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# Magnetic relaxation in GdFe/TbFe/GdFe trilayers: Dynamic study of the propagation of a 180° domain wall through an artificial energy barrier

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An experimental study of the dynamics of the propagation of 180° domain walls from a first GdFe layer to a second GdFe layer through a very thin TbFe layer is presented. In this system, TbFe constitutes a very hard magnetic layer that acts as an energy barrier. It is shown from relaxation and from quasistatic measurements that the propagation of the domain walls can be analyzed as the crossing of an energy barrier from a metastable state to a stable state. The relaxation data can be fitted with a unique relaxation time, which is quite unusual in magnetism. The system is modeled by an assembly of parallel and similar domain-wall junctions. The evolution of the energy barrier parameters with the thickness of the TbFe layer are reported.

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## INTRODUCTION

The magnetization reversal processes that are known to be of prime importance in most of the applications involving magnetic materials, as for example, in magnetorecording media, have been studied intensively, especially since the pioneering work of Néel<sup>1</sup> and Brown.<sup>2</sup> Since then, a lot of studies have been devoted to the dynamic of the magnetization reversal and its temperature and magnetic-field dependence.<sup>3–6</sup> In fact, most of the works have concerned complex systems, where different processes of domain nucleation, domain-wall propagation, and magnetization reversal of small grains were involved simultaneously.<sup>6,4</sup> Usually, the processes can be described by using models involving energy barriers that the system has to cross, by thermal activation, to reach more stable configuration states. However the distribution of the defects and/or of the size and shape of the domains and of the domain walls, makes the analysis very difficult. The ideal solution would be to study the behavior of individual entities such as a single magnetic domain or a single domain wall (DW). This goal has been recently reached with the measurement by micro-SQUID of the magnetization of individual ferromagnetic single domain nanoparticles. The micro-SQUID technique has been described and used by Wernsdorfer *et al.*<sup>5,7</sup> They have shown<sup>7</sup> that the magnetization reversal of a single-domain Co particle could be described by the crossing of a single energy barrier as originally proposed by Néel<sup>1</sup> and Brown.<sup>8</sup>

The study of the interaction between a single domain wall and a well-defined potential barrier is probably more complex. The problem has been investigated theoretically by

Gunther and Barbara<sup>9</sup> who have proposed an attractive system named domain-wall junction (DWJ). This device, sketched in Fig. 1, is made of three ferromagnetic regions: a first one, where a DW is created, a second one that acts as a pinning region for the nucleated DW, and the last one that is dedicated to the collection of the DW after the crossing of the pinning region. However, one of the biggest experimental difficulties of this device is the achievement of the nucleation of only a single DW in the first region. It could be reached by a reduction of the lateral size of the sample to a length of the order of magnitude of the radius of a single domain particle. This range of size (several thousand angstroms) is commonly obtained by lithography techniques, but

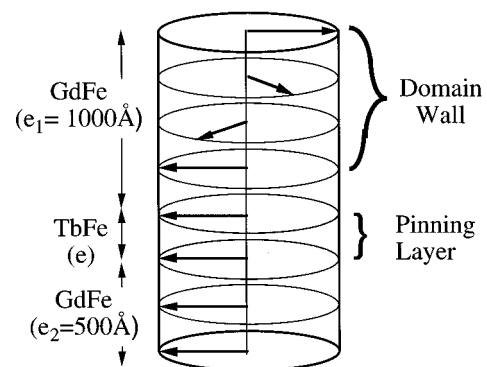


FIG. 1. Schematic figure of a domain-wall junction made of a hard magnetic material (TbFe) between two soft magnetic materials (GdFe). The TbFe layer acts as a pinning layer for a domain wall created in the thicker GdFe layer.

it is very likely that the lateral reduction induces dipolar fields and creates conditions that will modify the shape of the domain wall. A compromise is to study the behavior of an assembly of identical and quasi-independent DW's, nucleated in a planar thin film, propagating perpendicularly to the film and interacting with an extended artificial plane defect that acts as a barrier.

In fact, we have elaborated a device that behaves to a first approximation as such an assembly of domain-wall junctions. This system is an amorphous trilayer GdFe( $e_1$ )/TbFe( $e$ )/GdFe( $e_2$ ), where GdFe is a soft ferrimagnetic material and TbFe is a hard sperimagnetic layer (Fig. 1). In this system,  $e_1$  is larger than  $e_2$  with typically  $e_1 = 1000 \text{ \AA}$  and  $e_2 = 500 \text{ \AA}$ . The thickness  $e$  of the TbFe layer ranges between 2 and 20  $\text{\AA}$ , depending on the sample. In previous papers<sup>10,11</sup> we have demonstrated from quasi-static magnetization measurements and from resistivity measurements that the nucleation of domain walls occurs at first in the thicker GdFe( $e_1$ ) soft ferrimagnetic layer. Then, we have shown that, under the influence of the magnetic field and of the temperature, they can propagate to the thinner GdFe( $e_1$ ) soft ferrimagnetic layer through the TbFe hard magnetic layer.

In this paper, we present a dynamic study of the propagation of  $180^\circ$  domain walls in such a system. We show to what extent the propagation of the DW through the TbFe layer can be considered as the crossing of an energy barrier characterized by a single activation energy. We highlight the influence of thermal activation and determine the variation of the height of the energy barrier as a function of the external magnetic field and of the thickness of the TbFe layer. Finally, we confirm the analysis by comparing simulated quasi-static  $M(H)$  curves to the experimental data.

### THE SYSTEM GdFe/TbFe/GdFe

The GdFe( $e_1$ )/TbFe( $e$ )/GdFe( $e_2$ ) trilayers were obtained by evaporation and deposition on glass substrates first covered by 100- $\text{\AA}$  silicon layers. The substrates were kept at the liquid-nitrogen temperature during the deposition process and the samples were finally covered by 200- $\text{\AA}$ -thick silicon layers.

The Gd<sub>62</sub>Fe<sub>38</sub>( $e_1$ )/Tb<sub>55</sub>Fe<sub>45</sub>( $e$ )/Gd<sub>62</sub>Fe<sub>38</sub>( $e_2$ ) system has been chosen in order to satisfy the criteria described below.

(i) The layers have to be ferromagnetic or ferrimagnetic. These rare-earth alloys are ferrimagnetic. The compositions have been chosen in such a way that the magnetization of the rare earth be dominant and that the Curie temperatures of the alloys be close to room temperature.

(ii) An uniaxial anisotropy axis has to be present in the GdFe layers plane in order to allow the nucleation and the propagation of  $180^\circ$  domain walls along the direction perpendicular to the plane of the film. This condition has been fulfilled with the oblique evaporation from the Gd and Fe sources placed symmetrically about the substrate. As shown in Ref. 12, this leads to the occurrence of the in-plane uniaxial anisotropy axis.

(iii) The central layer (TbFe) has to act as a pinning plane for the DW created in the soft magnetic layer (GdFe). The very large anisotropy difference between the two alloys (several orders of magnitude) is due to the  $4f$  cloud of the rare

earth, which is isotropic in gadolinium and strongly anisotropic in terbium. Since the domain-wall energy in zero field is given by  $\sigma = 4\sqrt{AK}$ , where  $A$  is the exchange constant and  $K$  the anisotropy constant, the energy of a domain wall is lower in a soft magnetic material than in a hard magnetic material. The TbFe layer will then pin the domain walls because of its high anisotropy.

(iv) A good structural continuity is desirable in the trilayers so no parasitic structural defects would pin the DW at the interface between the layers. By using amorphous materials and quasi-isomorphous alloys, we expect to minimize this problem and to reach a good homogeneity, at least at the DW scale (some hundreds of angstroms).

(v) The domain walls have to be created in one of the GdFe layers, interact with the TbFe layer, and cross this hard magnetic layer, without any domain-wall nucleation from the outer surface of the second GdFe layer. This is actually achieved with unsymmetrical samples in which the two GdFe layers have unequal thicknesses: typically 1000 and 500  $\text{\AA}$ . Indeed, we have shown<sup>11</sup> that the nucleation field  $H_n$  at which a DW is nucleated from the outer surface of a GdFe layer deposited on a TbFe layer, depends strongly on the thickness of the GdFe layer. We have shown that  $H_n$  increases rapidly when the GdFe layer thickness decreases. The nucleation field (of a DW from the GdFe outer surface) is  $H_{n1} = 18 \text{ Oe}$  in the GdFe(1000  $\text{\AA}$ )/TbFe system, and is  $H_{n2} = 60 \text{ Oe}$  in the GdFe(500  $\text{\AA}$ )/TbFe system. The crossing of the TbFe layer by the domain wall nucleated in the GdFe(1000  $\text{\AA}$ ) layer can actually then be studied for fields between  $H_{n1}$  and  $H_{n2}$ .

### QUASISTATIC BEHAVIOR OF THE SYSTEM

The quasistatic  $M(H)$  behavior of the system has been presented in previous papers.<sup>10,11</sup> As explained above, it was demonstrated that there is no nucleation from the outer surface of the (500  $\text{\AA}$ ) GdFe layer below  $H_{n2} \approx 60 \text{ Oe}$  and that the propagation through the TbFe layer could be studied when the propagation field  $H_p$  was comprised between  $H_{n1} \approx 18 \text{ Oe}$  and  $H_{n2} \approx 60 \text{ Oe}$ . The variation of the propagation field  $H_p(e, T)$  measured as a function of the temperature for different thickness of the TbFe layer is shown in Fig. 2. We observe that for a given temperature  $T$ ,  $H_p$  increases with the thickness of the TbFe layer  $e$ , which means that the height of the energy barrier increases with the thickness of the TbFe layer. On the other hand, for a given thickness  $e$ ,  $H_p$  decreases when the temperature increases. This undoubtedly shows that the process is thermally activated.

Now, we focus on three different magnetization versus field [ $M(H)$ ] loops obtained from the GdFe(1000  $\text{\AA}$ )/TbFe(4.5  $\text{\AA}$ )/GdFe(500  $\text{\AA}$ ) sample at 15 K (Fig. 3). The magnetic field was applied along the easy anisotropy axis. Before the data for each loop were collected, the magnetization was saturated (Fig. 3, point A) by cooling the sample under a large positive magnetic field (1000 Oe). To ease the description of the magnetic loops, we defined two states for domain walls: state 1 [Fig. 4(a)], where the domain wall is stopped by the TbFe layer and compressed against it; state 2 [Fig. 4(b)], where the domain wall has crossed the barrier and has propagated in the 500  $\text{\AA}$  GdFe.

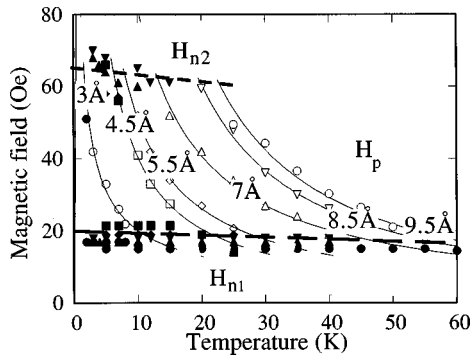


FIG. 2. Variation of the propagation field  $H_p$  as a function of temperature for a selection of GdFe(1000 Å)/TbFe( $e$ )/GdFe(500 Å) samples. The values indicated on each curve correspond to the thickness  $e$  of the TbFe layers.

(a)  $M(H)$  loop collected from GdFe(1000 Å)/TbFe(4.5 Å)/GdFe(500 Å) at 15 K in a magnetic field sweeping from +1000 Oe to -1000 Oe then from -1000 Oe to 1000 Oe

From A to B (Fig. 3), the system is kept saturated along the cooling field direction. At the field  $H_{n1}$  close to 18 Oe, a first step occurs. It is interpreted as the nucleation of the domain walls in the (1000 Å) GdFe layer. At C, the DW's are stopped by the TbFe layer and from C to D they are compressed against the TbFe layer.

Then at the field  $H_p(e, T)$  the magnetization of TbFe switches. The DW's propagate in the (500 Å) GdFe layer. At E the magnetization is completely reversed and is saturated along the field direction (opposite to the cooling field).

From  $H = -1000$  Oe to  $H = +1000$  Oe, the magnetization versus field curve is symmetrical to the first part described above. F, G, H, and I are points equivalent to B, C, D, and E, respectively.

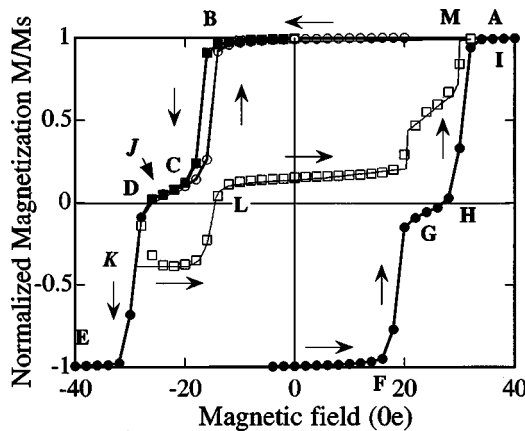


FIG. 3. Three hysteresis loops collected from GdFe(1000 Å)/TbFe(5 Å)/GdFe(500 Å) at 15 K. Loop a: (●) for magnetic field sweeping from +1000 Oe to -1000 Oe and then from -1000 Oe to +1000 Oe. Loop b: (■) for magnetic field sweeping from +1000 Oe to -24 Oe and then from -24 Oe to +1000 Oe. J (H, M) is the point at which the variation of the field is reversed. Loop c: (□) for magnetic field sweeping from +1000 Oe to -28 Oe and then from -28 Oe to +1000 Oe. K (H, M) is the point at which the variation of the field is reversed.

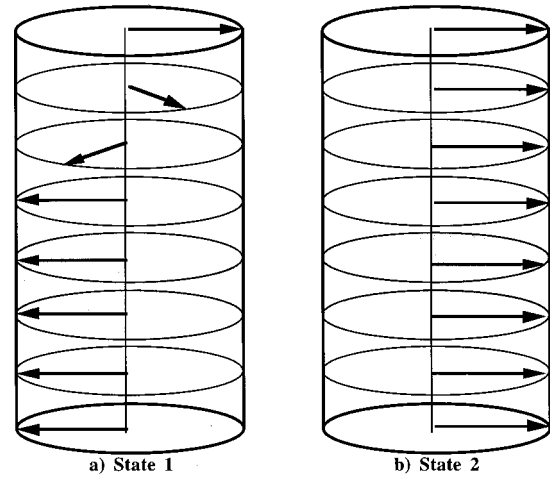


FIG. 4. Schematic figure of the two magnetic states of a domain-wall junction: State 1 (a): the DW is pinned by the TbFe layer and is compressed against the hard magnetic layer; State 2 (b): the DW has crossed the barrier, and the DWJ is saturated.

(b)  $M(H)$  minor loop measured on GdFe(1000 Å)/TbFe(4.5 Å)/GdFe(500 Å) at 15 K in a field sweeping from +1000 Oe to -24 Oe then from -24 Oe to 1000 Oe

From minor cycle (b), an interesting behavior is observed. This minor cycle was obtained by reversing the field from  $H = -24$  Oe at a point J located between the nucleation of the DW's (point C) and their propagation (point D). We observe that the magnetization is at first almost reversible, which corresponds to the decompression of the domain walls. Then, even before the zero field, the magnetization drops back to the initial saturated state. This means that no irreversible crossing of the energy barrier has occurred. The DWJ's have nucleated, been compressed, decompressed, and finally annihilated.

(c)  $M(H)$  minor loop measured on GdFe(1000 Å)/TbFe(4.5 Å)/GdFe(500 Å) at 15 K in a field sweeping from +1000 Oe to -28 Oe then from -28 Oe to 1000 Oe

The minor loop (c) is obtained when the field is decreased and reversed from  $H = -28$  Oe (point K) in the magnetization drop attributed to the propagation of the domain walls (located somewhere between D and E). The minor loop (c) can actually be described as the weighted superposition of two components: the full hysteresis loop (a) and the minor hysteresis loop (b), which means that some of the domain walls have crossed the barrier (state 2), whereas the rest of them are still compressed against the TbFe barrier (state 1). From K to L we observe the decompression and the annihilation of the domain walls that have not crossed the barrier [as for loop (a)]. From L to M we observe the new nucleation, compression, and propagation of the domain walls that have crossed the barrier between D and K. Note that the fields at which the DW nucleate, propagate, or are annihilated are the same for loop (c) as for loops (a) and (b).

## RELAXATION MEASUREMENTS

To obtain more information on the energy barrier due to the TbFe layer and on the propagation process of the domain

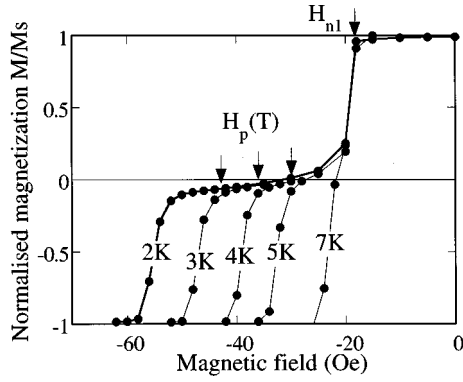


FIG. 5. Hysteresis loops collected from a GdFe(1000 Å)/TbFe(3 Å)/GdFe(500 Å) sample at different temperatures.  $H_{n1}$  is the nucleation field for the GdFe(1000 Å) layer.  $H_p$  is the propagation field (passage of the DW through the TbFe layer).

wall through this barrier, we have performed a set of magnetic relaxation measurements. As the height and the shape of the barrier are expected to be a function of the magnetic field, the relaxation measurements were performed at different temperatures  $T$  on samples submitted to several magnetic fields  $H$ . The experimental procedure was the following: (i) At first, the sample was cooled to the measurement temperature, under a 1000-Oe field applied along the easy magnetization axis. (ii) Then the system was brought from the initial saturation (point A of Fig. 3) to the measurement field  $H$ . The measurement field was smaller than the quasistatic propagation field  $H_p(e, T)$  that corresponds to points located between D and E of Fig. 3. (iii) Finally at the measurement temperature  $T$  and under the external field  $H$ , the magnetization  $M(t) = M(e, T, H, t)$  was followed as a function of time.

Very similar behaviors have been observed for all samples in which the TbFe thickness ranges from 3 to 10 Å. So, as an example, we describe in the following the time dependence of the magnetization of GdFe(1000 Å)/TbFe(3 Å)/GdFe(500 Å). The quasistatic propagation fields  $H_p$  of this sample are shown in Fig. 5. They are about 47 Oe at 3 K, 40 Oe at 4 K, and 35 Oe at 5 K. The relaxation measurements were performed under magnetic fields included in a range of about 10 Oe around the quasistatic propagation fields.

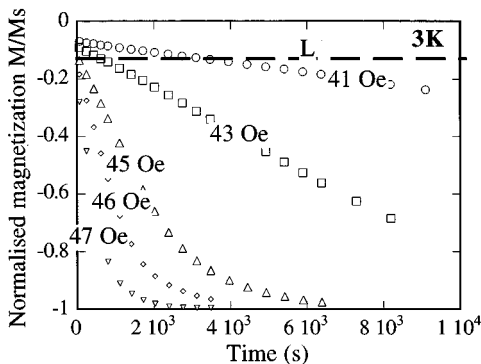


FIG. 6. Evolution of the normalized magnetization ( $M/M_s$ ) as a function of time at 3 K for a GdFe(1000 Å)/TbFe(3 Å)/GdFe(500 Å) sample under different magnetic fields. The horizontal line  $L$  shows the initial magnetization  $M_i$ .

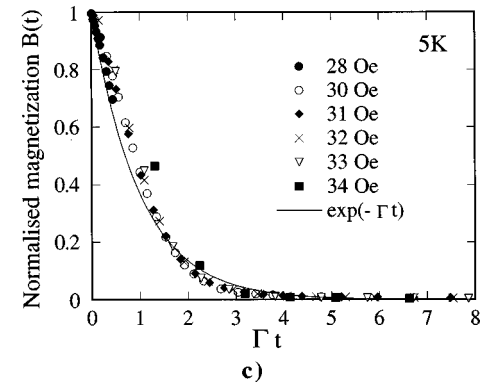
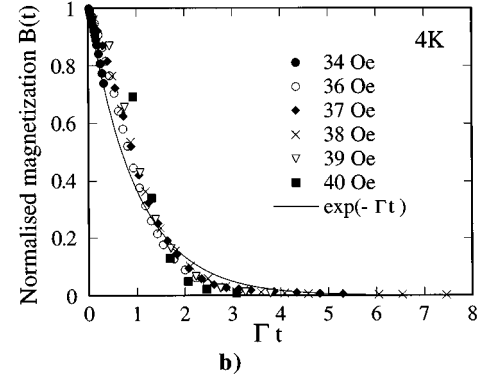
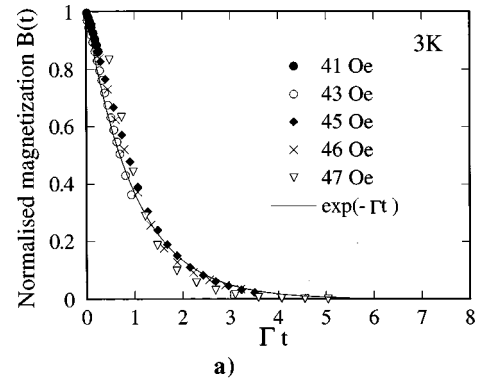


FIG. 7. Variation of the reduced magnetization  $B$  as a function of  $\Gamma t$  collected from a GdFe(1000 Å)/TbFe(3 Å)/GdFe(500 Å) sample under different magnetic fields (a) at 3 K, (b) at 4 K, (c) at 5 K. The  $\Gamma$  values are reported in Table I.

As shown in Fig. 6 for  $T = 3$  K,  $M(t)$  decreases with time, from the magnetization value obtained during quasistatic measurements at the given field towards the final magnetization  $-M_s$  corresponding to the reversal of the whole sample magnetization. The decreasing is rapid when the field is close to the propagation field and, as a matter of fact, it becomes slower and slower when the measurement field is shifted towards lower fields.

We then define the normalized quantity  $B(t)$ :

$$B(t) = \frac{M(t) + M_s}{M_i + M_s}, \quad (1)$$

where  $M_s$  is the magnetization of the saturated sample ( $-M_s$  is the magnetization in the final state) and  $M_i$  is the initial magnetization.  $M_i$  has been chosen as the magnetization of the sample when the domain walls are compressed

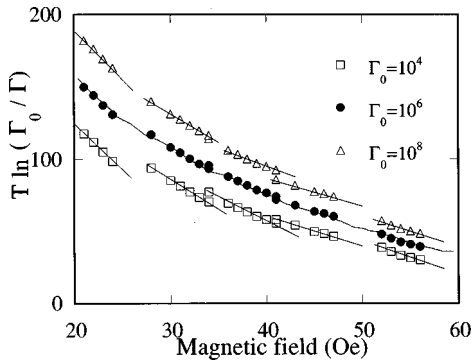


FIG. 8. Variation of  $T \ln(\Gamma_0/\Gamma)$  of a GdFe(1000 Å)/TbFe(3 Å)/GdFe(500 Å) sample, as a function of the magnetic field  $H$  for different  $\Gamma_0$  values.

against the TbFe layer. It is the value of the magnetization that just precedes the drop at  $H_p$ . The value of  $M_i$  is shown in Fig. 6 by the line  $L$ . For example  $M_i/M_s = 0.9$  in the GdFe(1000 Å)/TbFe(3 Å)/GdFe(500 Å) sample at 3 K. Note that in Eq. (1) we define  $t=0$  as being the time for which  $M(t=0) = M_i$ .  $B(t)$  turns out to correspond to the fraction of the sample in which the domain walls have not yet crossed the TbFe barrier.

The important qualitative point is that for a given field, with a corresponding barrier height  $\Delta E(e, H)$ ,<sup>13</sup> there is only one temperature for which  $B(t)$  varies from 1 to 0 within some hours. For example, if we consider the field  $H = 37$  Oe, we observe that  $B(t)$  varies from 1 to 0 at  $T = 4$  K, but that, for the same field, it remains equal to 1 at temperature  $T = 3$  K and drops immediately to 0 at  $T = 5$  K. Actually the effect is so sharp that the  $H = 37$  Oe curve cannot be placed in Figs. 4(a) and 4(c). Even if the 1 K step is relatively large in this temperature range, it is clear that such a behavior is consistent with a sharp distribution of the height of the energy barrier.

As shown in Figs. 7(a), 7(b), and 7(c), the plots of  $B(t)$  can be fitted by an exponential law  $\exp(-\Gamma t)$ , at  $T = 3$  K as well as at 4 and 5 K, which is quite consistent with the above remark. The  $\Gamma$  values are reported in Table I.

Such an exponential law is typical of the crossing of a potential barrier by an assembly of quasi-identical and independent objects.<sup>14</sup> It is typical of two states systems in which the objects would have a probability  $P(t)$  to cross the barrier and switch from state (1) to state (2),

TABLE I. Values of the passage frequency  $\Gamma$  for different temperature  $T$  and different applied magnetic field  $H$ .

	$T = 3$ K				
$H$ (Oe)	47	46	45	43	41
$\Gamma$ ( $10^{-4} \text{ s}^{-1}$ )	18.8	9.52	5.92	1.45	0.385
	$T = 4$ K				
$H$ (Oe)	40	39	38	37	36
$\Gamma$ ( $10^{-4} \text{ s}^{-1}$ )	50	28.6	13.3	6.25	2.86
	$T = 5$ K				
$H$ (Oe)	34	33	32	31	30
$\Gamma$ ( $10^{-4} \text{ s}^{-1}$ )	77	40	19	8.5	4.03

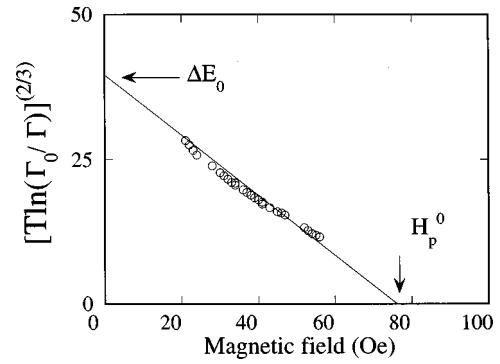


FIG. 9. Variation of  $[T \ln(\Gamma_0/\Gamma)]^{2/3}$  as a function of the magnetic field  $H$  obtained from a GdFe(1000 Å)/TbFe(3 Å)/GdFe(500 Å) sample for  $\Gamma_0 = 10^6 \text{ s}^{-1}$ .

$$P(t) = \exp(-\Gamma t), \quad (2)$$

where  $\Gamma$  is the passage frequency.

#### MODEL AND ANALYSIS OF THE RELAXATION DATA

In our system, the potential barrier is undoubtedly due to the TbFe layer and the objects could be an assembly of parallel and similar DWJ's that behave quasi-independently, which is the model that we develop below. Locally, the crossing of barrier by a domain wall can be considered as a transition between two states: *state 1* [Fig. 4(a)], the DW is pinned by the TbFe layer and is compressed against the hard magnetic layer; *state 2* [Fig. 4(b)], the DW has crossed the barrier, and the concerned DWJ is saturated.

$B$  is then equal to 1 when all DWJ's are in state 1 and  $B=0$  when the magnetization is reversed in each domain-wall junction and has reached  $-M_s$ .  $B(t)$  turns out to be the fraction of domain-wall junction that have *not* crossed the barrier at time  $t$ .

With this hypothesis,  $\tau$  is the relaxation time and  $\Gamma = 1/\tau$  is the passage frequency of the domain wall through the TbFe potential barrier. In the case of classical thermal activation,  $\Gamma$  follows an Arrhenius law:

$$\Gamma = \Gamma_0 [\exp(-\Delta E/kT)], \quad (3)$$

where  $\Gamma_0$  is the attempt frequency and  $\Delta E$  the height of the energy barrier that separates the two states. Following the

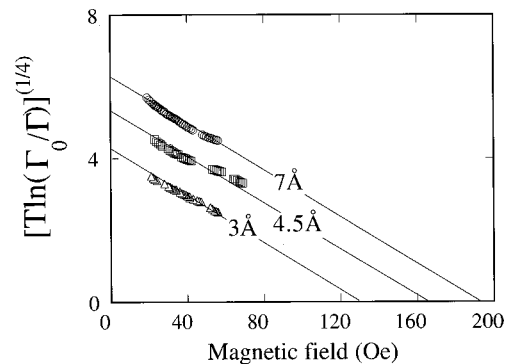


FIG. 10. Variation of  $[T \ln(\Gamma_0/\Gamma)]^{1/4}$  as a function of the magnetic field  $H$  collected from GdFe(1000 Å)/TbFe(3 Å)/GdFe(500 Å), GdFe(1000 Å)/TbFe(4.5 Å)/GdFe(500 Å) and GdFe(1000 Å)/TbFe(7 Å)/GdFe(500 Å) samples.

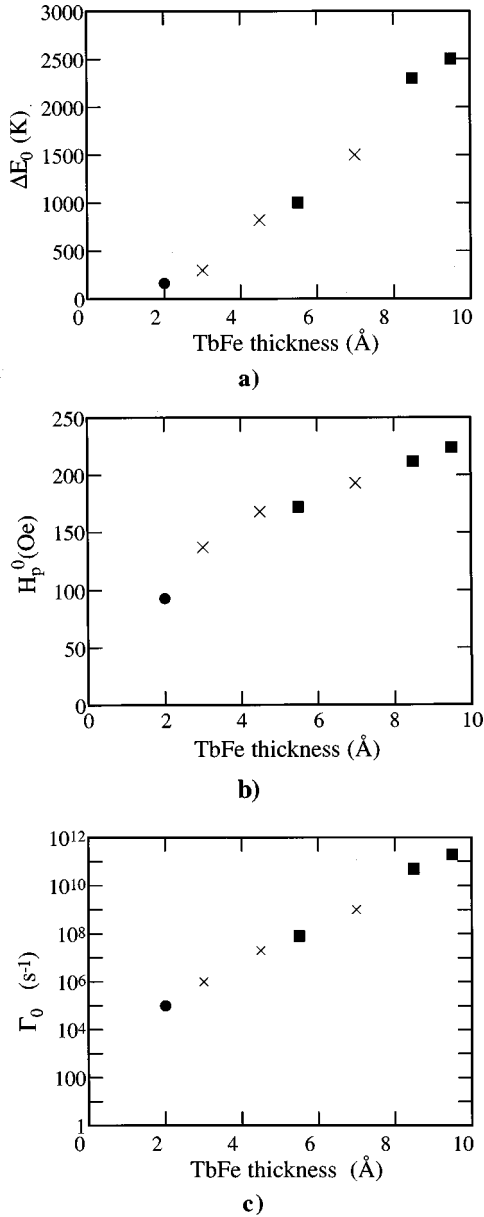


FIG. 11. (a)  $\Delta E_0$ , (b)  $H_p^0$ , and (c)  $\Gamma_0$  as a function of the TbFe nominal thickness  $e$  for GdFe(1000 Å)/TbFe( $e$ )/GdFe(500 Å) samples. The crosses (×) are obtained from relaxation measurements; the full squares (■) from quasistatic's magnetization measurements; and the full circles (●) from micro-SQUID measurements.

analysis of Gunther and Barbara<sup>9</sup> concerning isolated DWJ, we consider that the height  $\Delta E$  of the barrier follows the law

$$\Delta E(H) = \Delta E_0 \left[ 1 - \frac{H}{H_p^0} \right]^\alpha, \quad (4)$$

where  $\alpha$  is an exponent that the authors estimated to be equal to  $\frac{3}{2}$  (Ref. 9) and  $H_p^0$  is the critical field at which the barrier vanishes.  $\Delta E_0$  is the height of the energy barrier in zero field.

Three parameters that depend only on the TbFe thickness (in this model) have to be determined:  $\Gamma_0$ ,  $\Delta E_0$ , and  $H_p^0$ . To determine these parameters, we have used a method that we will refer to as a ‘‘continuity criteria.’’ According to this

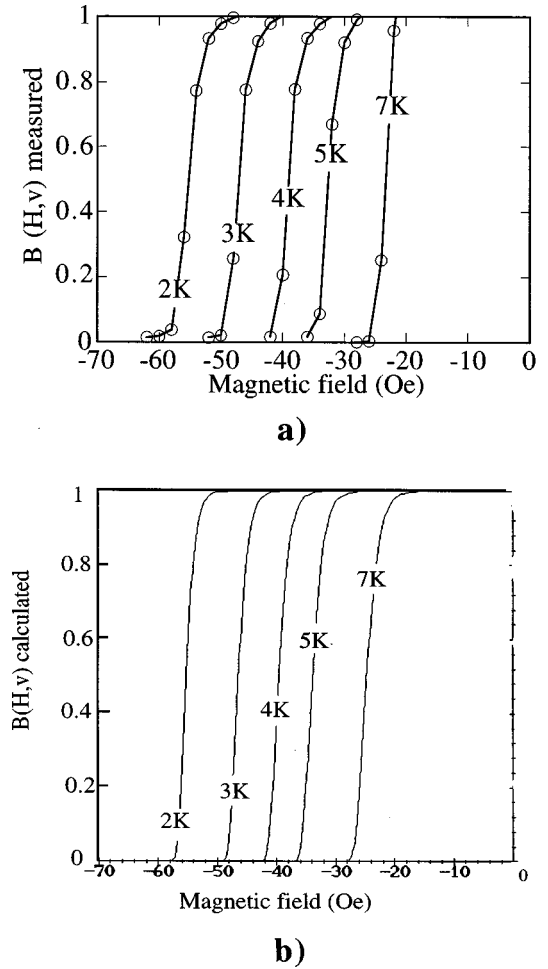


FIG. 12. Variation of the reduced magnetization  $B$  as a function of the magnetic field  $H$ . (a) obtained from quasistatic measurements on sample GdFe(1000 Å)/TbFe( $e$ )/GdFe(500 Å) and (b) by using expression (5) and the parameters obtained from the relaxation measurements on the same sample.

criterion, the actual value of  $\Gamma_0$  is that for which the height of the barrier  $\Delta E(H)$  plotted against the field makes a continuous line. As  $\Delta E(H)$  is equal to  $T \ln(\Gamma_0/\Gamma)$ , we have plotted  $T \ln(\Gamma_0/\Gamma)$  versus  $H$  for different  $\Gamma_0$  values. As shown in Fig. 8, for the GdFe(1000 Å)/TbFe(3 Å)/GdFe(500 Å) sample, each temperature provides pieces of the curve whose slopes and levels depend on  $\Gamma_0$ . The correct  $\Gamma_0$  is that for which the pieces of the curve make a continuous line, which is achieved here for  $\Gamma_0$  close to  $10^6$  s<sup>-1</sup>. Indeed, it appears that smaller or larger attempt frequencies lead to discontinuous sets of pieces of curve, which would be inconsistent with a continuous relation between the external field and the height of the barrier.

Then the plot of  $T \ln(\Gamma_0/\Gamma)^{3/2}$  versus  $H$  (Fig. 9), which is a straight line if Eq. (4) is correct, allows us to determine  $H_p^0$  and then  $\Delta E_0$  by extrapolation of the curve to the axis. The estimated values are  $H_p^0 = 76$  Oe and  $\Delta E_0 = 240$  K.

Similar relaxation measurements have been performed on several other samples as GdFe(1000 Å)/TbFe(4.5 Å)/GdFe(500 Å) and GdFe(1000 Å)/TbFe(7 Å)/GdFe(500 Å). The behavior of these are very close and show that  $B(t)$  can again be described by a unique relaxation time. The application of the continuity criteria to these samples

shows that the suitable  $\Gamma_0$  values are  $\Gamma_0 = 10^7 \text{ s}^{-1}$  for  $e = 4.5 \text{ \AA}$  and  $\Gamma_0 = 10^9 \text{ s}^{-1}$  for  $e = 7 \text{ \AA}$ . However, they show that the exponent  $\alpha$  has to be larger than  $\frac{3}{2}$ . Indeed  $T \ln(\Gamma_0/T)^\alpha$  versus  $H$  can reasonably be considered as a straight line for all samples, if  $\alpha$  is close to 4, as shown in Fig. 10. We can note that this value is rather high since it has been shown that in the case of uniform rotation of the magnetization,  $\alpha$  could not exceed 2. The parameters  $\Delta E_0$ ,  $H_p^0$ , and  $\Gamma_0$  deduced from this fit are shown in Figs. 11(a)–11(c) and are marked with a cross ( $\times$ ).

### QUASISTATIC BEHAVIOR

We used the same model and especially the same field dependence for  $\Delta E$  to fit the data collected in quasistatic measurements such as those reported in Fig. 5. Indeed, these measurements can be considered as dynamical, with a magnetic field that varies linearly with time, at a rate of 0.5 Oe per min. Following the Kurkijärvi analysis,<sup>15</sup> the passage rate of a magnetic entity through an energy barrier  $\Delta E(H)$  that depends only on the field can be expressed as a function of the rate  $v$  at which the external magnetic field is increased as

$$B(H, v) = \exp \left[ \frac{1}{(\tau_0 v)} \int_0^H \exp \left( \frac{-\Delta E_0 \left( 1 - \frac{H'}{H_p^0} \right)^\alpha}{kT} \right) dH' \right]. \quad (5)$$

In our model,  $B(H, v)$  would be the ratio of domain walls that have not yet crossed the barrier when the field  $H$  is reached.

Then, according to the Kurkijärvi analysis and assuming that  $\Delta E$  depends on the magnetic field through the relation (4), the propagation field  $H_p$  is given by

$$H_p(T) = H_p^0 \left[ 1 - \left[ \frac{kT}{\Delta E_0} \ln \left( \frac{H_p^0}{v \tau_0} \frac{kT}{\Delta E_0} \frac{1}{\alpha \varepsilon^{\alpha-1}} \right) \right]^{1/\alpha} \right]. \quad (6)$$

The comparison of the experimental  $B(H, v)$  data with the values calculated from the above relations, using the parameters deduced from the relaxation measurements, is shown in Figs. 12(a) and 12(b) for the GdFe(1000 Å)/

TbFe(3 Å)/GdFe(500 Å) sample. The experimental and calculated values are very close and, in the same way as the relaxation measurements, the quasistatic magnetization can actually be used to determine the relaxation time  $\tau$  and its thermal dependence.

The  $\Delta E_0$ ,  $H_p^0$ , and  $\Gamma_0$  values determined by the fitting of the quasistatic magnetization data are reported in Fig. 11 and marked with a full square. Finally the values reported for the GdFe(1000 Å)/TbFe(2 Å)/GdFe(500 Å) sample were collected from micro-SQUID measurements and are marked with a full circle.

We can note that those three parameters are increasing when the thickness of TbFe is increased. The increases of  $\Delta E_0$  (the height of the energy barrier when no field is applied) and  $H_p^0$  (the critical field for which the energy barrier vanishes) were expected. However, the large increase of the attempt frequency  $\Gamma_0$  has still to be understood.

### CONCLUSION

In conclusion, we elaborated a system that exhibits a quasistatic relaxation time, which in magnetism is extremely rare. Such behavior is probably due to the occurrence of an assembly of very few distributed domain walls in a well-defined model system. From the relaxation behavior, and using a simple one-dimensional thermal-activated model, we have deduced very important parameters, such as the field dependence of the height of the barrier due to a very thin layer of extremely hard material. We report the efficiency of the potential barrier created by TbFe layers with a nominal thickness of only 2 or 3 Å that is quite remarkable. The system is also a very demonstrative example of the potentialities of the concept of domain-wall junction.

However, from this study, a lot of questions remain open. To give an answer, we are now experimenting with magnetic force microscopy and transmission electron microscopy techniques to visualize the configuration of the magnetization in our sample as a function of the applied field. Also we still have to look for an explanation for the large increase of the attempt frequency  $\Gamma_0$  with increasing TbFe thickness and the large value of the exponent  $\alpha$ .

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