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Research articles

Magnetic anisotropies and rotational hysteresis in $Ni_{81}Fe_{19}/Fe_{50}Mn_{50}$ films: A study by torque magnetometry and anisotropic magnetoresistance

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ABSTRACT

Exchange bias properties of NiFe/FeMn thin films have been investigated through X-ray diffraction, hysteresis loops, angular measurements of anisotropic magnetoresistance (AMR) and magnetic torque. As first predicted by Meiklejohn and Bean we found a decrease on the bias field as the NiFe layer thickness increases. However such reduction is not as strong as expected and it was attributed to the increase on the number of uncompensed antiferromagnetic spins resulting from the increase on the number of FeMn grains at the interface as the thickness of the NiFe layer is increased. The angular evolution of AMR and the magnetic torque were calculated and compared to the experimental ones using the minimization of the free magnetic energy and finding the magnetization equilibrium angle. The free energy, for each grain of the polycrystalline sample, is composed by the following terms: Zeeman, uniaxial, unidirectional and the rotatable energies. While from the AMR curves we obtain stable anisotropy fields independently on the measuring fields, from the torque curves we obtain increasing values of the uniaxial and rotatable fields, as the measuring field is increased. These results were attributed to the physical origin and sensitivity of the two different techniques. Magnetoresistance is mainly sensitive to the inner portion of the ferromagnetic layer, and the torque brings out information of the whole ferromagnetic layer including the interface of the layers. In this way, we believe that the increase in the uniaxial and rotatable values were due to an increase on the volume of the ferromagnetic layer, near the interfaces, which is made to rotate with the measuring field. Studying the rotational hysteresis by both techniques allows to separately obtain the contributions coming from the inner portion of ferromagnetic layer and from the interface.

1. Introduction

The exchange bias phenomenon (EB) occurs due to the interfacial coupling of a ferromagnet (F) to an antiferromagnet (AF) [1,2]. The main features observed and studied in such systems are the shift of the magnetization curve by an exchange bias field (H_B) [1,9], the increase in the coercive field (H_C), the existence of the training effect, which is especially important for polycrystalline films [3,4] and the rotational hysteresis in the angular magnetic torque measurements [5,6].

The EB has been studied for 60 years due to its important technological drive [see for ex. [7] and references therein]. The phenomenon has already been verified in different systems within a plentiful diversity of materials, adding difficulties to achieve its total comprehension [2,8–10].

Different models have been developed, aiming to including specific characteristics of the EB in different systems [11,12]. Important hypotheses have been made in different models, for example: the splitting of the interfacial structures in stable and unstable [6,8]; the existence of a rotatable anisotropy associated to the unstable grains [13,14]; domain wall formation at the interfaces [15–17]; angular distribution on the anisotropy of interfacial grains [18]; misalignment between the unidirectional (AF – F coupling) and uniaxial anisotropies (F layer) [19–21].

The main techniques used to the study of EB systems are magnetometry (VSM, vector VSM, MOKE) and ferromagnetic resonance. Other techniques capable to provide additional information on the subject, but used less, are the torque magnetometry and anisotropic magnetoresistance (AMR).

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In an angular torque curve, the half of the area enclosed between the clockwise (CW) and counterclockwise (CCW) measurements is the energy lost in the cycle, the rotational hysteresis (RH) [1,22,23]. In ferromagnetic samples the RH depends on the degree of magnetic saturation [24]. In coupled F/AF bilayer systems, even in a saturated state, RH depends on the details of the interaction between layers: AF grain structure, coupling strength and others [23,25]. Similarly to AMR, we can define a RH, however the amplitude and field evolutions are different from that observed in a torque curve.

In this work we study the RH from torque and AMR measurements. We fitted a phenomenological model [26,33] to the AMR and the torque curves, extracting the parameters governing the studied magnetic system: the uniaxial, unidirectional and rotatable anisotropy fields, the misalignment between the anisotropy axes and the dispersion on the unidirectional anisotropy axis. The use of these two experimental techniques has shown to be fruitful to the study of exchange bias systems as their physical origin are different, while AMR arises from the spin-orbit interaction and gives the information on the relative orientation between the measuring current and the magnetic moment, the torque magnetometry gives the profile of anisotropic field and rotational hysteresis by mapping the relationship of external field and sample's magnetization. Also, considering that the measurement current is strongly scattered by the interfaces, AMR is mainly sensitive to the inner portion of the F layer and the torque brings out information of the whole F layer. This feature was confirmed by the differences on the rotational hysteresis measured by both techniques.

2. Experimental

The studied set of F/AF bilayer films were deposited onto glass substrate by magnetron sputtering. The nominal composition and thickness (in nm) of the samples were glass/Ta(15)/$Ni_{81}Fe_{19}(x)$/$Fe_{50}Mn_{50}(20)$/Ta(15) with $x = 40$, 50, 60 and 70 nm. All samples were grown with a base pressure in the sputtering chamber of less than 10^{-7} Torr. The argon partial pressure was kept at 2.1 mTorr during the deposition by an Ar flow of 32 SCCM. A pair of permanent magnets applied a field ($H \sim 1$ kOe) in the samples' plane in order to define the pinning direction during the deposition. No temperature control was made during the samples growth.

The structural character of the samples was checked via X-ray diffraction with Cu K_α radiation, using a diffractometer in Brag-Brentano geometry (θ-2θ). The diffractograms indicate an (111) out-of-plane preferential growth for both the Permalloy and FeMn layers.

The magnetization measurements were performed in an Alternating Gradient Field Magnetometer with an applied magnetic field maximum of 350 Oe. After 10 magnetizing cycles, no training effect was detected on all samples.

The in-plane torque curves were obtained using the torque magnetometer described in the Ref. [27]. In order to guarantee the same magnetic state of the samples at the beginning of the measurements, the following procedure was used: (a) the maximum negative field (−240 Oe) was applied along the easy axis of the sample by a pair of Helmholtz coils. (b) The field was reduced to zero and then (c) the positive measuring field (H) was applied and rotated in the clockwise (CW) and counterclockwise (CCW) directions and collected the torque versus field angle, returning to the initial position. This procedure was followed for each field measurement. Unfortunately, due to the torquemeter sensitivity limit, it was not possible to obtain reliable measurements from the sample with 40 nm of Permalloy.

The AMR measurements were obtained by means of a standard four-probe configuration with the in-plane magnetic field angle applied in a similar procedure used for the torque measurements. The electrical contacts on the samples were made using silver paint. The DC current of 2 mA was supplied by a current source and applied along the samples' easy axis. The voltage produced on the sample was measured with a nanovoltmeter.

3. Results and discussion

3.1. Magnetization measurements

As it can be seen on the Fig. 1(a), the samples present different interfacial F-AF coupling due to the Permalloy thickness and this is more pronounced in the bias field (H_B) than in the coercive field (H_C), inset of the Fig. 1. Also, the saturation field (H_S), measured along the hard axis, decreases linearly with the Permalloy thickness from 130 Oe to 80 Oe.

It can be observed on the easy axis magnetization curves, Fig. 1(a), a rounding shape in the approach to saturation, independent of the sample. This can be an indication of a system with an anisotropy axis not very well defined. The same curves present an asymmetry between the increasing and decreasing field branches of the magnetization loops. The increasing branch has a higher inclination compared to the decreasing one. Also, at the middle of the decreasing branches it can be seen a small change in the inclination, as indicated by the arrows in the Fig. 1(a). While the first feature may be intrinsic to exchange bias systems as described by Camarero et al. [28] which has used the Stoner-Wohlfarth model with the astroid center dislocated by H_B from the origin, the second feature is resultant of a complex interface

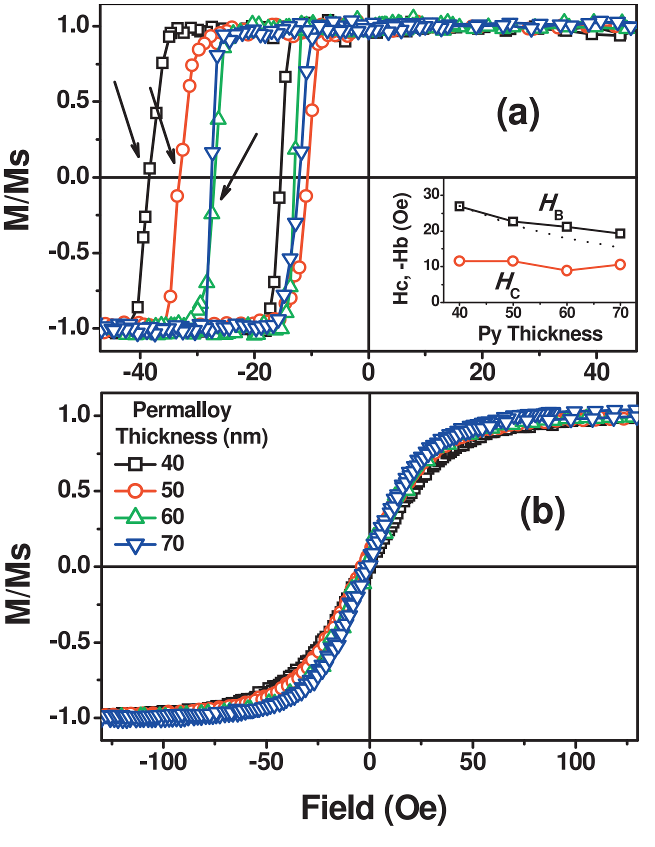

Fig. 1. Normalized magnetization loops measured along the easy (a) and hard axis (b). Symbols in the inset present the evolution with the samples' thickness of the coercive and bias field, measured along the easy axis. The dashed line in the inset presents the usually expected evolution of H_B with the FM layer thickness, meaning $H_B \propto 1/t_F$.