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Domain wall propagation in Fe-rich amorphous microwires

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ABSTRACT

The domain wall (DW) propagation in magnetically bistable $Fe_{74}Si_{11}B_{13}C_2$ amorphous microwires with metallic nucleus diameters of 12–16 μm has been investigated in order to explain high DW velocities observed in Sixtus–Tonks like experiments. In micrometric wires, the boundary between two head-to-head domains is very elongated. The DW mobility normal to the wall surface is reduced by the domain aspect ratio and is in the range of a few m/s/Oe in the linear regime. The experimental results in the viscous regime could be quantitatively explained in terms of the domain length and normal mobility limited by the eddy currents and spin relaxation losses.

1. Introduction

Novel magnetic micro- and nano-structures as magnetic nanowires offer prospects for a new generation of spintronic devices for applications in magnetic logics and magnetic memories [1,2]. Planar nanowires and circular cross section amorphous microwires are most suitable for achievement of fast and controllable domain wall (DW) propagation [2–7]. In both systems, quite large values of velocity have been reported. In particular, the DW velocity in glass-coated Fe-based microwires with positive magnetostriction and axial magnetic anisotropy can reach a few km/s in a linear regime exceeding the sound speed in these materials [3–5]. The maximum velocity value is at least one order of magnitude higher than that in nanowires and other magnetic fibres. At certain conditions, DW velocity in microwires experienced an abrupt increase for elevated magnetic fields, which could be interpreted as creation of an additional DW on defects in front of the moving DW [8]. Yet, the reported DW velocity in the viscous regime achieves 2.5 km/s [9], which is not reported for other magnetic systems.

The phenomenon of extremely fast magnetisation reversal in glass-coated magnetic microwires with diameters in the range of 1–30 μm has generated a considerable interest (see review in Ref. [10]). Glass-coated wires can be easily produced with amorphous or nanocrystalline structure of its metallic core [11–13]. In the absence of the crystalline structure, the magnetic anisotropy is mainly determined by the balance of magnetoelastic and magnetostatic energies. In the case of Fe-based positive magnetostriction wires the easy anisotropy is predominantly in the axial direction. Then, the domain structure comprises rather large axial domains in the central region of the wire and closure domains at the surface and the wire ends. This results in a bistable magnetisation process characterised by a propagation of a single domain wall along the entire wire [3,4,10]. Such magnetisation reversal requires a certain minimum length of the wire, which depends on a number of parameters including the metallic core diameter, saturation magnetisation, internal stresses, etc. The critical length is typically in a cm range but could be decreased down to few mm in thinner wires with the diameter below 10 μm. This already suggests the formation of very elongated domains. Large values of the axial domain wall mobility and velocity reported for these wires should be associated with the domain shape, which is the focus of this work. Recently, some results on the length of the propagating domain, its dependence on the wire diameter and velocity have been also reported [14,15]. The transverse wall structure was proposed and the obtained results do not seem to be consistent with the induced voltage pulse duration. The transverse and vertex walls separating head-to-head domains could form in planar nanowires [16] but in micrometric circular cross section wires the formation of elongated domains is more likely. This concept is assumed here and it is demonstrated that the experimental results in the viscous regime could be well explained in terms of the domain length and normal mobility limited by the eddy currents and spin relaxation losses.

2. Experimental

Samples of $Fe_{74}Si_{11}B_{13}C_2$ amorphous microwires with metallic core diameter of 12–16 μm showing almost rectangular hysteresis loops were used for measurement of the domain propagation

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speed. The wires have been prepared using the Taylor–Ulitovsky method allowing the fabrication of long homogeneous metallic wires coated by glass and having a circular cross section. The DW velocity was obtained in Sixtus–Tonks like experiments, as described recently elsewhere [3–5,9,10]. The domain was driven by the axial magnetic field H supplied by a long solenoid. One end of the wire sample is placed outside the solenoid to control the direction of DW propagation since such configuration provides the depinning of the DW only from one end of the wire [4,9]. We also used single layered wounding of the magnetising solenoid with reduced number of turns in order to reduce the time of transient process and in this way to avoid the situation when the DW can start propagating while H is still growing. The pick-up coils and the detection electronics are carefully designed to avoid substantial influence of the detection circuit on the induced voltage pulse (such as the ringing effect) [14]. In some cases, resistors have been connected in parallel to the pick-up coils to suppress the oscillations. We also were able to resolve in time the induced voltage from propagating DWs in order to evaluate the shape of moving DWs.

A modified set-up consists of a long excitation coil (with length of 140 mm and 10 mm in diameter) and three pick-up coils (2 mm long and 1 mm inner diameter) separated from each other by a distance of about 27 mm in order to ensure injection of a single DW and correct estimation of its velocity [9]. Each pick-up coil is connected to the corresponding input of the digital oscilloscope. We used 3 pick-up coils in order to detect the possible nucleation and subsequent propagation of several DWs. The detected voltage pulses in each pick-up coil are shown in Fig. 1, which represents screen-captured images displaying an averaged induction signal arising during the DW propagation. The voltage pulses have a width that is a substantial fraction of their spacing, indicating qualitatively that the domain walls indeed are far from abrupt.

The domain wall propagates along the wire with an axial velocity v, which in the viscous regime is linearly related with the driving field H

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

where μ is the DW mobility and H_0 is the critical propagation field. The velocity v in Eq. (1) was deduced from the time interval Δt between the induced voltage pulses at different pick-up coils separated by a distance b as

$$v=\frac{b}{\Delta t} \tag{2}$$

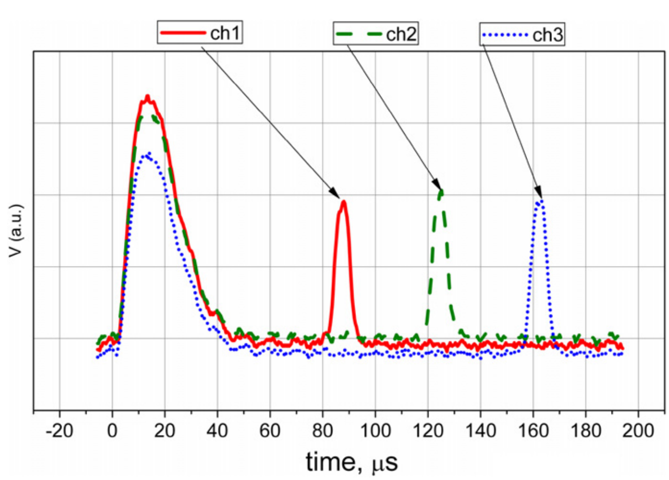

Fig. 1. Voltage pulses from pick-up coils measured in $Fe_{74}Si_{11}B_{13}C_2$ microwires.

The value of Δt in Eq. (2) was measured between the occurrences of peaks in the induced voltage pulses. Fig. 2 shows the dependence of the DW velocity on an applied magnetic field, which is almost linear (not very large driving magnetic fields were used). Yet, the velocity is reaching a value as high as about 1700 m/s.

3. Discussion

Analysing the results on the DW velocity and the inductive voltage pulses in the pick-up coils, it is possible firstly to explicitly confirm, that the moving domain length is indeed large. If the detected voltage pulse distortion is not essential and the wall moves uniformly and without oscillation, which is reasonable in the linear regime, the wall length L is directly proportional to the pulse duration τ: $L=v\tau$. Using the data of Fig. 1 where the pulse duration is about 6.5 µs and the DW velocity is 475 m/s, yields $L=0.31$ cm. It is also possible to extract the moving domain shape from the voltage pulse assuming that the wall has a cylindrical symmetry and its radial distribution with respect to the axial coordinate z at time t is described by some function $R(z-vt)$, $R(0)=0$, $R(L)=a$, where it is assumed that the axial domain expands through the whole metallic interior of radius a. The induced voltage pulse is proportional to $R\partial R/\partial \varsigma$, $\varsigma=z-vt$. Then, integrating the voltage pulse the DW shape can be obtained as shown in Fig. 3. It is seen that the wall shape is close to cylindrical at one end and has a narrow tail at the other. This result is very reasonable as it corresponds to decreasing the magnetostatic energy at minimum of the surface area. If we assume such a domain shape for the further analysis, the boundary between the

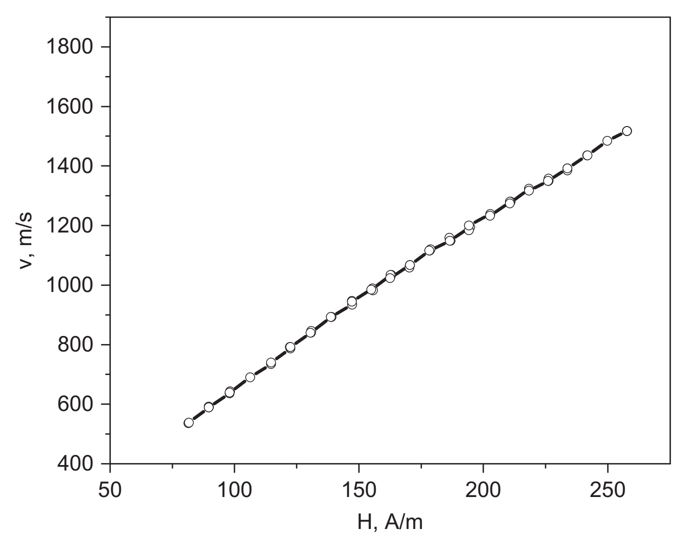

Fig. 2. Dependence of DW velocity on applied magnetic field measured in magnetically bistable $Fe_{74}Si_{11}B_{13}C_2$ amorphous microwire.

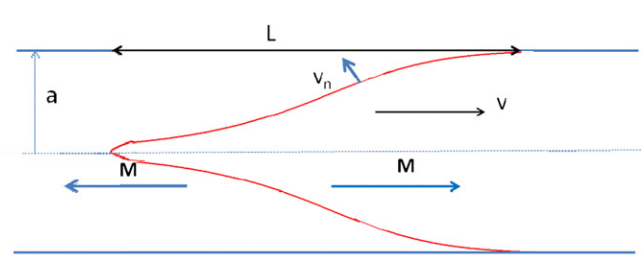

Fig. 3. Domain wall shape obtained from integration of the induced voltage pulse in the assumption of cylindrical symmetry.