Fast magnetic domain wall in magnetic microwires

R. Varga,* A. Zhukov, J. M. Blanco, and M. Ipatov
Dpto. Física Aplicada I, EUPDS, UPV/EHU, Plaza Europa 1, San Sebastián, 20018, Spain

V. Zhukova and J. Gonzalez
Dpto. Física de Materiales, Facultad de Química, UPV/EHU, 1072, 20080, San Sebastián, Spain

P. Vojtaník
Institute of Physics, Faculty of Sciences, UPJS, Park Angelinum 9, 041 54 Kosice, Slovakia
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The propagation of domain walls in magnetic microwires has been investigated over the temperature range 77–373 K. Very high domain wall velocities, up to 1800 m/s, were observed, in combination with enhanced domain wall mobilities at high temperature. In contrast, the domain wall mobility is low at low temperature, though the wires still exhibit relatively high domain wall velocities (~600 m/s). A mechanism for obtaining high wall velocities, based on a negative critical propagation field, is described.

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The magnetization process in small magnetic structures is of fundamental interest and a key factor for future applications in various sensors, and in memory or other electronic devices. In some magnetic devices, the information is transmitted along a magnetic wire by domain wall motion.[1] The speed of the device is obviously linked to the domain wall velocity v. Therefore, the domain wall propagation in such a structure has stimulated considerable interest over the past few years.[2,3] Recently, a very rapid magnetic wall was reported in submicrometer ferromagnetic wires, with a velocity of up to 1500 m/s at an applied field of 4000 A/m.[4] Other theoretical or experimental approaches have also been employed for achieving very rapid domain wall propagation.[5]

More recently, we have studied the domain wall dynamics in amorphous glass coated microwires.[6] These studies showed rapid wall propagation over a wide temperature range. The domain wall mobility S, which is defined as the rate of change of v with increasing external magnetic field, increases with temperature. The theoretical possibility of domain wall propagation without applied magnetic field was first reported in Ref. 6. The surprising results found during the study of the domain wall dynamics in microwires are believed to arise from the high shape anisotropy, in addition to the effect of the magnetoelastic anisotropy. Therefore, we focus our attention on the study of domain wall dynamics in glass coated FeCoSiB amorphous alloy microwires, which were found to have a very high anisotropy—much higher than in the FeSiB microwires studied in Ref. 6.

The purpose of this Brief Report is to present results of a study of rapid domain wall dynamics in glass-coated magnetic microwires with high anisotropy. We report a domain wall velocity of up to 1800 m/s in a relatively low magnetic field of about 1100 A/m.

Amorphous glass-coated microwires prepared by the Taylor-Ulitovsky method are unique materials that allow us to study the magnetization process in a single domain particle. They consist of a metallic core, of diameter in the range 1–30 μm, which is coated by a Pyrex-like glass of thickness in the range 2–30 μm.[7] The magnetic domain structure is composed of one large axial domain, with magnetization oriented along the longitudinal axis,[8] together with small closure domains which are created at the ends of the wire in order to minimize the stray fields (see Fig. 1). Additionally, an external domain structure with radial magnetization is manifested at the surface as a result of the radial stresses induced by the glass coating.[9,10] The magnetization process in the axial direction occurs via the depinning and subsequent propagation of the single closure domain.

Pyrex glass-coated $Co_{40}Fe_{36}Si_{1.15}B_{12.9}$ amorphous microwire was produced by the Taylor-Ulitovsky method. Selected samples for experimental investigation were of length 110 mm, with the diameter of the metallic core being 15.2 μm and total diameter being 27.4 μm. A simple method, based on the classical Sixtus-Tonks-like experiments, was used to study the domain wall dynamics in the microwires (see Fig. 2). The primary coil (100 mm long and 8 mm internal diameter) was supplied from a function generator producing a square-shaped current form in order to provide a homogeneous field. Two pickup coils (3 mm long and 0.5 mm internal diameter) were placed symmetrically and coaxially 60 mm apart within the primary coil. Secondary coils were connected in series to an oscilloscope. Two sharp peaks were recorded on the oscilloscope, corresponding to the passage of the propagating 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 influ-

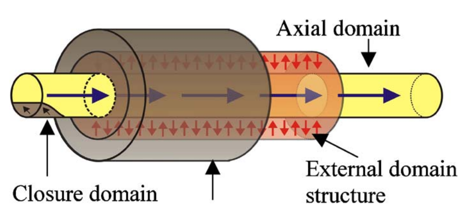

FIG. 1. (Color online) Schematic domain structure of glass-coated microwires.

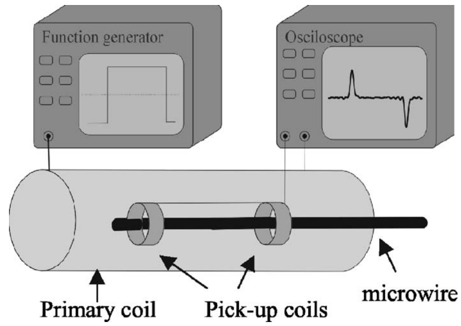

FIG. 2. Schematic diagram showing the experimental setup for the measurement of domain wall dynamics in magnetic microwires.

enced by the external magnetic field. In contrast to the classical Sixtus-Tonks experiment,[11] there was no need for the coils to nucleate a domain wall, since a closure wall already existed. 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 no signal was apparent up to the highest applied field.

The velocity v of the domain wall is simply calculated as $v=L/(\Delta t)$, where Δt is the time difference between the two maxima in the recorded emf wave form. The system was placed within a specially designed cryostat to facilitate measurements in the temperature range 77–373 K.

Figure 3 shows the domain wall velocity v as a function of the applied magnetic field H; v in microwires was very high, attaining values up to 1800 m/s at a field of 1050 A/m and a temperature of 373 K. A key dynamic parameter for the domain wall motion is the domain wall mobility S. The average mobility in microwires (taken from the linear fit of the data in Fig. 3) varies with temperature from 0.14 m^2/A s at 77 K up to 1.93 m^2/A s at 373 K (Fig. 4), in contrast to the domain wall mobility for a trilayer submicron magnetic wire, which was constant.[12] The value of S at 373 K is a factor of 5 higher than that reported in Ref. 4. On the other hand, the mobility at low temperature (77 K) is lower than that reported previously.[4] Nevertheless, the velocity remains relatively high (over 600 m/s) over the whole range of applied field investigated.

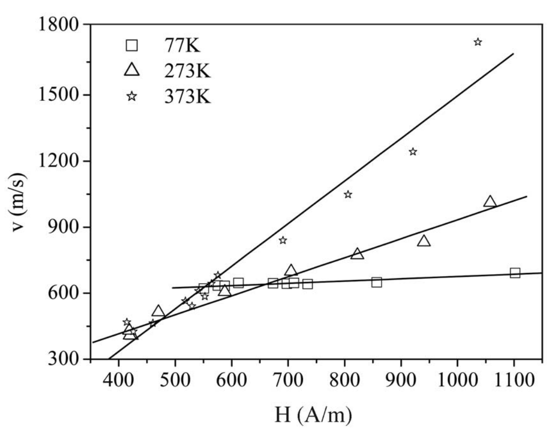

FIG. 3. Domain wall velocity as a function of magnetic field amplitude for various temperatures.

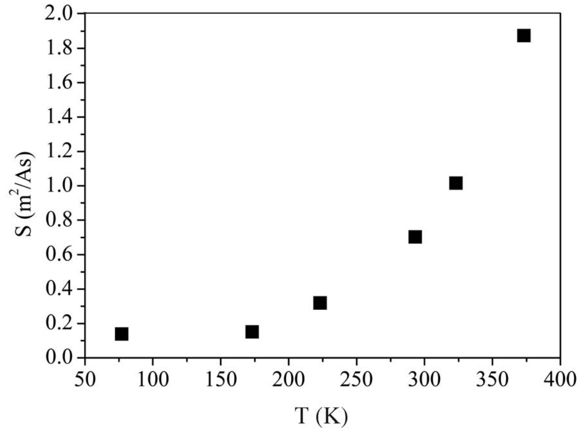

FIG. 4. Temperature dependence of the domain wall mobility.

The motion of the domain wall in a defect-containing ferromagnetic matrix is strikingly similar to the oscillation in a mechanical system.[13] In view of this property, the equation of motion for a 180° domain wall can be expressed by[14]

$$m\frac{d^2x}{dt^2}+\beta\frac{dx}{dt}+\alpha x=2M_SH, \tag{1}$$

where m is the effective mass of the domain wall, β is the damping coefficient, α is the restoring force constant, and $2M_SH$ is the driving force provided by the applied field H.

If the wall velocity is constant or only slowly varying, $d^2x/dt^2\rightarrow 0$ and the first term in Eq. (1) is negligible. Under this condition, Eq. (1) becomes[13]

$$v=S(H-H_0), \tag{2}$$

where domain wall mobility $S=2M_s/\beta$ and H_0 $(=\alpha x/2M_s)$ is the so-called critical propagation field, below which the domain wall propagation cannot be observed, even theoretically. According to Eq. (2), there are two possibilities for obtaining rapid domain wall motion. First, S must be maintained as high as possible. On the other hand, the critical propagation field H_0 should be decreased to its lowest possible value.

Using a linear fit according to Eq. (2), a strong positive temperature dependence of the domain wall mobility was observed. According to Ref. 15, S is inversely proportional to the domain wall energy γ_{dw}, which is proportional to the anisotropy constant. On increasing the temperature, the strong magnetoelastic anisotropy, arising from the stress induced by the glass coating, decreases, which results in an increase in S. Hence high values of S at high temperature are responsible for the high domain wall velocity.

On the other hand, a very surprising observation is the negative value of the critical propagation field H_0. Although such a negative value was reported in Ref. 6, in the present case, H_0 has values down to -4400 A/m, probably because of the higher anisotropy of the FeCoSiB wires in comparison with that of the FeSiB microwires studied in Ref. 6. As was mentioned above, decreasing H_0 down to negative values enhances the domain wall velocity. This could be an impor-

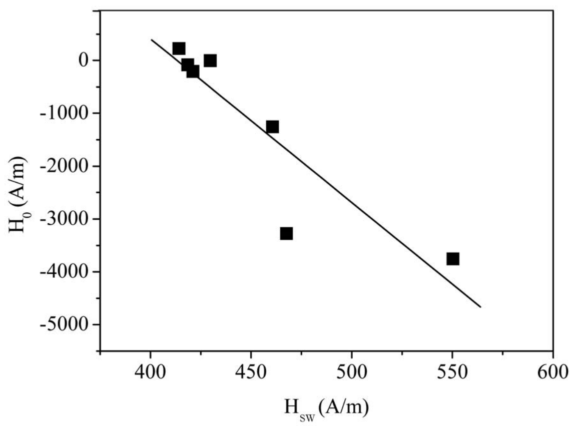

FIG. 5. Dependence of the critical propagation field on the switching field.

tant mechanism for maintaining a high v, even at low values of S. Moreover, the negative H_0 points to possible domain wall propagation without application of an external magnetic field. Therefore, understanding the mechanism by which a negative H_0 arises would be an important milestone on the way to obtaining very rapid domain wall propagation.

Although the model describing domain wall propagation was proposed over 70 years ago,[11] the role of H_0 is still not well understood. Some authors define H_0 simply as the critical propagation field for domain wall motion.[11,16] Other authors equate H_0 with the internal coercive force of the material.[13,17–19] In fact, there is a linear dependence between H_0 and the switching field H_{sw} (Fig. 5). The Achilles heel of this argument is hidden in the negative values of the proportionality constant. Hence the same mechanism, which is responsible for the increase in H_{sw}, causes the decrease of H_0 down to negative values. H_0 increases with increasing temperature and finally attains positive values at 373 K (Fig. 6).

The problem of the negative H_0 could also be treated in terms of an effective domain wall mass m_{dw}. Despite the absence of any mass displacement, a moving domain wall exhibits inertia.[13,14] It was predicted by Chikazumi in Ref. 14 that, if the propagating domain wall has a mass, it could continue to propagate, even in the absence of an external

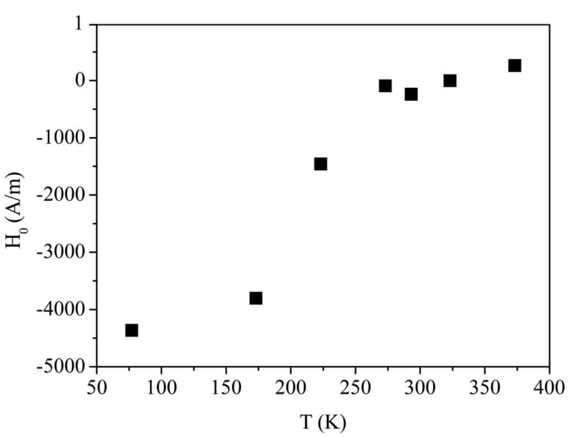

FIG. 6. Temperature dependence of the critical propagation field.

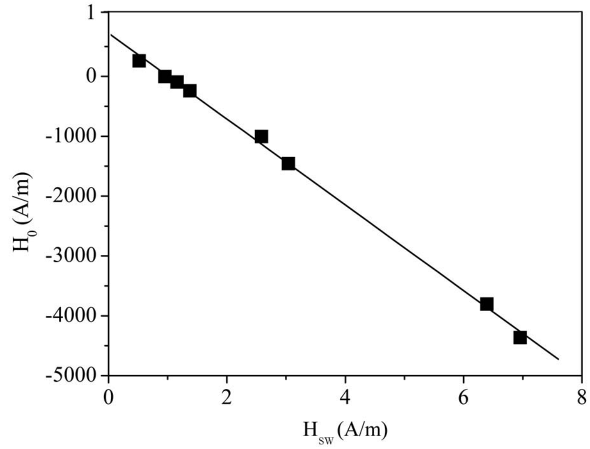

FIG. 7. The dependence of the critical propagation field on the reciprocal value of the domain wall mobility.

magnetic field. The connection between H_0 and the domain wall mass m_{dw} is confirmed also by the temperature dependence of H_0 as well as by the temperature dependence of S. According to Ref. 15, the mass m_{dw} of a 180° domain wall is proportional to the domain wall energy ($m_{dw} \sim \gamma_{dw}$). As was mentioned above, the domain wall mobility is inversely proportional to the domain wall energy ($S \sim 1/\gamma_{dw}$). To a simple approximation (neglecting other terms), an increase in S will result in a decrease in domain wall mass and vice versa. Such a trend is confirmed by our measurements (Fig. 7). When the domain wall mass increases, the inertia of the domain wall increases and H_0 decreases down to negative values (the theoretical velocity at $H=0$ increases).

Although the propagation of the domain wall without the field is just a speculation (and probably another domain wall propagation mechanism takes place at low field), the negative H_0 is an experimental fact found also previously for different magnetic microwires[6,20,21] in the field range where the domain wall moves in the viscous regime at a constant velocity. Moreover, it is the mechanism which maintains a high velocity in our experiment even in the case of low S. The experiments that will clarify the mechanism of negative H_0 are in progress.

Another important mechanism by which a high v could be maintained might be the existence of a complex domain structure. We can assume that the propagating closure domain wall does not interact with any surface irregularities because it is shielded by the external radial domain structure. Therefore, the strong damping that would arise from the pinning of the propagating domain wall within the inner axially magnetized core on such surface irregularities can be neglected. Another possible mechanism, which could result in very rapid domain wall movement, might arise from the external domain structure having a radial magnetization vector. Owing to the different thermal expansion coefficients of the metallic core and the glass coating strong, radial stresses are induced in the microwires. It has been shown that the maximum velocity can be enhanced by adding a transverse easy axis.[5,15] Moreover, introduction of defects below the surface would result in an increase of the domain wall velocity.[5] The external domain structure could assume the role of such defects, giving rise to an increase in v.

In summary, the rapid domain wall dynamics in microwires having high anisotropy has been studied in the temperature range 77–380 K. Very high domain wall velocities have been observed, with values up to 1800 m/s, together with a high domain wall mobility of 1.93 $m^2/A\,s$ at a temperature of 373 K. At low temperature the domain wall mobility decreases. However, the domain wall velocity remains relatively high at 600 m/s. Two mechanisms are used to explain the high domain wall velocity. An increase in the domain wall mobility at high temperatures and a decrease of the critical propagation field down to negative values at low temperatures were observed. The negative H_0 is treated in terms of the effective domain wall mass. It is assumed that, in glass-coated microwires, the domain wall does not interact with the surface irregularities, so that the domain wall is not damped through pinning by such features. Moreover, a transverse anisotropy, arising from the different thermal expansion coefficients of the metallic core and the glass coating, promotes high values of v. The external domain structure plays the role of the defects that are needed to enhance the domain wall motion.

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*Author to whom correspondence should be addressed. On leave from Inst. Phys. Fac. Sci. UPJS, Park Angelinum 9, 041 54 Kosice, Slovakia. Electronic address: rvarga@upjs.sk

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