Letter

Poisson's process in the propagation of magnetic domain wall in a perpendicularly magnetized film

T. Xing,[1,2] N. Vernier,[3,2,*] X. Y. Zhang,[1] Y. G. Zhang, and W. S. Zhao[1]

[1] *Fert Beijing Institute, MIIT Key Laboratory of Spintronics, School of Integrated Circuit Science and Engineering, Beihang University, Beijing 100191, China*

[2] *Centre de Nanosciences et de Nanotechnologies, CNRS, Université Paris-Saclay, 91120 Palaiseau, France*

[3] *Laboratoire Lumière, Matière et Interfaces, Université Paris-Saclay, 91405 Orsay, France*

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We present here a statistical study of the transit time required for a magnetic domain wall to go through a small laser spot focused on two-dimensional magnetic thin film. The domain wall velocity deduced this way is in good agreement with the other ways used to measure this parameter, but the main fact is that the transit time is not a reproducible parameter; we have observed a quite large distribution of this parameter. This distribution can be explained assuming the movement to occur through jumps, whose probabilities are given by Poisson's process. The fitting of this distribution has enabled us to get the required number of jumps to reverse the magnetization of the small area under the laser spot. This important parameter should lead to a better understanding of the creep regime.

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Dynamic domain wall (DW) interfaces are the result of complex interactions between disorder, elasticity, and thermal fluctuations [1–9]. In the low velocity limit, it has been successfully described by the creep theory, which can apply to the propagation of any interface in a medium, such as the boundaries of a crystal growing in a liquid, a fire front, or the expansion of a magnetic domain [10,11]. Roughly, creep theory can be described as stochastic successive jumps of the interface in a disordered medium with many defects acting as pinning points for the propagating interface. Due to thermal activation, a pinning point can be overcome, generating a jump to reach the next pinning points [11–13]. Creep theory gives an average propagation velocity: indeed, the interface is rough and the propagation length induced by a magnetic field pulse is not the same along the interface. One has to do an averaging along the interface to check the prediction of the creep theory [7,8,12,14]. At last, most of the experiments rely on a stroboscopic procedure, using a Kerr picture before and after the pulse to view the position of the DW before and after the magnetic field pulse. Using such a method, there is no information about what is happening in real time.

The stroboscopic way is not the only way; there are a few DW studies giving some clues about the real-time evolution. Several ways have been used: checking the extraordinary Hall effect on a wire at the position of a Hall cross [15–17], pulsed lightning using a picosecond laser, which requires doing the experiment many times and assumes it works each time the same way [18], or monitoring the Kerr signal below a laser spot focused on the sample [19–21]. But all these experiments were made using nanowires, not full film, and the behavior might not be a true intrinsic two-dimensional (2D) one.

In this Letter, we report an experimental work of DW movement with real-time detection in a true 2D magnetic film of $Ta(5\,nm)/Co_{40}Fe_{40}B_{20}(1.1\,nm)/MgO(1\,nm)/Ta(5\,nm)$ film with perpendicular anisotropy, already studied in a previous paper [22,23]. A linearly polarized laser spot was focused on the sample, and the reversal of the area under the spot was detected in real time through the Kerr signal $S(t)$ [19,24]. The laser beam was arriving perpendicular to the substrate and the configuration is a pure polar one, which probes only the perpendicular component of the film. The laser spot was approximately Gaussian, with a diameter of $2\omega_0$ ($1/e^2$ light intensity), which could be set from 5 to 60 μm by using an additional lens between the laser and the objective lens. In the following, most of the measurements were done with 6.5 μm. The laser power was 4.5 mW to ensure negligible local heating [23]. The time response of the detector was limited by an amplifier with a bandwidth of 100 kHz, enabling us to view the rise time as 2.4 μs (time period between 10% and 90% of maximum amplitude).

Figure 1 shows the corresponding magneto optical Kerr effect (MOKE) signal when a DW goes through the laser spot driven by a 2.82-mT out of plane field. For a Gaussian spot, assuming the DW to be a straight line moving at a constant velocity, this signal is predicted to have the behavior following the error function [19,25]:

$$S(t) = A\,\mathrm{erf}[k(t - t_0)] + C, \tag{1}$$

where $\mathrm{erf}(x)$ is the error function:

$$\mathrm{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x \exp(-u^2)du. \tag{2}$$

The transit time t_{tr} through the spot is defined as the time required for the domain to move $2\omega_0$ further. It can be deduced

*Corresponding author: nicolas.vernier@universite-paris-saclay.fr

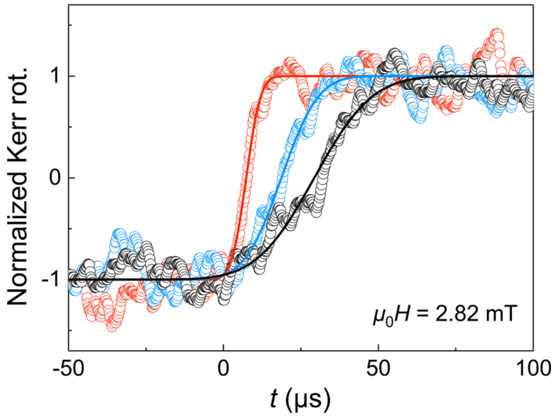

FIG. 1. Three typical cases for different transit times with spot width 6.5 μm.

directly from the fitting parameter k according to

$$t_{\rm tr} = \frac{2\sqrt{2}}{k}. \tag{3}$$

Here, it is important to point out that our experiment enables us to get the transit time of a one-shot experiment. So, we have first checked if the transit time was reproducible from one attempt to another, applying exactly the same magnetic field. On a big scale, average velocity is quite well reproducible, while on a small spot of diameter 6.5 μm, it is no longer true. Figure 1 presents the results; we have kept only three typical attempts, which gave an obviously different result, with transit times of 17.6, 33.4, and 60 μs. At this scale, we can see some stochasticity in the process of the propagation. This interesting phenomenon has already been found by some other authors [20,21].

We have used this stochastic behavior as a tool to get some information about the propagation process. First, we have determined experimentally the distribution of transit time. For one set of parameters, i.e., one value of the magnetic field, one size of the spot and one position, we have performed the experiment 100 times. A typical histogram of transit time arising from a set of experiments has been plotted in Fig. 2. In Fig. 1, the ratio signal over noise induces an error bar meaningfully lower than the step of the histogram and it allows a reliable histogram. Let us note that the size of the spot seems to be already big enough to get similar properties at any position on the sample. For the field of 1.90 mT, we have done the experiment at four different positions: the four histograms were identical within the error bars [see the Supplemental Material (SM) to view these histograms] [23]. This is a quite important result; it shows that the stochastic behavior is not due to a few specific defects in one area, it is an intrinsic property and, although quite small, the spot is already big enough to get a distribution of defects similar at any location on the sample. Note that, in Fig. 2, we have gathered altogether the results obtained at the four positions for 1.90 mT to get a better statistic; the four histograms can be seen in the SM [23].

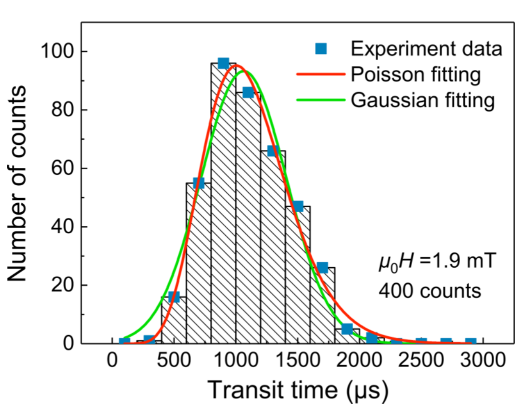

FIG. 2. Histograms of transit time frequency distributions using the Gaussian fit (green solid line) compared to the Poisson fit (red solid line).

Then, to fit these histograms, we have used the following model: (1) we have simplified things by assuming the meaningful defects are identical, (2) the DW propagates by jumps from one pinning defect to the next one, (3) the probability of a jump to occur during a short time interval dt is proportional to dt; this probability can be written as dt/τ, with τ being the average waiting time between two jumps, and (4) the duration of a jump is negligible as compared to the waiting time at the pinning defects. As the density of defects is quite well defined, the number of jumps required to pass through the laser spot must be also well defined. As a result, the probability of having a transit time of duration t in the spot identifies the probability of getting n jumps during t, where n is the required number of jumps to go through the laser spot. This is Poisson's process, and this probability is given by [26]

$$P_n(t) = \frac{t^{n-1}}{(n-1)!\tau^n} \exp\left(-\frac{t}{\tau}\right). \tag{4}$$

Note that $P_n(t)$ is normalized. So, to fit the histograms, this function has to be multiplied by the number N of sampling done. Here, usually $N = 1$. In addition, the step time δT between two successive channels of the histograms is always small enough to have roughly a probability on one channel of the histograms equal to $P_n(t)\delta T$. As a result, the function used to fit the histograms was

$$f(t) = NP_n(t)\delta T. \tag{5}$$

The result of the fit can be seen in Fig. 2. As a reference the fit using the usual Gaussian function has also been shown. Both fits are very satisfying, but Poison's fit is slightly better; it explains the slight asymmetry of the histogram. Here, it must be added that, depending on the parameters (amplitude of the applied field, size of the laser spot), we have made more than 15 histograms (see the SM [23]): each time, an asymmetry could be seen and Poisson's fit appeared to be slightly better than the Gaussian ones. So, the asymmetry is meaningful and Poisson's law seems to be a good model to describe our experiment.

The small difference between Gaussian and Poisson can be explained by the n values. Indeed, when n is bigger than 10, Poisson's law is not very different from Gaussian's law. In fact, using a Gaussian fit instead of Poisson's one, one can get

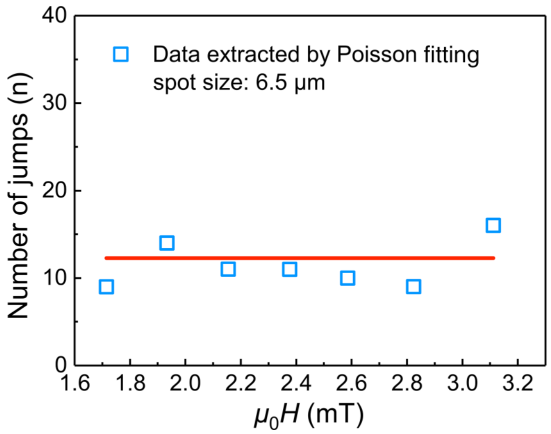

FIG. 3. Number of jumps (n) extracted by Poisson distribution fitting.

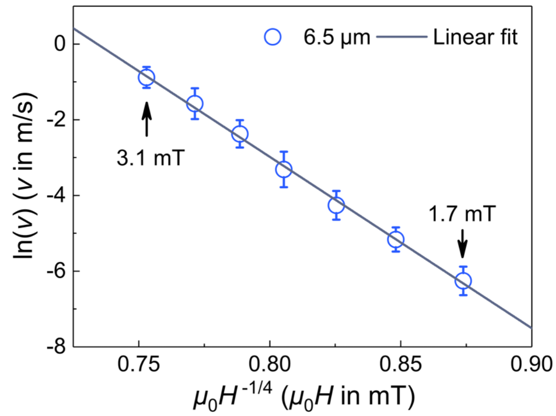

FIG. 4. DW propagation velocity as a function of the applied magnetic field, plotted to check the creep behavior.

also the right parameters:

$$f(t) = \frac{N\delta T}{\sqrt{2\pi(n-1)\tau}} \exp\left(-\frac{(t-n\tau)^2}{2(n-1)\tau^2}\right). \quad (6)$$

Now, we come to the most interesting result: from these fits, we can deduce how many jumps have to occur for the DW to go through the laser spot. For a laser spot of diameter 6.5 μm, n has been plotted as a function of the applied magnetic field in Fig. 3. In this range of field, within the error bars, n does not change—it is around 11. So, one jump would mean a reversal of an average area of 3 μm^2. Let us note that one jump would imply a movement of some 1 μm, which is much bigger than the Larkin length (usually around 100 nm [8]). At the present time, it cannot yet be completely excluded that one main jump is in fact an avalanche process, with many smaller jumps occurring very quickly. However, elementary movements are expected to be meaningfully bigger than the Larkin length, and the jumps found out here might be elementary ones. Other references are pointing to such a size for elementary jumps [11,27,28].

This result can be compared to propagation in nanowires: for narrow nanowires of width below one or two micrometers, some single pinning defects can stop completely the propagation of a DW [29]; some discrepancies in the creep law have been found [30]. It agrees with the scale of one jump, as we can expect problems to appear when the jump area covers the full width of the wire.

The fact that n does not change on the whole range of field has to be analyzed: indeed, when the magnetic field rises up, one expects the Zeeman energy to override the potential barrier keeping the DW pinned at the position of the defect. So, we were expecting the number n to decrease with the increase of the magnetic field amplitude. But, it did not. We think we did not reach fields high enough to reach the possibility of overriding any main defect potential. So, whatever the field was, pinning occurred for each relevant defect and the number of jumps was the same. Indeed, when looking at propagation as a function of magnetic field (see Fig. 4), we can see that even at the highest applied field, we are still in the creep regime, which means pinning by defects is still working.

To check our model, we have changed the size of the spot. Within the error bars, the first result is the fact the characteristic mean time τ between two jumps does not really change with the size of the spot for a given field, although the diameter of the spot goes from 5 to 60 μm. It seems consistent with our model, as τ is defined at a much lower scale. The second parameter which can be checked in this experiment is the number of jumps: it has been plotted in Fig. 5. As the area of the spot increases, as expected, the number of jumps increases. But, the dependency is not so easy to explain. Indeed, in a Markovian process, one could have expected it to increase linearly with the area of the spot, which means the square of the diameter. Obviously, it is more complicated (see DW pinning and depinning process observed with Kerr microscopy in the SM) [23]. In fact, the first idea implying the area might be wrong. Indeed, the length of the DW inside the spot might be a relevant parameter for the probability of getting one jump, as the number of possible jumps increases with this parameter. So, the bigger the spot is, the bigger should become the probability. Such an analysis requires first some more data as well as some more thinking and it goes

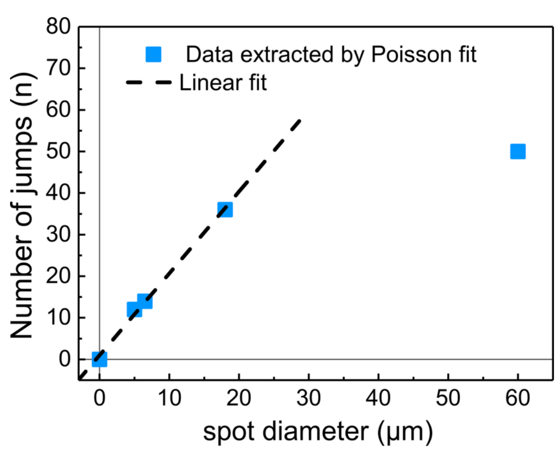

FIG. 5. The number of jumps as a function of probing area at 1.9 mT. Note that a point at zero has been added as there is no more pinning point when the area goes to zero, which means no jump over a defect to go through.

beyond the aim of this Letter. But, according to this idea, the number of possible jumps should increase linearly with the diameter of the spot, and we have indeed a linear behavior up to a diameter of 20 μm (Fig. 5).

In conclusion, we have carried a real-time detection of a magnetic DW transit in a small area defined by a laser spot. Using the same magnetic field, the transit time was not reproducible. To understand this stochasticity, we have studied the distribution of transit time obtained on a statistic of 100 experiments. To fit the histograms, we have assumed a propagation through stochastic jumps, ruled by a Poisson's statistic. We have got a very good agreement between experiments and model. In particular, the model has been able to explain the slight but systematic asymmetry of the histograms. As a result, we could get an important parameter, which is the required number of jumps of the DW to go through the spot: for a spot of diameter 6.5 μm, the fitting shows that there are around 11 jumps. It means an average reversal of a 3-μm^2 area during each jump. This is important information about the defects ruling propagation in magnetic thin films and inducing the creep behavior. Let us note that this kind of analysis can apply to any creep experiment; it is a powerful tool to get a better understanding of this phenomenon.

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