Magnetic reversal of perpendicularly biased Co/Pt multilayers

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IN-PLANE AND PERPENDICULAR EXCHANGE BIAS

Exchange-bias (EB) is a phenomena in which suitably prepared systems consisting of a ferromagnetic (F) phase in contact with an antiferromagnetic (AF) phase produces in an offset of the hysteresis loop of the F phase and an enhancement of its coercivity [1,2]. Although well established, a convincing microscopic description that explains experimental details of exchange bias has remained elusive [3,4]. A recent focus of experimental attention has been the interaction of EB with the details of the magnetization reversal of the F layer in thin film systems [5-7]. A common finding in thin film systems having in-plane anisotropy is that exchange bias produces an asymmetrical shape in the F layer hysteresis loop that is related to differences in its magnetic reversal mode on the ascending and descending branch [5-7].

A new class of EB film systems involves F layers having perpendicular, not in-plane, magnetic anisotropy (PMA) [8]. We are studying perpendicularly biased Co/Pt multilayers using laboratory measurements and resonant soft x-ray magnetic small-angle scattering (SAS) [9]. Hysteresis loops measured using SQUID magnetometry reveal the expected coercivity enhancement and loop shift, but do not show asymmetric loop shapes [9]. Our goal in ALS experiments was thus to use resonant SAS to study the distribution of magnetic domains around exchange biased hysteresis loops to determine if EB systems having PMA show differences in these properties compared to EB systems with in-plane anisotropy.

SCATTERING FROM MAGNETIC STRUCTURE THROUGH REVERSAL

Resonant magnetic SAS has been shown to be extremely sensitive to the presence and spatial distribution of magnetic domains in F Co/Pt multilayers [10]. This high sensitivity results because the predominant scattered intensity originates precisely from the magnetic heterogeneity associated with the ferromagnetic domains, and this scattering is orders of magnitude stronger than the scattering when the F films are saturated.

The sample studied here consists of a compound multilayer structure as indicated in Fig. 1, and can be described as a $\{[\mathrm{Co}(4\ \text{Å})/\mathrm{Pt}(7\ \text{Å})]_4\mathrm{Co}(6\ \text{Å})/\mathrm{CoO}(10\ \text{Å})\}_{10}$ superlattice. There are ten F sublayer regions each consisting of a Co/Pt multilayer of 4.5 periods. Each of these F sublayer stacks has PMA and is sandwiched between AF CoO layers just 1 nm thick. This sample thus has 20 F/AF exchange bias interfaces distributed in depth through its structure, and was grown onto a SiN_x membrane for transmission x-ray scattering measurements.

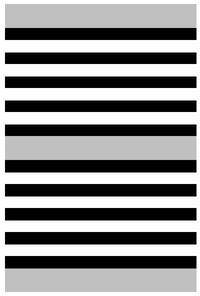

Figure 1. Schematic of part of the compound $\{[\mathrm{Co}(4\ \text{Å})/\mathrm{Pt}(7\ \text{Å})]_4\mathrm{Co}(6\ \text{Å})/\mathrm{CoO}(10\ \text{Å})\}_{10}$ structure forming the perpendicularly biased Co/Pt multilayer structure studied here. The 4.5 bilayer thick Co/Pt regions form ferromagnetic sublayers having perpendicular magnetic anisotropy. Each of these is sandwiched between two layers of antiferromagnetic CoO, producing a perpendicularly biased structure in which the bias is distributed in depth through the structure. In this schematic CoO layers are grey, Co layers are black, and Pt layers are white.

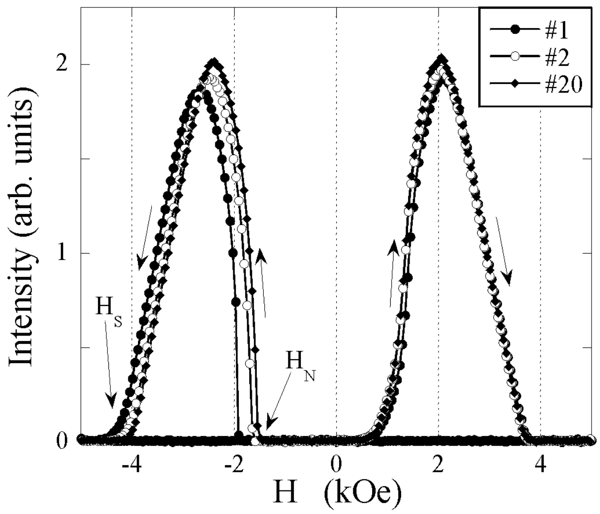

Figure 2. Field-dependent small-angle scattering measurements of a perpendicular {[Co(4 Å)/Pt(7 Å)]$_4$Co(6 Å)/CoO(10 Å)}$_{10}$ superlattice structure. The sample was positive field cooled to 85 K where the first, second, and twentieth field cycles are shown. H_N and H_S indicate the nucleation and saturation fields, respectively, for the descending branch of the hysteresis loop. The arrows indicate the field-sweep direction.

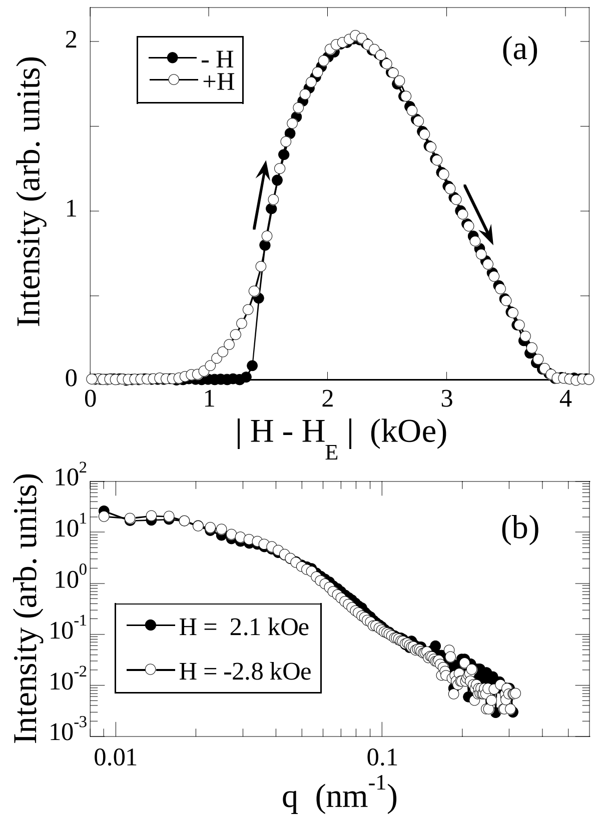

Figure 3. (a) Field-dependent small-angle scattering measurement of the perpendicular superlattice structure after field cycling 20 times. The data are corrected for the average bias field H_E and then plotted vs. absolute field tom compare the intensity distributions for decreasing (filled circles) and increasing (open circles) field sweeps. (b) q scans measured in an applied field of H = -2.8 kOe after positive saturation (descending branch) and H = 2.1 kOe after negative saturation (ascending branch).

Resonant SAS measurements tuned to the Co L_3 scattering peak can be made as a function of in-plane scattering vector q, applied perpendicular magnetic field H, and temperature. Measurements reported here were made after positive field cooling to 85 K to set the bias direction. The sample was thus saturated with no domains present during this cooling.

Shown in Figure 2 are several SAS hysteresis scans measured at 85 K and q = 0.027 Å^{-1} corresponding to an in-plane spatial frequency of $2\pi/q$ = 235 nm matching the periodicity of the labyrinth domains observed at room temperature. The scans show the first, second, and twentieth field cycles, each exhibiting expected strong scattering peaks resulting from the domains formed on reversal, and a negative bias field. Two effects are evident on repeated field cycling. First, there is a systematic shift of the nucleation fields H_N and saturation fields H_S toward the origin. Second is an increase in peak intensities on cycling. Both effects are more pronounced for the descending than the ascending branch of the loops, and can be understood as training effects (*i.e.*, relaxation of AF CoO grains) often observed in polycrystalline EB structures.

Scans of H and q after the 20th cycle, beyond which training effects were negligible, are shown in Figure 3. The H scans show the ascending and descending peaks overlaid after correcting for the bias field H_E. While there are differences in the initial reverse domain nucleation processes (i.e., the shapes of the curves as the peak starts to grow from low $|H - H_E|$, once nucleated the reversal behavior of the sample after training appears identical in both field directions.

The q scans in Fig. 3b are obtained at H = -2.8 and 2.1 kOe corresponding roughly to the peak intensities in Fig. 3a. The lack of a strong peak in these q scans is consistent with a relatively disordered domain structure during reversal. Because the q scans measure the spatial frequency spectrum of the magnetic domains, their near equivalence on ascending and descending branches confirms that on average the domain distribution is nearly identical on reversal in both directions in the biased state. We note that the q scans for this sample when it is demagnetized, either at room temperature or after zero-field cooling, do show pronounced peaks similar to that in Ref. 10, indicating that exchange bias does alter the spatial distribution of energies that determine the domain distributions during reversal.

CONCLUSIONS

This work further demonstrates the high sensitivity of resonant soft x-ray scattering to magnetic domain structure present during the reversal of ferromagnetic films. We find that there are clear differences in the initial nucleation properties of reverse domains on the ascending and descending branches of the hysteresis loops, in agreement with studies of in-plane EB systems. Once nucleated, however, the evolution of these reverse domains is quite symmetric with respect to positive and negative field sweeps for this and similar samples studied. This behavior for perpendicular EB films is in contrast to many experiments from in-plane biased systems. We can understand the differences to result from the collinear uniaxial magnetic anisotropy and unidirectional exchange bias axis in the perpendicular bias samples studied here, whereas samples having in-plane anisotropy rarely have a single, unique anisotropy axis. These results thus suggest that asymmetric reversal is not an inherent property of exchange bias systems but rather depends on the anisotropy and microstructure of the constituent layers.

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