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Extrinsic pinning of magnetic domain walls in CoFeB-MgO nanowires with perpendicular anisotropy

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In this work, we have studied the mechanism of domain wall motion in 0.2-1.5 μm wide nanowires based on Ta/CoFeB/MgO films with perpendicular magnetic anisotropy. We show that domain wall propagation can be completely stopped due to the presence of strong pinning sites along the nanowires. From the analysis of the distribution of the strongest depinning fields as a function of the wire width, we evidence the presence of extrinsic pinning sites in nanowires, probably induced by edge damages, that dominate over the intrinsic pinning of the magnetic films even for these large wire widths. © 2017 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/). https://doi.org/10.1063/1.5006302

I. INTRODUCTION

Promising Racetrack memory applications,1 rely on the motion of magnetic domain walls (DWs) in nanowires with perpendicular anisotropy (PMA). One main limitation of this technology is related to the presence of structural inhomogeneities leading to strong DW pinning in films with PMA.2-4 The origin of DW pinning results mainly from homogeneously distributed defects such as boundaries between crystallites5 or roughness at interfaces.6,7 In ultra-thin magnetic films, the interaction with the random disorder at low magnetic fields leads to the well known creep theory,6,8,9 which describes the motion of a 1D interface in a 2D random disorder. In addition to this so called intrinsic pinning originating from the random disorder of the magnetic films, in nanowires extrinsic pinning can be induced by the presence of edge damages such as edge roughness introduced by the patterning process.10–12 This leads to a modification of DW dynamics but in general DW can still propagate and DW creep due to the random disorder has been reported to be still valid down to very small dimensions below 100 nm.

In this work, we use Ta-CoFeB-MgO films with perpendicular anisotropy exhibiting a very low density of intrinsic pinning defects and present results of strong modification of DW dynamics in nanowires with width ranging from 0.2 to 1.5 μm.

II. EXPERIMENTS

The samples studied here are Ta(5nm)/Co40Fe40B20(1.0nm)/MgO(2.0nm)/Ta(5nm) stacks with perpendicular magnetic anisotropy. After annealing the samples at 300 °C for two hours, they were patterned by conventional electron beam lithography and ion beam etching into 50 μm long narrow wires connected with a 20μm×20μm square (nucleation pad), as shown in Fig. 1(a). The widths of the wires used for this study are 200nm, 400nm, 600nm, 1μm and 1.5μm respectively. The experimental

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FIG. 1. (a) Optical image of one of samples studied. Structure surrounded by the dashed blue line is the 1 µm wide wire connected with a nucleation pad. (b) Example of two field pulses with the same length and different magnitude, used to measure the DW depinning field. (c-f) DW pinning and depinning in a 200 nm wire: DW moves from (image c) to (d) by a lower field pulse 1 (12.1 mT), then trapped (d and e), DW is depinned and continue to move from (e) to (f) by a higher field pulse 2 (13.2 mT).

Magnetic parameters are found to be $M_S = 1.1 \times 10^6$ A.m$^{-1}$ for the saturated magnetization and $K_{eff} = 2.2 \times 10^5$ J.m$^3$ for the effective anisotropy. Also, the typical propagation fields in these films is about 3 mT and DW motion can be observed in the creep regime for fields as low as 0.1 mT.

Small coils with diameter of about 6 mm were used to nucleate a single DW in the nucleation pad and to drive the DW motion along the wire. Owing to the small inductance of coils, the rising time of the generated magnetic field pulse can be as short as 200 ns, as shown in Fig. 1(b). A Kerr microscope was used to image the magnetic state. Using a lens of numerical aperture 0.8, we could get sufficiently resolved Kerr pictures for all the nanowires, including the narrowest one of 200 nm, as shown in figure 1c to 1f.

DW nucleation was induced using short magnetic field pulses of a few µs and of high amplitude, up to 100 mT. Such monitored pulses were able to nucleate a single reversed domain in the nucleation pad but were short enough to prevent the overall reversal of the structure. In order to induce DW motion along the wire, pulses of very small amplitudes and 5 µs long were applied. As long as propagation could occur without pinning, the amplitude of the pulses was not changed (pulse 1 on figure 1b, and figure 1c and 1d for the magnetic state). After one or several pulses, it can be observed that propagation can be fully stopped (figure 1d and 1e), indicating that the DW cannot overcome the energy potential induced by the presence of defects. Several additional similar pulses were applied to check that it is not possible to unpin the DW at this location (figure 1e). Then, the amplitude of the pulse was increased step by step (pulse 2, figure 1b), until the depinning occurs (figure 1f). For a given pinning defect, the experiment was carried out several times and the depinning field values were reproducible with an error bar lower than 0.3 mT. In order to improve the statistics, for each width we have studied DW motion in several nanowires (from 3 to 6) and we have selected the five strongest pinning sites along the 50 µm wire.

III. DEPINNING FIELD DISTRIBUTION

The main important result of this study is the presence of several strong pinning sites along the wires that cannot be observed in the full films. These strong pinning sites prevent the DW to
move in a creep regime since the wall is fully stopped at several locations along the wires. The distribution of the strongest depinning fields as a function of the wire width is indicated in figure 2. It can be observed that the distribution is shifted towards higher values as the width of the nanowire is decreased. This shift can be explained by taking into account the different forces acting on the DW. First, the pressure $2M_S B$ due to the external applied field $B$ integrated over the section of the wire, gives a force $2M_S B e w$, where $e$ is the thickness of the film and $w$ the width of the wire. Then, the presence of intrinsic pinning defects in the films induces a force $F_F$. These intrinsic defects alone are not strong enough to stop the DW since the magnetic fields applied for observing DW depinning in the nanowires are much higher than those needed to move DW in the films (typically $<1$ mT).

The effect of intrinsic pinning can be described using a friction force that depends on the number $N$ of defects and is proportional to the section. It leads to a maximum force $e w F_F$, opposite to the induced motion. At last, the strong pinning defects evidenced here creates a force $F_{SD}$. The depinning occurs when the pressure overcomes the overall pinning forces $F_{SD} + e w F_F$. The depinning field $B_{dep}$ is deduced from this threshold condition:

$$B_{dep} = \frac{F_F}{2M_S} + \frac{F_{SD}}{2eM_S} \frac{1}{w}$$  \hspace{1cm} (1)

It has to be noted that the quantities $M_S$, $e$, $F_F$ can be assumed to be constant. However, $F_{SD}$ requires a more careful analysis. Indeed, $F_{SD}$ is related here to the tail of the distribution of the pinning forces. As such, the probability to get a very strong pinning force is small and increases with the overall number $N$ of defects. So, this parameter may depend on the surface and on the length of the wire as described below.

IV. AVERAGE EXPECTED VALUE FOR THE DEPINNING FIELD OF THE STRONG DEFECTS

To describe the distribution of $F_{SD}$, we have assumed it to be Gaussian and centered on zero. As the number of defect is huge, we have assumed that we have the same behavior for the average value of the five strongest defects as for the value of the strongest defect alone. Then, two cases can be considered. First, the strong pinning sites are of extrinsic origin such as the roughness of the edge. In this case, their number should depend on the length of the edges, which is the same for all wires, whatever the width is. So, the overall number of strong defects as well as $F_{SD}$ should be a constant and, according to equation (1), $B_{dep}$ should increase linearly as a function of $1/w$. 

FIG. 2. histogram distribution of depinning field obtained for the strongest defects, using the five strongest ones for each wire included in the statistics.
FIG. 3. expected distribution of the strongest pinning force as a function of the overall number N of defects, assuming a Gaussian distribution of defects centered on zero. The probability for four values of N are compared on this figure: $10^3$, $10^4$, $10^5$ and $10^6$.

Second, the strong defects are of intrinsic origin and they originate from the magnetic films. Then, their number N is proportional to the area of the wire, which means here to the width w of the wire. In order to get a depinning force at $F_M$ for the strongest pinning site, it means that all the other defects have a depinning force $F$ lower than $F_M$. In this case, the probability to get $F_M$ as the strongest pinning force is:

$$P(F_M) = NP^{N-1}(F < F_M)P(F_M)$$

where the function $P$ holds for the probability function. As we have assumed a Gaussian distribution, we get the following functions for $P(F_M)$ and $P(F < F_M)$:

$$P(F_M) = \frac{2}{\sqrt{\pi}} \exp\left(-\frac{F_M^2}{\sigma^2}\right)$$

$$P(F < F_M) = \frac{2}{\sqrt{\pi}} \int_0^{F_M} \exp\left(-\frac{F^2}{\sigma^2}\right) dF = \text{erf}\left(\frac{F_M}{\sigma}\right)$$

Injecting equation (3) and (4) in equation (2), the distribution probability of $F_M$ for several values of N can be simulated as seen in figure 3. It can be observed that the average value is shifted towards the high values as N increases. To get a meaningful shift, there must a quite big increase of N. For instance, when N is multiplied by ten, the increase of $F_M$ is around 20%. In our experiment, the width goes from 200 nm to 1.5 $\mu$m, which is almost a factor of ten. So, a decrease of $F_{SD}$ would be expected when $1/w$ increases. As a result, we expect a behavior different from a linear law (behavior predicted by equation (1) if $F_{SD}=$constant), with an increase of $B_{dep}$ slower than $1/w$. The experimental $B_{dep}$ as a function of $1/w$ is plotted in figure 4. We can observe a very good linear behavior indicating

FIG. 4. average depinning field of the strongest defects experimentally obtained as a function of $1/w$, where w is the width of the wire.
no evidence of a dependence weaker than 1/w. This result is consistent with an extrinsic nature for the strongest pinning sites in our samples, probably due to the edge roughness introduced by the patterning process.

V. CONCLUSION

In magnetic nanowires based on Ta-CoFeB-MgO with a very low density of pinning sites, we have shown that strong pinning sites prevent DWs from moving along the wire and as a result no creep behavior can be observed as for the continuous films. We have evidenced that the distribution of the strongest depinning fields depends on the width of the wire. Using a simple model, we have shown that our results are consistent with an extrinsic nature of the strongest pinning sites, probably due to nanopatterning defects at the edges of the wires.

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