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Vectorial mapping of exchange anisotropy in IrMn/FeCo multilayers using the reversible susceptibility tensor

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A method for probing exchange anisotropy based on reversible susceptibility tensor is proposed. The experimental results obtained on exchange biased IrMn/FeCo multilayers are supported by the theoretical analysis of the transverse and longitudinal susceptibilities in the case of exchange-coupled systems. The vectorial mapping of the exchange bias in the studied sample is performed by detecting a composite signal containing both transverse and longitudinal susceptibilities for different orientations of the applied field. This procedure, that is demonstrated both theoretically and experimentally, allows one to obtain the critical curve of the switching fields. The critical curve constitutes the fingerprint of the switching processes from which both magnitude and direction of the directional anisotropy can be determined.

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As discovered in 1957 by Meiklejohn and Bean, exchange anisotropy (EA) arises from the exchange coupling at the interface between a ferromagnet (FM) and an antiferromagnet (AFM).[1] There is renewed interest in AFM/FM exchange coupling in recent years because of its application to giant magnetoresistive heads for high-density recording systems and sensors. The typical signature of the EA is a displaced hysteresis loop along the field axis with a field value equal to the exchange field, from which the EA can be determined. Different measurement techniques, such as anisotropic magnetoresistance (AMR),[2] ac susceptibility,[3] ferromagnetic resonance (FMR),[4] Brillouin light scattering,[5] and polarized neutron reflectometry,[6] were proposed to assess the EA. In the present paper we propose a method to probe the exchange interaction using reversible susceptibility tensor containing transverse (TS) and longitudinal susceptibilities.[7] This method combines the advantages of reversible measurement techniques using a small ac field and the simplicity of an irreversible measurement technique, such as the hysteresis loop displacement.

Originally, transverse susceptibility was proposed as a versatile technique for determining the anisotropy in magnetic particulate media owing to the fact that it offers a simple method of direct evaluation of the anisotropy field H_K, independent of the size and orientation distributions of particles in the system. Uniaxial systems with random orientation in magnetic easy axes show sharp peaks located at H_K and switching fields H_S. Recent experimental developments of TS have afforded higher sensitivity to this method, enabling the study of systems with low concentration of magnetic moments like magnetic nanoparticles[8] and thin films.[9] Also, recent theoretical advancements of the original model of TS due to Aharoni *et al.*[7] allowed the possibility of describing the TS for systems with other types of anisotropy than was initially considered.[10]

Contrary to what one would expect for a method extensively used for determining the anisotropy in magnetic systems, we are not aware of a previous measurement of TS for magnetic systems with unidirectional anisotropy. In this paper we present, to the best of our knowledge, the first TS measurements on an exchange-coupled unidirectional magnetic system. The experimental data are analyzed using a model for TS that takes into account the uniaxial anisotropy and the exchange anisotropy. Moreover, we show that the vectorial character of EA, i.e., its magnitude and direction, can be revealed very accurately using the angular dependence of the reversible susceptibility tensor. In this case, both components of the reversible susceptibility tensor, parallel and transverse, contribute to the measured signal, allow the tracking of the angular variation of the switching fields in the exchange-coupled system from which the critical curve will be determined.

The material considered in our study is a [IrMn (12 nm)/FeCo (50 nm)]×4 multilayer with Cu (4 nm) seedlayer[11] deposited on a glass substrate. The sample is fabricated using a disc media sputter deposition system, Unaxis M12. The samples were cut into 5×5 mm pieces with the edges parallel to the direction of the EA. To probe the dynamic transverse susceptibility in the radio-frequency range, we employ a very sensitive method based on a tunnel-diode oscillator (TDO) technique.[8] The sample is placed in the sensing coil with both ac and dc fields lying in the sample plane. The dc magnetic field was created by an electromagnet placed on a revolving stage with a protractor for measurement of the field direction. Hysteresis loops at different angles are measured using a Lakeshore vibrating sample magnetometer.

Figure 1(a) shows the field dependent TS at room temperature with the static magnetic field H applied parallel to the easy axis of the film. For TS curves one observes a single peak per curve for increasing (open symbols) and decreasing

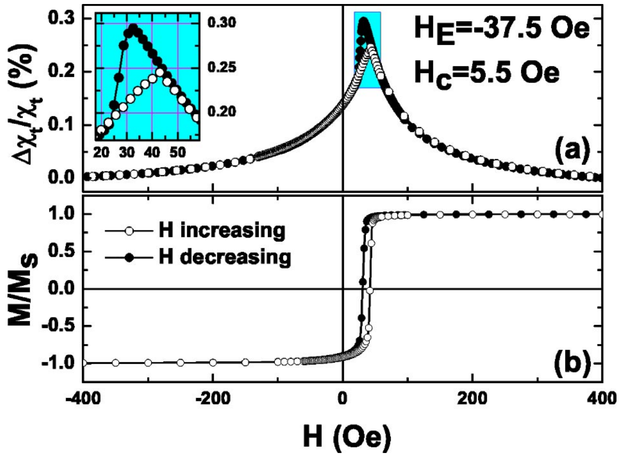

FIG. 1. (Color online) (a) TS and (b) magnetization hysteresis loops of IrMn/FeCo. The asymmetry of magnetization reversal mechanism is evident from TS plot.

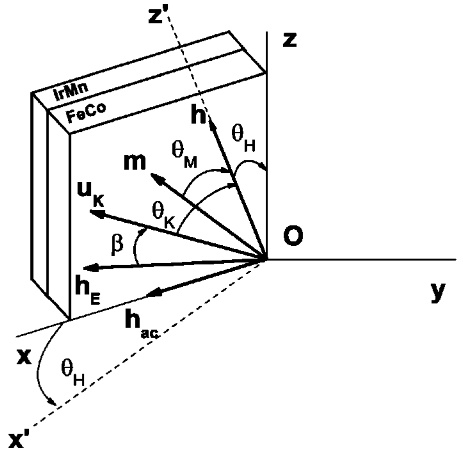

FIG. 2. The thin film sample with the coordinate system.

(full symbols) field ramps (i.e., from -400 to $+400$ Oe and vice versa). The observed TS hysteresis has features with symmetry similar to those of the magnetization hysteresis shown in Fig. 1(b) for the same field orientation. Thus, the shift of the transverse susceptibility hysteresis loop along the field axis clearly indicates the presence of the exchange anisotropy with an exchange field of $H_E = 35.5$ Oe and coercive field in the easy axis direction of $H_c = 5.5$ Oe. The experimental TS curves when the dc field H is applied perpendicular to the easy axis exhibit two peaks per field sweep, symmetrically located around $H=0$, as expected. For this orientation the effect of the exchange anisotropy is not present and this is similar with results obtained for uniaxial systems in the same geometry.[9]

We have calculated the TS for an exchange-coupled system based on a modified Stoner-Wohlfarth model that takes into account the unidirectional energy present in the system. For this one considers a magnetic system composed of FM and AFM layers interacting at their common interface. The exchange anisotropy at the FM/AFM interface can be modeled in terms of an exchange magnetic field, $\mathbf{H_E} = \mathbf{h_E} H_K$ (Ref. 12) in such a way that the total reduced free energy e can be written as

$$e \equiv \frac{E}{2K_1 V} = -\frac{1}{2}(\hat{\mathbf{u}}_K \cdot \hat{\mathbf{m}})^2 - \mathbf{h} \cdot \hat{\mathbf{m}} - \mathbf{h}_E \cdot \hat{\mathbf{m}}, \qquad (1)$$

where the first term represents the uniaxial anisotropy of the ferromagnetic layer directed along the unit vector $\hat{\mathbf{u}}_K$ direction, the second term is the Zeeman interaction of the magnetization $\mathbf{M} = \hat{\mathbf{m}} M$ with the applied field $\mathbf{H} = \mathbf{h} H_K$, the last term describes the interfacial exchange interaction between the FM and the AFM layers, and $H_K = 2K_1/M_s$ is the anisotropy field. The thin film sample lies in the xOz plane as shown in Fig. 2. For generality the easy axis of the FM layer, and the direction of the unidirectional anisotropy were considered both in the sample plane (xOz) but with an angle β between them. The static equilibrium direction of the magnetization vector $\hat{\mathbf{m}}$, assuming that rotates coherently, can be calculated from Eq. (1) by finding the polar (θ_M) and azimuthal (φ_M) angles of $\hat{\mathbf{m}}$ in the spherical coordinate system for which e is at a minimum. It can be easily demonstrated that $\varphi_M = 0$ is a solution for the equilibrium equation and the magnetization vector must lie in the film plane. For the TS experiment, small perturbations of the magnetization about its equilibrium position are produced using a small alternating field oriented perpendicular to the dc field direction. Thus, maintaining the dc field and the amplitude of the ac field constant, with an appropriate pick-up coil system, one detects the variation of the magnetization projection along the ac field direction (transverse with respect to the dc field). Using a similar perturbation approach as in Refs. 7 and 10 and considering the dc field oriented along the Oz axis ($\theta_H = 0$) the transverse susceptibility signal along the Ox direction can be calculated obtaining the following expression:

$$\chi_t \equiv \chi_x = \frac{3}{2}\chi_0 \frac{\cos^2\theta_M}{F(h,\theta_M,\theta_K,h_E,\beta)}, \qquad (2)$$

where $\chi_0 = M^2/3K_1$ and the denominator function is given by

$$F(h,\theta_M,\theta_K,h_E,\beta) = h\cos\theta_M + \cos 2(\theta_M - \theta_K) + h_E \cos(\theta_M - \theta_K - \beta). \qquad (3)$$

One observes that compared with the TS expression for a uniaxial anisotropy,[7,10] the TS expressions (2) and (3) in the case of an exchange biased system contains an extra term in the denominator function F due to the unidirectional anisotropy.

It is worthwhile noting that in general the denominator function F is in fact the second derivative of the free energy (1), i.e., $F = \partial^2 e / \partial \theta_M^2$. Therefore, similarly to FMR,[4] TS is essentially a measure of the ''curvature'' of free energy e or of the stiffness of magnetization **M**. In the TS experiment, the magnetization is perturbed by applying the ac field and e is modified by varying the dc field.

An example of the TS signal calculated using the Eqs. (2) and (3) is presented in Fig. 3. It corresponds to an aligned

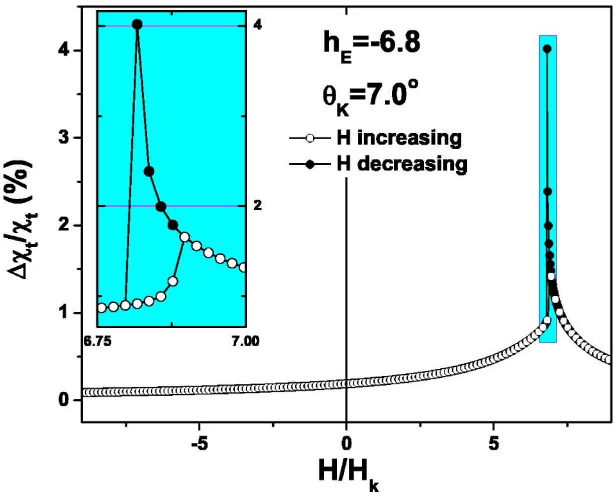

FIG. 3. (Color online) The calculated TS curves.

exchange biased system ($\beta = 0$) with the exchange field parallel to the easy axis and $h_E = -6.8$. The value for the exchange field was chosen based on the values for the exchange field H_E and coercive field H_c along the easy axis deduced experimentally. In order to account for the unequal height of the peaks observed experimentally in the simulated results, a small deviation of $\theta_K = 7°$ for the easy axis direction with respect to the applied field direction was considered. One observes that the theoretical TS curves very well represent the experimental findings shown in Fig. 1, with a shifted hysteresis loop along the field axis and unequal height of the peaks for the increasing and decreasing field curves.

Recently a lot of attention has been paid to the vectorial character of the exchange anisotropy.[12–18] The most used methods to probe the angular dependence of exchange anisotropy are FMR and AMR. We will show that the reversible susceptibility tensor can also provide information about the angular variation of the exchange anisotropy. The method we propose has the advantage that does not require a special sample preparation (no contacts as in the case of AMR) and it provides directly a vectorial mapping of the exchange anisotropy. With the sample in the xOz plane the obvious way to study the angular dependence of the exchange anisotropy using the TS would be to rotate the sample in the xOz plane while preserving the transverse geometry with the dc field along the Oz axis and ac field along Ox axis. However, this approach is very difficult to perform experimentally because usually one employs a small coil for the TS signal detection, and in order to preserve the TS geometry (dc and ac fields reciprocally perpendicular) it is necessary to rotate the sample inside the detection coil. Rotating with precision the sample inside the pick-up coil is too difficult to be effectively applied. However, it is much easier to maintain the position of the sample inside the coil (which is sensing the signal along the Ox axis) and to rotate the dc field direction in the xOz plane (see Fig. 2). In this case the signal along the Ox axis, picked up by the sensing coil, will be given by:

$$\chi_x(\theta_H) = \chi_{z'} \sin\theta_H + \chi_{x'} \cos\theta_H, \tag{4}$$

where $\chi_{z'}$ is the susceptibility along the dc field direction when the field vector has the coordinates given by $\hat{\mathbf{h}} = [\sin\theta_H, 0, \cos\theta_H]$ and $\chi_{x'}$ represents the susceptibility along a direction perpendicular to the direction of the dc field. It can be shown that the components $\chi_{x'}$ and $\chi_{z'}$ of the reversible susceptibility tensor written in the rotated coordinate system $x'Oz'$ can be represented as a function of the expressions of longitudinal and parallel susceptibilities and the detected signal along the ac field direction (Ox) becomes

$$\chi_x(\theta_H) = \frac{3}{2}\chi_0 \frac{\cos^2(\theta_M + \theta_H)}{F(h, \theta_M, \theta_K, h_E, \beta)}, \tag{5}$$

where the denominator function F is the same as in Eq. (2) for the TS.

The fact that the denominator function in Eq. (2) is the same as the one in Eq. (5) is extremely important. This signifies that for the signal detected along the Ox axis, even out of TS geometry ($\theta_H \neq 0$), one has the same singularities as in the case of a regular TS geometry, but for different orientations of the easy axis with respect to the applied dc field direction. In other words, as the field is ramped from positive saturation to negative saturation (or vice versa) the detected signal will present a singularity at the field value, called the switching field, $h_S = H_S / H_K$, for which $F = 0$, i.e., the curvature of free energy vanishes ($\partial^2 e / \partial \theta_M^2 = 0$). When the magnetic field is ramped from positive saturation to negative saturation for each field value the magnetization vector reaches an equilibrium position when $\partial e / \partial \theta_M = 0$. Further, for a specific field value h_S the second derivative also vanishes, $\partial^2 e / \partial \theta_M^2 = 0$. The locus of solutions of the two equations system $\{\partial e / \partial \theta_M = 0, \partial^2 e / \partial \theta_M^2 = 0\}$ represent the critical curve, which in the simple case of a magnetic system with only uniaxial anisotropy is an astroid.[19] The critical curve separates the single stable and bistable regions of the magnetization. As it has been shown[12] for the case of an exchange-coupled system, the critical curve is also an astroid, but shifted from origin by the vector $-\mathbf{h}_E$. Consequently, by performing experiments at different orientations of the applied field, and tracking the singularities in the detected signal, it is possible to obtain the critical curve for the exchange biased system. Both the magnitude and orientation of the exchange field $\mathbf{h}_E$ can be determined readily from the critical curve.

The theoretical procedure illustrated above was experimentally applied to our exchange biased system. The reversible susceptibility signal was recorded for different orientations of the applied field with respect to the sensing coil direction. Starting from perpendicular geometry ($\theta_H = 0$), the composite susceptibility signal (5) was recorded for 41 different orientations in a 200° angular domain separated by 5°. The electromagnet placed on a revolving platform was used as a dc magnetic field source. The detected signal for each field orientation shows a sharp peak located at the field value associated with the singularity in the detected signal (5). Using the switching field values determined, $H_S(\theta_H)$, one can present the results in a parametric fashion using the field coordinates $H_x = H_S(\theta_H)\sin\theta_H$ and $H_z = H_S(\theta_H)\cos\theta_H$. The obtained results are presented in Fig.

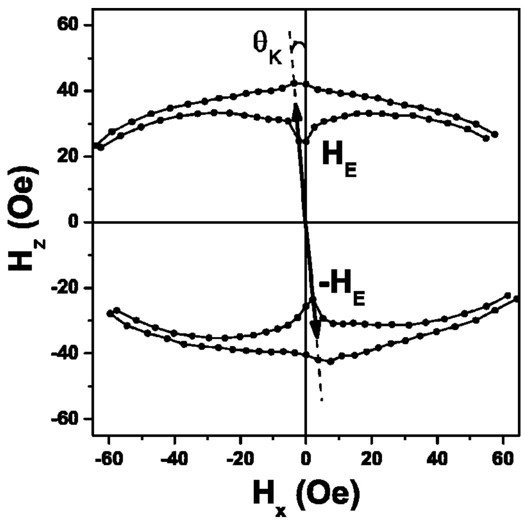

FIG. 4. Experimentally determined switching fields $H_S(\theta_H)$ represented as a critical curve in the plane (H_x, H_z), where $H_x = H_S(\theta_H)\sin\theta_H$ and $H_z = H_S(\theta_H)\cos\theta_H$. The two critical curves correspond to two different initial positions, 0° (bottom) and 180° (top), of the sample with respect to the sensing coil axis. The solid lines are guides for the eye.

4. The data for the same IrMn/FeCo exchange-coupled sample but for two different initial positions with respect to the sensing coil axis (axis Ox), 0° and 180°, determine two different critical curves, symmetrically positioned with respect to the field origin. The experimentally determined critical curves are not symmetric (as the theoretical astroid) but extended along the hard-axis direction. Also, one notes the openings along the hard axis, these being associated with the small hysteresis observed even for a field orientation where we would expect a reversible behavior.[12] This is determined by the existence of a small distribution of the easy axis orientation in our multilayer exchange-coupled sample. A striking feature of the experimentally determined critical curves is their perfect symmetry with respect to the origin for the two initial opposite orientations of the sample, which attests the accuracy of the employed experimental procedure. The small inclination of the critical curves with respect to the ordinate axis was evaluated to be $\theta_K = 7°$, which is consistent with the TS experimental and theoretical results presented in Figs. 1 and 3. Such a representation for the exchange-coupled system has the advantage that it provides comprehensive information about the system from which important features, such as exchange field magnitude and direction or coercivity for any field orientation, can be easily determined. The offset of the center of the critical curve with respect to the field origin gives exactly the magnitude and direction of the exchange field. In summary, using the reversible susceptibility tensor, a theoretical and experimental evidence for vectorial mapping of exchange anisotropy in a IrMn/FeCo exchange-coupled system was presented.

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