Single-Domain Wall Propagation and Damping Mechanism during Magnetic Switching of Bistable Amorphous Microwires

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The mechanism of nucleation and propagation of a single-domain wall is studied as a function of temperature in bistable Fe-based amorphous microwire with a unique simple domain structure. An extended nucleation-propagation model is proposed with a negative nucleation field. From quantitative analysis of the propagating wall characteristics, a new damping is theoretically introduced as arising from structural relaxation which dominates in the low temperature regime.

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Domain wall displacement plays a decisive role in the remagnetization process. This requires the essential mechanisms of nucleation of reverse domains and of propagation of domain walls upon their enlargement. But only in a few specific cases, with ideal domain structures, can a detailed quantitative analysis be performed on the conditions under which such a process takes place. This is, for example, the case of the renowned experiment proposed by Sixtus and Tonks where a single-domain structure is first artificially created by applying a mechanical stress [1]. Then, after a small reverse domain is locally nucleated by an exciting coil, the propagation of a single-domain wall is studied under different applied magnetic fields. The general equation of motion of a 180° domain wall is taken as that of a damped forced harmonic oscillator [2] as

$$m\ddot{x} + \beta\dot{x} + \alpha x = 2M_s H, \qquad (1)$$

where m is an effective mass of the wall, β the damping coefficient, α the restoring force constant, and $2M_sH$ the driving force by the applied field H. Once the wall propagates at constant velocity ν, Eq, (1) reduces to $\nu = (2M_s/\beta)(H - H_0)$, where H_0 correlates conventionally with the critical propagation field, and β determines the wall mobility, $S = 2M_s/\beta$. Two classical contributions to the damping mechanism are usually considered: eddy currents and spin relaxation [3].

In this Letter, we propose a drastically simplified experiment where there is neither the need for applying stress nor having a local exciting coil: we exploit the outstanding characteristics of the selected amorphous magnetic material that spontaneously exhibits a single-domain structure but at its very end where closure structures act as reverse domains. The analysis of experimental results allows us to propose an extended nucleation-propagation mechanism with negative nucleation field. Moreover, an additional damping mechanism arising from structural relaxation has been theoretically introduced.

Amorphous magnetic microwires are novel materials with very attractive properties [4]. Particularly, glass-coated microwires are characterized by an amorphous metallic nucleus covered by an insulating glass sheath. Stresses frozen in during the quenching and drawing fabrication process, and from the different thermal expansion coefficients of coating and nucleus, give rise to strong magnetoelastic anisotropy which together with shape anisotropy determines their unique magnetic behavior [5].

As a consequence of the strong uniaxial magnetic anisotropy, the simple domain structure at remanence of large and positive magnetostriction microwires (e.g., Fe rich alloys) consists of a longitudinal single domain: after first magnetization, the demagnetized state cannot be reached. Additionally, at finite applied fields, closure domains appear at the ends in order to decrease the magnetostatic energy [4,6]. The axial magnetization reversal process runs by the depinning of a single 180° domain wall from one closure structure when the switching field is reached and its subsequent propagation along the entire microwire: a square hysteresis loop is then observed with a giant single Barkhausen jump. In spite of the simple domain structure, ideal for micromagnetic studies, only a few works dealing with phenomenological aspects of domain propagation have been reported [7–9].

The objective of this work has been to study experimentally and theoretically the temperature dependence of the mechanism of nucleation and propagation of a single-domain wall during magnetization reversal and its damping mechanism. From the exciting results, we introduce new insight into the reversal mechanism as well as an additional contribution to the damping mechanism arising from structural relaxation predicted theoretically earlier.

Pyrex glass-coated $Fe_{77.5}Si_{7.5}B_{15}$ amorphous microwire was produced by the Taylor-Ulitovsky method. The selected piece for experiments was 9 cm long with a diameter of the metallic nucleus of 11 μm and total diameter of 29 μm. Measurements were performed using a Sixtus-

Tonks-like experiment. In our case, the setup consists of three coaxial coils: the primary coil (11 cm long and 10 mm in diameter) and two secondary coils (3 mm long and 1 mm inner diameter, 1500 turns) symmetrically placed and separated 8 cm. The primary coil generating the exciting field was fed by a 10 Hz frequency ac square current creating a homogeneous field along the wire that can be taken as static during wall propagation. Secondary coils are connected in series opposition so two sharp opposite peaks are picked up at an oscilloscope upon passing the propagating wall (see Fig. 1). The coil system allows us to identify the propagating wall direction for which velocity is calculated as $\nu = L/(t_2 - t_1)$, where L is the distance between pickup coils and t_1, t_2 are the time positions of the maximum in the emf recorded waveforms. The system is placed inside a specially designed cryostat system enabling the measurement in the temperature range from 77 to 380 K.

From the positions of the peaks, the magnetization reversal is inferred to be switched at one end and then it propagates along the entire wire. The profiles of the peaks are symmetric and paraboliclike shaped, which corresponds to a planar domain wall [10], in opposition to tubular-conical shaped walls that give rise to extremely asymmetric pulses [3]. Additionally, and contrary to the case of the other family of amorphous wires [3,10], the two peaks have the same shape, denoting that the domain wall propagates at constant velocity. The length of the wall is derived from the peak's width to be in the range from 10 to 12 mm (see Table I), that is, around 1000 times larger than the microwire diameter.

Figure 2 shows the expected linear dependence of the wall velocity on the applied magnetic field. At each temperature, the minimum field at which the domain wall moves corresponds to the switching field. Extrapolating the linear behavior (as indicated for the case of 77 K) to zero applied field and zero velocity, we obtain, respectively, the velocity, ν_0, of the wall at zero applied field and the field, H_0, at zero velocity (see Table I). Positive values of ν_0 and negative values of H_0 are certainly remarkable. This astonishing result leads to a first conclusion that the domain wall can theoretically move even in negative applied field, or that negative losses could exist during the wall propagation. In fact, negative H_0 values can be deduced from results reported in [8], but no further analysis was provided there even though the existence of negative nucleation field was somehow proposed in the nucleation-propagation theory [11]. Alternatively, a new insight into the current nucleation-propagation mechanism should be considered.

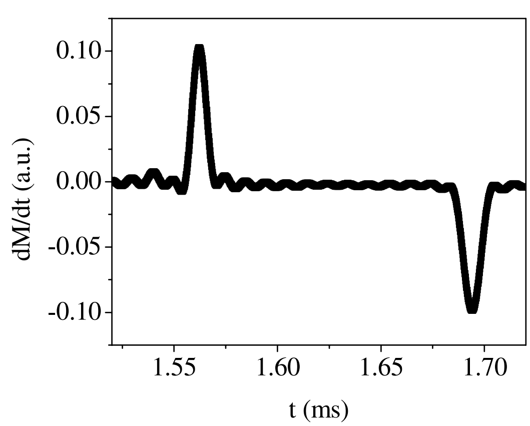

FIG. 1. emf pulse (dM/dt) induced at the secondary coils during the wall propagation at 77 K.

Let us analyze the meaning of the extrapolated field, H_0, ascribed to the wall propagation field according to the classical nucleation-propagation model [12]. A positive value of H_0, typically deduced in square hysteresis loops, is interpreted considering that the propagation field is smaller than the field required to nucleate a reverse domain. In turn, when the nucleation field is smaller than the propagation field, more rounded observed loops are a consequence of the distributed force at centers where walls are pinned. In the present case, nevertheless, we are dealing with a novel situation: reverse domains nucleate spontaneously for negative fields at the ends of the microwire to reduce the magnetostatic stray field energy. We can thus reinterpret the experimental results assuming that the nucleation field is smaller than the propagation field, and even it takes negative values. Propagation takes place by the depinning of a single wall pinned by a single force, and the subsequent single giant Barkhausen jump gives rise to the square loop. For higher applied fields, closure structures at the ends increase size [13] until they become energetically unstable at the applied field, H_{pr}, that corresponds to the measured switching field or lowest field necessary for the wall propagation.

Quantitative analysis of the propagating wall informs us of the intrinsic dynamic mechanisms promoting or hindering the wall motion. To explain the temperature dependence of H_{pr} we consider the expression for the temperature dependence of the switching field introduced in [14]:

$$H_{pr}(T) = pM_s^{3/2}[1 + r(\Delta T)]^{1/2} + nG(T, t)/(M_s T), \quad (2)$$

where $p = \text{const}\, \sigma_r$ (σ_r denotes the residual stresses), $r \sim E(\alpha_g - \alpha_m)$ (E is the Young's modulus of the nucleus, and

TABLE I. Domain wall length, L_w, velocity at zero field, ν_0, nucleation field, H_0, propagation field, H_{pr}, propagating wall mobility, S, and damping coefficient, β, at given temperatures.

T (K)	L_w (mm)	ν_0 (m/s)	H_0 (A/m)	H_{pr} (A/m)	S (m^2/A s)	β ($kg\,m^{-2}\,s^{-1}$)
77	12.1	428	−508	208	0.84	3.71
180	11.7	295	−130	136	2.25	1.39
297	12.5	177	−46	80	3.89	0.80
340	10.9	173	−42	75	4.04	0.77
380	10.7	97	−18	71	5.27	0.59

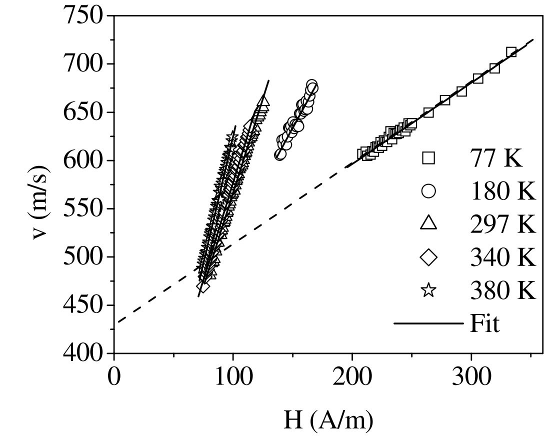

FIG. 2. Dependence of domain wall velocity on applied magnetic field at a range of measuring temperatures.

α_g, α_m are the thermal expansion coefficients of coating and nucleus, respectively), and $n \sim (\varepsilon_{\rm eff}^2 c_0/k)$ [$\varepsilon_{\rm eff}$ is an effective interaction constant, c_0 the density of mobile defects, kT the thermal energy, and $G(T, t)$ the relaxation function taken as temperature independent in a first approximation]. This dependence contains two contributions (see Fig. 3) [14]: the magnetoelastic term, dominating at high temperature, and the stabilization term coming from the structural relaxation, which becomes more important at low temperatures. The linear dependence between the field H_0 and propagation, $H_{\rm pr}$ fields (see inset) strongly suggests that both fields have similar contributions. Unlike the case of the propagation field, the expression for the field H_0 contains the magnetostatic and domain wall energy terms which have weak temperature dependence.

Let us now analyze the terms contributing to the damping mechanism during the wall motion in which experimental coefficients are collected in Table I. The eddy-current contribution, β_e, for an amorphous wire is given by [10]

$$\beta_e = [\mu_0 M_s(T)]^2 r_b[\ln(r_0/r_b) + 8/\pi^2]/\rho(T), \quad (3)$$

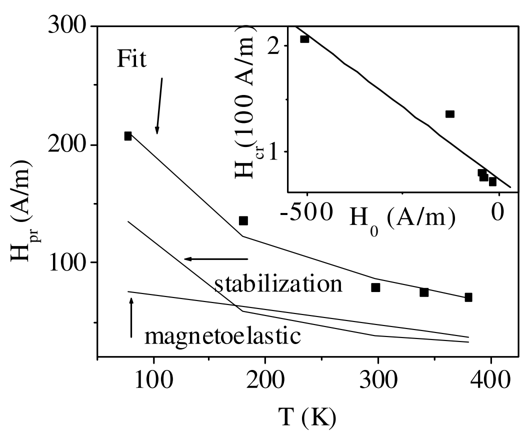

FIG. 3. Temperature dependence of the propagation field $H_{\rm pr}$. The inset presents the correlation between propagation $H_{\rm pr}$ and nucleation H_0 fields.

where ρ is the resistivity and r_0 and r_b are the radii of the wire and that of the inner domain core, respectively. Sixtus and Tonks [1] originally assumed a large influence of the change of resistivity. But now, a modest relative change of resistivity less than 4% (see also [15]) has been measured in the whole temperature range, which is not large enough to justify the observed variation of the wall mobility.

The contribution of the spin-relaxation damping coefficient, β_r, is (considering its inverse proportionality to the domain wall width, δ_0 [3])

$$\beta_r \propto M_s \delta_0^{-1} = M_s \pi^{-1}(K/A)^{1/2} = M_s \pi^{-1}(3\lambda_s \sigma/2A)^{1/2}, \quad (4)$$

where K is the magnetoelastic anisotropy energy density, A the exchange stiffness constant, λ_s the magnetostriction, and σ the mechanical stress. Taking into account the temperature dependence of magnetization, M_s, magnetostriction, λ_s (through the scaling law [14]), and stresses coming from the different thermal expansion coefficients [$\sigma = {\rm const}((\alpha_g - \alpha_m)\Delta T)$ [14]], a simple expression describing the temperature dependence of the spin-relaxation damping parameter is obtained: $\beta_r \propto [M_s(T)^{1/2}(1 + r\Delta T)^{1/2}]$.

Nevertheless, the sum of both contributions is not large enough to allow us a reasonable fitting to the experimental temperature dependence of β. Consequently, the large observed temperature dependence of β must be connected with some additional contribution (already suggested in [3]). One possible solution is considering the structural relaxation, originally assumed in a classical work [16] without detailed form or subsequent consideration to our knowledge. Glass-coated microwires are metastable in nature because of their amorphous character; therefore they should exhibit strong structural relaxation leading to the stabilization of the magnetization in the domain walls as well as in the domains [14,17]. Consequently, it is reasonable to introduce a new damping mechanism arising from the structural relaxation.

Let us imagine the nearly planar 180° domain wall propagating along the wire with an angle of about 90°. The wall interacts with the defects present in the amorphous structure. These defects are mobile and able to follow the change of the local magnetization direction in order to decrease the total free energy [18]. But they also play a role as pinning centers for the wall when they lose their mobility. The interaction energy of the wall with these defects has been expressed in the form [19]

$$E_s = (2/15)\langle(e_{\rm eff})^2\rangle(c_0/kT)[-2\delta_0]G(T, t). \quad (5)$$

As the wall propagates with velocity ν, local moments rotate 180°, and it takes a time, $t = \delta_0/\nu$, until the wall traverses the position of a mobile atomic defect. If t is much longer than the relaxation time τ of the defect, it will be able to follow the magnetization change and no damping is visible. This happens at high temperature since τ obeys the Arrhenius law [$\tau = \tau_0 \exp(Q/kT)$, Q being the activation energy of the mobile atomic defects having thermal energy kT]. However, at low temperatures τ increases, and for values of $\tau > t$, the magnetic moments in the atomic defects are no longer able to relax within t. This process enhances the wall pinning and contributes an additional damping. Consequently, this damping through the structural relaxation takes place when $\delta_0 = \nu\tau$. Introducing this into Eq. (5), considering the energetic balance between the interaction energy E_s and the energy provided by the external field $M_s H$, as well as the correlation between wall mobility and damping coefficient, yields an expression for the structural relaxation wall damping:

$$\beta_s \propto \tau\langle(e_{\text{eff}})^2\rangle(c_0/kT)G(T,t) \quad (6)$$

similar to that predicted in [16]. Finally, the temperature dependence of total damping can be expressed as

$$\beta = \beta_e + \beta_r + \beta_s = \beta = \frac{k_1 M_s(T)^2}{\rho(T)} + k_2[M_s(T)^3(1 + r\Delta T)]^{1/2} + k_3\frac{\tau}{T}, \quad (7)$$

where $k_1 = \mu_0 r_b[\ln(r_0/r_b) + 8/\pi^2]$, $k_2 = \text{const}\,\sigma_r$, and $k_3 = (4/15)\langle(e_{\text{eff}})^2\rangle(c_0/k)G(T,t)$. The fitting to the experimental damping in Fig. 4 denotes that the stabilization through structural relaxation plays a major role at low temperatures. From experimental results, an activation energy for structural relaxation per defect of around 20 meV is deduced, comparable to the thermal energy, kT, at temperatures when the structural relaxation becomes relevant.

In summary, the magnetization reversal in a bistable amorphous microwire has been studied in the temperature range 77–380 K. The propagating wall has a symmetric planar shape with length in the range 10–12 mm. A novel insight into the nucleation-propagation mechanism of magnetization reversal is introduced: reversal takes place by depinning of a single wall in which the propagation field is larger than the nucleation field (that can even take negative value) and results in a square loop. Moreover, from the temperature dependence of the propagating wall characteristics, a new damping mechanism originating in the structural relaxation of the amorphous microwires has been theoretically introduced. These exciting results are finally a consequence of the unique domain structure and characteristics of studied microwires.

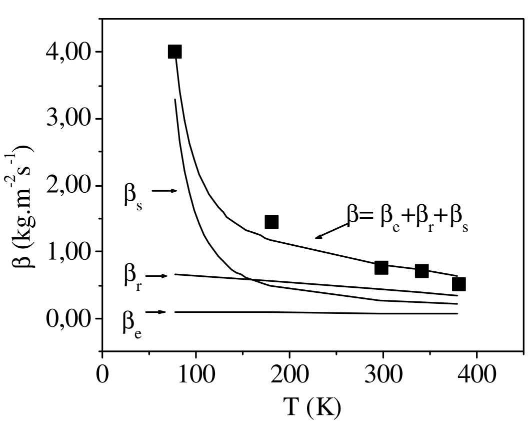

FIG. 4. Temperature dependence of the domain wall damping β: experimental (square points) and calculated through Eqs. (7) (β), (7)(β_s), (5)(β_r), and (3) (β_e).

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