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Report:

We proposed a continuation of our preeliminar investigations on the magnetisation reversal processes in complex multilayered systems by using a *unique* experimental set-up that we implemented at ID08 during our precedent beamtime HE-2840, which combines element-selective spectroscopy and holography measurements in the soft x-ray range [1]. This allows us to combine quantified information from element-selective spectroscopy data (simultaneuously measured in both TEY and transmission modes) with the magnetic imaging capability from holography experiments by using special sample-mask structures [1,2].

During the HE-2840 beamtime we could image for the first time the magnetisation reversal of a ferromagnetic $[Pt/Co]_n$ multilayer (with an equivalent Co thickness below 5 nm, 1.8 μm diameter field-of-view FOV and with 170 nm spatial resolution) exchange coupled to a IrMn antiferromagnetic layer [2]. In addition, spectroscopic measurements in Total Electron Yield mode (TEY) were successfully used to detect uncompensated Mn moments in the antiferromagnetic (AFM) IrMn layer [2], but we couldn't detected them in transmission geometry. Therefore, we could not image the uncompensated AFM domain structure in the $[Pt/Co]_n$/IrMn system.

During the HE-3272 beamtime we wanted to explore the capabilities of our set-up. We extended our studies to another perpendicular exchange biased FM/AFM system and we improved the design of the sample-mask structures, *aiming to image the domain structure of both FM and uncompensated AFM moments*. In particular, we used a FeMn layer as AFM

system. Macroscopically both FM/FeMn and FM/IrMn systems behave similarly, but different transmission sensitivities were found for them, as shown in this report, regarding to explore the capability to image the uncompensated AFM domain structure exploting the element-selectivity of the technique.

Spectroscopy analysis

The analysis of the XAS and XMCD spectra collected simultaneously by recording both TEY and transmitted signals, provides valuable (quantified) information about the magnetic properties of the exchange-coupled FM/AFM systems, about their depth location, as well as about the possibility to exploit the dichroism in the transmitted beam intensity for imaging.

Figure 1 shows raw XAS spectra (top) at the Fe and Co $L_{2,3}$ absorption edges of the $[Pt/Co]_8$/10 nm FeMn sample recorded at negative saturation with positive and negative photon helicities, and the corresponding XMCD spectra (bottom). The obvious difference between the absorption spectra can be understood by considering the different information depths of both detection modes. *Note that the small dichroism signal at the Fe-L edges is only seen by transmission detection.* This indicates that the moments contributing to this signal, i.e., referred as uncompensated AFM moments, are not homogeneously distributed over the AFM layer but deeply buried from the top AFM surface [3]. In addition, the same sign of both Fe and Co XMCD signals reveals a parallel alignment between the FM and the net (uncompensated) AFM moments. By using sum rule analysis, we estimate an *effective thickness of uncompensated Fe moments of (1.6±0.5) monolayers (ML) assuming that they are localized at the AFM/FM interface*, which is strongly supported by the vanishing TEY-XMCD signal.

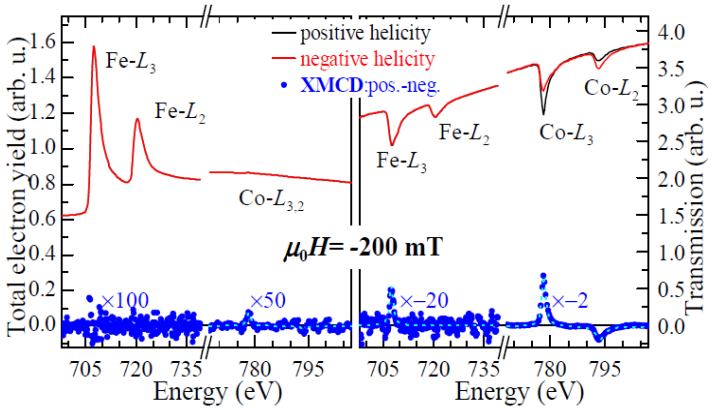

Fig. 1: Absorption and XMCD spectra at the Fe-*L* and Co-*L* edges of a [1.8 nm Pt/0.6 nm $Co]_8$/10 nm FeMn sample recorded by the detection of the TEY signal (left) and the transmitted photon intensity (right) [3]. The sample is placed with the FeMn layer facing the incoming x-ray beam in a external field of -200 mT. The x-axis of the graphs is split for clarity. Note that *the small dichroism signal at the Fe-L edges is only seen by transmission detection.*

Secondly, both spectroscopy and element-selective XMCD hysteresis loops measurements revealed the existence of two types of interfacial uncompensated AFM moments, which behave differently during FM reversal (see Fig. 2). For instance, the Fe-L_3 hysteresis loop reproduces the Co-L_3 one, i.e., it shows a horizontal shift to negative values (the exchange bias field $\mu_0 H_E < 0$), opposite to the field cooling FC direction $\mu_0 H_{FC}$= +200 mT. In addition, the Fe-L_3 hysteresis loop is slightly shifted vertically downwards [4]. This indicates that the majority (90%) of the uncompensated AFM moments rotates during FM reversal (*unpinned moments*) whereas a small amount (10%) stays aligned antiparallelly to the FC direction (*pinned moments*). This indicates a preferred antiparallel alignment between the FM and the pinned AFM moments, which suggests an antiferromagnetic coupling across the interface between them.

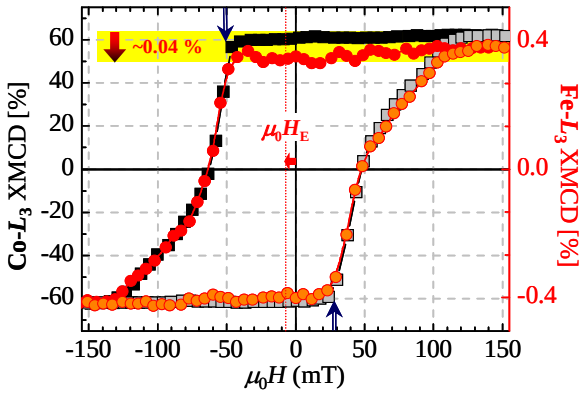

Fig. 2: Element-selective XMCD hysteresis loops of a [1.8 nm Pt/0.6 nm Co]$_8$/10 nm FeMn sample acquired in transmission geometry [4]. The symbols show the evolution of the XMCD signal with the external field recorded at the Co-L_3 (filled symbols, left y-axis) and Fe-L_3 (open symbols, right y-axis) edges, which reflect the hysteresis loop of the FM and the unpinned AFM moments, respectively. XMCD data are normalized to their corresponding absorption L_3 peaks.

Similar quantified results were obtained for the AFM/IrMn system [2], providing a general character of the perpendicular exchange bias phenomena. We have to notice that, for the FM/FeMn system, these uncompensated moments were quantified from XMCD-transmission experiments. The later suggested us the possibility to use holography measurements for imaging the domain structure of the uncompensated AFM moments.

Magnetic imaging

New and improved sample-mask structures, with smaller reference holes and thicker mask films, were used to study [Pt/Co]$_n$/FeMn systems. First, we studied the influence of reference hole size on the quality of the magnetic image by using a sample-mask structure with five reference holes of different size (see Fig. 2 of Ref. [3]). In short, the contrast increases with the reference hole size while resolution diminishes. In practice, the image is as if it was painted by a pencil of tip similar to the size of the reference hole.

Second, we checked the general microscopic behavior of the results obtained previously with the IrMn system with a better spatial resolution (as shown Fig.3). In general, the images showed that the magnetization reversal is characterized by nucleation of magnetic domains and domain wall propagation processes. Different magnetic domain configurations were also found in the increasing and decreasing field branches of the hysteresis loop, i.e., asymmetric reversal [4].

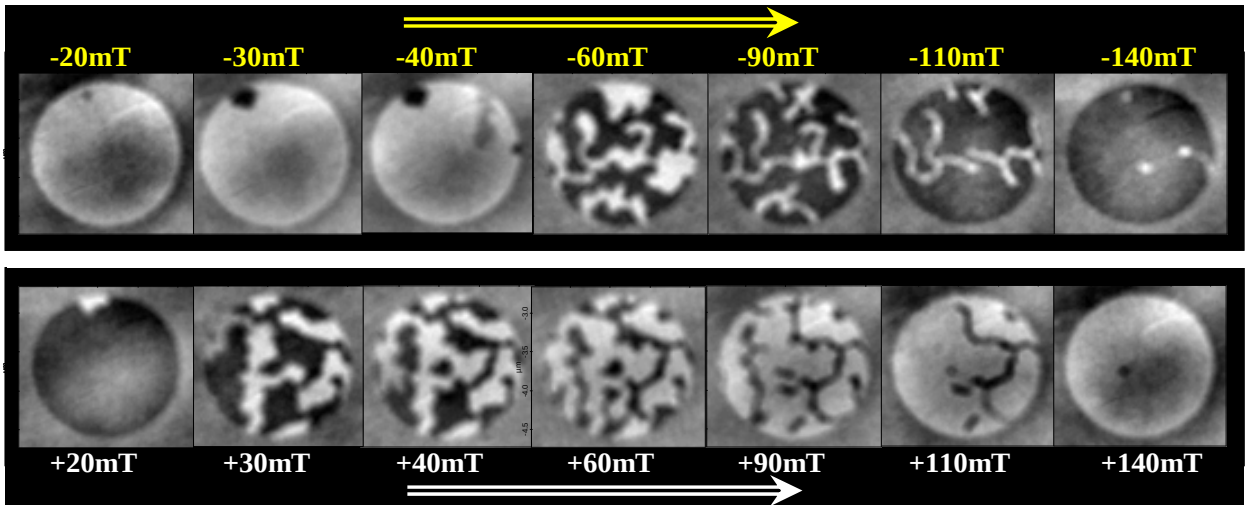

Fig. 3: Evolution of the magnetic domain structure of the FM layer along the decreasing (top panel) and increasing (bottom panel) field branches of the [1.8 nm Pt/0.6 nm Co]$_8$/10 nm FeMn sample [4]. The images were retrieved from the Fourier transform of magnetic holograms acquired at the Co-L_3 absorption edge during mangetisation reversal. The magnetic field values are given in each image. FOV= 1.8 μm.

Third, we could image for the first time the magnetization reversal of the uncompensated AFM moments [3]. The element-selectivity capability of soft x-ray holography has been exploited for the FM/FeMn sample. The small but significant XMCD signal in transmission at the Fe-L_3 edge (0.4% of the total absorption, much smaller than the signal at the Co-L_3 edge of about 60%) implies that long acquisition times had to be used for imaging the uncompensated AFM moments, i.e., fifteen times longer that for the Co images (for which we used ~1-2 min). Figure 4 displays element-selective magnetic images taken at positive saturation (right images) and during the decreasing field branch (left) of the hysteresis loop. At positive saturation, the element-selective magnetic images show just bright gray scale values whereas during the decreasing field branch several coincident magnetic domains (black) are observed. This reveals that *the uncompensated AFM moments replicate the magnetic domain structure of the FM layer, proving that the FM moments locally drag the unpinned AFM moments during magnetization reversal* [3]. The energy cost to do that would explain the coercivity enhancement found in FM/AFM systems. Thus, the holography imaging experiments allowed visualizing the magnetization reversal processes and the direct correlation between the magnetic structure of both FM and unpinned AFM moments (less than 1 ML)

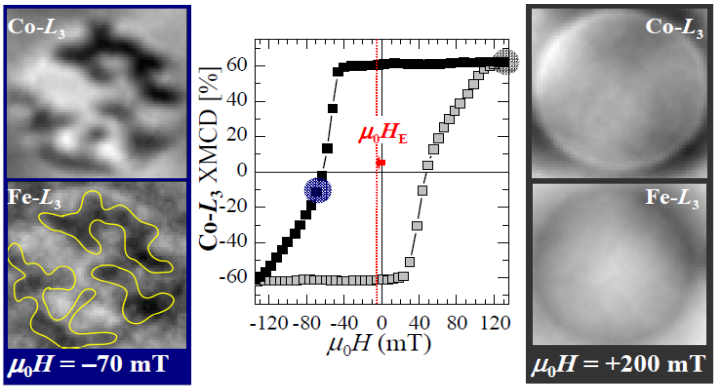

Fig. 4: Selected element-selective magnetic images of the [1.8 nm Pt/0.6 nm Co]$_8$/10 nm FeMn sample during magnetization reversal [3]. The images retrieved from magnetic holograms recorded at Co-L_3 (top) and Fe-L_3 (bottom) absorption edges represent the magnetic domain structure of the FM layer and the uncompensated moments of the AFM layer, respectively. FOV= 1.8 μm. Center: hysteresis loop recorded in transmission. Notice that *the magnetic contrast of the uncompensated AFM moments corresponds to an effective thicknes as small as one monolayer thick*, as derived from the spectroscopic analysis, *and that mimics the FM magnetic domain structure*.

Unfortunately, the total integrated dichroism signal of the pinned AFM moments was really small, i.e., effective AFM thickness of about 0.1 ML, meaning that we could not identify (image) where they were located. These pinned AFM moments will be the core subject of our interest in next proposals since they govern the exchange bias field in FM/AFM systems.

References

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