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N. Vernier, J.-P. Adam, S. Eimer, G. Agnus, T. Devolder, T. Hauet, B. Ocker, F. Garcia, and D. Ravelosona

Université Paris-Sud, 91405 Orsay, France
Institut d’Electronique Fondamentale, CNRS, UMR 8622, Orsay, France
Institut Jean Lamour, CNRS - Universite de Lorraine, Boulevard des aiguillettes BP 70239, F-54506 Vandoeuvre le’s Nancy, France
Singulus technology AG, Hanauer Landstrasse 103, 63796 Kahl am Main, Germany

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We present a method to map the saturation magnetization of soft ultrathin films with perpendicular anisotropy, and we illustrate it to assess the compositional dependence of the magnetization of CoFeB(1 nm)/MgO films. The method relies on the measurement of the dipolar repulsion of parallel domain walls that define a linear domain. The film magnetization is linked to the field compressibility of the domain. The method also yields the minimal distance between two walls before their merging, which sets a practical limit to the storage density in spintronic devices using domain walls as storage entities. © 2014 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4869482]

Recently, there has been a renewed interest in spintronic devices relying on the motion of narrow domain walls in magnetic nanowires. This includes the use of domain walls as storage units or as information vectors performing logic operations. Since they combine a high perpendicular anisotropy with a coercivity lower than the standard systems exhibiting perpendicular magnetic anisotropy (PMA), ultrathin CoFeB/MgO films are a promising system to study the motion of narrow domain walls. Indeed, walls in CoFeB/MgO systems are mobile in fields as low as 0.1 mT, and their motion seems not to be influenced by pinning phenomena for fields above 1 mT.

To fine tune the properties of such films, one can play with the Boron content, the Fe-to-Co composition, and their motion seems not to be influenced by pinning phenomena for fields above 1 mT.

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Fig. 1. Magneto-optical micrographs (110 × 45 μm²) of domain patterns in Co20Fe60B20 (1 nm)/MgO films. (a) Pair of well separated (d ≈ 6 μm) domain walls at remanence. (b) Same pair of walls under a field of 0.59 mT. (c) Picture obtained by subtracting the two previous images. The walls are now positioned at x2 and x3. To apply an external field to compress the central domain and it is repulsive. Here, we shall consider wall-to-wall distances greater than 300 nm (see Fig. 3) in high PMA systems where we expect Δ ≤ 30 nm, such that this condition is fulfilled. Under that approximation, the repulsive force is the analog of the Laplace force between two wires each carrying a charge current I = 2IMS and placed at separation d. On a given wall, the dipolar force per unit length is thus μd²/(2πε₀). The film finite thickness term (see Ref. 19) can be neglected in our case because our wall separation is substantially larger. An additional term exits in the presence of an external field, there is no zero propagation field (see below).

Let us now use the field dependence of the size of the central domain to get the film magnetization. If the domain wall width Δ is much smaller than the distance between the two walls, the wall-wall interaction is purely of dipolar origin and it is repulsive. Here, we shall consider wall-to-wall distances greater than 300 nm (Fig. 3) in high PMA systems where we expect Δ ≤ 30 nm, such that this condition is fulfilled. Under that approximation, the repulsive force is the analog of the Laplace force between two wires each carrying a charge current I = 2IMS and placed at separation d. On a given wall, the dipolar force per unit length is thus μd²/(2πε₀). The film finite thickness term (see Ref. 19) can be neglected in our case because our wall separation is substantially larger. An additional term exits in the presence of an external field, there is no zero propagation field (see below).

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The adjustable parameters are the four wall positions xi, the optical resolution δ, the contrast scale A₁, and an offset A₀. We estimate that central domain size is known with an accuracy of ±25 nm. This number was certified with specially designed samples consisting of thin aluminum wires on silicon with variable widths ranging from 100 to 1000 nm. Finally, we emphasize that the measurement procedure is repeated at various positions along the domain until a statistically reliable estimate of the dependence of d with Hext is obtained (Fig. 3). This minimizes the uncertainty associated to the wall roughness that is generally observed and results from pinning effects. Indeed, defects can stop locally a domain wall and one can get a width bigger than the equilibrium one when the magnetic field B is monotonically increasing as a function of time. However, the pinning is not strong, and a slight increase of field enables to override most of the pinning defects. The results are slight fluctuations of the central domain width (see Figure 1) and a non zero propagation field (see below).

FIG. 2. Profile of the magneto-optical contrast obtained on the annealed Co20Fe60B20 (1 nm) sample, in a field of 0.59 mT. The walls positions found using Eq. (1) are x₁ = 2.89, x₂ = 4.50, x₃ = 5.09, and x₄ = 8.89 μm. The wall-to-wall separation is thus d = 590 nm. Inset: magneto-optical image (12.2 × 3.1 μm²) used to get the contrast profile.

FIG. 3. Dependence of the wall-to-wall distance with the applied field for the as-grown Co20Fe60B20 sample. The slope is the compressibility of the central wall, which measures the inverse magnetization. Inset: sketch of the domain structure.

$$c(x) = A_0 + A_0 \sum_{i=1}^{4} (-1)^i \arctan \frac{x_i - x}{\delta}.$$
an additional Zeeman pressure tending to compress the central domain. This force per unit length is $-2\mu_0 M_s H_{ext}$. In a defect free sample, these two forces would cancel each other when $tM_s = \pi d_{H_{ext}}$. However, in real films, a finite propagation field $\mu_0 H_p \approx 0.1 \text{ mT}$ is needed to overcome pinning effects and to induce domain wall motion. As a result there is a hysteresis in $d$ as a function of the sweeping direction of the external field. Assuming the distance to be measured is a field compressing the central domain, the wall to wall distance $d$ is

$$d^{-1} = \frac{\pi}{C_0} \frac{H_{ext} - H_p}{tM_s}.$$  \hspace{1cm} (2)

Linear fits of $d^{-1}$ as a function of $H_{ext}$ (according to Eq. (2)) is very good, as shown in Fig. 3. The slope identifies to $\pi/tM_s$, from which one gets $M_s$. The error bars on Ms can be roughly estimated from the extreme possibilities for the slope of the straight line and from the error bars on each point ($\pm 10 \mu\text{T}$ for the external field, $\pm 25 \text{ nm}$ for the width of the central domain). From this, we can guarantee that the relative error on the final result for $M_s$ cannot be more than 10%.

Table I gathers the magnetizations independently obtained using either our present method or conventional magnetometry on larger samples (at least $2 \times 2 \text{ mm}^2$), on the various compositions of CoFeB. The values are given before and after annealing except for the as-grown Co$_{60}$Fe$_{20}$B$_{20}$ sample because it showed in-plane easy axis. A satisfactory agreement is found between the magnetization values deduced from SQUID, AGFM, and domain compressibility. We attribute the die to die dispersion of the $M_s$ values to the existence of composition and/or thickness fluctuations across the wafer, especially for the Co-rich compositions. These possible structural variations may exacerbate the inhomogeneity of the magnetization because of the proximity to the face-centered-cubic to hexagonal-compact phase boundary$^{1,24}$ in the FeCo binary alloy phase diagram. In all cases, annealing slightly increases the magnetization, confirming the previous reports.$^{22-24}$

The compositions leading to the highest magnetizations are Co$_{20}$Fe$_{40}$B$_{20}$ and Co$_{40}$Fe$_{40}$B$_{20}$. Position of ternary alloys on the Slater-Pauling curve is not obvious,$^{25,26}$ but it seems that boron has little influence on the magnetic properties apart from a dilution effect.$^8$ From the Slater-Pauling curve, a broad maximum of magnetization for a ratio of cobalt of around 28% is expected (corresponds to 35% for a Boron-free CoFe alloy), which is compatible with our findings (Table I).

During these experiments, we have been able to measure two additional interesting quantities. The first quantity is the magnetic field needed to merge the two neighboring domain walls and let the central domain disappears abruptly. We emphasize that although two different configurations are expected depending on the winding directions of each wall, a unique critical field was measured: statistical measurements indicated that this critical field is a reproducible metric, reported in Table I. Let us note this measurement was carried out 3 or 4 times for each of the 5 samples, it was reproducible for each sample within the precision of the field scan which was 0.1 mT, and one can reject a lucky arbitrary behavior. Above these applied fields, the number of domain walls changes inside a given sample: the data integrity in domain wall based memories$^1$ is then lost, which gives the working boundaries of such devices if based on soft PMA systems like ours. Besides, applying Eq. (2) at this critical destruction field yields the second interesting quantity: the minimal stable wall-to-wall distance, found between 180 and 500 nm, depending on sample (Table I). The measurement of this minimum wall separation $d_{min}$ is interesting from both applied and fundamental points of view. Indeed $d_{min}$ could be indicative of the effective profile of 180° domain walls since the disappearance of the central domain may just occur when the two walls are about to start overlapping. Also, this minimal wall-to-wall distance $d_{min}$ sets a practical limit to the storage density in racetrack memory applications.$^1$

In summary, we have presented a calibration-free method to measure the local magnetization in ultrathin magnetic film with perpendicular anisotropy. This technique allows site-specific measurements to be made, thus providing advantages for nanopatterned specimens, for which the sensitivity of conventional magnetometry methods is not sufficient. We have illustrated our method by studying the composition dependence of the magnetization of CoFeB ultrathin films. In addition, our method yields the minimal achievable stable distance between two domain walls in such soft films, which sets the storage density limit in memory paradigms based on domain walls.

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