Field driven ferromagnetic phase nucleation and propagation in antiferromagnetically coupled multilayer films with perpendicular anisotropy

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Field driven ferromagnetic phase evolution originating from the domain boundaries in antiferromagnetically coupled perpendicular anisotropy films

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Reversal processes in antiferromagnetically coupled $[Co/Pt]_{X-1}/\{Co/Ru/[Co/Pt]_{X-1}\}_{16}$ is investigated combining magnetometry and soft X-ray transmission microscopy (MXTM). Two samples with X =6 and X= 7 are compared to study the internal dipolar field influence. After demagnetization and during field cycles, the magnetic configuration consists in AF domains separated by either AF domain walls, "tiger-tail" domain. Ferromagnetic boundary domains are observed for both samples and the samples behave similarly over a threshold field as expected from domain wall energy calculations. The influence of the competition between internal dipolar field, exchange-coupling and external field on the domain wall shifts leading to the tiger tail and ferromagnetic boundary are discussed from comparison between with sub-100nm resolution imaging and simulations.

The stability limitations of the bits dimension in recording media as well as in the spin-RAM devices sizes has led recently to considerate magnetic multilevel system to improve the recording density and to develop new type of sensors [Alb05][Man06]. Strong perpendicular anisotropy systems consisting in Co/Pt multilayers anti-ferromagnetically coupled through a thin Ru or NiO layer have been proposed as a model system to study the competition between local and long-range interactions existing in multilevel devices [Hel03a][Bar06]. Studying the domain structure evolution induced by variation of extrinsic parameters such as an applied magnetic field defines a way to characterize the competition between dipolar interactions, anisotropy and exchange coupling occurring in these systems [Hel03b][Hell07]. Such experiments have been mostly performed by MFM which only allows detecting surface stray fields, i.e. cannot probe deep multilayer stack [Fu07][Bar06] and has been found to affect strongly the image of detailed non-uniform structure like "tiger-tail" pattern [Hel07].

In this letter, we present a study of the domain boundaries in the demagnetized state of thick $[Co/Pt]_{X-1}/\{Co/Ru/[Co/Pt]_X\}_{16}$ multilayers as well as their evolution under magnetic field. Magnetometry measurements and magnetic transmission X-ray microscopy imaging, compared with energy calculations, are reported for two samples of different magnetic stack thicknesses (X= 6 or 7), i.e. different dipolar fields amplitude. These samples have been tuned to be at the transition between remanent anti-ferromagnetic or "tiger-tail" domain wall regimes defined in [Hell03a].

For the presented experiments, two $[Co(4Å)/Pt(7Å)]_{x-1}/\{Co(4Å)/Ru(9Å)/[Co(4Å)/Pt(7Å)]_{x-1}\}_{16}$ multilayer were grown, where the number of Co/Pt repeat (x) is 6 and 7, referenced as sample A and sample B respectively. The multilayers were deposited by DC magnetron sputtering onto X-ray transparent SiN_x membranes kept at ambient temperature. We used a commercial vibrating sample magnetometer (VSM) to measure the component of magnetization along the field, applied perpendicular to the film.

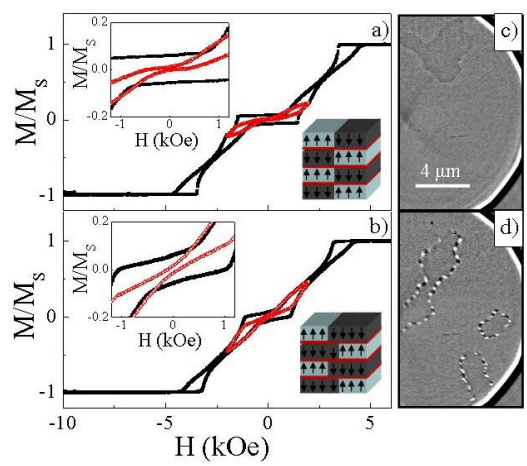

FIG. 1. Normalized magnetization as a function of field measured on sample A (a) and sample B (b) at 300 K. The black full symbol correspond to a complete loop measured from +10 kOe to -10 kOe while the red open symbol correspond to a minor loop realized after in plane demagnetization. The insets are zoom of the Fig 1a and 1b around zero field. c) and d) are MXTM images of demagnetized state of sample A and B respectively.

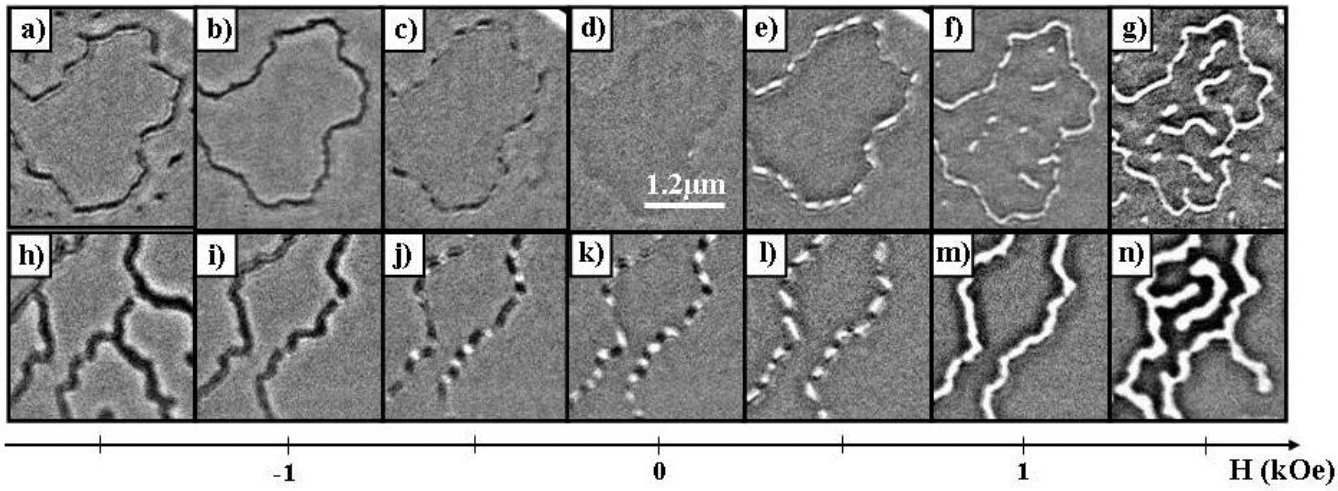

FIG. 2. MXTM images of sample A (a-g) and sample B (h-n) magnetic domain configuration under -1.5 kOe (a,h), -1 kOe (b,i), -0.5 kOe (c,j), 0 Oe (d,k), 0.5 kOe (e,l), 1 kOe (f,m) and 1.5 kOe (g,n).

Fig 1.a represents sample A hysteresis loop measured at 300 K. Starting from the positive saturation, the first continuous decrease of the magnetization corresponds to the reversal of 8 Co/Pt stacks on N=17 due to dipolar induced synchronized domain nucleation and propagation of every other bulk stack [Hell03a]. A plateau with persistent magnetization is observed around zero field, originated from the odd number of Co/Pt stacks. In negative field, the first step corresponds to the reversal of one of Co/Pt surface stack whose nucleation field differs from the bulk one since it feels only half the exchange coupling. As the negative field amplitude increases, the 8 remaining stacks switch during a second synchronized reversal. The behavior of the sample B during field cycle shown on Fig. 1b is similar to the sample A one except that no extra-step due to one surface stack reversal is observed because of the increase of dipolar field.

We perform high resolution magnetic transmission X-ray microscopy (MTXM) to image the domain states in samples A and B. MTXM uses the X-ray magnetic circular dichroism (XMCD) effect as magnetic contrast mechanism [Fis06]. Fresnel zone plates, used as optical elements, allows imaging lateral magnetic structures like domains or domain wall with spatial resolution down to 25 nm [Fis03][Cha05]. MXTM measurements were performed at the Advanced Light Source in Berkeley with the state-of-the-art XM1 set up under magnetic field up to 2 kOe [Fis07]. Fig. 1c and 1d presents MXTM images measured at 300 K, at the Co-L_3 edge, after in-plane demagnetization of samples A and B. On sample A (N=17, X=6), after demagnetization and under zero field, regions with up-down-up-…-down-up magnetizations in depth coexist with region with down-up-down-…-up-down magnetizations. A weak contrast exists between two regions of the sample (Fig. 1c and 3d) which comes from the odd number of Co/Pt stacks. Macroscopically the total magnetization is null as shown in the inset of Fig. 1a. Between the two regions of opposite magnetization lays an sharp AF domain wall within each Co/Pt sub-layer stack (drawing on Fig. 1a). All the domain wall are aligned vertically to minimize the AF inter-stack exchange-coupling energy (Fig. 3d). In positive field, the demagnetized domain state is conserved until a field of about 250 Oe where new domains of strong white contrast appears along the boundary between two domains (Fig. 3e). As the field increases, the small domains nucleate and grow until forming a continuous ring shape domain at 1kOe (Fig. 3f). The strong contrast indicates that these new domains consist in a ferromagnetic alignment of all Co/Pd stacks (Fig.3b). Individual domain walls in each sub-layer stack are no longer vertically aligned, but exhibit an alternate left and right shift d_{shift} with respect to the zero field domain walls location. The induce FM all-up ring is about X nm wide **[To be measure precisely]**. For field higher than 1 kOe, the FM boundary width increases slowly to X nm **[To be measure precisely]** with field. In the same time, other FM all-up domains nucleate inside the laterally uniform regions. We note that the dissymmetry due to the odd number of Co/Pt stacks favors the all-up domains appearance in one region more than in the other. In the case of a positive applied field (Fig. 2g), the first nucleations appear mainly in the dark down-up-down-…-up-down region. In the case of a negative field (Fig. 2a), the first all-down domains are nucleated in the lighter up-down-up-…-down-up region. In the minor loop presented on Fig.1a, the hysteretic character is mainly due to the irreversible process of FM domains nucleation/propagation. Only the original domain walls that separate AF domains are permanently trapped, leading to null magnetization at 0 Oe **[Refer to magnetic point memory ?]**

Fig. 2k presents MXTM image performed on sample B (N=17, X=7) at 0 Oe after in–plane demagnetization. FM domains with finite width of about X nm **[To be measure precisely]** separates up-down-up-…-down-up and down-up-down-…-up-down regions (Fig. 1b and 2k). Contrary to the homogeneous line shown on sample A (Fig. 2f or 2b), an alternating bit-like pattern of one dimensional all-up and all-down stripe domains is observed along the AF boundaries. Note that, in the MXTM images, each black and white stripe corresponds to the all-up and all-down domain magnetization summed over the sample depth. This alternating stripes pattern has recently been explained considering the internal dipolar fields that are generated inside the FM boundary [Hel03a]. Since sample B is thicker than sample A, the alternative pattern

appears only for sample B. When a positive field is applied on sample B, the up domains containing in the stripe FM line grow along the AF boundary to satisfy the Zeeman energy (Fig. 2l) and, at H= 1kOe, a uniform FM band with all-up magnetization is imaged (Fig. 2m). The band width has slightly increased from 0 to 1 kOe (X nm at 1 kOe) and then stays constant **[To be measure precisely]**. For higher field, new all-up FM domains nucleate and grow in the down-up-down-…-up-down region first and then in the up-down-up-…-down-up region (Fig. 2n). The opposite scenario happens in negative field. We remark that the nucleation or growth of the FM domains in sample A and B are different compared with results shown in previous paper based on system of 2 Co/Pt stacks where the dipolar field influence is weak so that the reversal of the uniform regions happens by extension of FM domains at the boundaries as well as by new nucleation of FM domains inside the uniform region [Fu07][Bar06].

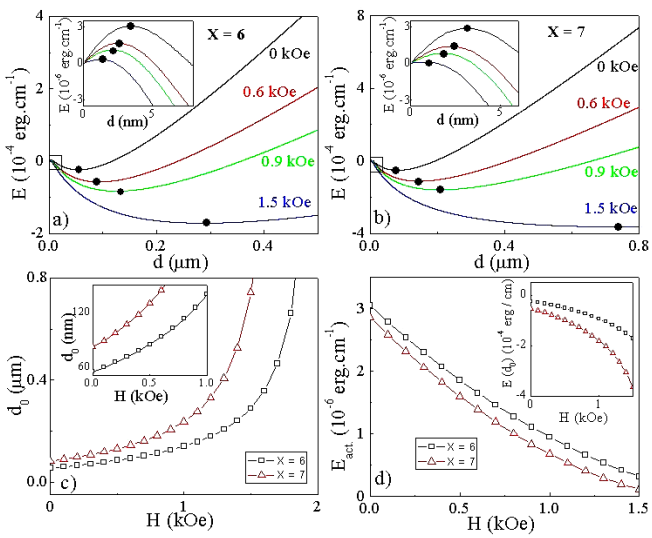

FIG.3.

To further investigate the difference of the sample A and sample B remnant state, we calculate the energy profile of the AF domain structure as a function of d_{shift} , i.e the domain wall shift relative to its zero field position, and as a function of the field intensity. The domain wall in each Co/Pt stack was assumed to be a Bloch-type wall with a fixed width chosen to be **X** nm **[Andreas ?]**……. Fig. 3a and 3b represent respectively the total energy profile of X = 6 and 7 samples for different applied field. In both cases, two energy minima are observed. The first energy well, choosed as reference, is located at d_{shift} = 0 nm and corresponds to the state where domain walls in each sub-layer stack are vertically aligned. The second energy minimum with non-null d_{shift} represents the existence of a FM domain boundary. As the field increases, the energy minimum of the second well is lowered and the d_{shift} position of the energy minima is slightly displace towards the larger d_{shift} values. In both cases, the second energy well minimum is lower than the first energy well minimum on the all range from zero to high field. **[To be completed]**

In conclusion, we have studied two thick $[Co/Pt]_{X-1}/\{Co/Ru/[Co/Pt]_{X-1}\}_{16}$ multilayers for which an in-plane demagnetization allows to trap AF domain structure correlated over the all depth due to the competition between inter-stack exchange coupling and dipolar interaction. We used the non-interacting and magnetization sensitive MXTM technique to image the evolution of the boundaries between domains of opposite magnetization after demagnetization and under magnetic field. For X = 7, i.e. for a strong internal dipolar field, a stable "tiger-tail" pattern is observed while, an AF domain wall is stable for thinner sample such as X = 6. Under field, over a certain threshold, a FM domain is nucleated along the domain boundary which propagates as the field increases. In the thinner sample, the threshold comes from……while the threshold is linked to hysteretic process for the thicker one. Our work gives novel enlightening on the field influence in the AF-coupled multilayer.

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