Stochastic domain-wall depinning under current in FePt spin valves and single layers

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In this paper, we report on the current-induced depinning of domain walls from structural defects in nanowires tailored in both FePt//MgO and FePt/Pt/FePt//MgO epilayers with high perpendicular magnetic anisotropy. In these systems, we show that the nature of domain wall depinning is stochastic. Our results indicate that there are two source of stochasticity: thermal activation and domain wall configuration degeneracy. We show that the depinning rate can be influenced with a strong efficiency by an applied dc current, whose effect on both thermal and configurational stochasticity is exactly similar to that of an additional magnetic field. Interestingly, Joule heating is found to cancel the bipolar effect of the current for quite low current densities. Contrarily to what was expected, the spin-transfer efficiency measured in single layers and spin valves are found to be similar. Results from micromagnetic simulations are shown to reproduce the observed statistical trends.

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I. INTRODUCTION

Electronic devices have recently been imagined, based on current-induced domain wall (DW) motion and allowing data storage or logical computing. Such devices require the precise control of the DW position, implying the use of artificial defects (constrictions, notches) to pin the DW reproducibly, and a deterministic control of the DW motion. However, an obstacle on the road toward DW control appeared in recent experiments: A random behavior of the depinning has been observed, with two distinct sources of randomness. First, the role of thermal activation cannot be neglected when studying field-induced depinning. Indeed, the critical depinning field is not well defined: at its vicinity, the pinning time is random, following an exponential probability law corresponding to the activation over a single energy barrier.[1] Similarly, for current-induced DW depinning experiments, and as predicted by a theoretical study,[2] the pinning time should still follow an exponential law. However, up to now, many experimental studies on this topic avoided the question, considering measured critical currents or fields as precisely defined values below which depinning does not occur. Second, another source of stochasticity arises whenever the pinning configuration of the DW is degenerate, i.e., when the DW can be randomly pinned on a single defect along different magnetic configurations. For example, Cowburn *et al.* showed that the depinning field of a transverse DW from an asymmetric artificial defect depends on the DW polarity, the latter being able to switch stochastically during the DW propagation.[3] Also, Meier *et al.*[4] and Im *et al.*[5] observed stochastic DW velocities linked to stochastic transformations of the DW geometry. Hayashi *et al.*[6] observed a similar stochastic behavior in their racetrack memory demonstrator, which underlines to what extent the control of the stochasticity of DW depinning can be crucial for spintronics applications.

In a recent study using FePt and CoNi based spin valves,[7] we focused on the value of the nonadiabatic parameter β in samples with perpendicular magnetization. It has been theoretically predicted that such materials with narrow DWs would be ideal candidates for improved spin-transfer-induced DW movement, because of the large magnetization gradient.[8] A model taking into account thermal activation was proposed, allowing the extraction of β and showing it was lower than anticipated. In this article, we will focus on the stochasticity of the depinning process in FePt systems under field and current, showing that there are two sources of stochasticity. We will also compare the effects observed in FePt-based spin valves and FePt single layers, showing that they are similar. Finally, we will show that Joule heating effects can appear at low current densities.

II. SAMPLE PREPARATION AND MEASUREMENTS

FePt(10 nm)//MgO samples and FePt-based spin valves [FePt(4 nm)/Pt(2.4 nm)/FePt(5 nm)//MgO] have been grown by molecular beam epitaxy at high temperature.[9,10] The FePt alloy is chemically ordered within the $L1_0$ phase, giving rise to ultranarrow DWs ($\Delta = \sqrt{A_{ex}/K_U} \approx 1$ nm, A_{ex} and K_U being respectively the exchange and anisotropy constants). In the spin valve, the microstructures differ in the FePt underlayer and overlayer, leading to different DW pinning strengths. The two FePt layers thus exhibit slightly different switching fields, allowing us to obtain between those fields an antiparallel state of the magnetization.[10]

High-quality 200-nm-wide wires with low edge roughness ($\leqslant$5 nm) were fabricated by means of electron beam lithography and ion milling. Along the wire electrical contacts are disposed to measure resistivities and Hall effects, and there is a large magnetic area at one end of the magnetic wire that acts as a DW reservoir, allowing the injection of a single DW into the wire as seen in the magnetic force microscopy (MFM) observation of Fig. 1(a).

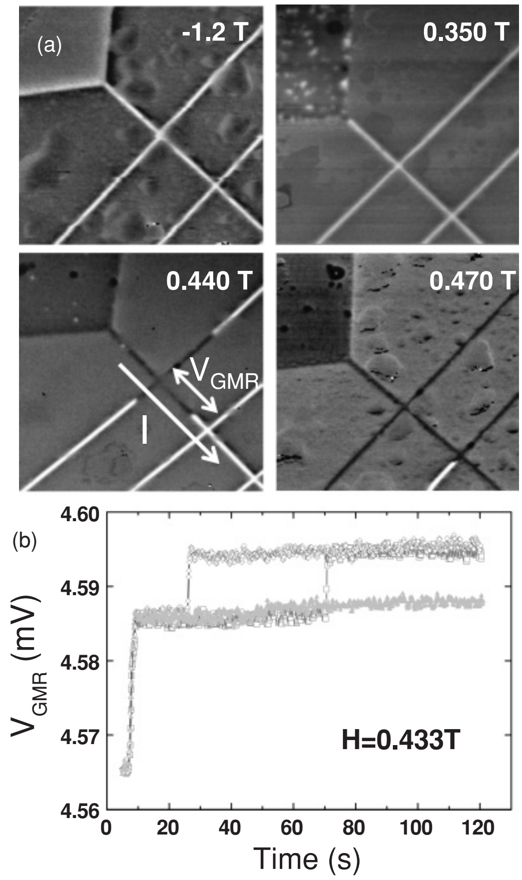

FIG. 1. (a) 20 μm $\times$ 20 μm series of MFM images of a nanostructure processed in a spin valve, showing a DW propagating through the central nanowire. These various states of the magnetization reversal are obtained by applying different field values. The reversed domain appears in dark gray. The wires are 200 nm wide. (b) GMR measurements of DW depinning, realized in exactly similar conditions. The pinning occurs always at the same position, but with a random pinning time.

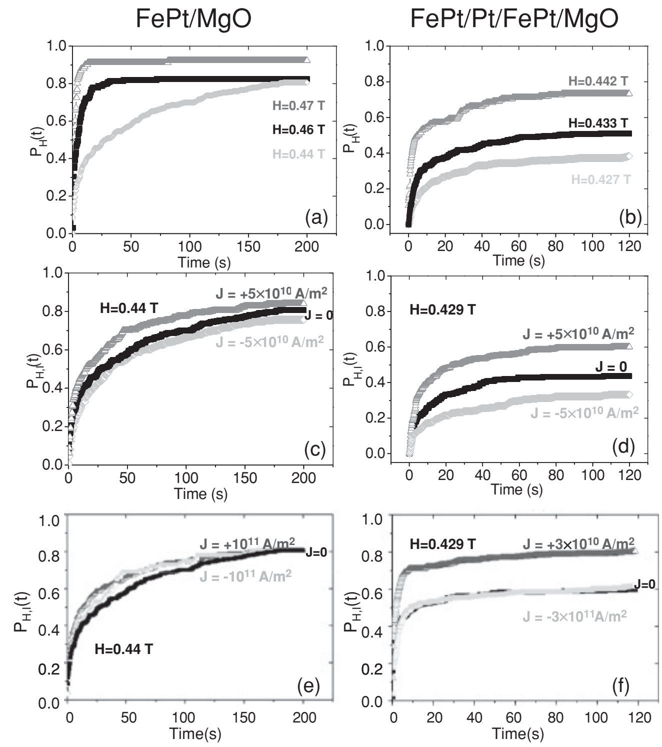

FIG. 2. Cumulative probability of depinning (i.e., probability to be depinned after time *t*) for [(a), (c), and (e)] FePt(10 nm)//MgO and [(b), (d), and (f)] FePt(4 nm)/Pt(2.4 nm)/FePt(5 nm)//MgO. [(a) and (b)] The effect of varying the applied field at zero current; [(c) and (d)] the effect of the applied current. [(e) and (f)] For moderately high current densities, the effect of heating cannot be neglected. Data of (d) have already been published in Ref. 7.

In the case of FePt-based spin valves, the giant magnetoresistance (GMR) measurement permits us to detect the position of the DW pinned on a defect. In the case of the FePt//MgO structures, we used two Hall crosses in order to measure the propagation time between these two structures, similarly to what had been done previously in FePt/Pt//MgO samples.[1] In both cases, the propagation time of the DW between the two Hall cross is dominated by the pinning on a single and strong pinning site [Fig. 1(b)].

Figure 1(b) shows multiple measurements of the GMR voltage as a function of time, at constant magnetic field, in the case of the FePt-based spin valve. The measurement procedure is conducted as follows. First, the hard and free layers of the spin valve are saturated with a strong negative field. Then a constant positive field is applied to nucleate and inject a single DW into the wire while measuring the GMR as a function of time. The variation of GMR vs. time corresponds to the DW motion, including a pinning event, between two Hall crosses that are 3 μm apart. In both cases, the FePt single layers and the spin-valve counterpart, because of the stochastic character of the depinning time, we had to perform several hundreds of repeated measurements (200 for FePt/MgO and 400 for spin valves).

III. EXPERIMENTAL RESULTS

In Fig. 2 we present the cumulative probability curve of depinning $P_{H,I}(t)$ (i.e., the probability to be depinned at time *t*), under both the action of an applied field [Figs. 2(a) and 2(b)] and of an applied field together with an applied dc current [Fig. 2(c) and 2(d)]. Similarly to what has been previously discussed in another kind of FePt-based sample (FePt/Pt//MgO),[1] the depinning is stochastic under the influence of an applied external field. The global shape of the $P_{H,I}(t)$ curve corresponds to the pinning on a single defect for both FePt/MgO samples and FePt-based spin valves. This last observation is comforted by the GMR measurements, where the pinning always corresponds to the same GMR value.

For a single energy barrier, the probability of being depinned as a function of time t is given by $P(t) = 1 - \exp[-t/\tau]$, where τ is the average pinning time.[11] τ is given by an Arrhenius law,

$$\tau = f_0^{-1}\exp[E(H)/k_B T], \tag{1}$$

f_0 being an attempt frequency. The energy barrier can be supposed in first approximation independent of the temperature, and its dependence with the applied field can be expressed as $E(H) = E_0 - 2M_S V_0 H$,[1,12] where E_0 is the energy barrier at zero field, M_S is the magnetization per volume unit, and V_0 is the activation volume.

However, a previous study[1] showed that it is impossible to fit directly the $P_H(t)$ curves with a simple exponential law. It was shown that this is due to the possibility for the DW to be pinned on the main defect along two different micromagnetic configurations, corresponding to different pinning strengths. In the first configuration, the DW depinning is easy and controlled by an exponential law whose parameter corresponds to a few seconds. This configuration is responsible of the exponential growth of $P_H(t)$. In the second configuration, however, the pinning strength is too high, the transition rate is too low, and the DW cannot get out of the defect. This explains why, at low fields, the probability of depinning does not increase up to 1 for long times. It has also been shown that a simple model allows to extract quite precisely the parameter of the exponential law that corresponds to the first configuration, i.e., the depinning from the configuration with the lowest pinning strength. Importantly, we can also rule out the possibility of having sequential pinnings, as the cumulative probability function would, in such cases, exhibit different features, as a zero derivative at $t = 0$.

In several studies on permalloy structures, the stochasticity was proven to arise from random changes in the type or polarity of the pinned DW.[3,13] Here, the small DW width in FePt does not allow direct observation of the DW micromagnetic structure when pinned. The internal degree of freedom of the DW in FePt might, for example, reside in its polarity (clockwise or counterclockwise rotation of magnetization) or in the presence/absence of Bloch lines, which are already known to be able to modify the dynamics of Bloch DW.[14] Because of the small DW width, we cannot provide direct observation of the magnetic configuration of the DW when pinned. Transport measurements do see a single pinning position: For the given width only one pinning site is observed for a 3-μm-long nanowires. As the noise on the GMR measurements is not infinitely low, it is impossible to distinguish different pinning configurations on this defect. Also, the MFM resolution is not small enough, and at some point it would be difficult even with the use of Lorentz microscopy.

However, our statement that there is configuration degeneracy is proven by the statistical analysis of the pinning time described in Ref. 1. In any case, the origin of the stochastic depinning behavior in the case of our FePt nanowires is thus double: one is related to the stochastic character of thermally activated depinning, and the other one is related to the randomness of the DW configuration when it is pinned on the defect.

In the following, we focus primarily on the effect of an additional dc-polarized current. We have used low current densities ($<10^{11}$ A/m^2) in order to minimize the Joule effect: The temperature increase, estimated from resistivity measurements, is below 5 K.

The influence of a current on the probability $P_{H,I}(t)$ at constant magnetic field is shown in Figs. 2(c) and 2(d). In our convention, a positive current acts to propagate the domain wall in the same direction as a positive magnetic field. We observe for both systems a clear current-induced effect, in agreement with the spin-transfer mechanism[8,15,16]: The average time of depinning is reduced (respectively increased) for a current acting in the same (respectively opposite) direction as the magnetic field.

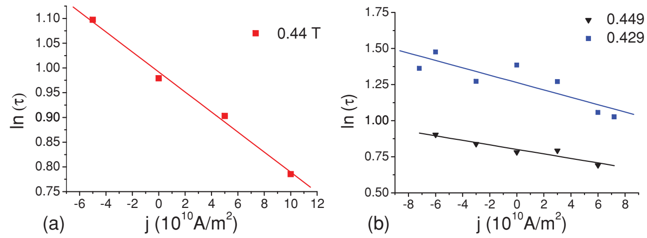

FIG. 3. (Color online) Characteristic pinning time τ as a function of the applied dc current for different applied magnetic fields, for the FePt/MgO sample (a) and for the FePt-based spin valve (b). The $\ln(\tau)$ is calculated with τ in seconds. Symbols represent experimental data and solid lines represent a linear fit.

These results clearly demonstrate that the stochasticity, observed previously in field-induced depinning experiments, is still present under spin transfer. The similarity of the curves obtained in Fig. 2(a) and in Fig. 2(c), as well as in Figs. 2(b) and 2(d), underline a very remarkable feature: the action of a polarized current density J is equivalent to the action of an effective magnetic field H_{eff}, affecting the stochastic behavior due both to thermal activation and to DW configuration.

In order to illustrate this equivalence, we have extracted the characteristic depinning times τ and plotted them for fixed values of applied field (Fig. 3). This equivalence of a current variation with a field variation is consistent with recent experimental studies[17] and allows the defining of a spin-torque efficiency $\xi = \Delta H/\Delta I$, the depinning energy barrier varying as:

$$E(H) = E_0 - 2M_S V_0(H + \xi J). \tag{2}$$

This spin-torque efficiency can be compared with those derived from previous experiments realized on other systems. If these experiments do not take into account thermal activation, the efficiency can be extracted from measurement of critical depinning currents vs. the applied field. When the critical current has been measured at zero field, the efficiency is given by the ratio of the coercive field and of the critical current. Contrarily to previous experiments,[18] where the use of spin valves enhanced the spin-torque efficiency, we find typical values of 10^{-13} T/A m^{-2} for both FePt single layers and spin valves. This discrepancy may be due to the fact that we use a Pt layer as separation layer, which could limit spin accumulation in our spin valves. In another paper,[7] we focused in extracting from these data the value of the nonadiabatical term β, showing that it is surprisingly small ($\approx$0.06) and that the high efficiency is due only to the narrowness of the domain wall.

In previous experiments the effect of the current in presence of a field has appeared to be less sensitive to the current polarity. This has opened up some questions for perpendicularly magnetized material, where, due to higher coercive fields, the spin torque is usually assisted by the external magnetic field.[17] At small current densities, our results clearly demonstrate that the action of the current depends on its sign. However, for current densities higher than 10^{11} A/m^2, our results suggest

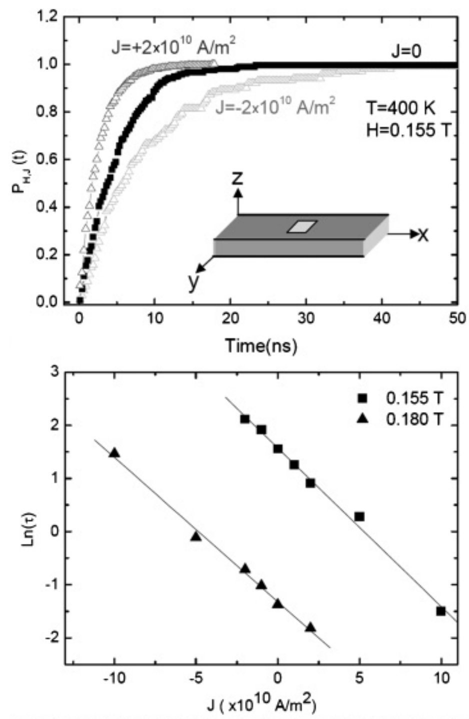

FIG. 4. (a) Probability to be depinned as a function of time. The material parameters used in these simulations are those of FePt. (Inset) Schematic diagram of the system geometry, with the defect highlighted, and (b) characteristic depinning time vs. the applied dc current. The $\ln(\tau)$ is calculated with τ in nanoseconds.

that the contribution of Joule heating cannot be neglected anymore [cf. Figs. 2(e) and 2(f)]. For negative currents, the Joule effect and the spin-transfer effect act in opposite directions: An increase of the temperature reduces the pinning time, whereas an increase of the current density (in absolute value) tends to increase the pinning time. For high current densities, the effect of the heating, quadratic with the current density, can compensate (or even overcome) the spin-transfer effect [cf. Figs. 2(e) and 2(f)]. The curves for $\pm 10^{11}$ A/m^2 and $\pm 3 \times 10^{11}$ A/m^2 are no longer found on each side of the zero current curve: When the current densities increase, the effect of the current on DW depinning, initially odd, becomes gradually even. Note that the effects of Joule heating are quite important for current densities as small as $\pm 10^{11}$ A/m^2.

IV. MICROMAGNETIC SIMULATIONS

Micromagnetic simulations were performed to support the experimental observations (cf. Fig. 4). The micromagnetic solver based on the modified Landau-Lifshitz-Gilbert equation takes into account both the thermal fluctuations and the adiabatic and nonadiabatic contributions of the spin transfer.[19,20] We considered a nanowire of single FePt thin film of size $80 \times 50 \times 5$ nm^3 exhibiting an out-of-plane uniaxial magnetocrystalline anisotropy of $K_U = 5 \times 10^6$ J/m^3. This simple system, which models the free layer of the FePt-based spin valves, captures the essential physics of stochastic DW depinning. The simulation parameters are as follows: $M_S = 1.03 \times 10^6$ A/m, $A_{\rm ex} = 6.9 \times 10^{-12}$ J/m, $\alpha = 0.1$, the mesh size of $0.5 \times 1 \times 5$ nm^3, sample temperature 400 K. The defect is represented by a grain of size $5 \times 10 \times 5$ nm^3 with reduced magnetocrystalline anisotropy $K_{\rm def} = K_U/2$ (see inset Fig. 4). The statistical analysis was done on at least 200 events.

V. CONCLUSIONS

In conclusion, we have provided a detailed experimental study of the stochastic process of thermally activated DW depinning from natural defects. We showed that the action of an applied current is equivalent to the action of an applied field, with the stochasticities due to thermal activation and the DW random configuration being modified similarly in both cases. The bipolar action of the current is only observed at low current densities and can be hampered by the joule heating at higher current densities. Moreover, our study underlines the fact that thermal stochasticity has to be considered thoroughly, both when analyzing spin-torque experiments data and when creating DW-motion-based devices.

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