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Rotational anisotropy in exchange-biased NiFe/FeMn bilayers

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The anisotropic magnetoresistance (AMR) model was improved in order to determine the magnitude and direction of the rotational anisotropy in NiFe/FeMn bilayer structures having different thicknesses of the ferromagnetic and antiferromagnetic layers. There are two important parameters in the model, namely the ratios $\alpha = H_{rot}/H_{ex}$ and $\beta = \theta_{rot}/\theta_a$, where H_{rot} and θ_{rot} are the effective magnetic field and the angle of the rotational anisotropy and H_{ex} and θ_a are the exchange bias field and the angle of the field applied, respectively. These parameters describe the magnitude and direction of the rotational anisotropy. As the thickness of FeMn layer decreased up to 3.5 nm, the α value increased from about 0.15 to 0.55. This proves that the regions of a weak exchange coupling extended as the antiferromagnetic layer thickness decreases. The parameters α and β almost did not change as the NiFe layer thickness increased from 7 nm up to 15 nm; even though H_{ex} was then reduced from 170 Oe to 70 Oe.

Key words: *exchange biasing; rotational anisotropy; antiferromagnet*

1. Introduction

Exchange anisotropy is a phenomenon arising from the direct exchange coupling at the interface between a ferromagnet (FM) and an antiferromagnet (AF). The best-known property arising from this anisotropy is a shift in the hysteresis loop of a ferromagnet. The field by which the loop is shifted is defined as the exchange-biasing field H_{ex} [1]. To explain such a behaviour theoretically, several models focused on the domain structure of the AF layer for compensated and uncompensated interfaces were proposed in which a single domain state or uniform magnetization of the FM layers was assumed [2]. Although these theories can explain the magnitude of the loop shift in polycrystalline bilayers, they fail to account for the enhanced H_C and a non-vanishing rotational hysteresis in high magnetic fields due to instability in the polycrystalline AF layer [3]. Recent models suggested that there are stable AF grains,

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which contribute to the unidirectional anisotropy, and unstable ones, which cause the rotational anisotropy [4, 5]. Magnetic domain observations in the AF/FM bilayers allowed concluding that the strength of H_{ex} varies at the microscopic scale across the sample [6].

In this work, we improved the AMR model introduced by Dahlberg et al. [7, 8] to determine the magnitude and direction of rotational anisotropy in the FeMn/NiFe and NiO/NiFe structures with a varying thickness of the AF layer. In our model, there are two important parameters of α and β, which represent the magnitude and the angle of rotational anisotropy. The influence of the applied magnetic field H_a on the parameters of the bilayer structures was also investigated.

2. Experimental

The bilayer films of NiFe (10 nm)/FeMn (3.5–20 nm) and NiFe (7–15 nm) /FeMn (20 nm) were deposited at a room temperature onto a Corning glass 7059 in an ion beam sputtering system. The base pressure was below 4.5×10^{-9} Torr. The ion gun was a 3-cm Kaufmann source using Ar gas at the pressure of 1.1×10^{-4} Torr. Ion beam voltage and current during deposition were equal to 800 V and 6 mA, respectively, and the thickness was monitored by a quartz set-up. An aligning field of 300 Oe was applied during the deposition of the ferromagnetic layers to induce uniaxial anisotropy. The magnetic properties were characterized considering the measured anisotropic magnetoresistance (AMR) curves in a 4-point terminal configuration.

The AMR curves varied in their shapes with the applied magnetic field. Particularly, the curves obtained at moderate fields close to H_{ex} have more complex shapes than those obtained at low and high magnetic fields. However, the AMR curve measured in the vicinity of $H_a = H_{ex}$ should be analyzed to understand better the phenomenon of rotational anisotropy in the biased bilayer structure. Three intensities of the applied field, namely $H_a = 0.5H_{ex}$, H_{ex} and $2H_{ex}$, were selected to compare the ratio of rotational and unidirectional anisotropy in the bilayers exhibiting different H_{ex}.

3. Results and discussion

Figure 1 shows the vector representation of our model, in which the rotational anisotropy is reflected by the effective anisotropy field H_{rot}. This field varies with the amplitude of H_a in both its strength and direction during AMR measurement, whereas the magnitude and direction of H_{ex} are fixed. Considering this representation, the magnetic energy density of the ferromagnetic layer in the field applied can be written as

$$E = -H_{ex}M\cos(\theta-\theta_{ex}) - H_{\mathrm{rot}}M\cos(\theta-\theta_{\mathrm{rot}}) - H_aM\cos(\theta_a-\theta) \qquad (1)$$

where M is the magnetization of the FM layer, and θ_{ex}, θ_a and θ_{rot} are the angles defining directions of H_{ex}, H_a, and H_{rot}, respectively. In Eq. (1), the demagnetizing energy is neglected, because it was calculated that the demagnetizing field is smaller than 0.5 Oe for the geometry of the samples used. From the condition of the minimum total energy in the equilibrium state, we can determine the angle θ defining the orientation of the magnetization M. The resistance R of the bilayers is given by

$$R = R_0 + \Delta R \cos^2(\theta - \theta_a) \tag{2}$$

where R_0 is the resistance at $H_a = 0$ and ΔR is the change of resistance due to the AMR effect. Therefore, the AMR follows on the behaviour of $\cos^2\theta$ at $\theta_a = 0$.

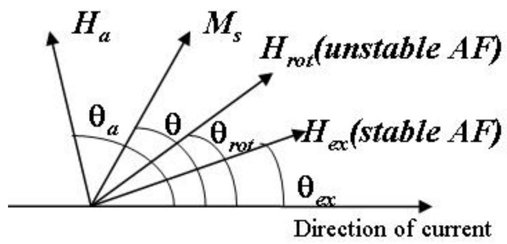

Fig. 1. Vector representation of the model

Minimizing the energy given by Eq. (1) and carrying out some algebraic transformations, one obtains

$$\cos^2\theta = \frac{\left[1 + \alpha\cos\beta\theta_a + \left(\dfrac{H_a}{H_{ex}}\right)\cos\theta_a\right]^2}{\left[1 + \alpha\cos\beta\theta_a + \left(\dfrac{H_a}{H_{ex}}\right)\cos\theta_a\right]^2 + \left[\{\alpha\sin\beta\theta_a + \left(\dfrac{H_a}{H_{ex}}\right)\sin\theta_a\right]^2} \tag{3}$$

where two introduced parameters $\alpha = H_{\mathrm{rot}}/H_{ex}$ and $\beta = \theta_{\mathrm{rot}}/\theta_a$.

Figure 2 shows the experimental points of AMR and the fitting curves as a function of the field applied and FeMn layer thickness in the NiFe(10 nm)/FeMn(4.2, 5, 14 nm) bilayers. As was mentioned earlier, the measurements were carried out at the field applied equal to $0.5H_{ex}$, H_{ex}, and $2H_{ex}$. At the field high enough, the AMR curve is symmetric, displaying two equal minima at 90 and 270 deg. These minima shift towards each other as H_a decreases, reaching $2H_{ex}$ (Fig. 2c). With a further decrease of the field, this shift becomes more pronounced and also a decrease of the central maximum is noticed (Fig 2b). As the field applied reaches a low intensity, the second minimum rises and the curve becomes asymmetric (Fig. 2a). At a very low field the curve becomes eventually periodic again [8]. The maximum peak shifts slightly to higher angles as the FeMn layer thickness decreases. All the AMR data of the FeMn bilayers were well fitted by Eq. (3), except the ones obtained at the low field for the FeMn (3.5 nm) bilayer which exhibited large coercive field.

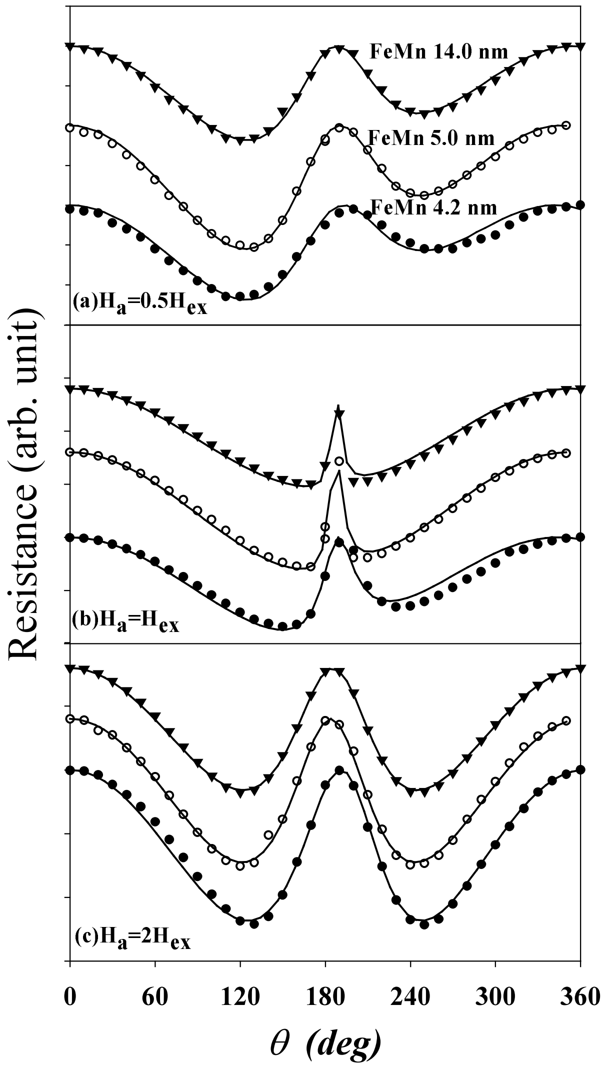

Fig. 2. Experimental dependencies of AMR on the direction of magnetic field of different strength related to bilayer structures of various thickness of FeMn layer (4.2 nm – solid circle; 5 nm – open circle; 14 nm – solid triangle). Solid lines – fits to experimental points

Figure 3 shows the dependence of the α and β ratios on the FeMn-layer thickness with H_a as the parameter. The measured H_{ex} is also shown in this figure as a function of thickness. The α ratio for all H_a increases from about 0.15 to 0.55 with a decrease of the AF-layer thickness in its range of 3.5–14 nm. In the range of above 5 nm, the value of AMR almost does not change. The observed behaviour of the AMR curves confirms the expectation that a number of unstable AF grain, which account for rotational anisotropy, increase as the AF-layer thickness decreases. The AMR curve for the 3.5 nm FeMn-bilayer measured at $H_a = 0.5H_{ex}$ cannot be fitted to Eq. (3). Since our model did not present the information on the hysteresis loss, the bilayer having high coercive field cannot be fitted. For example, the NiO(10, 30 nm)/NiFe(10 nm) bilayers have noticeably higher coercive field than NiFe/FeMn bilayer, therefore the measured AMR curves are not fitted at the central maximum peak.

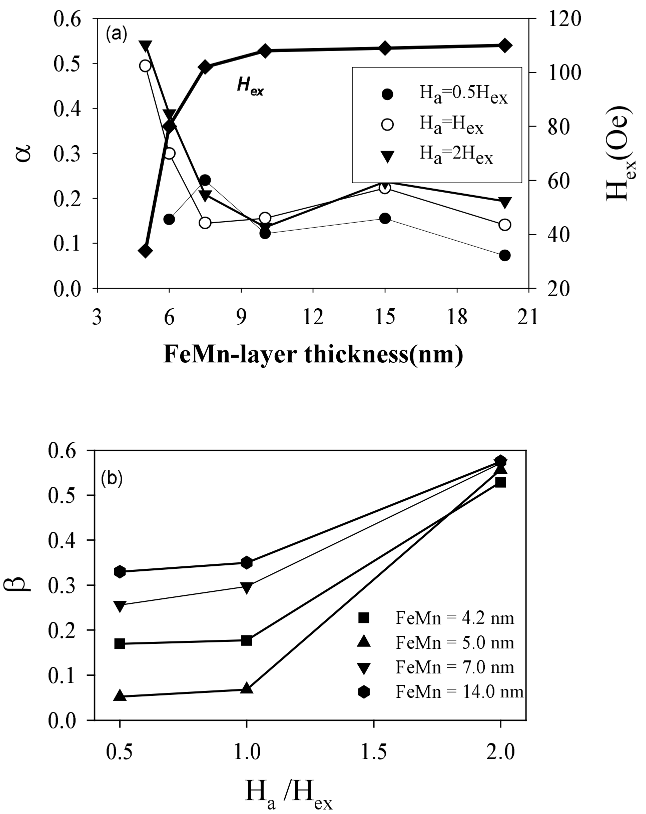

Fig. 3. Dependencies of measured exchange anisotropy field H_{ex} and calculated parameter α on the thickness of FeMn layer at various strengths of the applied field (a); dependence of the parameter β on H_a/H_{ex} at various thicknesses of FeMn layer (b)

The $\beta = \theta_{rot}/\theta_a$ means that the direction of rotational anisotropy lagged behind that of H_a. This ratio increases with H_a, as is shown in Fig. 3b. It is quite obvious that the direction of the rotational anisotropy strongly depends on the applied field. However, the β ratio was independent of the AF layer thickness.

Figure 4 shows the dependence of calculated α and β on the thickness of NiFe layer. As the NiFe thickness increases from 7 nm to 15 nm, H_{ex} decreases from 170 Oe to 70 Oe. However, α and β did not show any dependence. For all the exchange biased systems, H_{ex} is inversely proportional to the thickness of FM layer, because exchange bias is an interface effect. Although H_{ex} decreases with the FM layer

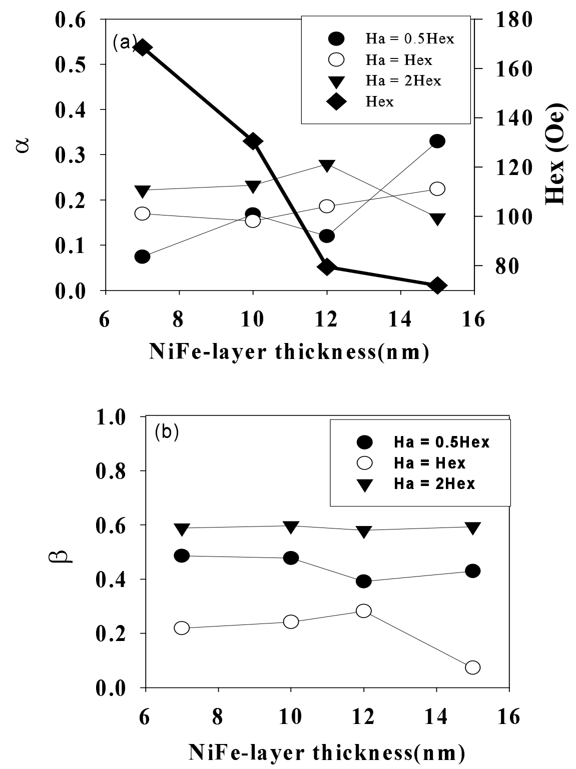

Fig. 4. Dependencies of measured exchange anisotropy field H_{ex} and calculated parameter α on the thickness of NiFe layer at various strengths of the field applied (a); dependence of the parameter β on H_a/H_{ex} at various thicknesses of NiFe layer (b)

thickness, the stable AF grains generating the exchange anisotropy at interface do not change. Therefore, the α and β ratios do not depend on the FM layer thickness, but only do on the stability of AF layer.

4. Conclusions

We have improved the AMR model introducing the parameters α and β which express the magnitude and direction of the rotational anisotropy in the exchange biased bilayers of different thickness of the AF-layer. From the calculated values of these parameters, we found the relative magnitude of the rotational anisotropy, which increased from 15% to 55% of the exchange anisotropy with a decrease of the AF-layer thickness. We also proved that its direction lagged behind the direction of the field applied by an angle less than a half of θ_a. As the thickness of ferromagnetic layer increased, the α and β parameters practically did not change. These parameters can explain the properties of rotational anisotropy due to unstable AF grains. However, the model cannot be applied to the bilayer structures exhibiting large hysteresis losses and large coercivity. Further modifications of the model are needed and such an attempt has already been undertaken.

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