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# Influence of lateral domains and interface domain walls on exchange-bias phenomena in GbFe/TdFe bilayers

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The effect of lateral magnetic domains on exchange-bias phenomena in a soft/hard $Gd_{40}Fe_{60}$(100 nm)/$Tb_{12}Fe_{88}$(50 nm) bilayer with antiferromagnetic interface exchange coupling is investigated. At low temperature, domains in the hard TbFe layer are found to behave independently of each other and to give rise to their own exchange-bias fields. Double hysteresis loops are observed when the sample is cooled with domains present in both the hard TbFe layer and the soft GdFe layer, whereas single hysteresis loops are observed when domains are only present in the hard layer. These features are understood by taking into account the presence of both lateral domains and planar interface domain walls in this strongly coupled system.

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## I. INTRODUCTION

Discovered in 1956,[1] the exchange-bias (EB) phenomenon in ferromagnetic (FM)/antiferromagnetic (AF) bilayer systems has received renewed interest in the last 15 years.[2–5] Its main effect is to shift the FM hysteresis loop by a field $H_E$, the exchange-bias field, after field cooling of the bilayer through the blocking temperature $T_B$ of the AF material. Once the magnetic order is set inside the AF layer, the latter is relatively insensitive to external fields by virtue of its low net magnetic moment. Hence, it can act as a pinning layer and produce a unidirectional magnetic anisotropy. Precise understanding of EB requires a good knowledge of the spin structure in the AF layer, especially close to the interface. Most models of EB are based on specific assumptions regarding the interfacial magnetic structure.[4,5] However, it is generally difficult to put these assumptions to the test since only very few experimental techniques can provide information about the AF spins[6] and their response during the reversal of the FM magnetization.

While most studies of EB have been performed on FM/AF stacks, related bias effects have also been observed on a variety of other systems such as bilayers of hard and soft ferromagnetic[7,8] or ferrimagnetic materials.[9] In these systems, the hard magnetic layer may, in moderate applied fields and at sufficiently low temperature, play a role analogous to that of the AF layer and act as a pinning layer. The biasing of the soft layer magnetization is then measured in minor loops with the applied field kept smaller than the coercive field of the hard material. The main advantage of these structures is that the controlling magnetic parameters, such as the interfacial coupling strength and the magnetic anisotropy of the pinning layer, can be measured easily.[10]

The exchange-bias field is usually negative.[2,3] However, in few cases, positive $H_E$ values have been reported. Examples of systems which exhibit positive EB may be found in the two categories of systems discussed before—that is, in FM/AF systems[6,11–13] and in soft/hard systems.[14–16] It was also observed for more complex stacks based on synthetic ferrimagnets, of the type CoO/Co/Ru/Co.[17] Most of these systems share the following features: (i) $H_E$ changes from negative to positive as the amplitude of the cooling field is increased, (ii) the coercive field $H_C$ reaches a maximum as $H_E$ goes through zero, and (iii) a significant shift of the hysteresis loop along the magnetization axis $M_{Shift}$ is observed. It has been posited that the occurrence of positive EB requires some kind of coupling of the pinning layer spins to the cooling field and an antiferromagnetic exchange interaction across the interface.

Recently, it has been observed that, instead of showing a maximum in coercivity when $H_E$ changes sign, the hysteresis loop may bifurcate into two subloops shifted in opposite directions.[17–19] This has been ascribed to the occurrence of large domains, with opposite spin orientations, in the AF or hard layer.[18] Indeed, if domains are present in the pinning layer which are larger than the characteristic magnetic length scale (e.g., domain size) in the exchange-biased (FM or soft) layer, they are expected to behave independently of each other and to give rise to their own exchange-bias fields, hence possibly to double loops. If, on the contrary, the domains in the pinning layer are small, the pinned layer is believed to average over many of these domains, giving rise to a single loop whose shift may vary continuously as the domain populations evolve.

In the amorphous ferrimagnetic soft/hard $Gd_{40}Fe_{60}/Tb_{12}Fe_{88}$ bilayer system studied here, the continuous transition from negative EB to positive EB observed when increasing the cooling field amplitude $H_{cf}$ does not involve lateral domains in the hard TbFe alloy. Clear evidence has been given that, as a result of the antiferromagnetic nature of the interfacial coupling, a planar domain wall forms upon application of large external fields, which extends in both GdFe and TbFe.[14] The portion of the interface domain wall (IDW) located in the TbFe pinning layer freezes upon field cooling from room temperature down to 5–20 K.[15,20] The resulting exchange-bias field is determined by the orientation of the quenched TbFe magnetization at the interface, which rotates continuously from antiparallel to parallel to the cooling field direction as $H_{cf}$ increases.[14,15]

In the present work, we address the influence of lateral domains in the pinning layer on EB in the strongly coupled

 

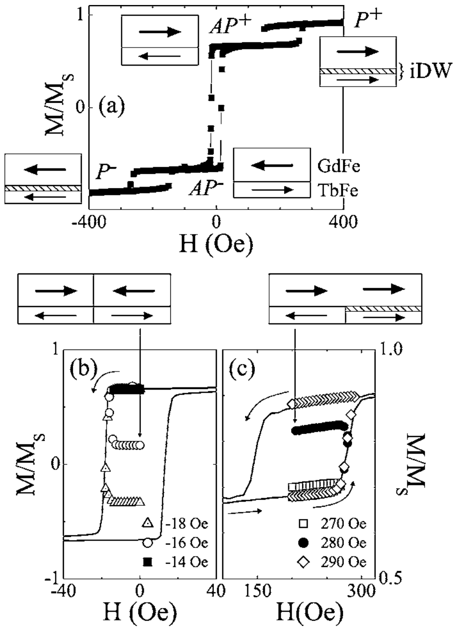


FIG. 1. (a) Easy-axis normalized magnetization loop of the GdFe(100 nm)/TbFe(50 nm) bilayer, at 300 K. The four different magnetic configurations ($P^+$, $AP^+$, $AP^-$, and $P^-$) adopted by the system are sketched. (b) Examples of minor loops performed to obtained $AP^+/AP^-$ mixed domain states: The applied field $H$ is swept from +10 kOe down to $-20\ \mathrm{Oe} \leq H_X \leq -14$ Oe and then up to 0 Oe. (c) Examples of minor loops performed to obtained $AP^+/P^+$ mixed domain states: $H$ is swept from +10 kOe down to 0 Oe, then up to $265\ \mathrm{Oe} \leq H'_X \leq 290$ Oe, and finally down to $H=200$ Oe. The corresponding values of $H_X$ and $H'_X$ are given in the legends. The solid line in (b) and (c) is the major loop shown in (a).

$Gd_{40}Fe_{60}/Tb_{12}Fe_{88}$ system. After presenting the sample and its room-temperature magnetic behavior, the procedures used to purposely induce lateral domains in the pinning layer are described. Then, the influence of these domains on the shape of the hysteresis loops after cooling to low temperature is shown. Finally, the origin of the exchange-bias phenomena observed is discussed, taking into account the influence of both interface domain walls and lateral domains in TbFe.

## II. EXPERIMENTAL DETAILS

The sample investigated consists of a $Gd_{40}Fe_{60}$(100 nm)/$Tb_{12}Fe_{88}$(50 nm) bilayer, grown by co-evaporation of the pure elements on a glass substrate kept at liquid nitrogen temperature and covered with a 30 nm-thick Si cap.[14,15] Its room-temperature magnetization loop, measured by superconducting quantum interference device (SQUID) magnetometry, is shown in Fig. 1(a). The characteristic shape of this $M(H)$ curve, with its three steps, is the signature of an antiferromagnetically coupled bilayer.[16] Four different magnetic configurations may be distinguished. In the $P^+$ configuration adopted in large positive fields, the magnetizations of the two layers tend to be parallel to each other. However, because of the antiferromagnetic interface coupling, an IDW is necessarily present. It is mainly located in TbFe. Its thickness changes reversibly as the field is varied, decreasing (respectively, increasing) with increasing (respectively, decreasing) field strength. As the external field is decreased towards zero, the interfacial coupling interaction eventually overcomes the Zeeman interaction: The TbFe magnetization reverses and the bilayer switches into the $AP^+$ configuration, in which the two layers are magnetized homogeneously, antiparallel to each other. Each of these two first configurations has a mirror-symmetric counterpart: The $AP^-$ configuration formed in small negative fields as a result of the simultaneous reversal of the magnetizations of the two layers and, finally, the $P^-$ configuration reached for large negative fields. At each irreversible transition, TbFe reverses its magnetization through a process of nucleation and propagation of lateral domains. One may then induce domains in TbFe by initiating any of these transitions and preventing its completion. Since the system exhibits two kinds of inequivalent transitions (involving or not the formation or annihilation of an IDW), there are two inequivalent types of mixed domain states to consider: One may have the coexistence of either the $AP^+$ and $AP^-$ configurations or the $AP^+$ and $P^+$ ($AP^-$ and $P^-$) ones.

### A. Preparations of domain states

To obtain mixtures of $AP^+$ and $AP^-$ lateral domains of varying proportions, the external field was swept from a large positive value of +10 kOe down to a small negative one, $H_X$, ranging from −20 to −14 Oe, and then back to 0 [Fig. 1(b)]. We name the remanent magnetization resulting from this procedure $M_0$. The fraction of the TbFe layer magnetized in the negative field direction (as in the $AP^+$ state), $\Delta_{\mathrm{TbFe}}$, is given by

$$\Delta_{\mathrm{TbFe}}(H_X) = \frac{M_0(H_X) - M_{AP^-}}{M_{AP^+} - M_{AP^-}}, \tag{1}$$

where $M_{AP^+}$ and $M_{AP^-}$ are the magnetizations of the $AP^+$ and $AP^-$ states, respectively. To produce $AP^+/P^+$ mixed domain states, the field was swept from a large positive value down to 0, then up to a small positive value $H'_X$ ranging from +265 to +290 Oe, and finally back to +200 Oe [Fig. 1(c)]. The magnetization measured at the end of this procedure, in $H=+200$ Oe, is named $M_{200}$. In this case, the fraction of the TbFe layer in which the magnetization is oriented in the negative field direction, $\Delta'_{\mathrm{TbFe}}$, may be estimated using

$$\Delta'_{\mathrm{TbFe}}(H'_X) = \frac{M_{200}(H'_X) - M_{P^+}}{M_{AP^+} - M_{P^+}}, \tag{2}$$

where $M_{P^+}$ is the magnetization of the $P^+$ state. Notice that Eq. (2) assumes implicitly that the amount of magnetization involved in the IDW is negligible—i.e., that $M_{P^+}$ is close to the saturation magnetization of the sample, $M_S$, which is only true in rough approximation.

### B. Biasing experiments on different domain states

For each multidomain state realized, the sample was cooled to 5 K in the same magnetic field $H_{cf}$ as applied at the very end of the procedure carried out to induce the domain

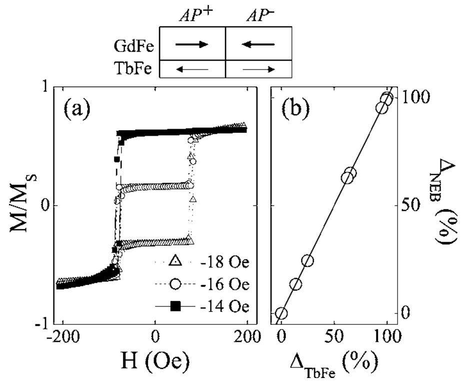


FIG. 2. (a) Examples of minor hysteresis loops measured at 5 K, after cooling the sample under zero field in various $AP^+/AP^-$ mixed states. Values of $H_X$ are indicated in the legend. (b) Fraction of the sample exchange-biased negatively at 5 K, $\Delta_{NEB}$ [Eq. (3)], as a function of the fraction of the TbFe layer magnetized in the negative field direction at room temperature, $\Delta_{\mathrm{TbFe}}$ [Eq. (1)]. Errors bars are shorter than the symbol size.

formation—i.e., either in $H_{cf}=0$ Oe or in $H_{cf}=+200$ Oe, whichever applied. At low temperature, the response of the exchange-biased GdFe layer was determined by measuring ±200-Oe minor loops. No evolution of the loops could be detected with the number of field cycles performed (i.e. absence of training effect). This proves that the micromagnetic structure of TbFe did not evolve significantly. Figures 2(a) and 3(a) show examples of minor loops obtained for $AP^+/AP^-$ mixed states and $AP^+/P^+$ mixed states, respectively. Although lateral domains formed at room temperature in both cases, it is obvious that the resulting low-temperature exchange-bias properties differ and depend in detail on the kind of micromagnetic structure frozen in TbFe.

## III. RESULTS AND DISCUSSION

In the case of $AP^+/AP^-$ mixed states, bifurcated hysteresis curves are observed [Fig. 2(a)]. This is consistent with the presence of large, independent domains in the TbFe pinning layer.[18,21] The $M(H)$ curves appear as linear combinations of two loops. One of them is shifted towards a positive exchange-bias field $+H_E^{Max}$, whereas the other one is shifted towards the exact opposite (negative) field $-H_E^{Max}$, $H_E^{Max}=80$ Oe being the largest possible exchange-bias amplitude for the particular bilayer system studied.[14,15] The widths of the two loops are identical ($H_C\sim 10$ Oe) and do not vary appreciably with $H_X$ ($\Delta_{\mathrm{TbFe}}$). Clearly, the sample behaves as if it consisted of two independent subsystems exchange biased in an opposite manner. The relative weights of the two subloops in a given bifurcated $M(H)$ curve—that is, the relative fractions of the sample the two subsystems occupy—may be readily obtained from the remanent magnetization of the bilayer at 5 K, $M_R$. For instance, the fraction which is exchange biased negatively is

$$\Delta_{NEB}(H_X)=\frac{M_R(H_X)-M_R^{AP^-}}{M_R^{AP^+}-M_R^{AP^-}}, \qquad (3)$$

where $M_R^{AP^+}$ and $M_R^{AP^-}$ are the low-temperature remanent magnetization measured after cooling the sample in pure $AP^+$ ($H_X=-14$ Oe, $\Delta_{\mathrm{TbFe}}=1$) and $AP^-$ ($H_X=-20$ Oe, $\Delta_{\mathrm{TbFe}}=0$) states, respectively. As may be seen in Fig. 2(b), $\Delta_{NEB}$ is, within experimental error, equal to $\Delta_{\mathrm{TbFe}}$, independent of $H_X$. Thus, we can conclude that (i) the domain patterns of type $AP^+/AP^-$ formed in TbFe at elevated temperature are essentially unchanged after cooling and that (ii) that part of the sample which is exchange biased negatively (respectively, positively) corresponds to the domains where TbFe is magnetized along the negative (respectively, positive) field direction.

In comparison, the results obtained after $P^+/AP^+$ mixed states were formed at room temperature are more intriguing. Indeed, the $M(H)$ curves show neither bifurcation nor any kind of transition from negative EB to positive EB [Fig. 3(a)]. All of the curves consist of single hysteresis loops, shifted negatively, with exchange-bias and coercive fields nearly independent of $H'_X$ (Ref. 22). The only evolution clearly discernible upon varying $H'_X$ is a change in the vertical offset of the GdFe minor loop.

To quantify this magnetization shift, let us consider the ratio

$$\bar{M}_{Shift}(H'_X)=\frac{M_R(H'_X)-M_R^{P^+}}{M_R^{AP^+}-M_R^{P^+}}, \qquad (4)$$

where $M_R^{P^+}$ is the low-temperature remanent magnetization after the sample was cooled in a pure $P^+$ state ($H'_X=290$ Oe, $\Delta'_{\mathrm{TbFe}}\sim 0$)—i.e., the largest value assumed by $M_R(H'_X)$, $M_R^{AP^+}$ being the smallest. As shown in Fig. 3(b), $\bar{M}_{Shift}$ scales linearly with the fraction of the TbFe layer magnetized negatively prior to field cooling. This is a clear indication that $AP^+$- and $P^+$-type domains are effectively present in TbFe at 5 K, in proportions close to those at room temperature, a point one might be tempted to question otherwise.

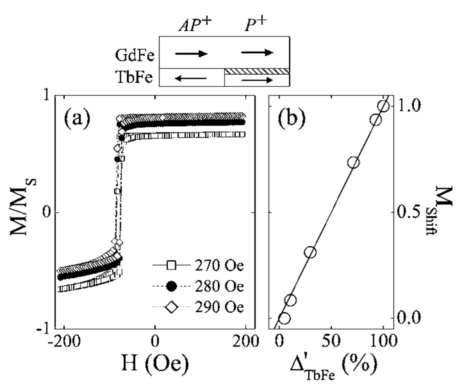


FIG. 3. (a) Examples of minor hysteresis loops measured at 5 K after cooling the sample under $H_{cf}=200$ Oe in various $AP^+/P^+$ mixed states corresponding to different values of $H'_X$, indicated in the legend. (b) Normalized magnetization shift $\bar{M}_{Shift}$ [Eq. (4)], at 5 K, as a function of the fraction of the TbFe layer magnetized in the negative field direction at room temperature, $\Delta'_{\mathrm{TbFe}}$ [Eq. (2)]. Errors bars are shorter than the symbol size.

It is known from previous investigations that EB in the $Gd_{40}Fe_{60}/Tb_{12}Fe_{88}$ system is determined by the orientation of the TbFe magnetization at the very interface.[15] In order to explain why single loops are recorded although the pinning layer contains lateral domains of opposite orientations, the nature of the spin structure at the interface needs therefore to be examined more carefully. In an $AP^+/AP^-$ mixed state, commensurate domains are present in the two magnetic materials (sketch in Fig. 2). In both $AP^+$ and $AP^-$ configurations, the TbFe magnetization is vertically uniform: The interface spins are aligned in the very same direction as in the bulk of the layer—i.e., in the positive field direction ($H_E=-H_E^{Max}$) for the $AP^-$ state. In the $P^+$ configuration, the magnetization in the bulk of TbFe is aligned in the positive field direction, as in the $AP^-$ state, but the interface magnetization $\mathbf{M}^i_{\mathrm{TbFe}}$ is not. One-dimensional micromagnetic calculations[14] indicate that, for $H=200$ Oe, TbFe contains a nearly complete 180° planar Bloch-like wall so that $\mathbf{M}^i_{\mathrm{TbFe}}$ is rather oriented almost parallel to the negative field direction. Thus, in an $AP^+/P^+$ mixed state, GdFe is magnetized almost uniformly, both in depth and laterally (sketch in Fig. 3).

Using anisotropic magnetoresistance measurements,[15] we have demonstrated that, upon cooling in the $P^+$ state, the partial IDW in TbFe freezes out and $\mathbf{M}^i_{\mathrm{TbFe}}$ gets quenched at an angle $\theta^i_{\mathrm{TbFe}}$ of approximately 170° from the cooling (positive) field direction. The corresponding exchange-bias field $H_E\sim-76$ Oe is extremely close to that associated with the $AP^+$ configuration ($\theta^i_{\mathrm{TbFe}}=180°$), $H_E=-80$ Oe. Although strongly different in their vertical magnetization profile, which is the reason why $\bar{M}_{Shift}$ varies with $\Delta'_{\mathrm{TbFe}}$ [Fig. 3(b)], TbFe lateral domains of $AP^+$ and $P^+$ types are then similar as far as the orientation of their interface magnetization is concerned. The asymmetry in the biased hysteresis loop comes from the fact that an IDW is present in the GdFe only when its magnetization is pointing along the field direction.[15]

Precise hysteresis loop measurements show a variation of the exchange bias field from −80 Oe to −78 Oe as shown in Fig. 4. This is coherent with the slight difference in the exchange bias field for $AP^+$ domains and $P^+$ (for $H_{cf}=200$ Oe). However, the changes shown in Fig. 4 are within the precision limits of the experimental setup and do not permit one to conclude if it results from two loops slightly differently shifted or from a single loop.

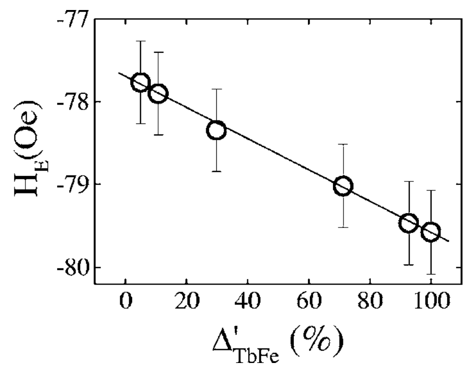


FIG. 4. Exchange-bias field $H_E$ for $H_{cf}=200$ Oe as a function of the fraction of the TbFe magnetization pointing in the negative field direction $\Delta'_{\mathrm{TbFe}}$ [Eq. (2)]. The line is a guide to the eye.

In conclusion, various types of shifted minor (GdFe) hysteresis loops are recorded, at low temperature, for an antiferromagnetically exchange-coupled soft/hard $Gd_{40}Fe_{60}$(100 nm)/$Tb_{12}Fe_{88}$(50 nm) bilayer depending on the multidomain magnetic structure imprinted in the hard layer during cooling. When the system is zero field cooled, with oppositely magnetized domains in both TbFe and GdFe, a double-shifted loop is obtained whose shape reflects the domain populations. When it is field cooled, with domains present only in TbFe, a single loop is obtained which changes only weakly with the domain populations. These observations may be perfectly understood by taking into account the combined effects of lateral domains *and* interface domain walls, in the latter case. The present work is a new illustration that exchange bias in the soft/hard $Gd_{40}Fe_{60}/Tb_{12}Fe_{88}$ bilayer is governed by the behavior of the pinning layer magnetization at the interface, not in the bulk. It suggests also that both lateral[23] and in-plane[24] modulations of the magnetization should be taken into account to provide a fully satisfactory theoretical model of exchange bias in such systems.

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