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Vortex magnetic structure in circularly magnetized microwires as deduced from magneto-optical Kerr measurements

Yu. P. Ivanov,1,2,a) R. P. del Real,1 O. Chubykalo-Fesenko,3 and M. Vázquez1,b)

1Instituto de Ciencia de Materiales de Madrid, CSIC, Madrid 28049, Spain
2Far Eastern Federal University, Vladivostok 690950, Russia

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The magneto-optic Kerr effect has been employed to determine the magnetization process and estimate the domain structure of microwires with circular magnetic anisotropy. The diameter of microwires was 8 μm, and pieces 2 cm long were selected for measurements. The analysis of the local surface longitudinal and transverse hysteresis loops has allowed us to deduce a vortex magnetic structure with axial core and circular external shell. Moreover, a bamboo-like surface domain structure is confirmed with wave length of around 10 to 15 μm and alternating chirality in adjacent circular domains. The width of the domain wall is estimated to be less than 3 μm. Finally, closure domain structures with significant helical magnetization component are observed extending up to around 1000 μm from the end of the microwire. © 2014 AIP Publishing LLC.

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The capability to control the magnetization process and particularly the motion of magnetic domain walls in low-dimensional magnetic nanowires has great importance for advanced technologies in magnetic memory and logic devices.1,2 While most studies are confined to nanostrip wires, less attention has been paid to cylindrical nanowires and their arrays.3,4 Particularly, cylindrical magnetic microwires have been proposed in sensors and transducer elements5 or magneto-tunable left-handed materials.6 Updated information on applications of such microwires can be found elsewhere.7 A deep knowledge of their magnetization reversal process and magnetic domain structure is thus essential for the optimization of applications. In the present study, we conduct a research work on the local magnetization reversal process and related domain wall motion in cylindrical magnetic microwire with circular magnetic anisotropy. This has been performed in glass-coated magnetic microwires composed by a ferromagnetic amorphous metallic core with a diameter in the range of 0.5–20 μm covered by an insulating Pyrex glass shell (2–20 μm thick). For recent updated information see Ref. 5.

These microwires are fabricated by quenching and drawing technique where the Pyrex, apart from insulating the core from electrical and corrosion viewpoints, induces strong mechanical stresses. Such stresses are frozen in during the quenching and drawing production, and result from different origins: (i) the thermal quenching, (ii) the drawing process, and (iii) from the strains arising due to the different thermal expansion coefficients of insulating coating shell and metallic core. These stresses result in significant magnetoelastically induced anisotropy due to the magnetostrictive effect, determined by the alloy composition. Thus, magnetic properties of amorphous microwires are determined by the balance between shape and magnetoelastic anisotropies.8–10 Regarding the domain structure, the middle part of wires is typically homogeneously magnetized while at the ends magnetic moments redistribute to minimize the stray field energy, which gives rise to local closure domain structures.

For positive magnetostriction (i.e., Fe-based alloys), a reinforced uniaxial longitudinal anisotropy is achieved. When magnetized along the axis, microwires exhibit the so-called bistable magnetic behavior and the magnetization reverses by depinning of a single domain wall from the closure domains at one end of the wire and their propagation along the wire. This process results in squared hysteresis loops.11,12 In the case of vanishing magnetostriction (i.e., Co rich CoFe alloys), the ultrasound wire exhibits a multidomain structure. In this case, the existing walls can almost freely move in a quasi-reversible way, giving rise to a very high initial susceptibility and to the giant magnetoimpedance effect.13,14

In the case of negative magnetostriction (i.e., Co-based alloys), the circular magnetoelastic anisotropy is strong enough to overcome the uniaxial longitudinal shape anisotropy and to define a circumferential easy magnetization direction. Under longitudinal applied field, the demagnetization process takes place by a quasi-reversible magnetization rotation from the circumferential to the axial direction.15 The corresponding nearly non-hysteretic loop is characterized by an almost constant susceptibility until reaching the circular anisotropy field at the region close to the magnetic saturation. In addition, a very small hysteresis can be detected while studying the remanence state in detail. Such nearly vanishing hysteresis was suggested to come from a small cylindrical domain around the wire axis and longitudinal magnetization direction. This structure corresponds to a vortex core and appears in order to reduce the exchange energy.

Recent studies have been performed on negative magnetostriction wires, and particularly on their static and dynamic
microwave response. The magnetic behavior of these circularly magnetized wires is relevant for the development of sensor technologies, as well as in applications requiring high controllable magnetic permeability. Particularly, the circular anisotropy field can be tailored simply by tuning the alloy composition as well as by suitable thermal treatments.

Most usually, magnetic behavior is experimentally determined by fluxmetric induction or VSM magnetometers where information of magnetization process in the whole sample is obtained. Alternatively, magneto-optical Kerr effect, MOKE, has been proved to be very powerful technique to gain information on local magnetic state, particularly at the micrometric scale. Several reports have been published recently on MOKE in microwires and their magnetization reversal process. The axial magnetization profile has been determined allowing one to unveil the complex magnetic domain structure near the ends of positive magnetostriction microwires. In negative magnetostriction microwires, the nucleation of circular domains has been successfully driven with alternating electric current excitation over a wide range of frequencies and amplitudes of the magnetization reversal process. The axial magnetization profile has been determined allowing one to unveil the complex magnetic domain structure near the ends of positive magnetostriction microwires. In negative magnetostriction microwires, the nucleation of circular domains has been successfully driven with alternating electric current excitation over a wide range of frequencies and amplitudes of the magnetization reversal process.

Although a number of studies have been performed specifically on the role played by the negative magnetostriction value and the strength of the stresses coming from the Pyrex coat of variable thickness, there are still some open questions. In this manuscript, we profit of a very sensitive magneto-optical Kerr effect device to determine the magnetic distribution profile with spatial resolution less than the microwire diameter. Also, the magnetization process associated to the vortex domain structure in circularly magnetized microwires is inferred.

The amorphous glass-coated wires were fabricated in the quenching and drawing cast unit of our laboratory. The nominal composition Co$_{77.5}$B$_{15}$Si$_{7.5}$ with negative magnetostriction constant ($\lambda_s \approx -1 \times 10^{-6}$) was selected to ensure the circular anisotropy. Pieces of 2 cm long microwires were taken for the magnetic measurements. The metallic core diameter of the microwire was $d_{mic} \approx 7.6 \mu m$ and total diameter $D_I \approx 30.8 \mu m$.

The magnetic characterization was performed by magneto-optical Kerr effect in a NanoMOKE-2 equipment, from Durham Magneto Optics Ltd. A polarized laser light with beam diameter of about 3 $\mu m$ was reflected from the microwire to the detector. In our MOKE configuration, the laser beam is incident on the sample with an angle of 45° so that, both the longitudinal (LMOKE) as well as the transverse (TMOKE) Kerr signals can be recorded simultaneously. In the case of LMOKE, the change of polarization is proportional to the in-plane component of the magnetization parallel to the light plane of incidence, that is, the wire axis. TMOKE signal is proportional to the in-plane magnetization component perpendicular to the wire axis. The non-planar surface of microwires and the glass coating introduce additional laser beam reflection This problem was solved using the laser beam with a very small diameter and a selection of a suitable diaphragm located just before the MOKE sensors. In our system, the diaphragm is the objective lens which collects the reflected beam. The experimental setup is schematically shown in Figure 1. A quadrupole electromagnet supplying the longitudinal magnetic field was incorporated to the setup. The electromagnet gap size is 3 cm, which allows one to achieve a homogeneous magnetic field on the whole 2 cm microwires length. The piece of the microwire was fixed on a Si substrate. The laser spot was focused at different distances from the end of the wire. Its spatial resolution was equal to the laser spot diameter ($\sim 3 \mu m$). At the center of the microwire, the measurements were taken at intervals of around 10 $\mu m$.

First measurements were performed in the central region of the microwire to determine the MOKE surface hysteresis loop under the AC sinusoidal (11 Hz frequency) magnetic field applied parallel to the wire axis. Figs. (a) and (b) show, respectively, typical LMOKE and TMOKE magnetic loops acquired simultaneously under longitudinal applied magnetic field. LMOKE loop in Fig. (a) demonstrates an almost reversible magnetization curve, typical for negative magnetostriction glass-coated amorphous microwires with a well defined circular anisotropy field ($H_c = 120 Oe$) and modest hysteresis (coercivity of $H_c = 5 Oe$). When the wire is magnetically saturated parallel to its axis (maximum LMOKE signal), the TMOKE signal is nearly constant with a vanishing value as shown in Fig. (b). As the applied field is reduced from its maximum value, and when the circular anisotropy field is reached the TMOKE signal starts to increase. Consequently, the transverse magnetization increases up to reach a maximum value at the transverse coercive field, $H_{cT} \approx 10 Oe$ ($H_{cT} \approx 2H_c$).

A complementary analysis of both, LMOKE and TMOKE, magnetization curves enables a simple interpretation of the local magnetization process at the given laser beam position as a nearly reversible magnetization rotation. The longitudinal hysteresis loop in Fig. (a) is typical for a sample (i.e., microwire) with magnetization easy axis transverse (i.e., circumferential) to the direction of the applied field. The wire is nearly magnetically saturated (i.e., single domain) along its axial direction for applied field above 150 Oe. Its remanence is very small which indicates a mostly circumferential orientation of magnetic moments. Such circumferential magnetic configuration is also confirmed by the maximum of the TMOKE in Fig. (b) for zero applied field. The magnetic state evolves from a single domain
magnetic state with longitudinal magnetization to the circumferential magnetization state at the remanence and back to the single domain state with the opposite direction of the longitudinal magnetization in negative applied fields. The observed relatively modest irreversibility’s of LMOKE and TMOKE curves should be ascribed to the presence of a vortex structure in the core of the microwire. At the vortex core, that is the wire axis, magnetization is axially oriented. As the distance from the wire axis increases, it rotates towards a circumferential orientation. The vortex radius, when magnetization is fully circumferentially oriented, depends on the strength of the circular magnetic anisotropy. In the present case, the vortex radius is smaller than that of the metallic microwire. As a result, magnetization is fully circularly oriented at the wire surface.

The difference between $H_l$ and $H_t$ should be related to the switching of the remaining longitudinal magnetization component (the vortex core) at $H^{c}_{t}$, as will be later analyzed. Note that due to the surface character of the MOKE measurements, the LMOKE surface loop is not directly sensitive to the magnetization in the vortex core of the microwire. However, the TMOKE loop is sensitive to the vortex core switching through the exchange coupling between surface and core magnetization.

Figure 3 shows the TMOKE loops recorded at different positions of the laser beam in the central region (nearly at $\approx 10 \, \mu m$ from the ends) of the microwire. These measurements indicate the occurrence of different magnetic responses. The loops in Figs. 3(a)–3(d) correspond to the most typical situations, measured at different laser spot positions along the central region of the microwire, showing similar or slightly different amplitudes and hysteresis. Particularly, Figs. 3(c)–3(e) were measured with spatial interval of $10 \, \mu m$. Note also that TMOKE signals show opposite signs in Figs. 3(a) and 3(b), that denotes a different rotation sense of circumferential magnetization at each local position of the laser beam (which can be ascribed to the local vortex chirality).

The observed types of the magnetization processes can be understood taking into account the surface domain structure of microwires with negative magnetostriction, schematically shown in Fig. 3(h). Owing to the dominant circular magnetic anisotropy, bamboo-like domain structure is formed with magnetization circumferentially oriented inside each domain denoted by red spots (1) and (2), with opposite chirality in adjacent domains, separated by a domain wall (3). When the laser beam is focused onto a circular domain (i.e., magnetization states marked by red spots (1) or (2) in Fig. 3(h)), TMOKE signal is maximum and nearly the same for both branches of the hysteresis loop (i.e., loops in Figs. 3(c) and 3(d)).

Nevertheless, less frequently, we measured the magnetization reversal loops presented in Figs. 3(e) and 3(f). At the position schematically marked by the red spot (3), the laser beam is located on the domain wall separating domains with opposite rotation senses (vortices with opposite chiralities). The amplitude of the TMOKE signal decreases significantly when the focused region contains domains with different chirality, and can be practically constant around zero value (i.e., see remanent states in Figs. 3(e) and 3(f)). From that, we infer that the domain structure is changed during magnetization reversal: at the same laser position, domain structure at remanence can be different after saturation in positive or negative magnetic field, that is, the position of DW with respect to laser beam is changed. In spite of the technical uncertainties introduced by the laser spot positioning that makes one to compare with much caution the absolute values of TMOKE signal, we observe a general trend in its amplitude when laser is located in the indicated positions 1-2-3 in the schematic view of Fig. 3(h). Thus, absolute values for TMOKE signals reach 20–30 mV in the case of Figs. 3(c) and 3(d), 10–15 mV in Fig. 3(a), 3(b), around 5 mV in Figs. 3(e) and 3(f), and 2 mV in Fig. 3(g).

The hysteresis loop presented in Fig. 3(g) is only found after extremely careful positioning of the laser spot. It corresponds to a critical situation when the domain wall at the remanent position is symmetrically placed with regards to the laser spot so that, it results in an opposite sense of magnetization rotation at each remanence. This result confirms us that the domain wall width is smaller than $3 \, \mu m$, the size of the laser beam, and that the distance moved by the wall between the two remanence states is larger than $3 \, \mu m$. From careful analysis of measurements at different regions, we deduce a domain width of around 10 to $15 \, \mu m$. While the magnetoelastic anisotropy is in the origin for the circumferential orientation of magnetization at the surface, the formation of bamboo domain structure with domain walls separating circular domains with opposite chirality has been for years a matter of discussion. Fully homogeneous distribution of circumferential magnetic moments along the wire’s length would not require the expense of energy required to form such domain walls. Nevertheless, small perturbations
of the axial symmetry, ascribed to fluctuations in the mechanical stresses during the fabrication process, would lead to the appearance of surface or even volume magnetic charges. Thus, domain walls would form to reduce the corresponding stray field energy. Proper micromagnetic simulations in microwires with realistic dimensions are rather difficult because of computing size limitations. Nevertheless, our experimental results are in general agreement with recently reported simulations on microwires 4 μm in diameter and about 100 μm in length.

Additional experiments have been performed to get finer information on the magnetic structure and the magnetization reversal process at the region close to the ends of the wires. The magnetization processes at the two regions close to the ends of magnetic wires are typically different. The difference comes from a different local domain structure owing to: (i) magnetostatic stray fields energy minimization, (ii) the presence of local defects (the very end of the microwire can be considered as the main defect), and (iii) in the case of glass-coated amorphous microwires, different stress distribution.

Figure 4 shows LMOKE and TMOKE magnetic loops acquired simultaneously at 40 μm distance from the end of the microwire. The LMOKE loop presents an enhanced remanence, and the coercivity is increased by an order of magnitude (\(H_c \approx 30\) Oe) in comparison with the measured in the central region of the microwire. The maximum amplitude of the TMOKE signal is decreased significantly to around 0.5 mV. This demonstrates an irreversible process with contributions from magnetization rotation and/or domain wall
motion owing to a more complex domain structure. Figure 4(c) shows the schematic view of the proposed magnetic configuration at the microwire end at the remanence when magnetization takes a helical direction. Consequently, local LMOKE loop remanence becomes larger while TMOKE signal is reduced.

In addition, the TMOKE signal rotation sense under applied longitudinal magnetic field shows that the magnetization chirality is opposite for two different directions of the applied field. Note also that the transverse coercivity, $H_{tc}$, i.e., the switching field of the vortex core, is the same as in the microwire center.

A study of MOKE signals at the region close to the ends indicates us that LMOKE loops show increased coercivity and remanence up to a distance of around 1000 $\mu$m. That would correspond to the size of the region near the ends where a kind of closure domain structure extends.

In summary, the magnetization process under axial magnetic applied field has been studied in 2 cm long microwire with circular magnetic anisotropy. From the measurements of the local surface longitudinal, LMOKE, and transverse, TMOKE, hysteresis loops with micrometric precision in different regions along the microwire, we extract the following conclusions: (i) a vortex structure is inferred from MOKE measurements with a longitudinal magnetization in the core and external shell with circumferential magnetization, (ii) surface bamboo-like domains, 10 to 15 $\mu$m long, with different alternating chirality are deduced, (iii) in the middle region, the domain wall moves a distance longer than 3 $\mu$m between opposite remanent states, and (iv) in the region near the ends, a closure domain structure with helical magnetization orientation is formed, extending up to around 1000 $\mu$m.

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