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2006 J. Phys.: Condens. Matter 18 L149

(http://iopscience.iop.org/0953-8984/18/12/L01)

INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS: CONDENSED MATTER

J. Phys.: Condens. Matter **18** (2006) L149–L153 doi:10.1088/0953-8984/18/12/L01

LETTER TO THE EDITOR

The angular dependence of the magnetization reversal in exchange biased multilayers

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Received 15 December 2005
Published 9 March 2006
Online at stacks.iop.org/JPhysCM/18/L149

Abstract

We investigate an exchange biased polycrystalline IrMn/CoFe sample, measuring along each full magnetization loop as we vary the direction θ of the applied field H_a with respect to the unidirectional anisotropy direction or the field cooling H_{FC} direction. Measurements are done using specular and off-specular polarized neutron scattering for increasing (negative to positive) and decreasing (positive to negative) field sweeping directions of H_a with respect to the negative direction of H_{FC}. For both the angles $\theta = 45°$ and 90°, remagnetization behaviours of all ferromagnetic layers occur *simultaneously* in a uniform mode (via coherent rotation) only. This is in contrast to the nonuniform reversal (via domain wall motion) previously observed by us for $\theta = 0°$. These variations of the relative strengths of the uniaxial and exchange anisotropies are thus found to be responsible for the reversal of magnetization via coherent rotation or via domain wall motion. Interestingly, off-specular spin-flip scattering shows that coherent rotation (where a significant specular spin-flip signal is observed) is accompanied by underlying concomitant in-plane magnetization fluctuations during reversal for both loop branches. These fluctuations—linked to the magnetization reversal—indicate the fluctuations from domain to domain in the system.

(Some figures in this article are in colour only in the electronic version)

For many groups [1–5], a common observation has been the asymmetric hysteresis loops due to asymmetric magnetization reversal processes in exchange coupled ferromagnetic (FM)/antiferromagnetic (AF) systems. The asymmetry is considered for increasing/decreasing applied field H_a for the hysteresis loop with respect to the field cooling direction H_{FC}. Magnetization reversal is symmetric when the process takes place in a uniform (reversal by

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coherent rotation) or nonuniform mode (reversal by domain wall motion) for the increasing (negative to positive) and decreasing (positive to negative) field sweeping direction of H_a for the hysteresis loop with respect to the negative direction of H_{FC}.

The neutron technique has been used to examine this phenomenon for various systems of AF–FM bilayers [2–5]. One may note that magnetization rotation is identified via a significant increase of the specular reflectivities in the spin-flip (SF) channels (R_{+-} and R_{-+}), which correspond to in-plane magnetization components perpendicular to the guiding field H_a applied collinearly with H_{FC}. Reversal by domain nucleation and propagation does not provide enhanced SF intensities, because the magnetization is always collinear with H_a.

The theoretical interpretation of the magnetization reversal was discussed in detail by Beckmann *et al* [6]. It was shown that depending on θ, the angle between the applied field H_a and the AF anisotropy axis or the field cooling axis H_{FC}, the reversal mode is either via coherent rotation for both loop branches or asymmetric with a nonuniform reversal for the increasing branch and uniform for the decreasing branch. Here 'nonuniform' refers to the reversal of magnetization with no component perpendicular to the H_a direction. This is basically governed by an effective field H_{eff} arising from the anisotropy of the FM, the exchange bias field H_x of the AF, and the applied field H_a. The H_{eff} and the torque it exerts on the FM magnetization depend on the angle θ.

Recently we observed an increasing strength of the exchange bias field when FM and AF layers are repeated a number of times forming a multilayer (ML). The increase in the strength of the bias field was directly related to the evolution of the grain size along the stack. This eventually led to the observation of sequential reversal of the FM layers along the stack in $[IrMn/CoFe]_{10}$ [7] and also in $[Co/CoO]_{20}$ MLs [8] using neutron reflectometry. For these sequentially reversing FM layers, we observed nonuniform reversal of each FM layer which was found to proceed symmetrically via domain wall motion for both remagnetization directions. We were readily able to exclude reversal by coherent magnetization rotation for the layers due to too weak specular spin-flip intensity. Unlike the usually observed asymmetric reversals in epitaxial bilayer specimens [3–5, 8], this reversal mode—symmetric, but nonuniform—corresponds to the situation for $\theta = 0°$ for our polycrystalline ML specimens.

Now for different angles θ (other than 0°), we were able to vary the relative strengths of ferromagnetic and exchange anisotropies which are predicted to be responsible for the reversal of magnetization via coherent rotation or domain wall motion. This is particularly possible with our single multilayered system which has different strengths of the bias fields along the stack. In the present report, we investigate the same polycrystalline IrMn/CoFe sample for two different angles of applied fields, $\theta = 45°$ and 90°. Polarized neutron scattering spectra across the specular and off-specular geometries were measured along each full magnetization loop: increasing and decreasing. For both loop branches and for both the angles, we observe the coherent and *simultaneous* rotation of all the layers in contrast to the nonuniform and sequential switching of the layers for the case $\theta = 0°$. The reversal is accompanied by fluctuations of the in-plane magnetization component perpendicular to H_a as also observed earlier [7] irrespective of θ.

The exchange biased polycrystalline $[Ir_{20}Mn_{80}(6.0\ nm)/Co_{80}Fe_{20}(3.0\ nm)]_{10}$ ML is prepared by dc magnetron sputtering. Neutron scattering measurements are performed at the polarized neutron reflectometer with polarization analysis HADAS at the Jülich research reactor FRJ-2 (DIDO). The details of the instrumental and experimental conditions and microstructural investigations on the specimen were reported previously [7].

We perform PNR measurements on both sides of the hysteresis loop at 15 different fields applied at two different angles to the H_{FC} direction. We show the measurements with $\theta = 45°$ for increasing and decreasing branches of fields with respect to H_{FC} direction in figure 1. The

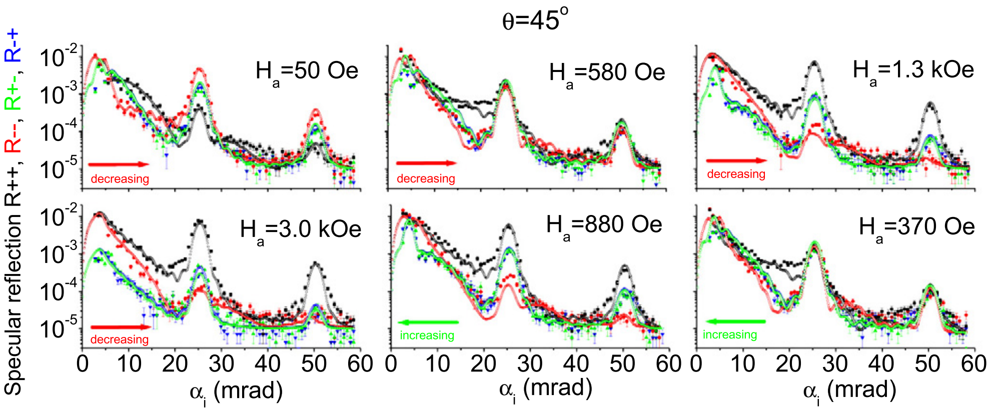

Figure 1. NSF and SF specular reflectivity patterns (solid symbols) along with their fits (open circle) for $[Ir_{20}Mn_{80}(6.0\ \text{nm})/Co_{80}Fe_{20}(3.0\ \text{nm})]_{10}$ ML with $\theta = 45°$ for decreasing and increasing branches of fields.

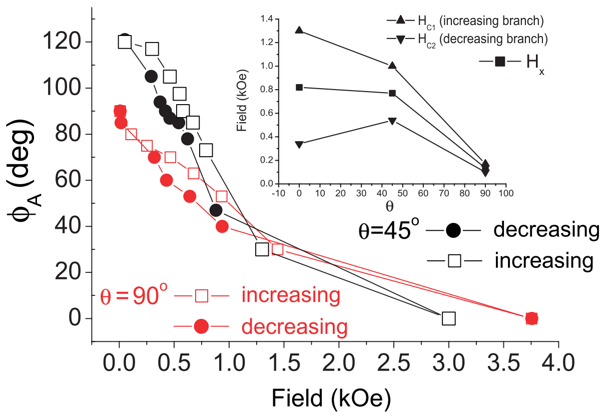

Figure 2. Angular variation of magnetization ϕ_A for a $[Ir_{20}Mn_{80}(6.0\ \text{nm})/Co_{80}Fe_{20}(3.0\ \text{nm})]_{10}$ ML with $\theta = 45°$ and 90° for increasing and decreasing branches of fields as resolved from the fits of the specular reflectivity patterns. The lines are guides to the eye. The inset shows the strength of H_x and the coercive fields $H_{c1,c2}$.

specular intensity along the line $\alpha_i = \alpha_f$ shows first order and weaker second order Bragg peaks at $\alpha_{i,f} \approx 25$ and 50 mrad corresponding to the bilayer thickness.

The fittings of the specular reflectivities for the NSF and SF channels are done taking into account the non-ideal polarization efficiencies. The details of the fitting procedure have been described earlier [7]. In figure 2 we show the angular variation of magnetization ϕ_A extracted from the fits to the specular data in figure 1. When the magnetization is parallel to the applied field $\phi_A = 0$, the increase in ϕ_A is from an increase in the SF signal. For $\theta = 90°$ and 45°, we observe a large specular SF signal along the whole hysteresis loop, indicating uniform magnetization reversal. The fits to the data are done considering all the layers to rotate *coherently* with the field. The variation is monotonic and gradually follows the H_a direction with increasing field strengths. For $\theta = 45°$, the remanent ($H_a = 0$) angle (ϕ_A) is only 120° and not 135°; this is because the sample has some hysteretic behaviour which is more prominent when $\theta = 45°$. The inset of the figure 2 shows the change in the strength of the H_x values with θ.

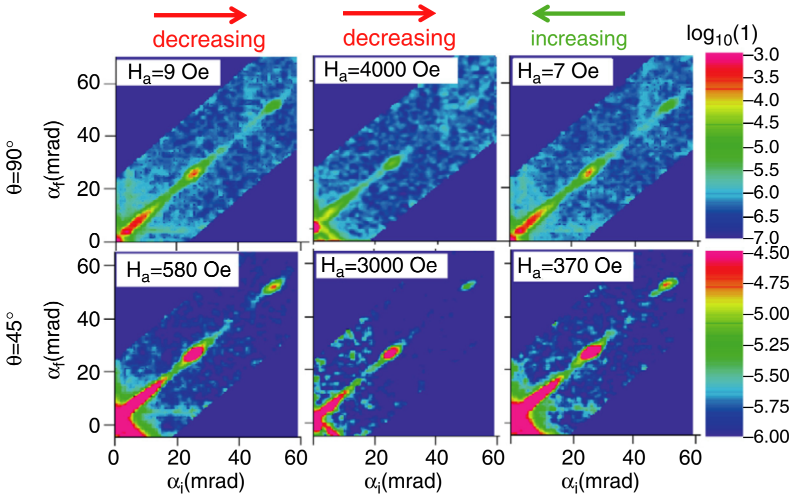

Figure 3. SF intensity maps (R_{+-}) for the $[Ir_{20}Mn_{80}(6.0\ nm)/Co_{80}Fe_{20}(3.0\ nm)]_{10}$ ML at the respective reversal points 9 Oe (decreasing branch) and 7 Oe (increasing branch) for $\theta = 90°$, followed by 580 Oe (decreasing branch) and 370 Oe (increasing branch) for $\theta = 45°$.

Figure 3 shows the SF intensity (R_{+-}) maps as a function of α_i and α_f at different representative H_a for $\theta = 45°$ and 90°. Enhanced off-specular intensity in the SF channel appears near the critical angle $\alpha_c \approx 4$ mrad of total reflection for the reversal points compared to that in the saturation state. The presence of off-specular SF intensity confirms that the in-plane magnetization component perpendicular to the guiding field $M_\perp$ is laterally inhomogeneous on a length scale smaller than the lateral coherence length of the neutron beam. When the domain sizes are small and comparable with the domain wall width it is reasonable to think of such small scale variations across the domain wall as fluctuations. Off-specular SF scattering shows that the coherent rotations of layers are accompanied by underlying concomitant in-plane magnetization fluctuations. These fluctuations—linked to the magnetization reversal—are owing to the variation of the mean magnetization from domain to domain. At saturation the diffuse intensities disappear, which confirms their purely magnetic origin. Such small scale fluctuations which are comparable to the grain size ($<1\ \mu$m) were also observed earlier in case of $\theta = 0°$ [7]. These fluctuations are observed even at $\theta = 45°$ and 90° where reversal is by coherent rotation only, thus indicating the small scale fluctuations in the system from domain to domain which are smaller than the neutron coherence length.

We compare these observations of coherent rotation of all layers with the sequential switching of layers as observed earlier for $\theta = 0°$ [7]. For a finite θ, the strength of the anisotropy field (H_A) and that of the exchange field of the AF (H_x) govern the angle between the effective field H_{eff} and the M_{FM} direction at equilibrium [6, 8]. Here M_{FM} is the saturation magnetization of the FM layer. Larger angle means larger torque which favours rotation of the magnetization whereas a small angle favours flipping by domain wall motion. Thus at $\theta = 0°$ we observed layer by layer flipping as the exchange bias field strength is increasing from layer to layer but the torque exerted is sufficiently small, while at $\theta = 45°$ or 90° we observe simultaneous rotation of all layers, as the torques on all the layers are always large enough for rotation to occur. In particular, the different strengths of the exchange bias in our multilayered system enabled us to vary or tune the ratio between the FM–AFM coupling and the uniaxial anisotropy, in an effort to understand the underlying basic mechanism for reversal.

Thus one may note that even if the H_x values for $\theta = 0°$ and $\theta = 45°$ are similar (figure 2), the reversal mechanism is completely different as the corresponding H_A values are different.

In conclusion, we have studied in detail the remagnetization behaviour of an exchange biased multilayer for different directions θ, between the field cooling and applied field directions. Uniform modes of *simultaneous* magnetization reversal for all the layers for both remagnetization directions are observed for $\theta = 90°$ and 45° compared to the nonuniform and sequential switching of layers for $\theta = 0°$. These observations are understood in general terms via the large torque exerted on the system due to the large angle of the effective field strengths with the magnetization axis. All reversal modes are accompanied by small scale domain to domain fluctuations of the perpendicular component of the in-plane magnetization on a length scale comparable to the grain size in the system. We gained insight into the reversal mechanism for the exchange biased system as we varied the relative strengths of the exchange and uniaxial anisotropies for our single multilayered system with varying exchange field strengths along the stack.

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