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Microwave response of amorphous microwires: magnetoimpedance and ferromagnetic resonance

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Abstract

It has been established that giant magnetoimpedance (GMI) in amorphous wires is due to a rapid change in the skin depth, caused by the low-field sensitivity of the azimuthal dynamic permeability (a classical electromagnetic effect). In 5 μm diameter glass-covered amorphous wires, GMI may be observed at the microwave range. A correlation between GMI and ferromagnetic resonance (FMR) was proposed in this microwave range. We have measured the microwave response of amorphous microwires for several alloys from the system $(Co_{100-x}Fe_x)_{75}Si_{15}B_{10}$ ($x = 2$, 6, 10) with positive, zero, and negative magnetostriction, respectively. Our main results indicate: (i) GMI and FMR effects are well separated at different fields, (ii) GMI follows the magnetization process, confirming its classical electromagnetic origin, and (iii) FMR fields are also affected by the skin effect.

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Keywords: Amorphous wires; Magnetoimpedance; Ferromagnetic resonance

1. Introduction

Giant magnetoimpedance (GMI) has attracted a considerable attention during the last years mainly because of its potential use in magnetic sensors [1], but it also raises some fundamental questions that remain unanswered about the physical process. There is general agreement [2,3] that the phenomenon in the MHz regime is a classical electromagnetic effect caused by the rapid reduction in skin depth $\delta = (2\rho/\mu_0\mu_\phi\omega)^{1/2}$ due to the low-field sensitivity of the azimuthal (or circumferential) dynamic permeability μ_ϕ, in a material with DC resistivity ρ exposed to an azimuthal AC field of angular frequency ω. According to these models, the smaller the radius of the wire, the higher the frequency range needed for the GMI effect to occur. With wire diameters in the range of a few μm, the effect can be observed at the microwave (GHz) range. It was suggested [4,5] that in this microwave frequency range, a correlation between

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the GMI effect and ferromagnetic resonance (FMR) may exist.

Although FMR would make the azimuthal permeability change dramatically, according to previous results on similar samples [6,7], this effect only appears at high fields (much higher than those needed for GMI at microwave frequencies). For the magnetic fields of interest from the viewpoint of GMI (tens of Oe or less), the samples cannot be saturated, a requirement for FMR which, consequently, clearly separates it from GMI. With all this in mind, we have measured the microwave response of several glass-covered 5 μm wires both at the low- (<10 kA/m) and high-field (up to 725 kA/m) ranges. Our data confirm the dominance of classical electromagnetic effects related to the initial magnetization processes at low field, while FMR clearly dominates the response at high fields. Only in some cases, the low-field response is affected by ferromagnetic antiresonance (FMAR), but both effects can be easily distinguished in the field scans.

2. Experimental

Pyrex-coated amorphous microwires were prepared by the Taylor–Ulitovsky technique. The samples consisted of a metallic core (5 μm diameter), covered by an insulating Pyrex glass coating (3 μm thick). Several alloys of the system $(Co_{100-x}Fe_x)_{75}Si_{15}B_{10}$ with $x = 2$, 6 and 10 were chosen for the ferromagnetic core. Saturation magnetization ranges from 0.8 to 0.9 T, while saturation magnetostriction changes from -2 to $+4$ ppm, both on increasing Fe content. The magnetization processes have been published in detail elsewhere [8]. The magnetic anisotropy is controlled by magnetoelastic effects via the stresses frozen during the fabrication process. They also determine the spontaneous domain structure. In positive magnetostriction alloys, a core domain of axial magnetization is surrounded by a surface domain where spins are transversely oriented. In the case of negative magnetostriction, the easy axis of magnetization is essentially circumferential. The "compensation" composition (that for which magnetostriction vanishes) lies around $x = 7$.

Microwave losses were measured using a simple cavity perturbation technique [9]. A specially designed rectangular cavity was built, in which small holes were made on each two opposite faces to slide the wires through them, and place the wires where the microwave magnetic field, h_{RF}, is a maximum. Thus, it was possible to position the different samples exactly in the same place, minimizing the influence on the measurement of variable coupling between the sample and the cavity. Additionally, measurements were made with h_{RF} perpendicular to microwires axis which was parallel to DC fields. The microwave spectrometer operates at around 10 GHz and the maximal magnetic field was 1.6 T. In the following, both magnetoimpedance and FMR response are represented by the relative change in microwave loss, $\Delta R/R$, as a function of H. That is,

$$\frac{\Delta R}{R} = \frac{R(H) - R(0)}{R(0)}. \tag{1}$$

The magnetic characterization of the samples was previously done by measuring the axial hysteresis loops of the wires with an induction technique at 0.1 Hz. From these loops, coercive field, initial permeability and remanence were obtained.

3. Results and discussion

Previous reported results [10,11] at lower microwave frequencies (0.045–8 GHz) using a coaxial technique, shown that microwires dynamical properties were simultaneously affected both by the magnetization process and by ferromagnetic resonance. This coincidence prevents the detailed analysis of each contribution which could supply some interesting information from each one. Ferromagnetic resonance field strongly depends on the frequency range, and thus, if the working frequency is increased, larger magnetic fields are needed for the FMR to show up. However, magnetization processes always occur at very low fields, since all these alloys are soft magnetic materials. In this manner, at 9.67 GHz for example, both effects can be clearly separated at quite different field ranges.

Fig. 1(a) shows the low-field microwave losses curve at 9.67 GHz for the sample $(Co_{98}Fe_2)_{75}Si_{15}B_{10}$ (negative magnetostriction). Additionally, Fig. 1(b) shows the hysteresis loop from which it can be followed that magnetization process is characterized in this sample by a marked transverse anisotropy. This is a consequence of its negative magnetostriction. Coupling of mechanical stresses in the microwire produces a domain structure with circumferential easy axis. Comparing both figures, the region with significant microwave losses can be easily associated with the range where the magnetization process takes place. Both loops are essentially anhysteretic as well. It is remarkable that, unlike GMI at the MHz range, the microwave losses curve does not show a peak at the anisotropy field (around 1.5 kA/m in the present case). Here, the microwave GMI, as defined in Section 2, does not directly depend on transverse permeability (like in the MHz range), but on the magnetization itself. Thus, when the magnetization process finishes (at the anisotropy field), the low-field microwave GMI saturates [7].

Similar results can be obtained at low fields for the sample $(Co_{94}Fe_6)_{75}Si_{15}B_{10}$ (vanishing magnetostriction) and $(Co_{90}Fe_{10})_{75}Si_{15}B_{10}$ (positive magnetostriction) as shown in Figs. 2 and 3. In the first case, the hysteresis loop shows irreversibility below 500 A/m and the starting of the approach to magnetic saturation around 2.5 kA/m, which are reproduced by the microwave losses curve. In the last case, the magnetization process takes place by the displacement of a single wall from one end along the entire wire. As a consequence, microwave losses curve shows peaks around the coercive field (35 A/m).

All these measurements, made with three microwires with different magnetic domain

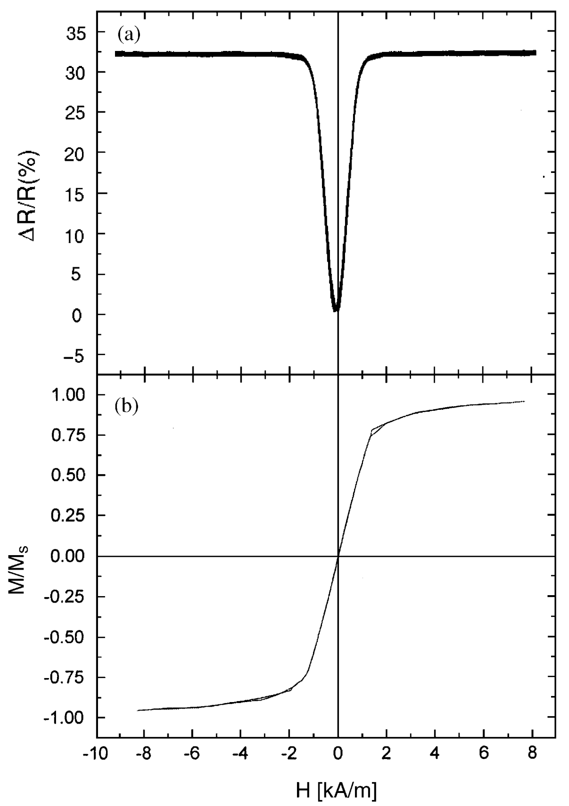

Fig. 1. (a) Microwave magnetoimpedance curve at 9.67 GHz and (b) hysteresis loop for the $(Co_{98}Fe_2)_{75}Si_{15}B_{10}$ microwire.

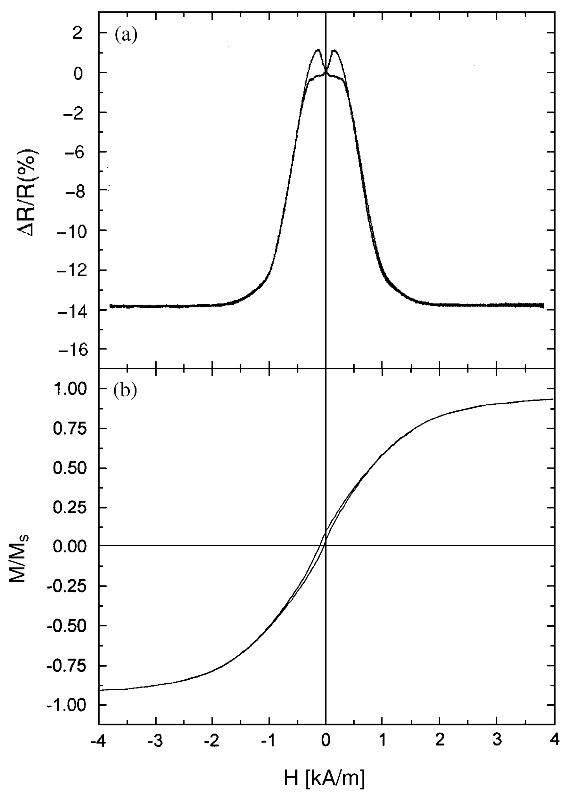

Fig. 2. (a) Microwave magnetoimpedance at 9.67 GHz and (b) hysteresis loop for the $x = 6$ microwire.

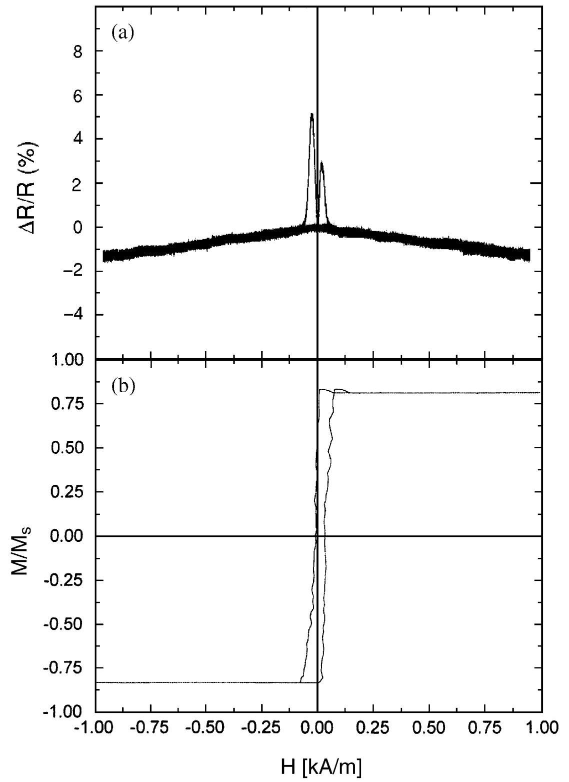

Fig. 3. (a) Microwave losses curve at 9.67 GHz and (b) hysteresis loop for the $x = 10$ microwire.

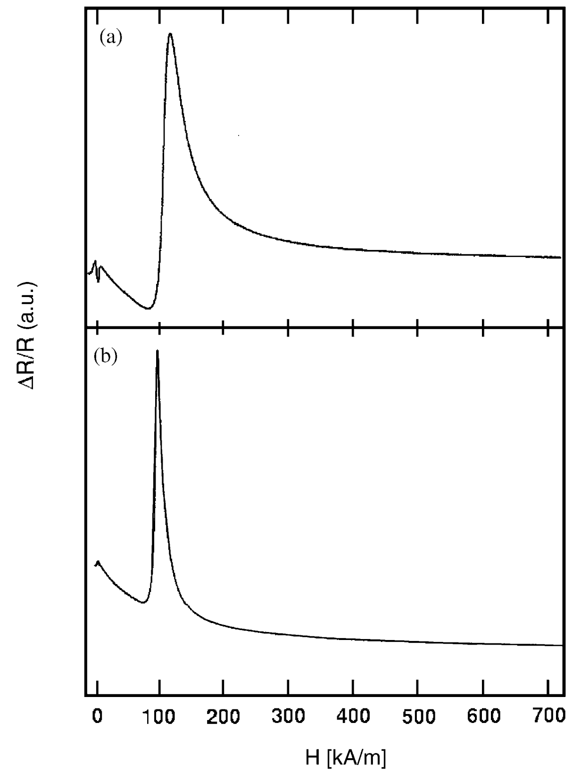

Fig. 4. Microwave absorption at 9.67 GHz, showing the FMR and FMAR peaks, for (a) $x = 6$ and (b) $x = 2$ amorphous microwires.

structure and, consequently, different magnetization processes, point out the clear correlation between quasi-static hysteresis loops and the dynamic permeability at microwave frequencies for the low-field range. No influence of FMR is observed in this low-field range. According to this conclusion, even at a frequency as high as 10 GHz, GMI is fundamentally due to classical electromagnetic effects.

On the other hand, Fig. 4 shows the high-field response for samples with $x = 6$ and 2 at 9.67 GHz. Resonance peaks appear at 115 kA/m for the first sample and at 98 kA/m for the second one, well away from the fields where GMI shows up. It may be seen in this figure, at low fields, the small variation in microwave loss due to GMI (more easily in the vanishing magnetostriction sample). This low-field GMI effect could only be affected by the initial FMAR effect, although it was not significant in the low-field scans, and it is necessary to span the field range to even notice this FMAR effect.

Regarding these FMR measurements, from Landau–Gilbert equation, one may obtain a relationship between frequency and resonance magnetic field. For wires, this equation is

$$\omega_0 = \gamma\mu_0(H_0 + \tfrac{1}{2}M_s), \quad (2)$$

H_0 being the resonance field. However, the saturation magnetization deduced from FMR experiments using Eq. (2) is lower than the one obtained in DC field experiments. For $x = 2$, DC saturation magnetization is 599 kA/m while the one deduced from FMR experiments is 474 kA/m. Similarly, for $x = 6$, both values are 640 and

516 kA/m, respectively, while for $x = 10$ we obtained 687 and 575 kA/m, respectively. A possible explanation for this discrepancy comes from the same fact that explains the GMI effect. At such a high frequency, penetration depth is smaller than the microwire radius, given the metallic character of these materials. Thus, only a certain surface layer of the wire is actually sensing the external AC field. In that case, the saturation magnetization in Landau–Gilbert equation must be substituted by an ‘‘effective’’ magnetization (that of the material fraction actually affected by the external AC field). Additionally, when the skin depth is lower than the sample characteristic dimension (in the case of wires, their radius), the microwave absorption on increasing fields would show not only a positive (FMR) peak, but also a negative (FMAR) peak [12], a feature that can be also seen in Fig. 4. Finally, from this microwave absorption technique, some useful information for any realistic micromagnetic model of the wire may be obtained, that about the surface magnetization of the sample.

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