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Comparison of ferromagnetic resonance between amorphous wires and microwires

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ABSTRACT

Measurements of magnetoimpedance in amorphous wires and microwires at the GHz region are presented here. The maxima observed in the magnetoimpedance of different samples in the high frequency range are attributed to the ferromagnetic resonance (FMR) that occurs when a sample is submitted to a longitudinal static magnetic field and an oscillating transversal field. While the appearance of a peak on the resistance and the drop of the inductance is explained by means of FMR, the dependence of the width of that resonance with different parameters (magnetic field, stress distribution, sample size, etc.) is not clearly understood, and therefore additional works to explain the value of the resonance width are needed. It is interesting to consider firstly, the influence of the diameter of the sample and thus the stress distribution on the FMR. The size and position of the FMR is found to be completely different for diameters ranging from 24 to 171 μm. The dependence of the frequency value at which the peak of the resistance is found can be explained by the different values of the anisotropy field in the sample. The width of the FMR changes drastically with the diameter of the sample and with the applied magnetic field and they will be discussed in this paper.

1. Introduction

The magnetoimpedance (MI) effect is observed in soft magnetic materials and phenomenologically consist of the change in the AC impedance, Z, when submitted to a static magnetic field, due to the modification of the transverse permeability. The MI effect originates from the skin effect as a consequence of the changes in the penetration depth induced by the static external magnetic field through the modification of the transverse susceptibility [1–3]. For a wire of radius r_0 and DC resistance R_{DC} the impedance is given in terms of the Bessel functions as

$$\frac{Z}{R_{DC}} = \frac{kr_0}{2}\frac{J_0(kr_0)}{J_1(kr_0)} \tag{1}$$

with

$$k = \sqrt{-j\omega\mu\sigma} \tag{2}$$

where σ is the conductivity of the sample, μ is the magnetic permeability and ω is the angular frequency. At frequencies of tens of MHz the domain structure of wires with diameters of nearly 100 μm suggests to use a core shell-model, but at higher frequencies (100 M Hz or higher) only the external shell dominates their impedance due to the reduced penetration depth. While this model explains the main aspects of the MI in amorphous wires, when increasing the working frequency to the GHz range we must take into account new phenomena like the ferromagnetic resonance that is present in both wires and microwires. Then, the dynamics of the magnetization is given by the Landau–Lifshitz equation of spin motion [4,5]:

$$\frac{\partial \vec{M}}{\partial t} = \gamma \vec{M}\left[H + \left(\frac{2A}{M_S^2}\right)\nabla^2\vec{M} - \left(\frac{\lambda}{\gamma M_S^2}\right)\vec{M} \times \vec{H}\right] \tag{3}$$

where A is the exchange constant, λ is the Landau–Lifshitz phenomenological damping constant and γ is the gyromagnetic ratio. Following the procedure described in [5] we can obtain the frequency-dependent magnetic permeability:

$$\mu(\omega) = \frac{\mu_{DC}}{1-(\omega/\omega_r)^2 + 2j\omega\Delta\omega/\omega_r^2} \tag{4}$$

with μ_{DC} the magnetic permeability at low frequencies, ω_r the frequency at which ferromagnetic resonance occurs and $\Delta\omega$ its linewidth. Introducing this in Eq. (1) we can obtain a peak in the resistance of the sample and a drop in the inductance at the resonance frequency [6].

In this paper we will present a comparison of the FMR for a set of amorphous wires and microwires and a correlation of the parameters governing the FMR with their magnetic properties.

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2. Experimental

Amorphous wires and microwires of compositions $Fe_{77.5}Si_{7.5}B_{15}$, $Co_{68.15}Fe_{4.35}Si_{12.5}B_{15}$, $Co_{68.5}Mn_{6.5}Si_{10}B_{15}$ and $Co_{67}Fe_{3}Cr_{3}Si_{12}B_{15}$ are investigated. The amorphous wires have been prepared at the laboratory by in-rotating-water quenching technique while amorphous glass-covered microwires were prepared by the Taylor–Ulitowsky method. Total and metallic diameters (in glass-covered samples) are presented in Table 1.

For the measurement of the MI we have prepared a system similar to the one described in [7]. To increase the upper frequency limit we substituted the LCR bridge by the Agilent 4287A which allowed us to measure up to 3 GHz and we used a specific test fixture (Agilent 14194A) for this impedance bridge. To ensure the quality of the measurements we performed a calibration considering the transmission line theory to make the corresponding translations of the measuring plane to the sample plane and checked the results with a set of calibrated samples. We found that the error on the impedance was smaller than 10% in the whole frequency range.

3. Results and discussion

In Fig. 1 we have shown the experimental values (circles) for the resistance (a) and inductance (b) for the $Co_{68.5}Mn_{6.5}Si_{10}B_{15}$ microwire at a static magnetic field of 6400 A/m as a function of frequency. We can clearly see the peak of the resistance and the drop of the inductance at 1.1 GHz.

This shape of the curves cannot be explained by the conventional theory of magnetoimpedance, which leads to a progressive increase of the resistance and a decrease of the inductance with frequency. By introducing the frequency-dependent magnetic permeability, (Eq. (4)) we can reproduce the experimental data. To fit those data we proceeded as follows. The conductivity and diameter of the sample were previously measured, then we obtained the μ_{DC} from the lower frequency region, where the resonance has negligible influence (typically frequencies under 500 MHz). The resonance frequency ω_r was obtained from the peak of the resistance, and finally we fitted the linewidth $\Delta\omega$ of the theoretical curve to the experimental data. Very good agreement between theory an experimental data is achieved for most of the samples as shown in Fig. 1, revealing that the model is adequate for these kind of samples. All the studied wires and microwires present similar behavior except the $Fe_{77.5}Si_{7.5}B_{15}$ wire in which the FMR occurs at higher frequencies and no relevant information were obtained for this sample from the measurements.

When increasing the magnetic field, the frequency at which the peak of the resistance is found, displaces towards higher frequencies. It is usual to plot the resonance frequency as a function of the applied magnetic field. When the skin depth is much smaller than the radius of the sample [2], the resonance frequency is given by [6]:

$$\omega_r = \mu_0 \gamma \sqrt{(H - H_k)(H + M_s)} \tag{5}$$

where, M_s is the saturation magnetization and H_k is the anisotropy field. This is the Kittel relation, which has been proved to work with wires although it was obtained for planar samples. In Fig. 2 we have plotted the experimental and theoretical values of the resonance frequency for the $Co_{69.5}Fe_{4.35}Si_{12.5}B_{15}$ amorphous wire where we can see how Eq. (5) describes the field dependence correctly.

In the smaller diameter microwires some discrepancies with respect to the theoretical curve of the resonant frequency versus

Table 1
Metallic and total diameters of the samples.

Composition	Metallic diameter (μm)	Total diameter (μm)
Wires		
$Fe_{77.5}Si_{7.5}B_{15}$	130.0	–
$Co_{68.15}Fe_{4.35}Si_{12.5}B_{15}$	125.0	–
$Co_{68.5}Mn_{6.5}Si_{10}B_{15}$	171.4	–
$Co_{67}Fe_{3}Cr_{3}Si_{12}B_{15}$	124.9	–
Microwires		
$Fe_{77.5}Si_{7.5}B_{15}$	24	39
$Co_{68.15}Fe_{4.35}Si_{12.5}B_{15}$	27	58
$Co_{68.5}Mn_{6.5}Si_{10}B_{15}$	27	59
$Co_{67}Fe_{3}Cr_{3}Si_{12}B_{15}$	25	48

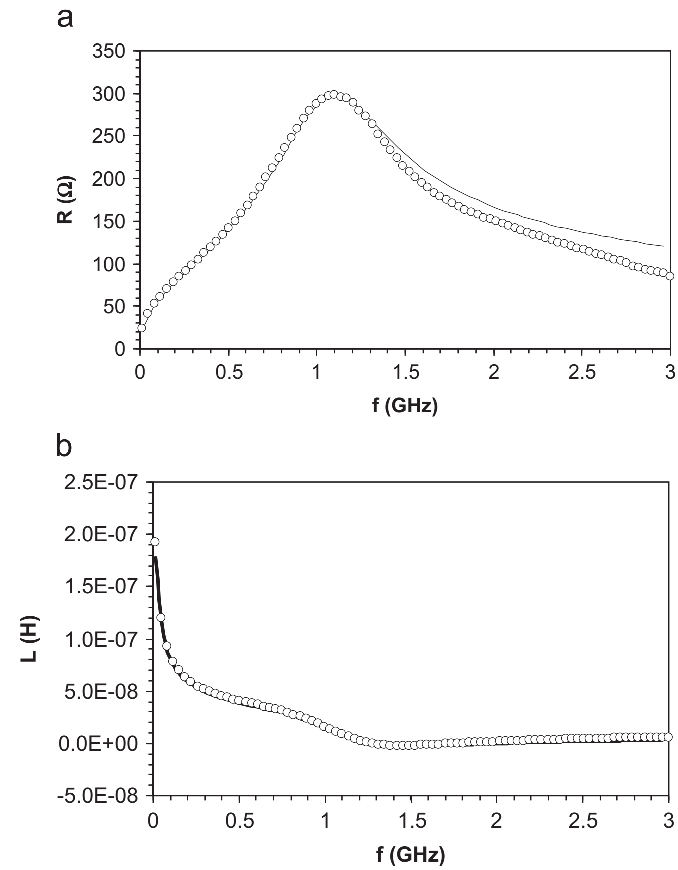

Fig. 1. Experimental (circles) and theoretical (lines) resistance (a) and inductance (b) for the $Co_{68.5}Mn_{6.5}Si_{10}B_{15}$ microwire at 6400 A/m.

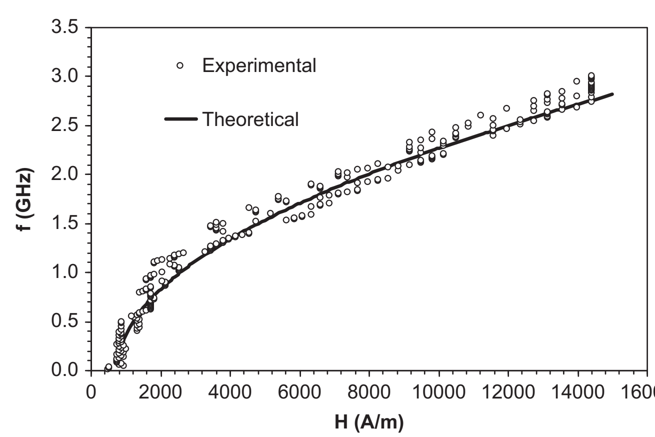

Fig. 2. Experimental (circles) and theoretical (line) resonance frequency versus the external magnetic field strength.