Domain Wall Creep in an Ising Ultrathin Magnetic Film

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We have studied the motion of a magnetic domain wall (MDW) driven by a magnetic field H in a 2D ultrathin Pt/Co/Pt film showing perpendicular anisotropy and quenched disorder. MDW velocity measurements down to the so called creep regime show that the average energy barrier scales as $(1/H)^{\mu}$ with $\mu = 0.24 \pm 0.04$ and that the correlation function along a MDW is governed by a wandering exponent $\zeta = 0.69 \pm 0.07$, in very good agreement with theories giving $\mu = 0.25$ and $\zeta = 2/3$. This is the first direct measurement of the creep regime for a moving interface in a disordered medium. [S0031-9007(97)05075-8]

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The statics and dynamics of lines or surfaces (manifolds) in random media is an extremely challenging and active field involving many areas of physics. It is relevant for describing vortex systems [1], fluid invasion of porous media [2,3], growth phenomena [4,5], charge density waves [6], and magnetic domain wall (MDW) motion [7]. In all cases, the crucial factors are the competition between an elastic energy (tending to keep the lines straight) and the disorder. Such a competition leads to glasslike properties having important consequences for both the static configuration of the lines and their dynamics. Each of these aspects has been the subject of intense theoretical study [1,5,7–13].

The dynamics offers a variety of theoretical challenges. At $T = 0$ K, the interface is pinned until a critical force f_c is reached. The structure of the interface at f_c and the shape of the velocity-force characteristics are important features to determine, with directly observable consequences (such as the MDW velocity-field and voltage-current characteristics for magnetic systems and vortices in superconductors). The effect of finite velocity v on the physical characteristics of the interface is also of crucial importance. At finite temperature, the interface can move even for forces f below the threshold f_c. Then, existing theories, mostly in the framework of vortices, assumed that the motion occurs between pinned states separated by finite barriers [14]. However, as realized more recently, because of the glassy nature of the pinned interfaces, barriers between pinned states diverged as the applied force is reduced [1,12]. This lead to the proposal of a phenomenological theory of creep having nonlinear v-f characteristics of the form $v \propto \exp(-\beta U_c (f_c/f)^{\mu})$ where $1/\beta = kT$, U_c being a scaling energy constant and μ an exponent related to the static exponents.

Unfortunately, this collective creep theory remains phenomenological and can be checked only in simplified cases, since most of the powerful methods to treat the dynamics of lines or surfaces are limited to forces above the threshold. Additionally, the large range of velocities needed to test such a theory makes it difficult to confirm unambiguously experimentally and in particular to check for the connection between the dynamic exponent μ and static exponents, despite the great effort which has been expended in connection with vortex physics [15].

In this paper, we investigate the motion of an isolated domain wall in a two dimensional (2D) ultrathin Pt/Co/Pt magnetic film with perpendicular anisotropy, using the magneto-optical polar Kerr imaging technique. Very generally, an interface is characterized by its dimension d ($d = 1$ for a line or 2 for a surface) and can move in n transverse directions. Since in our system there is no change of the magnetization with thickness (we have only 0.5 nm of Co), the MDW is described by $d = 1$ and $n = 1$ (compared to $d = 1$ and $n = 2$ for vortices). Such a system is particularly interesting because it allows a measurement of the static exponent characterizing the correlations along a MDW; good agreement with the theory is obtained. Furthermore, since it is possible to measure the interface velocity over a wide range of the driving force (which is proportional to the applied magnetic field H in our case), clear experimental evidence of the creep regime at sufficiently low field values, as well as the relation linking dynamic and static exponents, was obtained. We show, for the first time, to our knowledge, a connection between MDW motion and creep theory.

We shall use a phenomenological approach, similar to that already developed for vortices in superconductors [1], to understand better the behavior of a single MDW or interface submitted to a magnetic field. As Ref. [1], let us consider a MDW segment of length L and denote by u the amplitude of the displacement of this segment. The total free energy is

$$F(u,L) = \varepsilon_{\mathrm{el}} \frac{u^2}{L} - (\Delta \xi^2 L)^{1/2} - M_S H t L u\,, \qquad (1)$$

where t is the magnetic layer thickness, $\Delta = f_{\mathrm{pin}}^2 n_i \xi$ scales the pinning strength of the disorder (n_i is the surface density of pinning centers, f_{pin} is the local pinning force and ξ the characteristic length of the disorder potential), and $\varepsilon_{\mathrm{el}}$ is the MDW energy density per unit length. In our case, walls are of the Bloch type and $\varepsilon_{\mathrm{el}} = 4(AK)^{1/2}t$, where A is the exchange stiffness and K the anisotropy constant. The second term is the pinning energy where the one half power reflects the fact that only fluctuations of pinning center density and/or of the amplitude of the pinning force will contribute to pin the wall [1,16]. The last term is the Zeeman energy and is equivalent to the Lorentz energy for a vortex in a superconductor.

It is appropriate to define a characteristic collective pinning length L_c (the Larkin-Ovchinikov length in vortices) defined by $E_{\mathrm{el}}(L_c, u = \xi) \approx E_{\mathrm{pin}}(L_c)$, the value of which is $L_c = ({\varepsilon_{\mathrm{el}}}^2 \xi^2/\Delta)^{1/3}$. At lengths $L > L_c$, the wall can adjust itself elastically to reach the optimal local configuration. It is important to note that from this point of view, the wall may be seen as a succession of segments of length L_c which can move independently from one another. A rough estimate of L_c can be obtained if one considers, for example, in our system, defects arising from steps bounding two atomically flat Co terraces of average extension ξ (ξ is the step to step spacing) and with thicknesses, respectively, t_1 and t_2. Then, to first order, local pinning force is $f_{\mathrm{pin}} = (t_2\gamma_2 - t_1\gamma_1)\xi/2\delta$, where $\gamma_i = 4(AK_i)^{1/2}$ is the Bloch wall energy density for a thickness t_i and $\delta = \langle (A/K_i)^{1/2} \rangle$ is the average wall thickness. For our sample, the Co surface roughness was estimated from AFM measurements to ± 0.2 nm and ξ was chosen equal to the average size $\xi = 10$ nm of atomically flat Co terraces. Additionally, we did anisotropy measurements on Pt/Co/Pt samples with different Co thicknesses grown in the same conditions as our 0.5 nm thick Co film. For small Co thicknesses ($0.5 \leq t < 0.8$ nm), the product Kt saturates at a value of 0.45 ergs/cm^2. Assuming $n = 1/\xi^2$, we then find $L_c \approx 25$ nm, which is far smaller than the typical resolution length of our magneto-optical imaging experiments (≈ 1 μm).

Another interesting quantity is the critical field [1,17] $H_{\mathrm{crit}} = (\varepsilon_{\mathrm{el}}\xi/M_S t)(1/{L_c}^2)$, which may be calculated equating the pinning to the Zeeman force for $L = L_c$. Strictly speaking, at $T = 0$ K, no wall movement is expected if $H < H_{\mathrm{crit}}$, which allows a direct experimental determination of H_{crit}. On the contrary, at finite temperature, thermal activation always induces some wall movement even below H_{crit}, making impossible a direct estimation of its value. Unfortunately, in ultrathin magnetic layers, the determination of H_{crit} through low temperature experiments is not sufficient to obtain H_{crit} at room temperature since it depends on temperature dependent anisotropy constants [18].

In the creep regime ($H \ll H_{\mathrm{crit}}$), scaling relations that link both the displacement u and energy barriers (without any driving force) to the size L of the interface, must be considered. For this purpose, much work has been performed on elastic strings (for an overview, see [19]). One basic quantity which characterizes the roughness of the string in this regime is the spatially and thermally averaged correlation function $\langle\langle [u(x+L) - u(x)]^2 \rangle\rangle$. For $n \leq 2$, at static equilibrium, i.e., without any driving force, disorder is relevant and the string is always in a pinned phase characterized by a wandering exponent $\zeta > 1/2$,

$$\langle\langle [u(x+L) - u(x)]^2 \rangle\rangle \propto u_c^2 \left(\frac{L}{L_c}\right)^{2\zeta}, \qquad L > L_c\,, \tag{2}$$

where u_c is a transverse scaling parameter. Besides, it has been proven that for $n = 1$ [9–11], $\zeta = 2/3$, whereas, for $n = 2$, only simulations are available [20,21] suggesting $\zeta = 3/5$. Assuming a scaling law for the displacements u, $u(L) \propto u_c(L/L_c)^{\zeta}$, the typical energy barrier E then scales as $E(L) \propto U_c(L/L_c)^{2\zeta-1}$. Thus, in the quasistatic approximation, the free energy becomes

$$F(u,L) = U_c\left(\frac{L}{L_c}\right)^{2\zeta-1} - 2M_S H t L_c u_c \left(\frac{L}{L_c}\right)^{\zeta+1}. \tag{3}$$

Note that expression (3) formally reduces to a nucleation problem, as in bubble materials [22]. The first term tends to decrease the length of the interface, whereas the second one increases it. Minimization of expression (3) with respect to L leads to the smallest energy barrier and, assuming an Arrhenius law as in Ref. [1], the MDW velocity becomes

$$v(H) \propto \exp\left[-\beta U_c \left(\frac{H_{\mathrm{crit}}}{H}\right)^{\mu}\right], \qquad H \ll H_{\mathrm{crit}}\,, \tag{4}$$

with $\mu = (2\zeta - 1)/(2 - \zeta)$. For $n = 1$, as in our system, one expects $\zeta = 2/3$ and $\mu = 1/4$, whereas for $n = 2$ (a single vortex), $\zeta = 3/5$ and $\mu = 1/7$. For an arbitrary d value, one gets $\mu = (d + 2\zeta - 2)/(2 - \zeta)$ and, for $d = 2$ and $n = 1$ (a MDW in a thick magnetic film), where the mean field value of ζ is $(4-d)/(4+n) = 2/5$ (a more exact value is $\zeta = 4/9$), it gives $\mu = 1/2$. Expression (4) is known as the collective creep law [12]. Note that this expression rules out at low magnetic field the usual MDW velocity expression found in literature [23].

The sample studied is a high quality Si/Si_3N_4/Pt (6.5 nm)/Co (0.5 nm)/Pt (3.4 nm) ultrathin magnetic film structure with perpendicular anisotropy, sputtered in high vacuum at room temperature. In this sample, magnetization reversal is dominated by domain wall motion. This means that only very few nucleation centers are present, from which domains grow with a nearly circular shape. Thus, when the field of view of our microscope is far away from any nucleation center, MDW appear to be rather flat, which greatly simplifies data treatment.

The room temperature imaging technique uses magneto-optic polar reflection Kerr effect ($\lambda = 638.1$ nm). Our microscope uses a sensitive CCD camera and gives a 1 μm optical spatial resolution, the images being subsequently digitized and improved by image processing [24].

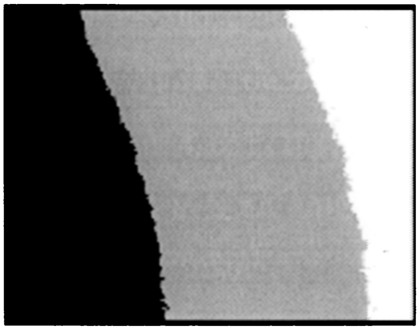

FIG. 1. Typical magneto-optical image (size $90 \times 72\ \mu\text{m}^2$, $\lambda = 638.1$ nm). The gray part corresponds to the surface swept by the domain wall during 111 μs at 460 Oe ($T = 23\ ^\circ\text{C}$). The dark part is the original domain.

To measure the average MDW velocity $v = L_{\text{avg}}/\tau$, one simply generates a pulse of field during a time τ and measures the average distance L_{avg}, swept by the domain wall. An electromagnet is used at low fields ($H < 120$ Oe) and long times τ ($10 < \tau \leq 6300$ s). For higher fields ($100 \leq H \leq 1893$ Oe) and shorter times, a set of small coils was used ($524\ \text{ns} \leq \tau \leq 2$ s). MDW velocities from 0.35 nm/s to 41.4 m/s were explored. Figure 1 shows a typical image obtained at a field $H = 460$ Oe, without processing other than thresholding. The errors of the average velocities measurements were estimated to be less than 5%. The curve v-H, displayed in Fig. 2(a), is also shown as a semilog plot in Fig. 2(b). As can be seen in Fig. 2(a), the critical field H_{crit} is not easy to determine. Following previous studies of Au/Co/Au sandwiches [25] and extrapolating the high field linear part of Fig. 2(a) to $v = 0$, we obtain $H_{\text{crit}} \approx 692$ Oe (in Ref. [25], H_{crit} was called the propagation field). Since MDW motion was observed down to $H = 38$ Oe, the condition $H \ll H_{\text{crit}}$ was fulfilled and the creep regime explored. This explains the strong decrease of the velocity [Fig. 2(b)] in the low field regime. This behavior could not be observed in Au/Co/Au since the MDW propagation was too slow to carry out experiments at $H < H_{\text{crit}}/2$. In order to check Eq. (4), a plot of $\ln(v)$ versus $(1/H)^{1/4}$ is shown in Fig. 3. The variation is effectively linear in the low field range [$H < 0.15$ kOe, i.e., $(1/H)^{1/4} > 1.6$]. A slight curvature is observed above, which suggests that the system leaves the creep regime. To verify $\mu = 0.25$, we plot $\ln(v)$ versus $(1/H)^{\mu}$ (still for $H < 150$ Oe) for several μ values in the range 0.05–1.00. Linear and polynomial fit studies then lead to $\mu = 0.24 \pm 0.04$. This rules out the possibility of a three dimensional exponent, $\mu = 1/7$ or $\mu = 1/2$, a further proof of the 2D behavior of our system. This is the first direct evidence of the creep regime for an interface moving in a disordered medium.

As was pointed out previously, the creep regime expression (4) comes directly from the scaling of the static correlation function (2). To test the validity of expression (2), 36 measurements of the correlation function were

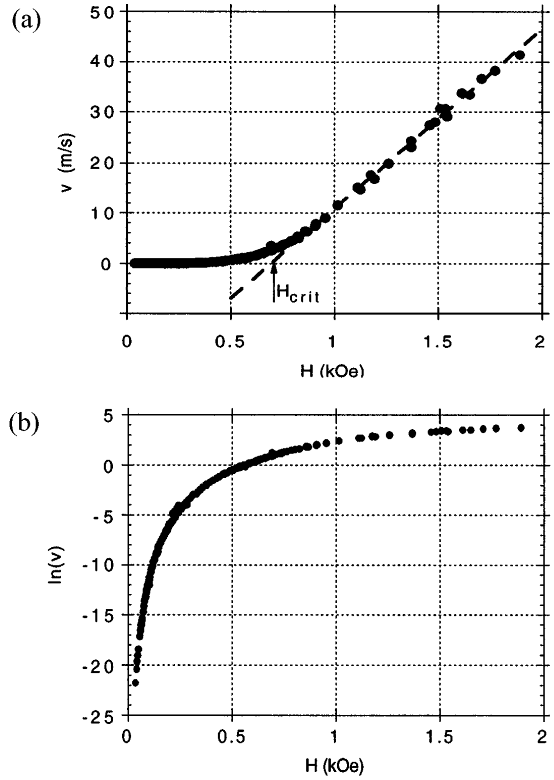

FIG. 2. (a),(b): MDW velocity versus applied magnetic field at room temperature (v in m/s). The dashed line in (a) is the linear fit of the high field part ($H > 0.86$ kOe) and the arrow marks its intersection with the line $v(H) = 0$. This is the definition of H_{crit}.

performed on 36 different MDW, on different parts of the sample at room temperature. For each measurement, the sample was saturated, a domain wall was created and driven for 20–45 min at $H = 50$ Oe (i.e., at a MDW velocity $v = 7$ nm/s). A sufficiently small field was applied so that the system was in the quasistatic regime. Then, just after switching off the field, the image of the MDW was stored and the wandering exponent ζ determined. A typical variation of the correlation function is displayed in

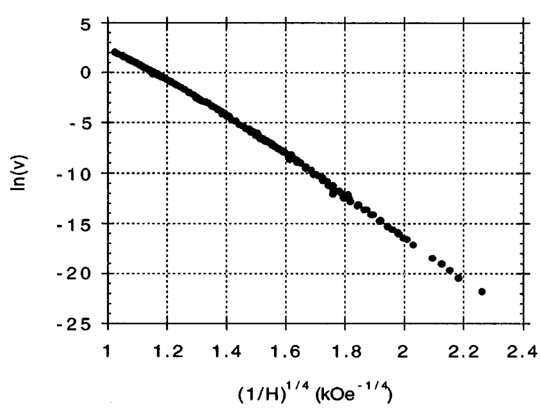

FIG. 3. Natural logarithm of MDW velocity as a function of $(1/H)^{1/4}$ (room temperature, $H \leq 955$ Oe).

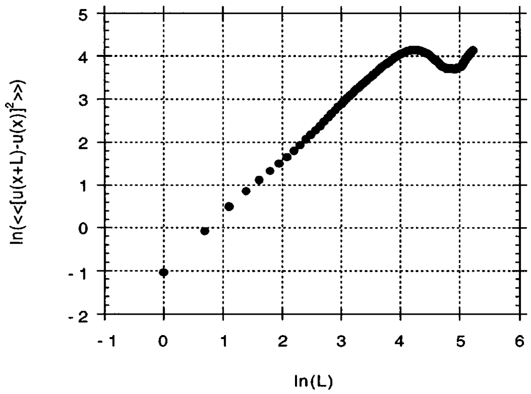

FIG. 4. Typical correlation function drawn in a ln-ln plot. The unit of L is the pixel of the CCD camera, i.e., 0.28 μm.

Fig. 4 (L is now expressed in pixels of the CCD camera). To get an exponent from a correlation function such as the one displayed in Fig. 4, we did a linear fit of the lower part of the curve, i.e., $\ln(L) < 4$. We did not consider the four first L values since they correspond to lengths smaller than our resolution length. The saturation at high L is due to the finite size of our MDW.

The deduced exponents are depicted in Fig. 5. One reason for their scatter is that the disorder may be not perfectly homogeneous over the sample. Nevertheless, the average value of ζ is found to be 0.69 ± 0.07 which is close to the theoretical value $\zeta = 2/3$. To ascertain this result, we tested whether the measured ζ were actually equilibrium exponents, doing MDW aging studies on measurements 18 and 19 of Fig. 5. Both first images of the MDW were stored 4s after switching off the field, giving wandering exponents $\zeta = 0.68 \pm 0.015$ and $\zeta = 0.79 \pm 0.015$. Then, the walls were left with no applied magnetic field for 3860 and 5640 s, respectively, and a second image of the MDW was recorded. The wandering exponents became, respectively, $\zeta = 0.066 \pm 0.015$ and $\zeta = 0.80 \pm 0.015$, indicating a lack of temporal evolution. The data of Fig. 5 may thus be considered as static or quasistatic exponents.

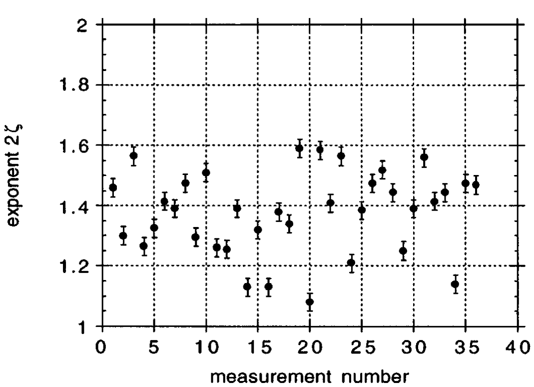

FIG. 5. Wandering exponent 2ζ. Measurements on different MDW driven at $H = 50$ Oe during 20–45 min and then frozen ($T = 300$ K, estimated error on 2ζ for a given image: ± 0.03).

In this paper, we prove experimentally the creep model and determine the corresponding wandering exponents. The success of these experiments is due to the high quality of Pt/Co/Pt films which are particularly appropriate for such moving interfaces studies. This represents a flexible model experimental system to investigate interface growth problems, making possible connections with many other areas in physics.

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