measurements [8] and spin Hall magnetoresistance investigations [9] in Pt/NiFe$_2$O$_4$ (NFO) bilayers. We prepared NFO films of up to 1 µm thickness on MgAl$_2$O$_4$(001) (MAO) substrates by direct liquid injection chemical vapor deposition (DLI-CVD) [8]. Fe and Pt were deposited by dc magnetron sputtering in an Ar atmosphere.

The reflectivity was taken for circularly polarized light and different external magnetic field directions with a photon energy of the Pt $L_3$ absorption edge (11568 eV). The degree of polarization was 98.4% for right circular and 99.7% for left circular polarization during our experiments. We used the 6-circle diffractometer at the first experimental hutch P09-EH1 to measure the reflectivity in $\theta - 2 \theta$ scattering geometry, while an external magnetic field was applied. The observed asymmetry signal $I_+ - I_-$ between different alignment of circular polarization and different magnetic field directions ($\pm 85$ mT) is directly sensitive to the induced Pt spin polarization at the interface. The setup is pictured in Fig. 1. The reflectometry curves have been fitted using the recursive Parratt algorithm [10] and the analysis tool iXRR [11]. The asymmetry was simulated with ReMagX using additional magnetooptic profiles for the change of optical constants [12].

Figure 1: (a) Sketch of the measurement geometry. The external magnetic field is aligned parallel to the plane of incidence and to the sample surface. (b) XRMR setup at the beamline P09 at DESY.

For all Pt/Fe samples we observed an asymmetry magnitude of 2% independent from the Pt thickness as shown exemplarily for Pt(3.4 nm)/Fe(9.1 nm)/MAO in Fig. 2. Therefore, the magnetic proximity in Pt can be directly investigated independent from the Pt thickness.
Figure 2: (a) XRMR curves for Pt(3.4 nm)/Fe(9.1 nm)/MAO. (b) Asymmetry of 2% and simulated data.

For Pt/NFO the asymmetry vanishes within the sensitivity limit of 0.2% (cf. Fig. 3). For comparison, a simulated asymmetry is shown using the magnetooptic profile of Pt/Fe for the Pt/NFO sample. Due to the different optical constants for NFO compared to Fe, the amplitude of the asymmetry signal is larger for Pt/NFO compared to Pt/Fe using the same magnetooptic profile. The oscillations from the simulation can not be observed in the experimental data. Therefore, a static proximity effect and the proximity anomalous Nernst effect can be excluded in our previously performed SSE investigations on Pt/NFO bilayers.

Figure 3: (a) XRMR curves (averaged over 8 curves) for Pt(3.2 nm)/ NFO(∼ 900 nm)/MAO. (b) Asymmetry of the XRMR curves in (a) and simulated data. (c) XRMR curves averaging over 52 curves for the reflectivity from $q = 0.2\,\text{Å}^{-1}$ up to $q = 0.6\,\text{Å}^{-1}$. (d) Asymmetry of the XRMR curves in (c).

References