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# Magnetic behavior of systems composed of coupled ferromagnetic bilayers with distinct anisotropy directions

A. Bollero,<sup>1,\*</sup> L. D. Buda-Prejbeanu,<sup>1</sup> V. Baltz,<sup>1</sup> J. Sort,<sup>2</sup> B. Rodmacq,<sup>1</sup> and B. Dieny<sup>1</sup>

<sup>1</sup>*SPINTEC (URA 2512 CNRS/CEA), CEA-Grenoble, 17 Avenue Martyrs, 38054 Grenoble Cedex 9, France*

<sup>2</sup>*Institució Catalana de Recerca i Estudis Avançats (ICREA) and Departament de Física, Facultat de Ciències, Universitat Autònoma de Barcelona, 08193 Bellaterra, Spain*

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A shift in the hysteresis loop of a NiFe thin film (with in-plane anisotropy) exchange coupled to a [Pt/Co] multilayer (with out-of-plane anisotropy) is observed after in-plane saturation of the system. The origin of this effect and the related magnetic properties are investigated by means of in-plane and out-of-plane magnetometry techniques, magnetic force microscopy imaging, and micromagnetic simulations. Both the number of Pt/Co repetitions in the multilayer and the NiFe thickness are found to have an influence on the magnitude of the loop shift and the in-plane and out-of-plane coercivity values of the system. This is correlated with variations in the number and average size of the magnetic domains formed in the [Pt/Co] multilayer which, as revealed by micromagnetic simulations, pin the NiFe magnetization via formation of closure domains with a preferential orientation at the interface between the [Pt/Co] multilayer and the NiFe.

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## I. INTRODUCTION

Interfacial exchange interactions between a ferromagnetic (FM) and an antiferromagnetic (AFM) material typically lead to a displacement of the hysteresis loop along the magnetic field axis by a quantity termed the exchange-bias (EB) field  $H_E$ .<sup>1</sup> This shift is usually accompanied by an increase in the coercivity and it is frequently used to obtain a reference layer for giant-magnetoresistance- or tunneling-magnetoresistance-based devices.<sup>2</sup> Usually, the FM-AFM bilayer must be cooled under an applied field through the blocking temperature of the system,  $T_B$ , in order to induce  $H_E$ . Thus, structural degradation of the multilayered structure can take place during the heating up procedure prior to the field cooling. It has been shown that the use of an AFM material with a low anisotropy allows modifying the magnitude of the EB by isothermally applying sufficiently large fields, hence avoiding the annealing process. The resulting  $H_E$  is attributed to field-induced changes in the domain structure of the AFM.<sup>3,4</sup> Alternatively, it has been recently reported that a shift in the hysteresis loop of a NiFe thin film can be obtained, without need of any heating or cooling procedure, by depositing it on top of a [Pt/Co] multilayer (with perpendicular anisotropy) and subsequently applying a sufficiently strong in-plane magnetic field.<sup>5</sup>

In this work, we investigate the origin of such an effect by means of magnetic force microscopy (MFM) imaging together with micromagnetic simulations. The obtained results indicate that the pinning of the magnetic domain structure of the [Pt/Co] multilayer induced after saturating the system along an in-plane direction plays a fundamental role in order to obtain a shift in the hysteresis loop (“EB-like” effect). Micromagnetic simulations reveal the presence of Néel-type flux closure caps at the interface between the two FM for the [Pt/Co]-NiFe system. After applying the strong in-plane saturating field, a magnetic configuration consisting of unequal closure domains explains the EB effect originated in

this system without the necessity of a field cooling procedure. Furthermore, the evolution of  $H_E$  with the number of Pt/Co repetitions ( $n$ ) and the NiFe thickness ( $t_{\text{NiFe}}$ ) has been systematically studied both experimentally and numerically, in order to make a comparison with EB effects observed in conventional FM-AFM systems.

## II. EXPERIMENTAL PROCEDURE

The composition of the magnetic multilayer films is  $\text{Pt}_{20\text{nm}}/(\text{Co}_{0.6\text{nm}}/\text{Pt}_{1.8\text{nm}})_n/\text{Co}_{0.2\text{nm}}/\text{NiFe}(t_{\text{NiFe}})/\text{Cu}_{2\text{nm}}/\text{Pt}_{2\text{nm}}$ . The first series under study consisted of films with a NiFe layer of constant thickness  $t_{\text{NiFe}}=3$  nm while  $n$  was varied from 3 to 10; a second series was prepared keeping constant the number of Pt/Co repetitions ( $n=6$ ) and varying  $t_{\text{NiFe}}$  from 1 to 5 nm. To accomplish the comparison, single [Pt/Co] multilayers were also prepared. The films were deposited at room temperature onto thermally oxidized Si substrates by dc magnetron sputtering. The Pt buffer layer with a thickness of 20 nm was deposited on the Si substrate prior to the deposition of the multilayer. The base pressure was  $4.9 \times 10^{-8}$  mbar and the Ar gas pressure was maintained at  $2.5 \times 10^{-3}$  mbar during deposition. The procedure to induce an EB-like effect comprised first the application of an in-plane field of 15 kOe to fully saturate the magnetization of all the layers; and second, the measurement of the in-plane hysteresis loop in the same field direction with a maximum applied field ( $H_{\text{hyst,max}}=1.5$  kOe), large enough to saturate the NiFe but insufficient to saturate the [Pt/Co] multilayer. In-plane hysteresis loops were measured by means of vibrating sample magnetometry at room temperature. The extraordinary Hall effect (EHE) has been used to record hysteresis loops along the perpendicular to the film direction after saturating the system with a field applied in the measurement direction. This technique is sensitive to the perpendicular-to-film-plane component of the magnetization,<sup>6,7</sup> allowing us to

probe the influence of varying the number of repetitions  $n$  and the NiFe layer thickness  $t_{\text{NiFe}}$ . The magnetic domain structures of selected samples were imaged by MFM. Two-dimensional (2D) periodic micromagnetic simulations were performed in order to extract information about the magnetic domain structure in the [Pt/Co]-NiFe system at remanence after application of a large in-plane magnetic field. In the micromagnetic model,<sup>8</sup> the [Pt/Co] multilayer was considered as a single FM layer having the same characteristics as the multilayer. The material parameters used for the [Pt/Co] multilayer were the exchange constant  $A_{\text{ex}}=3 \times 10^{-7}$  erg/cm, the out-of-plane uniaxial magnetocrystalline anisotropy constant  $K_u=2.195 \times 10^6$  erg/cm<sup>3</sup>, and the saturation magnetization  $M_s=388$  emu/cm<sup>3</sup> resulting in a quality factor  $Q=K_u/(2\pi M_s^2)=2.3$  comparable to values reported in the literature.<sup>9,10</sup> Standard values for the NiFe were considered:  $A_{\text{ex}}=2 \times 10^{-6}$  erg/cm,  $M_s=800$  emu/cm<sup>3</sup>, and no magnetocrystalline anisotropy. The mesh size was  $2.5 \times 0.2$  nm<sup>2</sup>, i.e., smaller than the magnetic characteristic lengths of the system (exchange length and domain wall width).

### III. RESULTS AND DISCUSSION

We first focus on the series with  $t_{\text{NiFe}}=3$  nm and variable  $n$ . The hysteresis loops measured by the EHE, i.e., with the magnetic field applied perpendicular to the film plane, exhibit a square shape similar to that of single [Pt/Co] multilayers, indicating that magnetization reversal takes place first by nucleation of reversed domains (with perpendicular magnetization) followed by rapid domain wall motion [see inset in Fig. 1(a), corresponding to  $n=6$ ].<sup>11</sup> By comparison with single [Pt/Co] multilayers, the coupling between the NiFe and the [Pt/Co] multilayer leads to several effects: increased out-of-plane saturation field  $H_s^\perp$  (with values of 550 and 850 Oe for  $\text{Pt}_{20\text{nm}}/(\text{Co}_{0.6\text{nm}}/\text{Pt}_{1.8\text{nm}})_5$  and  $\text{Pt}_{20\text{nm}}/(\text{Co}_{0.6\text{nm}}/\text{Pt}_{1.8\text{nm}})_5/\text{Co}_{0.2\text{nm}}/\text{NiFe}_{3\text{nm}}/\text{Cu}_{2\text{nm}}/\text{Pt}_{2\text{nm}}$ , respectively), decreased out-of-plane coercivity  $H_c^\perp$  (475 and 350 Oe, respectively) and slightly reduced remanence to saturation ratio  $M_r^\perp/M_s$  (1 and 0.95, respectively). Figure 1(a) shows the evolution of  $H_c^\perp$  as a function of  $n$  for the [Pt/Co]-NiFe( $t_{\text{NiFe}}=3$  nm) system. The initial increase of  $H_c^\perp$  has been already observed for single [Pt/Co] multilayers and has been explained as being due to the increased number of interfaces when increasing the number of Pt/Co bilayers which enhance the perpendicular anisotropy and act as pinning sites for magnetization reversal.<sup>12</sup> For  $n>6$ ,  $H_c^\perp$  progressively decreases. This can be ascribed to a decrease of the effective magnetic anisotropy constant, similar to what happens in a single [Pt/Co] multilayer when increasing the Co thickness.<sup>9,13</sup> The in-plane hysteresis loop of the  $\text{Pt}_{20\text{nm}}/(\text{Co}_{0.6\text{nm}}/\text{Pt}_{1.8\text{nm}})_6/\text{Co}_{0.2\text{nm}}/\text{NiFe}_{3\text{nm}}/\text{Cu}_{2\text{nm}}/\text{Pt}_{2\text{nm}}$  system, obtained after application of a strong in-plane field  $H_0=15$  kOe, is shown in the inset of Fig. 1(b). Remarkably, this loop is shifted along the magnetic field axis. The dependences of the loop shift  $H_E$  and the in-plane coercivity  $H_c^\parallel$  on the number of Pt/Co repetitions are shown in Fig. 1(b). Interestingly, both  $H_E$  and  $H_c^\parallel$  increase with increasing  $n$ . Actually, these two quantities and  $H_c^\perp$  all increase with  $n$ , up to

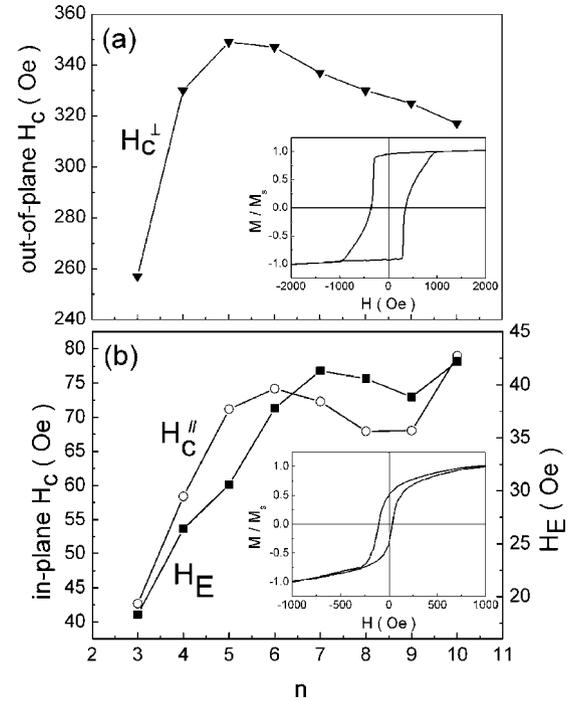


FIG. 1. (a) Evolution of the out-of-plane coercivity  $H_c^\perp$  with the number of Pt/Co bilayers,  $n$ , after saturating the  $\text{Pt}_{20\text{nm}}/(\text{Co}_{0.6\text{nm}}/\text{Pt}_{1.8\text{nm}})_n/\text{Co}_{0.2\text{nm}}/\text{NiFe}_{3\text{nm}}/\text{Cu}_{2\text{nm}}/\text{Pt}_{2\text{nm}}$  in the perpendicular to the film plane direction. (b) Evolution of the in-plane coercivity  $H_c^\parallel$  and the loop shift  $H_E$  with  $n$  after applying an in-plane field  $H_0=15$  kOe and subsequent measurement of the in-plane hysteresis loop with  $H_{\text{hyst,max}}=1.5$  kOe. The lines are guides to the eye. Insets: Corresponding (a) out-of-plane and (b) in-plane hysteresis loops measured for  $\text{Pt}_{20\text{nm}}/(\text{Co}_{0.6\text{nm}}/\text{Pt}_{1.8\text{nm}})_6/\text{Co}_{0.2\text{nm}}/\text{NiFe}_{3\text{nm}}/\text{Cu}_{2\text{nm}}/\text{Pt}_{2\text{nm}}$ .

$n=6$ . This similar trend indicates that all these parameters may be directly related to the magnetic configuration in the [Pt/Co] multilayer.

MFM studies on selected samples after in-plane saturation were thus performed in order to obtain deeper understanding on the magnetic behavior of the system. MFM imaging, at remanence, of the sample with  $n=6$  and  $t_{\text{NiFe}}=3$  nm in the remanent state after in-plane saturation [see Fig. 2(a)] exhibits a disordered pattern due to the overlapping between the domain structure of the [Pt/Co] multilayer and that of the NiFe layer, which does not allow one to extract information about the multilayer domain structure. In order to overcome this problem, single [Pt/Co] multilayers (with  $n=3, 5, 7$ , and 10) have also been imaged, at remanence, after application of the in-plane magnetic field  $H_0=15$  kOe [Figs. 2(b)–2(e)]. It should be noted that micromagnetic simulations indicate that the presence of the NiFe on top of the [Pt/Co] multilayer does not significantly modify the evolution of the domain structure with  $n$  in the multilayer. Hence, the images shown in Fig. 2 are also representative of the trend followed by the domain pattern in the [Pt/Co]-NiFe system when varying  $n$ . The MFM images indicate the existence of magnetic domains with antiparallel magnetization, orientated preferentially out-of-plane (downward and upward) and disposed in a pattern relatively segmented with

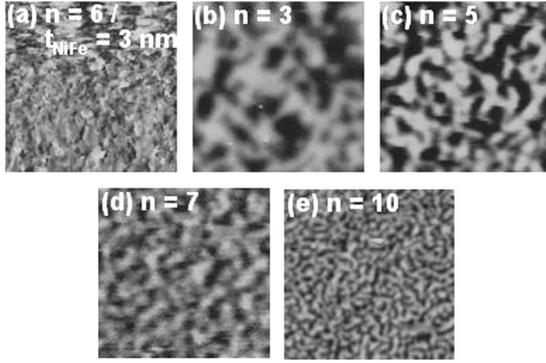


FIG. 2. MFM images for (a)  $\text{Pt}_{20\text{nm}}/(\text{Co}_{0.6\text{nm}}/\text{Pt}_{1.8\text{nm}})_6/\text{Co}_{0.2\text{nm}}/\text{NiFe}_{3\text{nm}}/\text{Cu}_{2\text{nm}}/\text{Pt}_{2\text{nm}}$  and (b)–(e)  $\text{Pt}_{20\text{nm}}/(\text{Co}_{0.6\text{nm}}/\text{Pt}_{1.8\text{nm}})_n$  ( $n=3, 5, 7,$  and  $10$ , respectively) at remanence after in-plane saturation with  $H_0=15$  kOe. Scanned areas:  $5 \times 5 \mu\text{m}^2$ .

nonuniform widths for the lower number of repeats ( $n=3$  and  $5$ ). Although the length scale of these patterns is somewhat poorly defined, the average domain size clearly decreases with increasing  $n$  (with the largest value of  $1.2 \mu\text{m}$  obtained for  $n=3$ ). The finer domains observed for larger  $n$  ( $n=7$  and  $10$  with average values of about  $700$  and  $300$  nm, respectively) are more regular in their spacing. Similar domain patterns have been observed by MFM after in-plane saturation in Pt/Co multilayer<sup>14</sup> and Co/Au multilayer<sup>15,16</sup> films with perpendicular anisotropy and have been attributed to a flux closure pattern inside the stack. Additionally, a study based on an exchange-coupled NiFe-TbCo (ferrimagnetic) bilayer explained the observed EB effects as being due to a variation of the magnetization in the TbCo layer from in-plane at the interface to perpendicular at the top surface.<sup>17</sup> In a similar manner, in the [Pt/Co]-NiFe system, a remanent multidomain configuration consisting of enlarged closure domains oriented parallel to the in-plane  $H_0$  field and shortened along the antiparallel direction to  $H_0$  at the interface, was proposed to be responsible for the loop shift.<sup>5</sup> However, up to now no direct proof of the existence of closure domains could be found for this system.

The use of 2D micromagnetic simulations of both single [Pt/Co] multilayers and [Pt/Co]-NiFe systems in the remanent state after in-plane saturation confirms the existence of Néel-type flux closure caps. Figures 3(a) and 3(b) illustrate, as an example, cross-sectional views obtained for the single [Pt/Co] multilayer with  $n=10$  and for the  $\text{Pt}_{20\text{nm}}/(\text{Co}_{0.6\text{nm}}/\text{Pt}_{1.8\text{nm}})_{10}/\text{Co}_{0.2\text{nm}}/\text{NiFe}_{3\text{nm}}/\text{Cu}_{2\text{nm}}/\text{Pt}_{2\text{nm}}$  system, respectively. The length of the arrows displayed is proportional to the magnetization component in the plane of the figure. Bloch-like walls are located in the film center while a clear magnetization circulation takes place at the upper interface and at the bottom surface, leading to the Néel-type flux closure caps. This circulation results in Bloch wall cores between domains pointing along the  $z$  axis (Fig. 3). By adding a layer of  $3$  nm of NiFe onto the [Pt/Co] multilayer two main effects appear: first, enlarged closure domains and, second, an asymmetry between the bottom and the top caps [indicated by the black dashed lines in Fig. 3(b)]. In fact, a considered  $t_{\text{NiFe}}$  of  $1$  nm in the model was

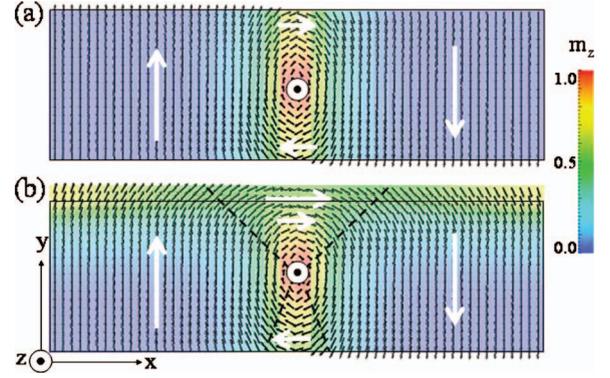


FIG. 3. (Color) Cross-section view of the magnetization distribution simulated for  $\text{Pt}_{20\text{nm}}/(\text{Co}_{0.6\text{nm}}/\text{Pt}_{1.8\text{nm}})_{10}/\text{Co}_{0.2\text{nm}}/\text{NiFe}(t_{\text{NiFe}})/\text{Cu}_{2\text{nm}}/\text{Pt}_{2\text{nm}}$  with  $t_{\text{NiFe}}=$  (a)  $0$  nm and (b)  $3$  nm. The  $y$  axis is along the direction perpendicular to the film plane. The [Pt/Co] multilayer appears framed by thin black lines. The black dashed lines in (b) illustrate the breaking in the symmetry between the bottom and top flux closure caps resulting from adding the NiFe layer onto the [Pt/Co] multilayer. The scale bar indicates the values for the magnetization component in the  $z$  direction.

enough to produce the observed breaking in the symmetry. This type of asymmetry has been previously reported by Labrunne and Thiaville<sup>16</sup> when studying the depth dependent magnetization of a  $(\text{Co}/\text{Au})_n$  system by the Mössbauer effect. Furthermore, the simulations show a decreased mean domain size with increasing  $n$  for single [Pt/Co] multilayers in good agreement with MFM studies [Figs. 2(b)–2(e)]. The observed trend is similar to that obtained from the model proposed by Kaplan and Gehring<sup>18</sup> in the regime of low thickness where an increased film thickness leads to decreased domain sizes, although this latter approximation is only valid in the case of having an ideal system and an equilibrium configuration which would consist of parallel stripes. As shown in Fig. 2, this is not strictly the case for the system under study here.

The NiFe is coupled to the [Pt/Co] multilayer simultaneously by exchange and magnetostatic interactions. At remanence, after the preliminary in-plane saturation with an in-plane field  $H_0=15$  kOe, closure domains are created at the interface between the [Pt/Co] multilayer and the NiFe which in the real system, most probably, are in a nonequilibrium configuration with unequal sizes. This is the origin of the observed shift of the hysteresis loop along the field axis; namely, the uncompensated moments stemming from unequally oriented closure domains at the [Pt/Co]-NiFe interface play the equivalent role to uncompensated spins in the AFM in conventional FM-AFM exchange-biased bilayers. Furthermore, the reduction in the domains size with increasing  $n$  results in an increased number of domain walls, i.e., an increased number of unequal closure domains. The similar evolution observed in  $H_c^\perp$ ,  $H_E$ , and  $H_c^\parallel$ , with  $n$  (Fig. 1) probably results from the enhanced effective pinning of the magnetic domains in the [Pt/Co] multilayer as  $n$  is increased. After in-plane saturation and subsequent measurement of the in-plane hysteresis loop, enlarged  $H_c^\perp$  and  $H_E$  values are the consequence of the pinning of the resulting Néel-type flux closure caps.

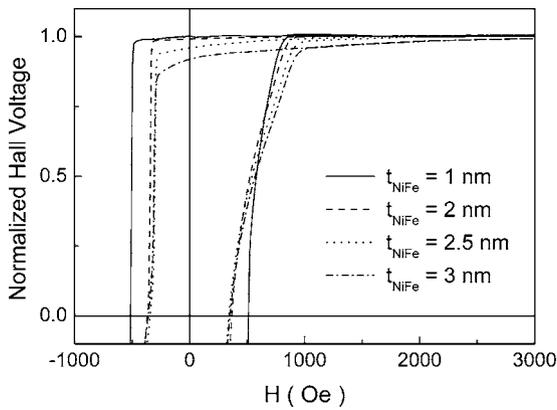


FIG. 4. Detail of the out-of-plane hysteresis loops measured by the extraordinary Hall effect after saturating the  $\text{Pt}_{20\text{nm}}/(\text{Co}_{0.6\text{nm}}/\text{Pt}_{1.8\text{nm}})_6/\text{Co}_{0.2\text{nm}}/\text{NiFe}(t_{\text{NiFe}})/\text{Cu}_{2\text{nm}}/\text{Pt}_{2\text{nm}}$  (with  $t_{\text{NiFe}}=1, 2, 2.5,$  and  $3$  nm) in the direction perpendicular to the film plane.

The second series of samples  $\text{Pt}_{20\text{nm}}/(\text{Co}_{0.6\text{nm}}/\text{Pt}_{1.8\text{nm}})_6/\text{Co}_{0.2\text{nm}}/\text{NiFe}(t_{\text{NiFe}})/\text{Cu}_{2\text{nm}}/\text{Pt}_{2\text{nm}}$  was prepared and characterized in an analogous manner as the first series. Figure 4 shows a detail of the hysteresis loops measured by extraordinary Hall effect for samples with  $t_{\text{NiFe}}=1, 2, 2.5,$  and  $3$  nm after saturation in the perpendicular to film direction. The hard axis contribution from the NiFe to the loop becomes relevant when increasing the thickness of this layer, as it can be seen in Fig. 4 from a reduced  $M_r^{\perp}/M_s$  ratio for  $t_{\text{NiFe}} \geq 2.5$  nm, while  $M_r^{\perp}/M_s \approx 1$  for  $t_{\text{NiFe}} < 2.5$  nm due to the strong perpendicular anisotropy of the [Pt/Co] multilayer. MFM images of selected samples at remanence after out-of-plane saturation are shown in Fig. 5. In good agreement with the measured hysteresis loops, MFM images show that the [Pt/Co]-NiFe system remains in a single domain state with an out-of-plane magnetic moment for  $t_{\text{NiFe}} < 2.5$  nm [Figs. 5(a) and 5(b)]. It is for  $t_{\text{NiFe}}=2.5$  nm that a clear magnetic domain pattern appears [Fig. 5(c)] indicative of a clear transition in the orientation of the magnetic moments of the upper NiFe layer from an out-of-plane direction ( $t_{\text{NiFe}} < 2.5$  nm) to an in-plane direction [ $t_{\text{NiFe}} \geq 2.5$  nm, Figs. 5(c)–5(f)]. In a similar manner, the evolution of  $H_c^{\perp}$  with  $t_{\text{NiFe}}$

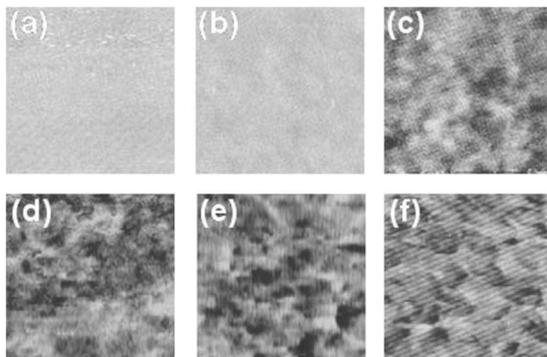


FIG. 5. MFM images for  $\text{Pt}_{20\text{nm}}/(\text{Co}_{0.6\text{nm}}/\text{Pt}_{1.8\text{nm}})_6/\text{Co}_{0.2\text{nm}}/\text{NiFe}(t_{\text{NiFe}})/\text{Cu}_{2\text{nm}}/\text{Pt}_{2\text{nm}}$  with  $t_{\text{NiFe}}=1$  (a), 2 (b), 2.5 (c), 3 (d), 4 (e), and 5 nm (f), at remanence after out-of-plane saturation. Scanned areas:  $2.5 \times 2.5 \mu\text{m}^2$ .

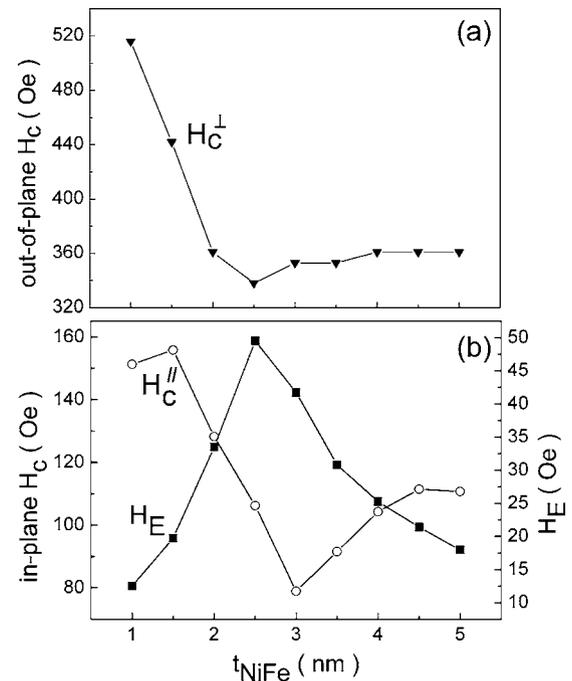


FIG. 6. (a) Evolution of the out-of-plane coercivity  $H_c^{\perp}$  with the NiFe thickness  $t_{\text{NiFe}}$ , after saturating the  $\text{Pt}_{20\text{nm}}/(\text{Co}_{0.6\text{nm}}/\text{Pt}_{1.8\text{nm}})_6/\text{Co}_{0.2\text{nm}}/\text{NiFe}(t_{\text{NiFe}})/\text{Cu}_{2\text{nm}}/\text{Pt}_{2\text{nm}}$  in the direction perpendicular to the film plane. (b) Evolution of the in-plane coercivity  $H_c^{\parallel}$  and the loop shift  $H_E$  with  $t_{\text{NiFe}}$  after applying an in-plane field  $H_0=15$  kOe and subsequent measurement of the in-plane hysteresis loop with  $H_{\text{hyst,max}}=1.5$  kOe. The lines are guides to the eye.

[Fig. 6(a)] shows two differentiated regions. In the first one, for  $t_{\text{NiFe}} < 2.5$  nm,  $H_c^{\perp}$  decreases with increasing  $t_{\text{NiFe}}$  due to the tendency for the magnetic moments in the NiFe layer to orient in the film plane as the layer thickness is increased, in spite of the coupling with the [Pt/Co] multilayer. This is due to the increasing role of the shape anisotropy of this layer. For  $t_{\text{NiFe}} > 2.5$  nm (second region) the orientation of the successive upper NiFe spins is already in plane and thus the measured  $H_c^{\perp}$  tends to become constant.

In-plane measurements performed with  $H_{\text{hyst,max}}=1.5$  kOe after saturation with the in-plane large field  $H_0=15$  kOe show a somewhat unexpected behavior; namely,  $H_E$  increases and  $H_c^{\parallel}$  decreases for increasing  $t_{\text{NiFe}}$  in the range  $0 < t_{\text{NiFe}} < 2.5$  nm [Fig. 6(b)] but further increase of  $t_{\text{NiFe}}$  results in the opposite trends. This behavior can be intuitively understood taking into account that an increased in-plane orientation of the magnetic moments in the NiFe with increasing  $t_{\text{NiFe}}$  will favor a net in-plane magnetization of the [Pt/Co] multilayer at the interface, i.e., an enhanced EB effect in the system. Indeed, 2D micromagnetic simulations reveal that for a fixed  $n$  the mean domain size increases with decreasing  $t_{\text{NiFe}}$  (in the studied range  $t_{\text{NiFe}} \leq 3$  nm), the increment being larger when considering a lower number  $n$ . MFM observations have been carried out for samples with  $n=6$  and  $t_{\text{NiFe}}=1, 2, 2.5,$  and  $3$  nm at remanence after in-plane saturation with  $H_0=15$  kOe. A slight decrease in the domain size with increasing  $t_{\text{NiFe}}$  is shown in Fig. 7, in good agreement with the trend observed in the simulations. As

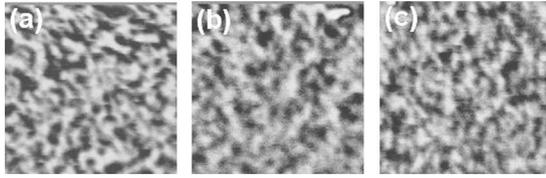


FIG. 7. MFM images for  $\text{Pt}_{20\text{nm}}/(\text{Co}_{0.6\text{nm}}/\text{Pt}_{1.8\text{nm}})_6/\text{Co}_{0.2\text{nm}}/\text{NiFe}(t_{\text{NiFe}})/\text{Cu}_{2\text{nm}}/\text{Pt}_{2\text{nm}}$  with  $t_{\text{NiFe}}=1$  (a), 2 (b), and 2.5 nm (c), at remanence after in-plane saturation with  $H_0=15$  kOe. Scanned areas:  $5 \times 5 \mu\text{m}^2$ .

previously noted, a thickness of 3 nm for the NiFe [Fig. 2(a)] leads to a pattern difficult to interpret as a consequence of the contribution of the in-plane magnetic moments of the NiFe upper layer. Conversely, the observed domain patterns [Figs. 7(a)–7(c)] consist of segmented and nonuniform stripes analogous to those observed for single [Pt/Co] multilayers after identical saturating procedure [Figs. 2(b)–2(e)]. The formation of a domain pattern consisting of enlarged, unequally oriented, closure domains can explain the observed evolution for  $H_E$  with  $t_{\text{NiFe}}$  for  $t_{\text{NiFe}} < 3$  nm plotted in Fig. 6(b). However, for  $t_{\text{NiFe}} > 3$  nm, a decrease in  $H_E$  with  $t_{\text{NiFe}}$  is obtained [Fig. 6(b)], indicating the prevalence of the interfacial, i.e., short-range character, of the observed EB-like effect in the [Pt/Co]-NiFe system, by analogy with conventional EB systems consisting of exchange coupled FM and AFM materials.

The reduction of the EB-like effect is accompanied with an increase of  $H_c^{\parallel}$ . This is attributed to a more pronounced dragging of the uncompensated, in-plane, magnetic moments at the [Pt/Co]-NiFe interface, which progressively results in more equally oriented closure domains, i.e., a decreased net in-plane magnetic moment at the interface. During the in-plane hysteresis loop, the extra energy required to switch the in-plane interfacial magnetic moments of the [Pt/Co] multilayer causes the  $H_c^{\parallel}$  increase. To prove the enhanced dragging effect when increasing  $t_{\text{NiFe}}$ , an investigation of the training effects (i.e., the effect of repeated hysteresis loops on  $H_E$  and  $H_c^{\parallel}$ ) has been pursued, for the systems with  $t_{\text{NiFe}} = 3$  and 4.5 nm. These repeated in-plane hysteresis loops were all recorded with  $H_{\text{hyst,max}} = 1.5$  kOe after saturation

with an in-plane field of 15 kOe prior to the measurement of the first hysteresis loop. For both samples  $H_E$  decreases abruptly from the first to the second recorded hysteresis loop (20% and 30% decrease for  $t_{\text{NiFe}}=3$  and 4.5 nm, respectively) and more gradually with the subsequent cycles (25% and 50% decrease, respectively, after nine repetitions). The steeper reduction of  $H_E$  when increasing the loop number observed for  $t_{\text{NiFe}}=4.5$  nm confirms that this sample is more prone to training effects and, consequently, that the dragging effects are more pronounced for larger  $t_{\text{NiFe}}$  values.

#### IV. CONCLUSIONS

The magnetic properties of a system consisting of NiFe deposited onto a [Pt/Co] multilayer have been shown to be closely related to the magnetic domain configuration in the [Pt/Co] multilayer. This domain structure can be modified by varying either the number of Pt/Co repetitions in the multilayer or the NiFe layer thickness. Interestingly, a shift in the in-plane hysteresis loop of the system is observed. Remarkably, by comparison with conventional EB systems, no AFM material is present here and no field cooling is required to induce  $H_E$ . Actually, the loop shift is induced by simply applying a strong in-plane magnetic field  $H_0$  to the system.

As revealed by micromagnetic simulations and experimental results, the key point for the interpretation of the EB phenomena in this system is the creation of Néel-type flux closure caps in the [Pt/Co] multilayer, with unequal in-plane orientations (i.e., enlarged domains parallel to the  $H_0$  direction), which couple to the NiFe layer, hence pinning its magnetic moment during the magnetization reversal. The dependence of the loop shift and the in-plane and out-of-plane coercivities on the sample composition can be understood as a result of the interplay between the resulting number and size of unequal closure domains and the short-range character of the phenomenon.

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\*Email address: abollero@cea.fr

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