Investigation of coupling parameters in MgO-based magnetic tunnel junctions

Ł. Gładczuk, L. Gładczuk, P. Dłużewski, K. Lasek, P. Aleshkevych, D. M. Burn, G. van der Laan, and T. Hesjedal.

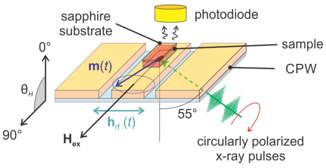
Heterostructures composed of ferromagnetic layers that are mutually interacting through a non-magnetic spacer are at the core of magnetic sensor and memory devices. In the present study, layer-resolved ferromagnetic resonance was used to investigate the coupling between the magnetic layers of a Co/MgO/Permalloy magnetic tunnel junction. Two magnetic resonance peaks were observed for both magnetic layers, as probed at the Co and Ni L3 x-ray absorption edges, showing a strong interlayer interaction through the insulating MgO barrier. A theoretical model based on the Landau-Lifshitz-Gilbert-Slonczewski equation was developed, including exchange coupling and spin pumping between the magnetic layers. Fits to the experimental data were carried out, both with and without a spin pumping term, and the goodness of the fit was compared using a likelihood ratio test. This rigorous statistical approach provides an unambiguous proof of the existence of interlayer coupling mediated by spin pumping.

INTRODUCTION

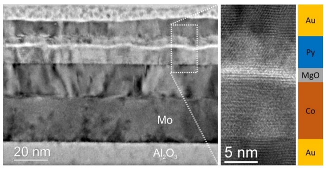
Magnetic tunnel junctions (MTJs) are composed of two ferromagnetic films separated by an ultrathin layer of insulating material. Due to spin-dependent tunneling, the current flow in such systems is affected by the relative direction of the magnetization in the layers. MTJs have attracted much attention in the past years as promising candidates for spintronic devices, offering a broad range of practical uses, e.g., at the core of sensor elements and memory devices. MgO-based MTJs are particularly attractive due to their high tunneling magnetoresistance ratio.

In this study we shed new light on layer coupling and spin pumping phenomena by performing a detailed study of the magnetic layer dynamics in a Co/MgO/Permalloy (Py = $Ni_{80}Fe_{20}$) MTJ heterostructure using layer- and time-resolved x-ray detected ferromagnetic resonance(XFMR). XFMR employs x-ray magnetic circular dichroism (XMCD) to detect ferromagnetic resonance (FMR) from magnetic alloys and multilayers of thicknesses as thin as a few nanometers in an element-specific way. For heterostructures composed of chemically distinct magnetic layers, each of the constituent layers can be probed separately. XFMR is therefore ideally suited for characterizing interlayer coupling unambiguously in many device-relevant heterostructures.

SAMPLE PREPARATION AND EXPERIMENTAL

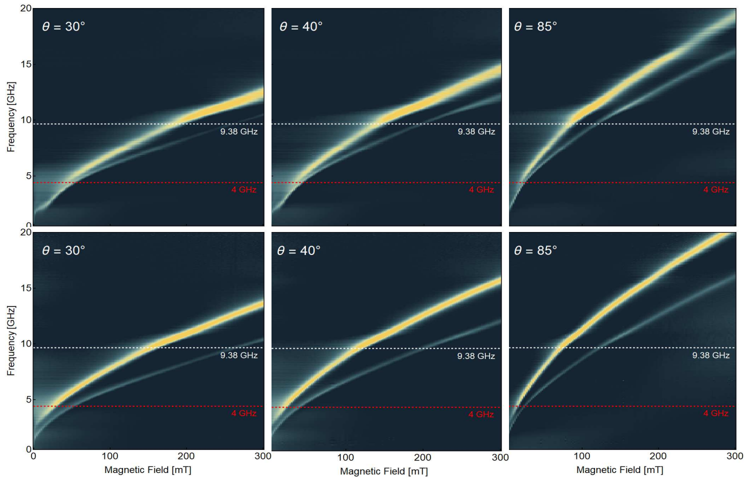


Schematic of the XFMR measurement in transverse geometry. The sample is placed face down onto the central conductor (CPW). A microwave signal $h_{rf}(t)$ is fed to the CPW and the magnetization m(t) precesses about the direction of the applied static magnetic field H_{ex}(here the θ_H = 90° in-plane). Due to the pulsed nature of the synchrotron radiation, the component of m(t) along the beam dire-ction can be detected stroboscopically.



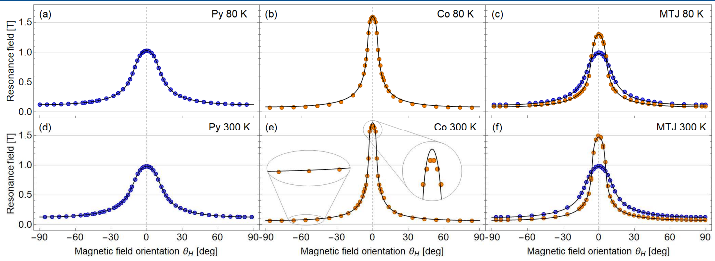
XTEM image of the a-plane sapphire/ Mo/Au/Co/MgO/Py/Au MTJ. In the overview on the left-hand side, the layer stack can be seen. In the close-up on the right-hand side, the core of the MTJ is highlighted, consisting of the ferromagnetic Co and Py layers, separated by a continuous, insulating MgO barrier. The samples were grown using molecular beam epitaxy (Riber EVA 32 IFPAN ON-3.4)

VNA-FMR ABSORPTION



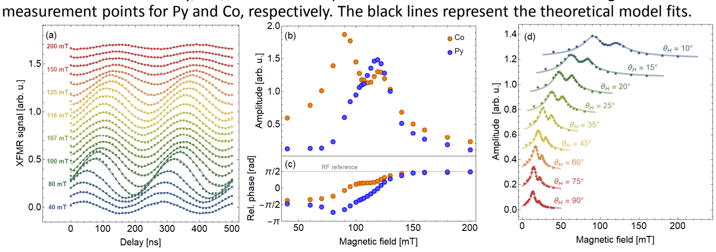
VNA-FMR absorption as a function of applied magnetic field (θ_H = 30°, 45° and 85°) and excitation frequency for the MTJ sample held at 80 and 300 K. The brightness of the signal corresponds to the strength of the absorption. As the sample consists of two distinct magnetic layers, two resonance curves are visible. White and red dashed lines indicate the frequencies at which the cavity FMR and XFMR were performed, respectively.

FMR



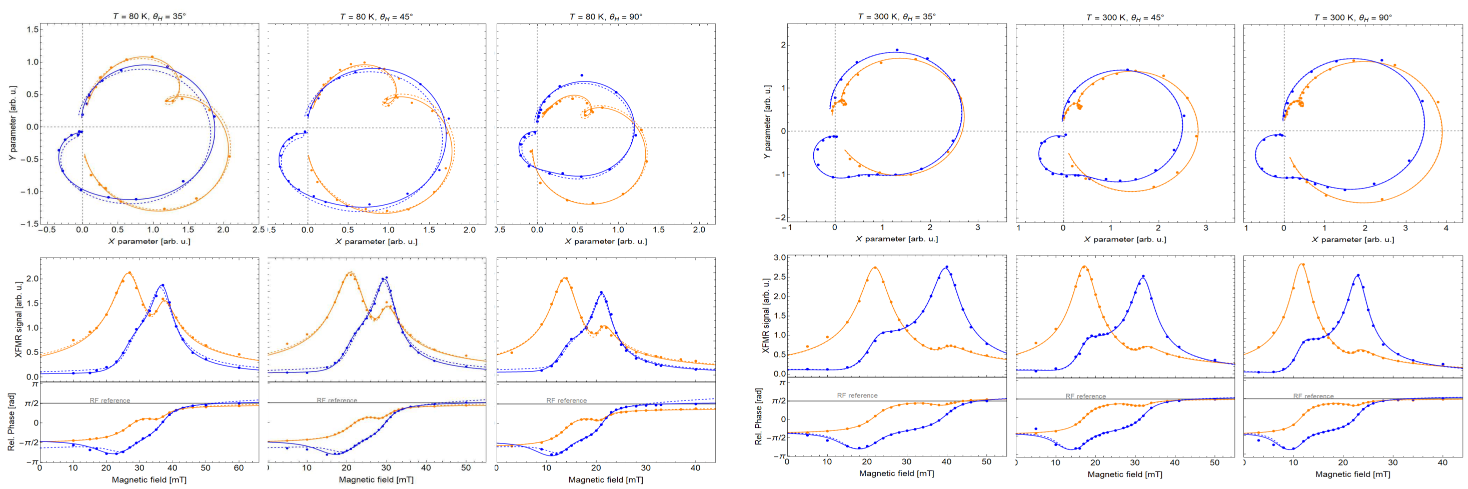
Cavity FMR resonance curves as a function of external magnetic field direction (θ_H) with respect to the surface normal for the Py, Co, and MTJ samples at 80 and 300 K. Blue and orange dots refer to measurement points for Py and Co, respectively. The black lines represent the theoretical model fits.

XFMR



XFMR measurements of the MTJ sample at 80 K. (a) XFMR delay scans for the Co layer with the magnetic field oriented at θ_H = 10°. The continuous lines represent the fitted sinusoidal functions. Their amplitude and phase as a function of magnetic field strength is plotted in panels (b) and (c), respectively. (d) Magnetic field direction dependence of the XFMR amplitude for the Co layer.

DATA ANALISIS



Comparison of the results for model I (EC only, dashed lines) and model II (EC+SC, solid lines) for different external magnetic field angles and temperatures: T= 80 K and T= 300 K. The experimental data is shown as circles for the Co (orange) and Py (blue) layers. The top row shows the FMR plots in the (X,Y)-plane, for the field increasing going counter clockwise along the curves. The middle and bottom row show the corresponding amplitude (C) and relative phase (ψ) plots, respectively, as a function of field.

CONCLUSIONS

An in-depth study of Co/MgO/Py MTJs was per-formed using layer- and time-resolved XFMR. A theoretical model, based on micromagnetic theory, was derived for the system under investigation. By fitting the model to the acquired data, parameters characterizing the magnetization dynamics of the MTJ were determined. The spin pumping mediated co-upling between the magnetic layers has been confirmed by performing a rigorous statistical analysis. Two alternative hypotheses were considered, the first only considering inter-layer exchange coupling and the second also including spin pumping. The hypotheses were compared using a likelihood ratio test, allowing us to conclude with great confi dence that spin pumping is present in the MTJs. The improvement of the fit that is achieved by including spin pumping is most clearly visible at 80 K. The fitted spin pumping coefficient $a^{\uparrow\downarrow}$ is more than twice as high for the MTJ sample at 80 K than at 300 K. This shows that spin pumping is more effective at lower temperatures, which agrees with the theoretical understanding. In summary, using a rigorous statistical approach for the analysis of XFMR data, we are able to provide unambiguous proof of the existence of spin pumping in MTJs, thereby supplying a reliable tool set for the systematic temperature-dependent study of spin transfer phenomena in heterostructures. Published: **Phys. Rev. B 103, 064416 (2021)**