Macroscopic probing of domain configurations in interacting bilayers with perpendicular magnetic anisotropy

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(Received 26 January 2006; published 8 March 2006)

Magnetostatic interactions in perpendicularly magnetized Co/Pt bilayers lead to the formation of mirror domains in both soft and hard layers. We show that it is possible to take advantage of domain replication in order to probe the microscopic domain configuration of the hard layer through macroscopic hysteresis minor loop measurements on the soft layer. The minor curves consist of two loops, which magnetization amplitudes and field shifts can be quantitatively related to the domains sizes, shapes, and up/down relative proportion in the hard layer.

DOI: 10.1103/PhysRevB.73.092405 PACS number(s): 75.60.Ch

Since the late 1980s and the discovery of giant magnetoresistance (GMR) in antiferromagnetically coupled multilayers or in uncoupled bilayers,[1–4] a lot of experimental and theoretical work has been carried out in such systems. Direct applications of this phenomenon are magnetic read heads or magnetic random access memories (MRAM), in which the nonmagnetic spacer can be either metallic or insulating.[5,6]

The smaller the coupling between magnetic layers, the higher the sensitivity of the device to external fields (stray fields from the magnetic medium in recording read heads or writing fields in MRAMs). This has motivated a significant effort on the study of interlayer coupling in multilayers. This coupling can have different origins: direct magnetic coupling through pinholes in the thin metallic or insulating spacer,[7] indirect exchange coupling through RKKY interactions,[8] orange peel (Néel) magnetostatic coupling in the presence of a correlated roughness at both spacer interfaces,[9,10] and finally magnetostatic coupling through stray fields.[11] In the latter case, although these interactions are mostly negligible in uniformly magnetized macroscopic samples, it is no more the case when the magnetic layers are in a multidomain state, or when the lateral size of the sample is reduced.

It has been shown, for example,[12] that cycling the soft layer of a spin valve in an ac field (with an amplitude much smaller than the nucleation field of the hard layer) can lead to a progressive demagnetization of that hard layer. It has also been shown in bilayers with in-plane magnetization[13,14] or in hybrid in-plane/perpendicular systems[15] that stray fields from domain walls are efficient enough to lead to replication of the domain structure in both magnetic layers.

The same phenomenon indeed exists in systems with perpendicular magnetization.[16] However, since in that case stray fields emanate from the domains themselves, different domain sizes or shapes lead to different stray field amplitudes. In this Brief Report we show that it is possible to take advantage of domain replication in order to probe the microscopic domain configuration of a hard layer through macroscopic magnetic measurements on a soft layer. In such bilayers made of a soft and hard magnetic layer with perpendicular anisotropy, the interaction can be tailored so as to lead to domain replication. However, when the interaction is weak enough, it is possible to manipulate the magnetization of the soft layer without perturbing that of the hard one. Under theses conditions, the hysteresis curve of the soft layer is affected by stray fields from the demagnetized hard layer, and consists of two loops, one being shifted positively along the field axis, and the other one negatively by the same amount. Moreover, when the domain structure of the hard layer becomes nonsymmetrical, this is perfectly reflected by the nonsymmetrical shape of the hysteresis loop of the soft layer.

$Si/SiO_2/Pt_{1.8\ nm}/(Co/Pt)_s/Pt_{13.2\ nm}/(Co/Pt)_h$ samples were prepared by dc sputtering in a 2.5×10^{-3} mbar Ar atmosphere. $(Co/Pt)_s$ and $(Co/Pt)_h$ stand for $(Co_{0.6\ nm}/Pt_{1.8\ nm})$ multilayers, with 1 repeat ("soft" layer) and 4 repeats ("hard" layer), respectively. Thanks to the different Pt buffer thicknesses (either 1.8 or 15.0 nm) and repeat numbers, both multilayers exhibit very different coercive fields.[17] Magnetic measurements were performed at room temperature using extraordinary Hall effect.[18] Images of the different magnetic domain configurations were obtained from magnetic force microscopy (MFM) experiments in the remanent state. The demagnetization procedure consists of rotating the sample (the rotation axis being parallel to the sample plane and perpendicular to the field axis) in the presence of a magnetic field of constant direction and decreasing amplitude.

The perpendicular magnetization curve obtained from Hall effect is shown in Fig. 1. On the major loop, both soft and hard layers display very sharp transitions. The first magnetization curve also displays two transitions. The first transition is ascribed to the saturation of the soft layer and occurs for applied fields between 100 and 200 Oe. These values are surprisingly much larger than the 12 Oe measured from the major hysteresis loop. This is a first indication that the magnetization reversal of the soft layer strongly depends of the magnetization state of the hard one, either demagnetized or saturated.

Still starting from the demagnetized state, Fig. 2(a) shows a minor loop recorded with a maximum field of 200 Oe (i.e., up to the plateau in Fig. 1). One can observe a striking difference with the minor loop obtained when the hard layer is in a single domain state [Fig. 2(b)]. The loop in Fig. 2(a) is made of two symmetrical lobes with a zero remanence. This

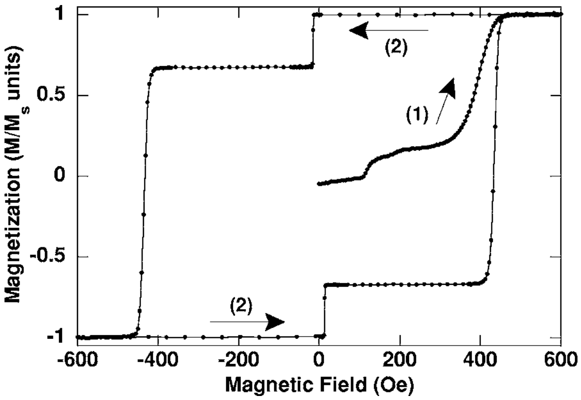

FIG. 1. First magnetization curve and major hysteresis loop obtained from Hall effect measurements. The magnetic field is applied perpendicular to the sample plane. The magnetization is normalized to the total magnetization of the sample. (1) is the first magnetization curve, and (2) is the major hysteresis loop.

zero remanence implies that, although it is possible to saturate the soft layer in a 200 Oe field, it demagnetizes itself spontaneously as soon as the applied field goes back to zero. This clearly shows that the stray fields from the still demagnetized hard layer, which favor a parallel alignment of the magnetizations in both layers, are large enough to imprint in zero field the same domain configuration into the soft one. These stray fields effectively act on the soft layer as local "bias fields" and lead to shifts of the hysteresis loops from zero field. When the hard layer is saturated, almost no stray field is sensed by the soft one, and one obtains the usual loop of Fig. 2(b), only slightly shifted by 3 Oe from the origin as a probable consequence of an "orange peel" coupling mechanism due to correlated roughness.[10]

One can also note in Fig. 2(a) that the loops are symmetrically shifted with respect to the applied field. This means that stray fields emanating from up and down domains in the hard layer are of similar amplitude. In other words, since stray fields depend on the particular domain shape and size, one can infer that up and down domains in the hard layer play a symmetric role. The MFM image of Fig. 2(c) confirms this interpretation. Both up and down domains are of similar size (about 1.6 μm) and shape.

Let us now turn to the case where the net magnetization of the hard layer differs from zero. Starting from the situation of Fig. 2(a), one increases the (positive) applied field field$+H_{max}$, following the first magnetization curve of Fig. 1(a), and then records minor loops between -200 Oe and $+H_{max}$. The results are shown in Fig. 3(a). For the sake of clarity, the vertical shift between successive loops has been artificially increased. A lot of information can be derived from these curves.

First, as H_{max} increases, the remanent magnetization increases, since the net magnetization of the hard layer increases from zero to one (in M_s reduced units). At the same time, the relative amplitude of the two loops changes, that of the negative one increasing from 0.5 to 1, while that of the positive one decreases from 0.5 to zero. A plot of the net magnetization of the hard layer (measured from the vertical loop shift) as a function of the net magnetization of the soft

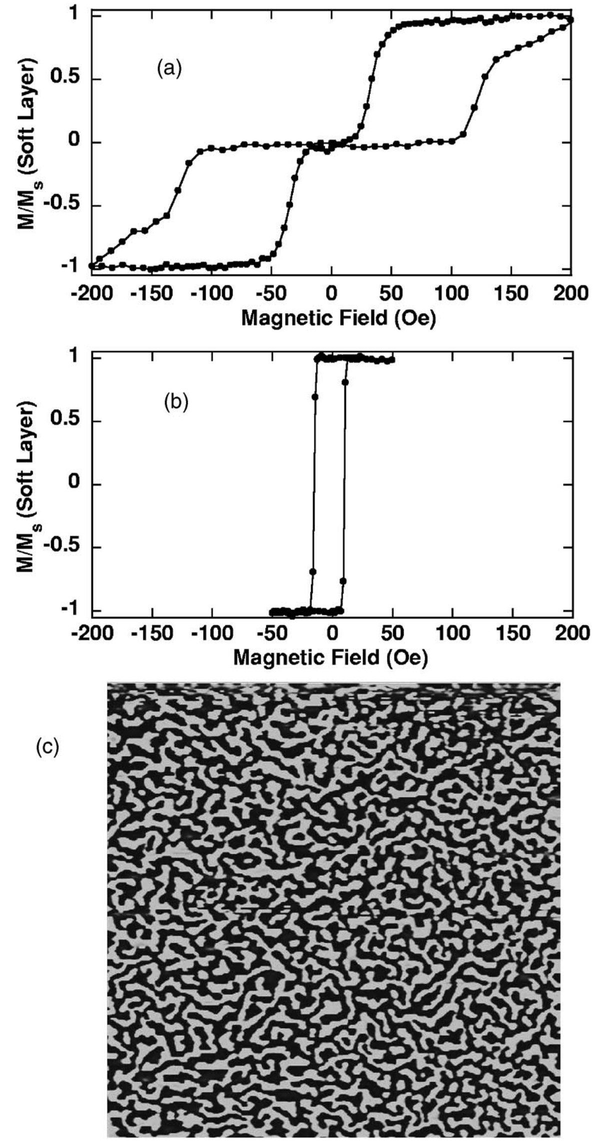

FIG. 2. Minor hysteresis loops for the soft layer. The hard layer is either (a) demagnetized or (b) saturated. The magnetization is normalized to that of the soft layer. (c) is a 110×110 μm^2 MFM image in the demagnetized remanent state.

layer (determined from the normalized difference between loops amplitudes) is shown in Fig. 3(b). The perfect matching of both quantities is an additional proof of domain replication whatever the net magnetization of the sample, as already reported for systems with in-plane magnetization.[13,14]

Second, the shift of the negative loop along the field axis decreases from about 80 Oe to zero, while that of the positive one increases from 80 to about 200 Oe. These opposite variations reflect both the decreasing strength of the stray fields emanating from growing domains and the increasing strength of stray fields emanating from disappearing domains. Figure 3(c) shows the variation of these shift fields as a function of the total magnetization. The lower branch corresponds to growing domains, whereas the upper branch corresponds to disappearing domains.

It is possible to calculate the theoretical variation of the

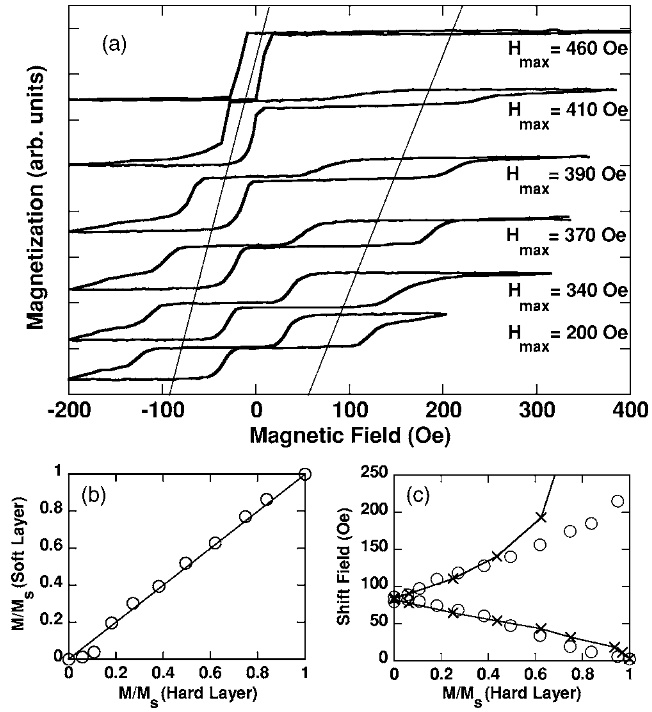

FIG. 3. (a) Hysteresis loops recorded with increasing the maximum positive applied field. Curves are shifted vertically for clarity. Oblique lines are a guide to the eyes and give the trend of variation of the loop shifts. (b) Variation of the net magnetization of the soft layer as a function of the net magnetization of the hard layer. (c) Variation of the shift fields as a function of the net magnetization of the hard layer. The solid line gives the variation of the calculated stray fields.

stray fields acting on the soft layer as a function of the net magnetization of the hard one. We use a simplified model which considers a periodic array of infinitely long parallel up and down stripe domains of constant period P and variable width w (from P/2 to P for one domain type and from P/2 to zero for the other one). Such a configuration is represented by a periodic array of +V and −V potentials for up and down stripe domains, respectively.[19] The potential is a function of period, domain width, cobalt thickness, and lateral position. The resulting stray field along the perpendicular z direction is given by

$$H_Z = 2M_S dV/dz,$$

where M_s is the cobalt magnetization. The calculated stray fields (averaged over the domain extension) are those emanating from the hard layer and sensed at the upper interface of the soft layer. The domain period is considered, in a first approximation, as constant whatever the value of the net magnetization.

It is noteworthy that the approximation of stripe domains considering the real domain morphology [see Fig. 2(c)] already proved to be rational.[20] The results of the calculation are scaled (with a factor of 1.25) onto the experimental results for M=0 and plotted in Fig. 3(c) as continuous lines. One observes a very good agreement with the experimental results, up to about $M/M_s=0.5$ for the upper branch. This confirms that the loop shifts are directly related to the stray fields. The deviation above $M/M_s=0.5$, where the calculated stray field starts increasing more rapidly than the loop shift, can have different origins. First, it is very probable that, as one reaches a state where the minority domains are very small, their real morphology becomes quite different from very narrow parallel stripes alternating with much thicker ones. Second, even in this simplified model, some of these narrow stripes, from a statistical point of view, are certainly capable of disappearing before others, thus increasing the average period, with a concomitant decrease of the corresponding stray field.

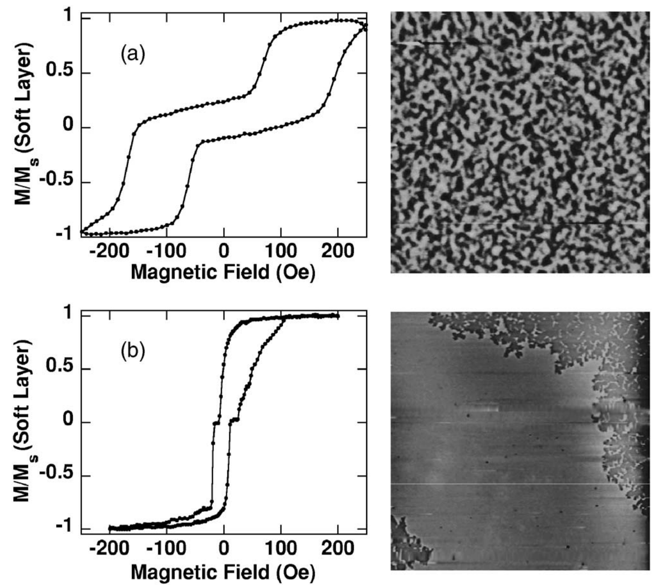

FIG. 4. Minor hysteresis loops and corresponding MFM images. (a) Sample demagnetized with a saturating in plane magnetic field (25×25 μm^2 image). (b) Sample demagnetized at the coercive field of the hard layer (110×110 μm^2 image).

Finally, Fig. 4 illustrates both the variety of domain structures which can be obtained depending on the demagnetization procedure used, and the great sensitivity of the corresponding minor hysteresis loops to that domain structure. In Fig. 4(a), the sample is demagnetized by applying a magnetic field (12 kOe) strong enough to saturate the magnetization parallel to the sample plane. The MFM image, although similar to that of Fig. 2(c), gives a much smaller characteristic domain size (0.9 μm instead of 1.6 μm). The corresponding minor loops are still symmetrical with respect to the field axis, but shifted from zero field by about 120 instead of 80 Oe. This 50% increase in the shift field exactly corresponds to that calculated from the above model, which gives a variation of the stray field from 70 to 105 Oe, that is also an increase of 50%.

In Fig. 4(b), demagnetization is performed by first saturating the sample in a let say negative perpendicular field, and then applying a positive field equal to the coercive field of the hard layer. The MFM image is no more symmetrical, showing very large entirely bright domains, whereas the black ones have a dendritic appearance. The corresponding minor loops, although of equal amplitudes, are no longer symmetrical with respect to the field axis, the negative loop being almost centered around zero field and corresponding to the large bright domains, with a small tail up to 200 Oe (due to the small bright filaments in the black domains seen on the MFM image), while the positive loop displays a more gradual transition ending at about 100 Oe.

To conclude, we have shown in this Brief Report that it is possible to take advantage of domain replication in magnetostatically interacting bilayers with perpendicular magnetic anisotropy. Minor hysteresis loops recorded on interacting soft and hard layers can be used to explore the microscopic magnetization state and magnetic domain configuration of the hard layer just by measuring the macroscopic magnetic response of the soft layer, strongly influenced by the stray fields emanating from the hard one. Only techniques such as Kerr microscopy or MFM experiments, for example, would allow obtaining this information in the absence of the soft layer. A deeper quantitative interpretation of the present results would certainly require more sophisticated models than the one used here. It must also be noted that the soft layer slightly influences the magnetic configuration of the hard layer, its characteristic domain size increasing from 1.6 to 1.9 μm when the soft layer is saturated. This reciprocal effect is analogous to tip-sample interactions in MFM experiments. However, such an effect could be strongly minimized by increasing the magnetization of the hard layer, for example up to values where the domain size becomes more or less independent of the total magnetization (Kaplan's law[21,22]).

We thank O. Redon, I. L. Prejbeanu, A. Marty, S. Wiebel, J.-P. Jamet, N. Vernier, A. Mougin and J. Ferré for valuable discussions. This work was partly funded within the MAGLOG-STREP European Project (FP6-510993).

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