Ferromagnetic domain wall manipulation using optically induced thermal gradients

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Supplementary Material

Determination of the Curie temperature. We determined the Curie temperature (T_C) of the [Pt(0.7 nm)/Co(0.4 nm)]$_3$ multilayer thin films using vibrating sample magnetometry (Quantum Design PPMS DynaCool^{TM}). The measurement was performed under zero applied field after the sample was saturated at a field of >1 Tesla. Fig. 1(a) shows the magnetic moments as a function of the temperature. The inset depicts the hysteresis loop obtained by MOKE magnetometry. The loops exhibits 100% remanence magnetization and a coercive field of 40 kA/m. We imaged the magnetic domains, which were initially induced by laser illumination, near the critical temperature. The magnetic contrast vanishes at 595±10 K, as shown in Fig. 1(b).

Magneto-optical images. We present magneto-optical images from a set of optically-induced domains, see Fig. 2(a). We note these domains are different from those imaged by XMCD-PEEM technique. The horizontal linear domain patterns were imprinted across a vertical domain wall. The beam polarization was set to σ^+, and the beam was swept at different speeds from 1 to 20 μm/s. We measured the intensity profiles in the direction of the red and black arrows. The intensity profiles relative to the background domains are shown in Fig. 2(b). The size of the island domains are beyond the resolution of the microscopy. In addition to this, the intensity profiles do not show the lateral distribution of the domains as shown in Fig. 1 in the main text.

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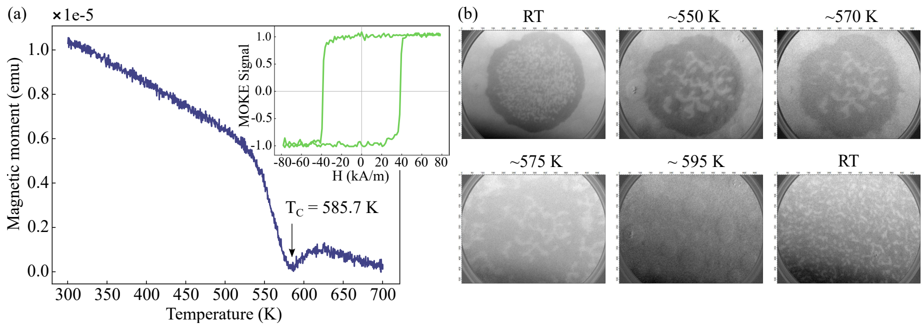

Figure 1: (a) Magnetic moments (emu) in $[Pt/Co]_3$ multilayer as a function of the temperature. T_C of this sample is at 585.7±0.4 K. A hysteresis curve obtained by MOKE technique in perpendicular geometry is given in the inset. (b) XMCD-PEEM imaging near T_C indicates the vanishing magnetic contrast at around 595±10 K. FoV = 43 μm.

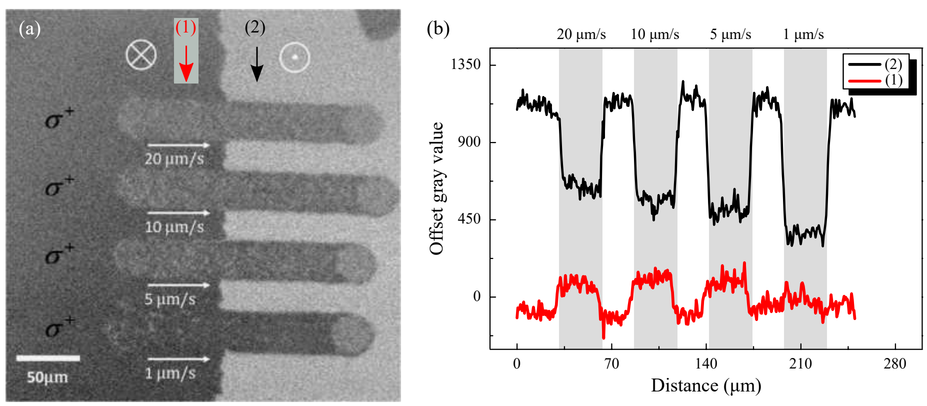

Figure 2: (a) Magneto-optical image of linear domain patterns imprinted at different speeds from 1 to 20 μm/s across a vertical domain wall. The laser beam polarization was set to σ^+. (b) The intensity profile of the corresponding optically-induced domains measured in the direction of the arrows.

XMCD Contrast. We calculated the XMCD spectra (Fig. 3(b)) by subtracting the XAS of the 'in' and 'out' domains, instead of subtracting the C- spectrum from the C+ spectrum. The method is physically equivalent to measuring the XAS in two orientations of an applied magnetic field, owing to the fact that the magnetization has two stable states (the 'in' and 'out' domains), and is corroborated by giving the same results, apart from the sign, for both polarizations. The reason for calculating the XMCD spectra in such a way is to mitigate the effect of beam drift (i.e., the uneven illumination of the focused photon beam mentioned in the Materials and methods section), which is exaggerated in the spectra due to large acquisition times necessitated by the need of sufficient statistics to be obtained through the Pt capping layer.

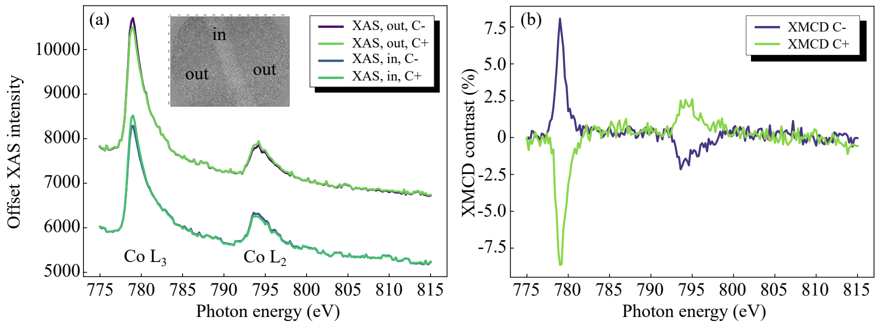

Figure 3: (a) Normalized x-ray absorption spectra of $[Co/Pt]_3$ multilayer measured for the ‘in’ and ‘out’ domains depicted in the inset image. The XMCD-PEEM images presented in this work were obtained by at photon energy of Co L_3-edge (779.0 eV). (b) XMCD spectra calculated for C+ and C- polarizations.

Image processing and binarization. In order to carry out the quantitative analysis of the XMCD-PEEM images presented in the main manuscript, we employed image processing tools [1]. First, the effects of uneven illumination were removed using a flat-field correction technique. This allowed us to obtain thresholdable images. Finally, we applied an adaptive threshold correction method [2], and binarized the images between the integer values of 0 and 255 stored in 8-bits.

The black-to-white domain ratio was calculated by counting the total number of 0-valued and 255-valued pixels in the illuminated area.

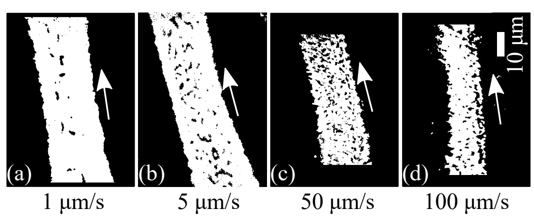

Figure 4: Binarized XMCD-PEEM images of optically induced magnetic domains on a dark background domains. Laser fluence and polarization state were constant while the sample was swept in the direction of arrows at various speeds: (a) 1 μm/s, (b) 5 μm/s, (c) 50 μm/s and (d) 100 μm/s. The white-black domain ratios are determined in the region of interest with image processing software.

References

[1] C. A. Schneider, W. S. Rasband, K. W. Eliceiri, Nih image to imagej: 25 years of image analysis, Nature methods 9 (7) (2012) 671–675. doi:https://doi.org/10.1038/nmeth.2089.

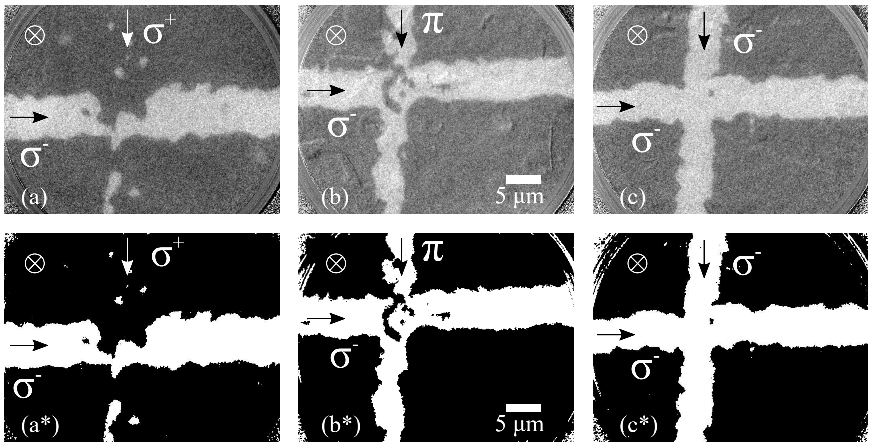

Figure 5: XMCD-PEEM images of magnetic domains formed due to perpendicularly scanned laser beams with different polarizations: (a) $\sigma^- - \sigma^+$, (b) $\sigma^- - \pi$ and (c) $\sigma^- - \sigma^-$, (a*), (b*) and (c*) show the corresponding images after the above-described binarization procedure.

[2] Tseng, Q. AdaptiveThreshold - ImageJ plugin, Available from: `https://sites.google.com/site/qingzongtseng/adaptivethreshold`, Accessed: 2021-07-14.