Size dependence of exchange bias in ferromagnetic/antiferromagnetic bilayers

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When the lateral size of exchange-coupled ferromagnetic-antiferromagnetic bilayers is reduced to a deep submicron size (below 0.2 μm), both the exchange bias and the coercive field increase compared to those of macroscopic samples. We attribute this size dependence to the increasing importance of the magnetostatic interaction. By using the Landau-Lifshitz-Gilbert equation, the size dependence of the hysteresis loops of polycrystalline films is calculated and quantitative pictures are established to describe the crossover from small to large samples.

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An exchange interaction at the interface of a ferromagnetic (F) and an antiferromagnetic (AF) layer results in several unique macroscopic magnetic properties. Among many distinct experimental observations, the most interesting properties are the shift of the hysteresis loop and the enhanced coercivity of the ferromagnetic layer.[1] A number of theoretical models have been developed to explain the origins of these phenomena.[2–10] Most of these theories address the exchange bias in a macroscopic sample where the magnetostatic (MS) interaction in the ferromagnetic layer is expected to play insignificant roles in exchange-biased films. Indeed, it has been experimentally shown that the exchange bias and enhanced coercivity of F/AF layers are independent of the lateral size for lateral sizes larger than 0.5 μm.[11] In a large film, the magnetization reversal of the ferromagnetic layer in the exchange-biased film is mainly controlled by interfacial-exchange coupling between F and AF layers. The interfacial-exchange interaction, which is usually random for a polycrystalline film, creates random pinning centers during the hysteresis process of magnetization reversal. This results in random-field-induced magnetic domains in the ferromagnetic layers and the magnetic properties are strongly correlated with these domains.[7] The MS energy between each domain is small when one averages over the area of a macroscopic film. Therefore, it is justified that the theoretical models of exchange bias do not need to include this complicated MS interaction for a large film.

As the size of bilayers is shrunk down to a few nanometers or to a deep submicron size, which will be required for next-generation magnetic nanostructure devices, the magnetostatic interaction is increasingly important in determining the reversal behavior of the ferromagnetic layer. The MS interaction competes with other energies (interface random energy and ferromagnetic exchange energy); this leads to formation of new domain structures during the magnetization reversal, and both exchange-bias shifts and coercivities are significantly altered as the size of the film decreases. In this paper, we study these new domain structures in the presence of the random field and MS interaction, and determine magnetic properties of the exchange-biased film as a function of sample size. In particular, we introduce a critical sample size under which current theoretical models that neglect magnetostatic interactions fail to describe magnetic properties of exchange-biased films.

We consider a polycrystalline exchange-biased film consisting of antiferromagnetic grains whose lateral size is D. To focus our attention on the interplay between the magnetostatic energy and the interfacial random field, we choose the anisotropic energy of the AF grains large enough so that irreversible transitions of the AF grains are minimized. The energies involved in our study are the exchange and anisotropy energies of the F and AF layers, the random interfacial-exchange coupling between F and AF layers, the MS energy of the F layer, and Zeeman energy due to the external magnetic field. The magnetic hysteresis is calculated by solving the standard Landau-Lifshitz-Gilbert (LLG) equation using the following procedure. The sample was laterally divided into $N\times N$ blocks. Each block represents a grain that consists of $n\times n$ atomic spins in each plane parallel to the interface so that the grain size is $D=na_0$, where a_0 is the lattice constant. The sample size (length) is thus $L_N=ND$. We choose the sample to be a square shape. In the layer thickness direction, we assume the F layer to be uniform; this assumption may limit our model to the cases where the F layer is thin and the anisotropy of the F layer is small. Since the AF grain size in typical experiments is of the order of 10 nm, we need to choose grid size smaller than the grain size in order to obtain reliable results from micromagnetic computations.[12] In our calculation, we divide each grain into 4×4 grids so that the grid size is 2.5 nm for a 10 nm grain size. The AF layer has a fixed anisotropic axis for a given grain (the direction of the anisotropy for *different* grains is random and is in the plane of the layer). Note that we do not freeze the magnetization of the AF layer, instead, the direction of each atomic AF sublattice moment near the interface slightly rotates during magnetization reversal of the F layer. As we have taken the AF anisotropic constant to be large (see the caption of Fig. 1), these variations are, nevertheless, quite small. The explicit forms of each energy term in the absence of magnetostatic energy have already been reported.[7] The magnetostatic energy between ferromagnetic grids is calculated via the standard fast Fourier transform technique.

Before we present our numerical results on the size dependence of the hysteresis loops, it is interesting to qualitatively estimate the relative importance of the interfacial exchange interaction and MS interaction. Let us assume that the ferromagnetic layer breaks up into domains during its magnetization reversal. The average domain size L is deter-

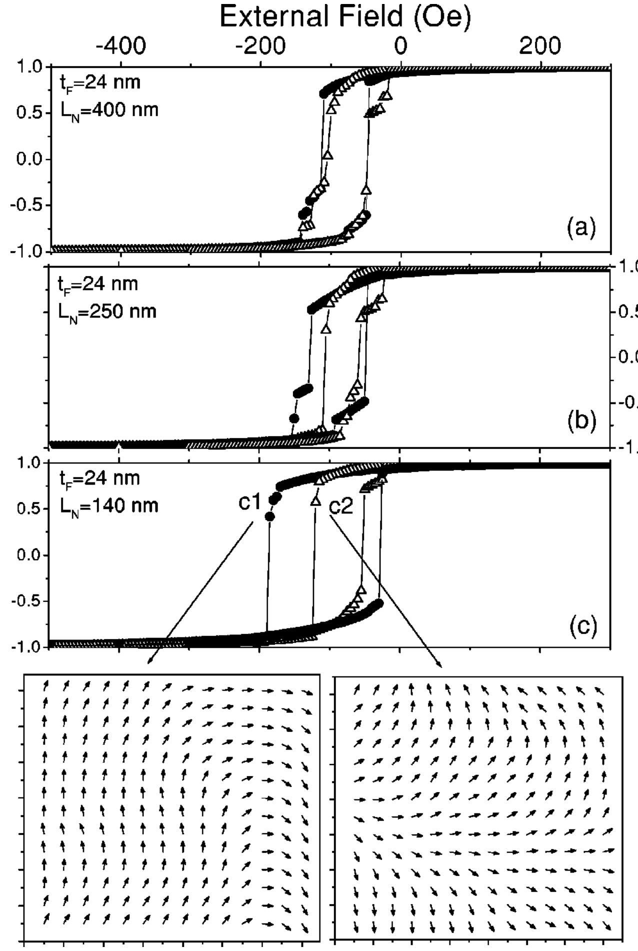

FIG. 1. Hysteresis loops of exchange-biased films for three different lateral size (a) $L_N = 400$ nm, (b) $L_N = 250$ nm and (c) $L_N = 140$ nm. The F layer thickness is $t_F = 24$ nm and the AF grain size $D = 10$ nm. The solid-circle and open-triangle loops are with and without the magnetostatic interaction. The magnetization patterns at the bottom panels for the coercive points at $C1$ and $C2$ as marked in the figure. Note that each arrow represents the average direction of magnetization of 4×4 grids. The parameters are the same as those used in Ref. 5: the ferromagnetic exchange constant $J_F = 16$ mev, the average interfacial-exchange constant $J_s = 2$ mev, the AF exchange constant $J_{AF} = 2$ mev, the anisotropic constant $K_{AF} = 3$ mev, and the thickness of AF layer is 5 ML.

mined by minimizing the ferromagnetic exchange energy, the random exchange interaction at the F/AF interface, and the MS interaction E_d,

$$E = (1/2) t_F J_F L_N^2 / L^2 - J_s L_N^2 / L + E_d, \qquad (1)$$

where t_F is the thickness of F layer, J_F and J_s are the exchange constants in F layer and at the interface, and L_N is the sample size. Here we have discarded the anisotropic energy of the F layer since it is usually very small for the soft magnetic materials, e.g., Permalloy, considered here. In the absence of E_d, the domain size is clearly independent of the sample size L_N and one obtains $L \approx t_F J_F / J_s$ by minimizing the first two terms of Eq. (1).[7] In the presence of E_d, however, one expects that the domain size will be reduced. While the precise form of E_d depends on detailed domain patterns, we simply estimate E_d by a Néel wall whose length is the sample length and whose width is the order of the domain size L, i.e., $E_d = K_m t_F^2 L^2 / (t_F + L_N)$, where $K_m = (1/2) \mu_0 M_s^2$ (M_s is the saturation magnetization).[13] By minimizing the energy of Eq. (1), we obtain a new domain size. If we compare the domain size due to the random interfacial energy and that due to MS energy separately, we obtain from Eq. (1) that

$$L_N = \left(\frac{2 J_F^3 K_m}{J_s^4} \right)^{1/3} t_F^{5/3} \qquad (2)$$

is the critical sample size such that the two mechanisms are equally important. Note that the critical sample size depends on the thickness of the F layer, this is because the magnetostatic energy increases when the F layer thickness increases while the interfacial-exchange interaction is independent of the F layer thickness. From Eq. (2) we estimate that the MS energy becomes important when the size is of the order of 200 nm for t_F of the order of 10 nm.

To predict quantitatively the size dependence of the magnetic properties in exchange-biased films, we solve the LLG equation with and without magnetostatic interactions. As expected, we have found that the calculated hysteresis loops for different sample sizes have only small variation if we do not take into account the magnetostatic interaction. The small variation comes from the random fluctuations in choosing the random interfacial interaction. As long as the sample contains a sufficient number of grains (over 100), the variation is negligible, i.e., the hysteresis loops are independent of the sample size. If the MS energy is added to the calculation, we find that the calculated hysteresis loops are practically no difference compared to those without the MS energy for *large sample sizes*. This justifies the current theoretical models of exchange bias by neglecting the MS energy for large films. In Fig. 1, we show the calculated results for a fixed F layer thickness. For $L_N = 400$ nm, Fig. 1(a), the two hysteresis loops with and without MS are almost identical. This indicates that the random interface interaction dominates and MS is unimportant when the sample size is larger than $L_N = 400$ nm. However, for $L_N = 140$ nm, Fig. 1(c) two hysteresis loops are distinctly different; both the loop shift and coercivity are larger when the MS interaction is taken into account.

It is interesting to take a close look at the magnetization patterns near the coercive fields with and without MS interaction, shown at the bottom of Fig. 1. Each arrow in the diagram represents the *averaged direction* of 4×4 ferromagnetic grids above an AF grain. It is noted that these two patterns are quite different. When the MS interaction dominates ($C1$), it becomes difficult to identify the locations of larger interfacial interaction. The strong MS interaction makes the magnetic moments at the sample boundaries favor parallel alignment to the sample surface. The boundary supplies additional pinning centers to compete with random interface-exchange interaction. Thus, we can understand the enhanced coercivity as follows. In a large film, the coercivity is mainly from the random interfacial interaction that ener-

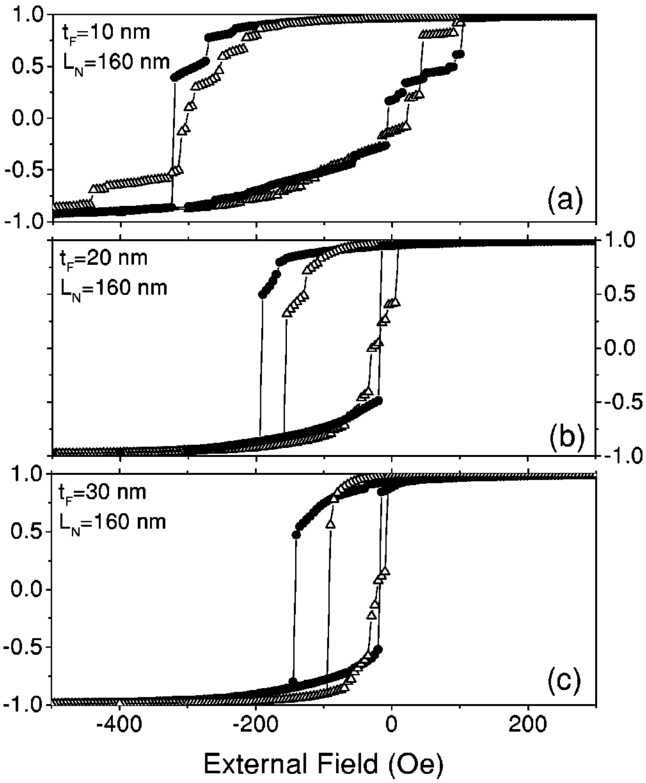

FIG. 2. Hysteresis loops of exchange-biased films for three different F layer thicknesses. The sample size is $L_N = 160$ nm and the other parameters are those in Fig. 1.

getically favors the breakup of the ferromagnetic domains. The coercivity is correlated with the size of domains: the smaller the domain size the larger the coercivity.[7] For a small sample, the MS interaction introduces an additional pinning mechanism and results in a smaller domain size, and thus, the coercivity increases.

Since the magnetostatic energy grows when the ferromagnetic layer thickness increases, the influence of the magnetostatic energy is more significant for the thicker F layer. In Fig. 2, the hysteresis loops for a fixed sample size are shown for three different layer thicknesses. For the thinner F layer $t_F = 10$ nm, Fig. 2(a), $L_N = 160$ nm is characterized as a ''large'' sample since the hysteresis loop is almost unaffected by the MS interaction. For the thicker F layer $t_F = 30$ nm, Fig. 2(c) the same sample size $L_N = 160$ nm shows significant alteration of the hysteresis and one should classify the sample as a ''small'' size. This thickness dependence is consistent with our qualitative argument given by Eq. (2). Therefore, in order to define the ''small'' or ''large'' samples one must specify the thickness of the F layer.

To quantitatively address the critical sample size below that one needs to include the MS interaction in modeling exchange-biased films, we define a dimensionless parameter ξ by

$$\xi = \frac{\int dH |M_z(H) - M_z^d(H)|}{\int dH |M_z(H)|}, \tag{3}$$

where $M_z^d(H)$ and $M_z(H)$ are the magnetization with and without MS interaction. If ξ is appreciable, one has to include MS in modeling the exchange biased films. More specifically, let us choose the critical sample size by $\xi = 5\%$, i.e., if ξ is less than 5%, it is reasonable to omit the MS interaction and current theories for exchange biasing are applicable. In Fig. 3, we show the critical sample size as a function of the F layer thickness. Clearly, the thinner is the F layer, the smaller is the critical size. If the $L_N - t_F$ ''phase diagram'' falls into the region above the ''phase line'' in Fig. 3, one can justify the use of models by omitting the MS interaction. Otherwise, one must include the MS in the modeling. To see whether this ''phase diagram,'' Fig. 3, is sensitive to the choice of the polycrystal AF grain size, we have varied the AF grain size from 10 nm to 20 nm. We found that the phase boundary shown in Fig. 3 remain valid. Thus, the critical sample size is insensitive to the grain size.

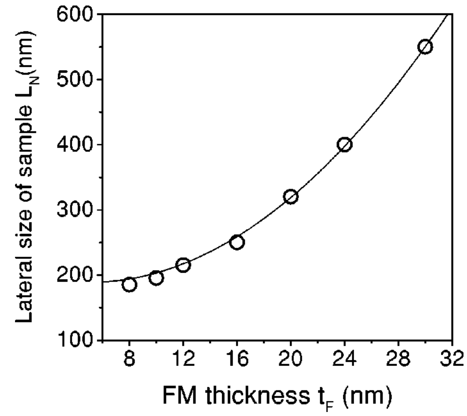

FIG. 3. The critical line as defined in the text. The parameters are the same as those in Fig. 1.

Finally, we show the change of exchange bias H_e as the sample size becomes small. In Fig. 4, we compare the relative increase of H_e for two different F layer thicknesses. H_e can be more than 30% larger than those of large films for a particular range of the sample size. We note that the effect of MS disappears when the sample is too small (below 50 nm)

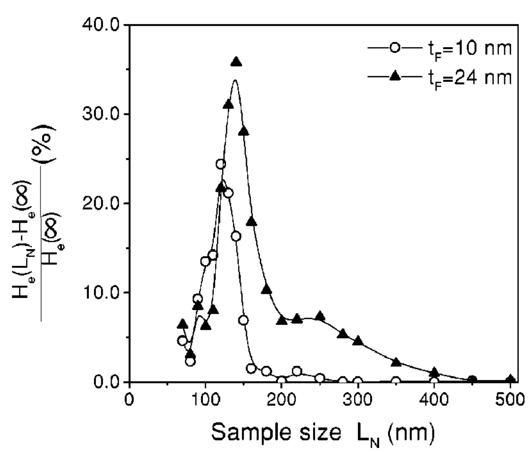

FIG. 4. Percentage enhancement of the exchange bias as a function of the sample size for $t_F = 10$ nm (open circles) and $t_F = 24$ nm (solid triangles). The parameters are the same as in Fig. 1.

since the MS interaction is unable to break the F layer into domains and the magnetic reversal is almost coherent rotation. Therefore, the exchange bias is simply given by the average of the interfacial random field.

The size dependence of the hysteresis loop shift shown in Fig. 4 leads us to conclude that the hysteresis loop shift is *not* an intrinsic property to characterize the average interfacial interaction between F and AF layers. The several competing interactions make the magnetization reversal *nonrotational* so that the loop shift depends on the details of the reversal processes. This point has also been pointed earlier when the different loop shifts were obtained from the experiments via usual hysteresis measurement and via rotating the direction of a large applied magnetic field to eliminate the domains in the F layer.[14] In our case, the determination of H_e in small size is much more difficult due to more complicated magnetic domain structures. Therefore, the most commonly used relation between the loop shift H_e and the average interfacial energy [3] is not valid.

In conclusion, we have shown how the boundary effects that are known to affect the magnetization reversal in a free film, affect the magnetization reversal and, therefore, measured exchange bias. While most of experiments were carried out for samples whose sizes are much larger than the critical size introduced here, it is certainly possible to fabricate devices smaller than the critical size with present experimental techniques.[15] In fact, the present magnetoresistive (MR) heads based on exchange-biased films have already in the range of submicrometers and the next generation MR heads will be certainly below the critical size. The theoretical model presented here provides a prediction on the behavior of exchange-biased films in small structures.

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