Supersonic domain wall in magnetic microwires

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Here, we present experimental evidence for the very fast domain wall in microwires that can reach wall-motion velocity approaching 18.5 km/s, which is much higher than the sound velocity in the magnetic wires. We show that the domain wall speed can be adjusted by counterbalancing between the longitudinal magnetic anisotropy leading to small damping and the strong transversal anisotropy.

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Magnetic domain wall propagation in a wire is an important research because of its potential use in magnetic devices such as magnetic random access memory, integrated circuits, hard disks, etc., to transmit information along the magnetic wire of submicrometer diameter.[1,2] This motion can be driven both magnetically or electronically. However, the speed of such devices depends on the velocity of the domain wall. The understanding of the mechanism, involving the fast domain wall propagation, is the key for the future applications. Recently, very high velocities have been reported reaching the values of up to 1500 m/s.[3]

A magnetic glass-coated microwire is a composite material[4] that consists of a metallic nucleus of 0.6–30 μm in diameter and glass coating of thickness of 1–20 μm [Fig. 1(a)]. It is prepared by the Taylor-Ulitovski method, which involves simultaneous rapid quenching and subsequent drawing of the metallic core inside a glass capillary. As a result, strong stresses are introduced in the metallic nucleus arising from the drawing and quenching, as well as from the different thermal expansion coefficients of the coated glass and metallic nucleus. Thus, the magnetoelastic anisotropy induced by the stresses plays an important role in their magnetic properties. Since the amorphous microwires studied here has a positive magnetostriction, the wire fabrication process described above results in the following domain wall structure: one large domain in which the magnetization is oriented axially (as a result of the axial stresses coming from drawing and quenching) and the outer domain structure consists of domains with magnetization oriented radially[5] (as a result of the quenching and the stresses coming from the different thermal expansion coefficients of the glass coating and metallic nucleus), as shown in Fig. 1(b). Moreover, a small closure domain appears at the end of the wire in order to decrease the stray fields.

Regarding the magnetization process of such magnetic microwires, it has been demonstrated that the magnetization process runs through depinning and subsequent propagation of the single closure domain.[6] This provides us with the possibility of studying the single domain wall dynamics. The experiments were simple but have led to interesting results such as negative critical propagation field and new damping mechanism based on structural relaxation.[7] In addition, very fast domain walls were observed in glass-coated microwires reaching a velocity of 2000 m/s.[8]

On the basis of the previous results,[8] we focused on the crucial condition to achieve fast domain wall motion. The domain wall dynamics was measured by the classical Sixtus-Tonks[9] experiments. The system essentially consists of three coaxial coils [Fig. 1(c)]. The primary coil of 10 cm in length generating the exciting field was fed by a 30 Hz ac square current creating a homogeneous field along a 10.5-cm-long wire. The exciting field was kept constant during the wall propagation. Two secondary coils, symmetrically placed at the center of the primary coils and separated by $L=6$ cm, are connected in series in an opposite polarity so that two sharp opposite peaks are picked up at an oscilloscope upon passing of the propagating domain wall. The microwire was placed coaxially within the primary and pickup coils, so that only one end was located within the primary coil. The other end of the microwire was located outside the primary coil, so that the closure domains at this end were not influenced by the external magnetic field. In order to ensure that nucleation of the domain walls in the center of the wire did not occur, the microwire was checked with both ends outside the system and that no signal was apparent up to the highest applied field.

The coils system allows us to identify the propagating wall direction, the velocity of which is calculated as $v=L/t$,

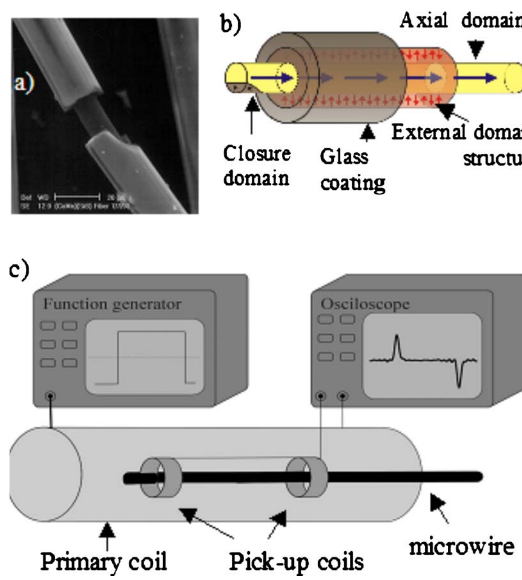

FIG. 1. (Color online) (a) Scanning electron microscopy image. (b) Schematic magnetic domain structure. (c) Diagram of the measuring setup of the glass-coated microwire.

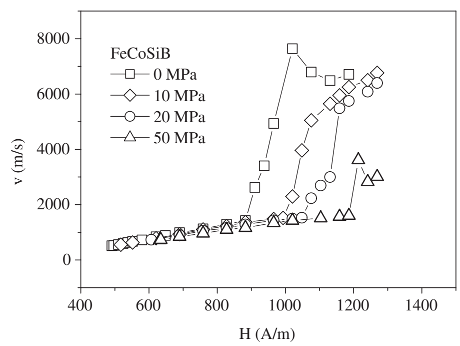

FIG. 2. Domain wall velocity **v** as a function of the magnetic field amplitude **H** for FeCoSiB microwire with the applied tensile stress as a parameter.

where t is the time between the two maxima observed on the oscilloscope. The domain wall dynamics in a viscous medium and at slow rates is governed by a mobility relation[9,10]

$$v = S(H - H_0), \tag{1}$$

where S is the domain wall mobility and H_0 is the critical propagation field, below which the domain wall propagation is not possible.

Figure 2 shows the dependence of the domain wall velocity on the applied magnetic field for an $Fe_{36}Co_{40}Si_{11.1}B_{12.9}$ microwire (with the diameter of the metallic core being 15.2 μm and total diameter being 27.4 μm and a length of 10 cm), exhibiting a high anisotropy (because of the material's high magnetostriction $\sim 30 \times 10^{-6}$) and very fast domain wall propagation.[8] Three regions of the domain wall dynamics are clearly recognized. Firstly, the linear dependence of the domain wall velocity was found at low fields (0–900 A/m) with the domain wall mobility of 2.3 m^2/A s up to the velocity of 1400 m/s. In the second range (900–1000 A/m), the domain wall mobility increases 20 times, reaching the value of 45 m^2/A. The domain wall velocity increases steeply in this range reaching its maximum at 7700 m/s. Finally, the domain wall mobility becomes negative and the domain wall velocity decreases.

Observed domain wall propagation is very fast, exceeding the sound velocity ($\sim$4500 m/s) measured in similar magnetic microwires.[11] One possible explanation for the slope change could be attributed to the change of the domain wall structure. It was shown by micromagnetic simulations that the vortex-type domain wall is faster than transversal one.[12,13] The transversal domain wall creates the surface stray field that interacts with the radial domain structure. The vortex-type domain wall does not create surface stray fields. Therefore, it does not interact with the radial domain structure and the movement is faster. On the other hand, it has complicated structure with higher exchange energy. Therefore, the vortex domain wall is more preferable for the case of thick magnetic wires than the transversal one.[12]

At low fields, a transversal-type domain wall structure should be expected due to the axial and radial anisotropies present in the microwire. Increasing the axial field leads to the increase of the diameter of the internal single domain. Moreover, the rise time of the applied square magnetic field is very short and the change of the field is abrupt. Therefore, instead of depinning of the closure domain wall, the nucleation of a reversed domain could occur. This fact is supported by the change of the critical propagation field H_0, which is much higher for the structure. Vortex-type domain wall should now be expected, since the velocity of the domain increases steeply. As the micromagnetic simulations show,[12] once the wall is nucleated into a certain structure, this structure remains the same configuration during wall motion. However, we have no direct evidence for the domain wall structure change.

The maximum domain wall velocity is fixed by the restoring forces that oppose precession inside the domain wall (DW) (Walker model).[14] Thus, it could be increased by adding an anisotropy with transverse easy axis. Theoretically, the domain wall velocities can reach up to 1000 m/s.[15–17] However, domain wall velocities up to 2000 m/s have recently been experimentally observed.[3,8] The main problem of the micromagnetic simulations in Refs. 12, 13, 15, and 16 is that they do not take into account the anisotropy. It was shown that the domain wall velocity increases with the presence of the transversal anisotropies.[14,18] Glass-coated microwires exhibit strong radial anisotropy arising from the stresses induced by the glass coating through the difference in the thermal expansion coefficients of the metallic nucleus and the coated glass. In the case when both anisotropies (axial as well as transversal) are compensated, the restoring force that opposes precession inside the DW is minimum. This happens just at the boundary in between the axial and radial domain structures. Moreover, the critical field H_w at which the maximum velocity appears is enhanced[18] ($H_w = \alpha H_k / \mu_0 M_s$, where α is the damping, H_k is the transversal anisotropy field, μ_0 is the permeability of the vacuum, and M_s is the saturation magnetization).

Additionally, the domain wall does not interact with the surface of the wire (due to the presence of the radial domain structure), avoiding the surface pinning of the domain wall. The ends of the propagating domain wall are moving at the interface between the axial and radial domain structures, where both axial and radial anisotropies are exactly compensated. This surely helps the domain wall to achieve the fast propagation. It was shown by a micromagnetic simulation[17] that introducing defects just below the surface of the wire helps the domain wall to reach high velocities. The radial domain structure plays the role of such defects in glass-coated microwires.

The effect of the stress-induced anisotropy on the domain wall propagation is shown by applying a tensile stress on the microwire (Fig. 2). The threshold field associated with the nucleation of the vortex domain wall increases as a result of the nucleation field increase. At the same time, the velocity at which the type of the domain wall changes remains roughly the same for all applied stresses. The application of a tensile stress increases the domain wall damping and therefore the domain wall velocity decreases. Although such an effect is not very clear at low fields, maximum is not observed at high fields, where the maximum velocity is expected. We assume that to obtain high velocity of the domain wall, strong anisotropy is needed, but in opposition, strong anisotropy results in an increase of the domain wall damping and the decrease of the domain wall velocities.

As a result of their amorphous nature, the glass-coated microwires have high resistivities. Therefore, the eddy current damping is very low in these materials.[7] The most important damping mechanism in glass-coated microwires at room temperature was found to arise from spin relaxation. It was shown in Ref. 7 that damping contribution coming from the spin relaxation (β_r) is proportional to the square root of the anisotropy.[7,19] In the case of amorphous glass coated microwire, the anisotropy is determined mainly by the magnetoelastic interaction of the local magnetic moments with the stresses σ introduced during the microwire's preparation [so, $\beta_r \sim (\lambda_s \sigma)^{1/2}$, where λ_s is the saturation magnetostriction]. In contrast to the first microwire, the second microwire that we have studied has a nominal composition $Co_{68}Mn_7Si_{10}B_{15}$ (with the diameter of the metallic core being 8 μm and total diameter being 20 μm), which is characterized by the lowest possible magnetoelastic anisotropy[20] (due to its low magnetostriction λ_s) among the microwires with single domain axial structure [see Fig. 1(b)]. In fact, it has ten times smaller magnetoelastic anisotropy (in comparison with the FeCoSiB microwire) and therefore extremely small domain wall damping. Anyway, the stresses applied on the metallic nucleus are of the same directions like in the FeCoSiB microwire, and it presents the same domain structure.

As a result of the small damping, the domain wall mobility is extremely high (16 m^2/A s at low fields) and it reaches the maximum value of 272 m^2/A s at the field of 255 A/m (Fig. 3). Although the Walker field is small (~300 A/m), the maximum velocity reaches a value of 18 500 m/s. We think that the maximum velocity is given not only by the transversal anisotropy but mainly by the high mobility as well as by the counterbalance between the uniaxial and transversal anisotropy.[21]

Application of a tensile stress shifts the Walker fields to higher values, but the effect on the maximum velocity is not so strong as in the case of FeCoSiB microwire. We think that this behavior is as a consequence of the magnetoelastic anisotropy ($E_\sigma \sim \lambda_s \sigma$) depending on the magnetostriction, which is quite small,[20] in this case $\lambda_s \sim 10^{-7}$.

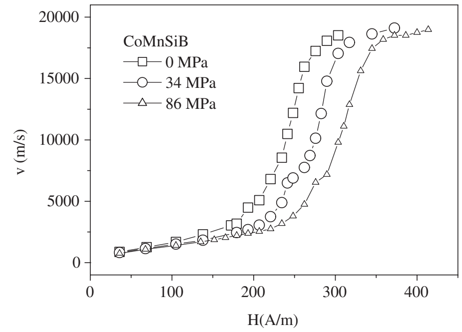

FIG. 3. Domain wall velocity **v** as a function of the magnetic field amplitude **H** for CoMnSiB microwire with the applied tensile stress as a parameter.

Concluding, the experimental results presented here show a way to obtain very fast domain wall propagation. They confirm that the strong transversal anisotropy (maintaining a high Walker field) and small anisotropy, on the other hand (keeping the domain wall damping small), must be counterbalanced to obtain a very fast domain wall. If such condition is fulfilled, very fast domain wall ($v > 10\,000$ m/s) can be achieved in thin wires. Under such conditions, we experimentally observed supersonic domain wall propagation with the velocity exceeding 18 km/s. Observed domain wall propagation is almost 2 orders faster than that used at present in magnetic devices.

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[1] G. S. D. Beach, Nistor, C. Knutson, M. Tsoi, and J. L. Erskine, Nat. Mater. **4**, 741 (2005).
[2] D. A. Allwood, G. Xiong, C. C. Faulkner, D. Atkinson, D. Petit, and R. P. Cowburn, Science **309**, 1688 (2005).
[3] D. Atkinson, D. A. Allwood, G. Xiong, M. D. Cooke, C. C. Faulkner, and R. P. Cowburn, Nat. Mater. **2**, 85 (2003).
[4] M. Vázquez and A. Zhukov, J. Magn. Magn. Mater. **160**, 223 (1996).
[5] H. Chiriac and T. A. Ovari, Prog. Mater. Sci. **40**, 333 (1996).
[6] R. Varga, K. L. Garcia, M. Vazquez, A. Zhukov, and P. Vojtanik, Appl. Phys. Lett. **83**, 2620 (2003).
[7] R. Varga, K. L. Garcia, M. Vazquez, and P. Vojtanik, Phys. Rev. Lett. **94**, 017201 (2005).
[8] R. Varga, A. Zhukov, J. M. Blanco, M. Ipatov, V. Zhukova, J. Gonzales, and P. Vojtanik, Phys. Rev. B **74**, 212405 (2006).
[9] K. J. Sixtus and L. Tonks, Phys. Rev. **42**, 419 (1932).
[10] H. J. Williams, W. Shockley, and C. Kittel, Phys. Rev. **80**, 1090 (1950).
[11] H. Chiriac, E. Hristoforou, M. Neagu, I. Darie, and A. E. Moga, J. Non-Cryst. Solids **287**, 413 (2001).
[12] H. Forster, T. Schrefl, W. Scholz, D. Seuss, V. Tsiantos, and J. Fidler, J. Magn. Magn. Mater. **249**, 181 (2002).
[13] R. D. McMichael and M. J. Donahue, IEEE Trans. Magn. **33**, 4167 (1997).
[14] N. L. Schryer and L. R. Walker, J. Appl. Phys. **45**, 5406 (1974).
[15] A. Kunz, IEEE Trans. Magn. **42**, 3219 (2006).
[16] N. A. Usov, A. Zhukov, and J. Gonzalez, J. Magn. Magn. Mater. **316**, 255 (2007).
[17] Y. Nakatani, A. Thiaville, and J. Miltat, Nat. Mater. **2**, 521 (2003).
[18] A. Thiaville, J. M. Garcia, and J. Miltat, J. Magn. Magn. Mater. **242-245**, 1061 (2002).
[19] D. X. Chen, N. M. Dempsey, M. Vazquez, and A. Hernando, IEEE Trans. Magn. **31**, 781 (1995).
[20] A. Zhukov, V. Zhukova, J. M. Blanco, A. F. Cobeno, M. Vasquez, and J. Gonzalez, J. Magn. Magn. Mater. **258-259**, 151 (2003).
[21] A. Hubert and R. Schafer, *Magnetic Domains* (Springer-Verlag, Berlin, 1998), p. 271.