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Diffusion-damped domain wall dynamics

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\textbf{Abstract.} In the given work, the influence of diffusional damping on the domain wall dynamics of heat treated FeSiBP microwires is presented. Two regions of the domain wall dynamics have been found. At low applied fields diffusion damping prevails, keeping the domain wall velocity and mobility low. At higher fields, the diffusional effects are overcome and domain wall velocity increases steeply and so does the domain wall mobility.

1. Introduction
Modern spintronic devices employ domain wall dynamics in thin magnetic wires to store or transfer information [1,2]. Therefore, the interest of scientists in the motion of domain walls has grown up over the last years. Generally, the displacement of a domain wall subjected to an applied magnetic field $H$ is mainly driven by the domain wall damping $\beta$ [3]:

$$v \sim (\mu_0 M_s/\beta)(H-H_0)$$

where $v$ is the domain wall velocity, $\mu_0$ is the magnetic permeability of vacuum, $M_s$ is the saturation magnetization and $H_0$ is a critical propagation field, below which the domain wall cannot propagate.

Two contributions to the domain wall damping have been identified in the last century: eddy current based damping [4] and damping due to magnetic relaxation of moments [5]. Few years ago, a third contribution to the domain wall damping (based on the diffusional structural relaxation) was discovered in thin magnetic wires [6]. This contribution becomes relevant when eddy currents are negligible (ferrites because of high resistivity or nanowires due to small dimensions) and when magnetic relaxation is very small too (materials with very low anisotropy and thus with small Gilbert damping; i.e. FeNi (81% of Ni) nanowires [2]). Hence, in those cases the locally induced anisotropy (via structural relaxation or atomic pair ordering [7]) could be the most important one driving the domain wall dynamics.

In this contribution, a study of the influence of structural relaxation damping on the domain wall dynamics of heat treated amorphous glass-coated microwires is presented. Their unique magnetization process (single Barkhausen jump) due to their quasi-monodomain structure makes them ideal materials to investigate single domain wall dynamics. The stabilization of the domain structure during the thermal treatment increases the domain wall damping. Such stabilization can be removed by applying a high enough applied field or by increasing the measuring frequency.

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2. Experimental

Positive magnetostriction glass-coated amorphous microwires with nominal composition Fe$_{76}$Si$_{9}$B$_{10}$P$_{5}$ were produced by the quenching and drawing method. This novel alloy composition exhibits a combination of high glass-forming ability, high saturation magnetization and low coercive field [8] and therefore it is ideal to study the structural relaxation effects. The diameter of the ferromagnetic nucleus of the wires was 14 $\mu$m and the total diameter about 45 $\mu$m; pieces 10 cm in length were selected for the experiments. The sample was annealed at 473 K in He atmosphere for 1 hour. The domain wall dynamics were studied by means of a Sixtus and Tonks-like set-up [4,6] composed of three coaxial coils: A magnetising solenoid plus two symmetrically disposed pick-up coils 60 mm apart. The damping was investigated varying the frequency of the square-shaped applied magnetic field between 20 Hz and 2 kHz and temperature dependent measurements were carried out in the range from 80 K up to 450 K.

3. Results and discussion

As previously discussed, structural relaxation damping, $\beta_s$, should be the most important one in the case of alloys having high resistivity and low anisotropy. This is the case of amorphous microwires that can relax even at low temperatures (due to their metastable state consequence of the amorphous structure). The structural relaxation damping $\beta_s$ is given by [6]:

$$\beta_s \propto \tau <(\varepsilon_{\text{eff}})^2>(c_0/kT)G(T,t)$$

(2)

where $\tau$ is the relaxation time of the defects, $\varepsilon_{\text{eff}}$ is the interaction energy of the domain wall with the defects, $c_0$ is the density of defects, $k$ is the Boltzmann constant and $G(T,t)$ is a so-called relaxation function [9]. The effect of such damping can be tailored by varying experimental parameters ($T, t$) [6], by means of a thermal treatment [10] or by a combination of both. Thermal treatments below the Curie temperature usually lead to a stabilization of the domain structure (through diffusional directional ordering), particularly in materials exhibiting noticeable structural relaxation [7]. Such effect is manifested in the wires here considered by measuring the domain wall dynamics (see figure 1). As it can be noticed, the domain wall damping, $\beta_s$ strongly varies with temperature being extremely high at low temperatures (where the domain wall mobility $S \sim 1/\beta_s$ is almost zero) and decreases with temperature (see figure 2). Small variations of resistivity (and anisotropy) with temperature cannot explain such variation of $\beta_s$. Consequently, the most important contribution to damping must arise from structural relaxation (given by eq.2) due to a stabilized domain structure [6].

![Figure 1. Domain wall dynamics on a FeSiBP microwire heat treated at 473 K measured at a frequency 20 Hz, Measuring temperature as a parameter.](image1)

![Figure 2. Temperature dependence of the domain wall damping of a FeSiBP microwire heat treated at 473 K. Frequency of the applied field as a parameter.](image2)
As shown in figure 3, the structural relaxation damping can be removed by measuring at a higher frequency (when the measuring frequency is higher than the inverse of relaxation time of the defects, 1/τ) since the defects have no time to increase the local anisotropy through the structural relaxation. Hence the structural relaxation damping as well as the overall damping are very low (see figure 2). However, the domain wall dynamics measured at 2 kHz have a complex behaviour consisting of three regions. This phenomena has already been studied and was theoretically explained in [11,12]. At low fields the domain wall damping is governed by structural relaxation. In this area, the domain wall propagates at low velocity and is damped by the diffusion motion of the mobile defects that try to follow the spin precession within the domain wall. Such regime is called the diffusion-damped regime [11]. However, as the velocity of the domain wall increases, the domain wall detaches from the cloud of the defects. This happens when the precession frequency of the spins in the wall is higher than the inverse relaxation time of the defect structure. This region corresponds to the viscous regime. Theoretically, the border between both regions is abrupt and discrete [11]. However, the wide distribution of defects in amorphous materials results in a wide range where the domain wall dynamics changes from diffusion to viscous-damped. The relaxation time of the defects, τ, decreases with temperature according to the Arrhenius law so that increasing temperature results in a faster domain wall propagation at lower fields (even within the diffusion damped regime).

Figure 3. Domain wall dynamics on a FeSiBP microwire heat treated at 473 K measured at a frequency of 2 kHz, which results in a low stabilization effect.

Figure 4. Domain wall dynamics on a FeSiBP microwire heat treated at 473 K. Diffusion-damped dynamics prevails at low frequencies, while for higher frequencies the viscous regime appears in the high field region.

Figure 4 shows the domain wall dynamics measured at 123 K in a wide range of measuring frequencies (20 Hz - 2 kHz). Here, several characteristic frequencies can be identified [13]: The measuring frequency f, the relaxation frequency f_r (inversely proportional to the relaxation time of the defect, f_r~ 1/τ), and the precession frequency of the spin within the domain wall f_p. For low measuring frequencies (f<f_r) the system is in thermal equilibrium but its response to the precession frequency is in the adiabatic regime; hence the defects cannot follow a fast domain wall displacement [13]. Structural relaxation damping is high and diffusion damped domain wall dynamics prevails in the whole measured range of applied magnetic fields. For higher frequencies (f>f_r), the system remains in a metastable state, and the defects are in non-thermodynamical equilibrium. The distribution of the
defects is random and structural relaxation damping is small. Consequently, the domain wall can propagate much faster. However, the propagation at low fields is slow since it is still damped by diffusion defect motion. When the domain wall velocity increases over the limit \( f_c < f_p \), the domain wall detaches from the cloud of the defect and its velocity increases steeply. This happens for a domain wall velocity at around 550 m/s. It can be noticed that the overall domain wall damping in the diffusion-damped regime is influenced by the frequency of the applied magnetic field through the structural relaxation damping (as given by eq. 2) that decreases with frequency. However, this dependence is no longer observed in the viscous regime, observed at higher fields and frequencies, since the effect of relaxation takes no place in that regime.

4. Conclusions
The influence of structural relaxation on the domain wall damping of a heat treated \( \text{Fe}_{76}\text{Si}_{9}\text{B}_{10}\text{P}_{5} \) amorphous microwire has been presented. The stabilization of the domain structure due to annealing at 473K leads to the appearance of two domain wall dynamics regimes. At low fields, the diffusion-damped regime is strongly influenced by structural relaxation. At high fields, the domain wall detaches from the defects and a viscous regime with higher domain wall mobility and lower damping appears. Structural relaxation damping allows manipulating the domain wall dynamics particularly in materials exhibiting high resistivity (thus eddy current damping can be ignored) and small anisotropy (thus magnetic relaxation damping can be neglected).

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