Quantifying and imaging magnetization reversal of buried interfaces by soft x-ray spectroscopy and holography

J. Camarero,[1,2,*] E. Jiménez,[1] J. Vogel,[3] C. Tieg,[4,5] P. Perna,[2] A. Bollero,[2] F. Yakhou-Harris,[4] C. Arm,[6] E. Gautier,[6] S. Auffret,[6] B. Delaup,[6] G. Gaudin,[6] B. Rodmacq,[6] B. Dieny,[6] and R. Miranda.[1,2]

[1]*Departamento de Física de la Materia Condensada and Instituto de Física de Materiales "Nicolás Cabrera", Universidad Autónoma de Madrid, 28049 Madrid, Spain.*
[2]*IMDEA-Nanoscience, Campus de Cantoblanco, 28049 Madrid, Spain.*
[3]*Institut Néel-CNRS, 38042 Grenoble, France.*
[4]*ESRF, F-38043 Grenoble, France*
[5]*Laboratory Helmholtz-Zentrum Berlin Albert-Einstein-Strasse 15 D-12489 Berlin Germany.*
[6]*SPINTEC, URA2512 CNRS/CEA, 38054-Grenoble, France.*
julio.camarero@uam.es

The spin arrangement at the interface in layered magnetic nanomaterials is often crucial for the understanding of their magnetic properties and has profound consequences for practical applications. The most striking feature is the unidirectional coupling between the spins in an antiferromagnet (AFM) and those in an adjacent ferromagnet (FM), referred to as exchange bias [1]. FM/AFM structures are at the heart of today's spintronic devices, stabilizing the direction of FM reference layers, while taking advantage of the interfacial exchange interaction effects [2]. In addition, there are a plethora of other magnetic phenomena associated in exchange-coupled FM/AFM systems, such as coercivity enhancement, magnetization reorientation, modified antiferromagnetic spin structures, and asymmetric magnetization reversal, which are not fully understood. Prospects for control, tailor, and enhancement of desirable effects depend upon a clear understanding of the mechanisms governing exchange bias. However, the lack of techniques capable of providing detailed magnetic information of buried interfacial layers with element selectivity and upon external fields is delaying this understanding.

Only very few experimental techniques can address the microscopic magnetization reversal behavior of the different magnetic layers in a multilayered system with element selectivity. Scattering based techniques, such as soft x-ray magnetic resonant scattering (SXMRS) [3] and lensless holographic imaging [4], have been established as a powerful tools for studying magnetic structures in surfaces and thin films on the nanometer length scale. The soft x-ray range hosts the largest magnetic resonances of the magnetically important transition-metal and rare-earth series. Additionally, holographic imaging combines the magnetic sensitivity obtained with x-ray magnetic circular dichroism in transmission geometry with the spatial resolution from a simple Fourier inversion of a reciprocal space soft x-ray interference pattern from an object (sample) and a reference aperture (which defines the final spatial resolution). In addition, the technique can image deeply buried magnetic systems and, as a pure photon-based technique (photon-in/photon-out), can be used in applied magnetic fields. Up to now, soft x-ray holography has focused on $[\text{non magnetic/magnetic}]_n$ multilayers with perpendicular magnetic anisotropy for both remanence and field-dependent measurements. However, only relatively large (> 5 nm) effective magnetic thicknesses have been studied, and both element-specificity and quantification-availability has not been yet exploited.

We have recently spread out the capabilities of soft x-ray holography for imaging the magnetization reversal, by adding the quantitative aspects of magnetic spectroscopy [5]. We have implemented a unique experimental set-up at beamline ID08 of the European Synchrotron Radiation Facility (ESRF) combining soft x-ray holography and spectroscopy capabilities. This new set-up allows performing element-selective soft x-ray holography measurements for imaging the domain structure of buried magnetic ultrathin films with perpendicular anisotropy under applied magnetic fields, adding the quantitative aspects of magnetic spectroscopy measurements in both total electron yield (TEY) and transmission detection modes. We have investigated ferromagnetic (FM) $[\text{Co/Pt}]_n$ multilayers with perpendicular anisotropy exchange coupled with antiferromagnetic (AFM) FeMn and IrMn films. From

the spectroscopy analysis, both spectroscopy and element-selective XMCD hysteresis loops measurements confirm the existence of interfacial uncompensated AFM moments, i.e., ~1 ML (monolayer) thick, which behave differently during FM reversal. We have quantified the unpinned (pinned) uncompensated AFM moments, providing direct evidence of its parallel (antiparallel) alignment with respect to the FM moments. In addition, the Fe-L_3 hysteresis loop reproduces the Co- L_3 one, i.e., it shows a horizontal shift to negative values (opposite to the field cooling FC) direction, exchange bias field $\mu_0 H_E<0$) and, it is slightly shifted vertically downwards (see Fig.1.a). 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).

The holography experiments allow to image the magnetization reversal of an exchange-biased FM layer with an equivalent Co thickness below 3 nm in real space (1.8 μm diameter field-of-view FOV with 50 nm spatial resolution) and in external magnetic fields [5]. The field dependence images shows that the reversal mechanism of the FM layer is via nucleation, propagation and annihilation of magnetic domains and, in addition, different nucleation sites were found in both hysteresis branches, pointing out a possible deterministic nature of the reversal. A remarkable highlight is that we could image for the first time the magnetization reversal of the uncompensated AFM moments, which correspond to an equivalent thickness of less than one monolayer only [6], and under applied fields [7]. The images show that the uncompensated AFM moments reproduce the magnetic domain structure of the FM layer during the whole hysteresis loop (see Fig1.b) , which prove that the FM moments locally drag the unpinned AFM moments during reversal.

Our results provide new microscopic insights into the exchange coupling phenomena and explore the sensitivity limits of these techniques. Future trends will be also discussed.

References

[1] W. H. Meiklejohn and C. P. Bean, Phys. Rev. **102**, 1413 (1956).

[2] J. Nogués and I. K. Schuller, J. Magn. Magn. Mater. **192**, 203 (1999).

[3] J. Miguel, J. Camarero, J. Vogel, J. Peters, N. B. Brookes, and J. Goedkoop, Appl. Surf. Sci. **254**, 335 (2007).

[4] S. Eisebitt, J. Lüning, W. F. Schlotter, M. Lörgen, O. Hellwig, W. Eberhardt, and J. Stöhr, Nature **432**, 885 (2004).

[5] C. Tieg, E. Jiménez, J. Camarero, J. Vogel, C. Arm, B. Rodmacq, E. Gautier, S. Auffret, B. Delaup, G. Gaudin, B. Dieny, and R. Miranda, Appl. Phys. Lett. **96**, 072503 (2010).

[6] J. Camarero, E. Jiménez, J. Vogel, C. Tieg, P. Perna, A. Bollero, F. Yakhou-Harris, C. Arm, E. Gautier, S. Auffret, B. Delaup, G. Gaudin, B. Rodmacq, B. Dieny, and R. Miranda, 55th-MMM Conf. invited paper. To appear in J. Appl. Phys. (2011).

[7] E. Jiménez, et al. submitted

Figure

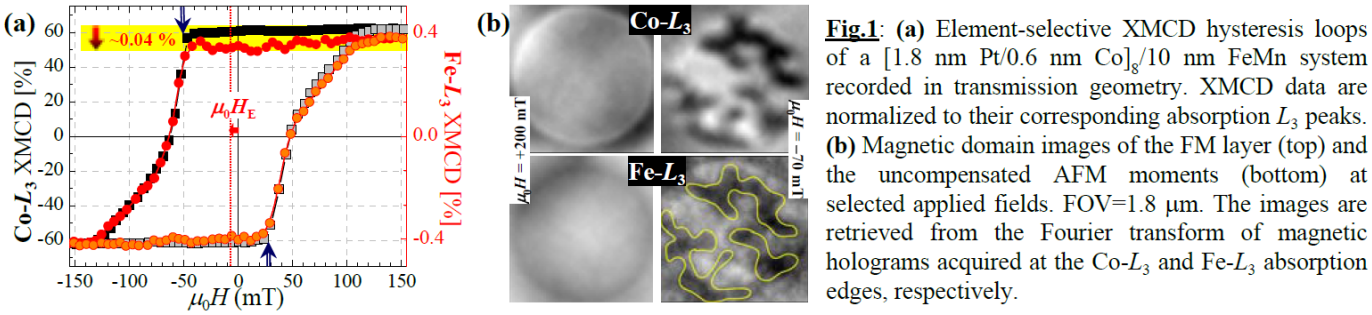

Fig.1: **(a)** Element-selective XMCD hysteresis loops of a [1.8 nm Pt/0.6 nm $Co]_8$/10 nm FeMn system recorded in transmission geometry. XMCD data are normalized to their corresponding absorption L_3 peaks. **(b)** Magnetic domain images of the FM layer (top) and the uncompensated AFM moments (bottom) at selected applied fields. FOV=1.8 μm. The images are retrieved from the Fourier transform of magnetic holograms acquired at the Co-L_3 and Fe-L_3 absorption edges, respectively.