The Effect of Metal-to-Glass Ratio on the Low-Field Microwave Absorption at 9.4 GHz of Glass-Coated CoFeBSi Microwires

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We present an investigation of the effects of the variations in the metal-to-glass ratio of Co-rich microwires, on the low field microwave absorption (LFA) at 9.4 GHz. LFA as a function of the DC applied field exhibited a double peak; its separation increased as the metal-to-total diameter ratio, p, decreased ($p =$ metal diameter/total diameter.). We show that the magnetic field between the double peak is associated with twice the microwire anisotropy field, H_{K}, and that the obtained results can be explained in terms of the magnetoelastic dependence of H_{K}. A decrease in p led to an increase in the stresses, which in turn produced an increase in the total anisotropy field. In contrast, the removal of glass decreased H_{K} down to values in the 0.9–1.6 Oe range.

Index Terms—**Amorphous magnetic wires, magnetic resonance, magnetoelasticity.**

I. INTRODUCTION

GLASS-COATED amorphous ferromagnetic microwires, prepared by rapid quenching from the melt have recently attracted attention by their magnetic properties which can be tailored to a considerable extent by means of the metal-to-glass ratio, as well as by their small dimensions with many potential applications [1], [2]. The local anisotropy distribution in these materials is strongly dependent on the magnetoelastic effects originated by the internal stresses, produced essentially by the differences in thermal expansion (contraction) coefficients between glass and metal during cooling to room temperature. The effects of these stresses on magnetic properties, especially on giant magnetoimpedance (GMI), are now well understood [3].

We have recently shown during ferromagnetic resonance (FMR) experiments in amorphous ribbons, that there exists a microwave absorption process at very low fields (low field absorption, LFA). It is clearly different than FMR and very similar to GMI [4]. Here, we present an investigation of the effects of the metal-to-glass ratio in glass-coated microwires on LFA.

II. EXPERIMENTAL TECHNIQUES

Amorphous microwires of nominal composition $\mathrm{Co}_{69.4}\mathrm{Fe}_{3.7}\mathrm{B}_{15.9}\mathrm{Si}_{11}$ with different metal-to-glass diameter ratios were prepared by the Taylor–Ulitovski technique [5], [6]. The metal and glass diameters were measured by using scanning electron microscopy (SEM). To distinguish clearly the metal from the glass, the latter was partially or totally removed by means of a solution of hydrofluoric acid. We use the metal-to-total diameter ratio, p, to characterize them; for metal diameters of 24, 12, and 7 μm, with total diameter $(\mathrm{metal} + \mathrm{glass})$ of 30, 22, and 22 μm, we get $p = 0.8, 0.55$, and 0.32, respectively. FMR measurements were carried out on samples 5 mm long, in a JEOL JES-RES 3X spectrometer operating in the X-band at 9.4 GHz, with a 100 kHz modulation, in the $-1 \geq H_{\mathrm{DC}} < 12$ kOe DC field range. Low-field measurements were performed by using a JEOL ES-ZCS2 zero-cross sweep unit, which compensates for any electromagnet remanence, allowing precise absorption determinations at low magnetic (positive and negative) fields around zero. In all cases, the microwire axis was oriented parallel to the DC magnetic field and perpendicular to the AC microwave excitation.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A run in the full DC field range showed the characteristic ferromagnetic resonance (FMR), see inset in Fig. 1. A resonance field of 1129 Oe was obtained for the $p = 0.8$ sample. At very low fields about zero field an additional absorption appears, which is shown magnified in Fig. 1. This absorption is clearly different from FMR. It does not fullfil the Larmor condition and has no resonant character. We have recently shown [4] that this phenomenon, which we call low-field absorption (LFA) is very similar to giant magnetoimpedance (GMI). As in GMI for samples with transverse anisotropy, a double-peak plot is obtained where the separation between peaks is associated with twice the value of the anisotropy field, H_{K}. By symmetry of the microwave absorption in FMR experiments, the peak at $-H_{\mathrm{K}}$ appeared inverted.

LFA measurements were carried out on the other microwire samples leading to similar plots as Fig. 1, but with values of peak-to-peak fields that increased as p decreased. A more complex plot was observed for $p = 0.32$, see Fig. 2, where variations in the microwave response appeared for field values between the two peaks. This can probably be explained in terms of a complex distribution of anisotropy (instead of a simple uniaxial anisotropy) for this level of stresses.

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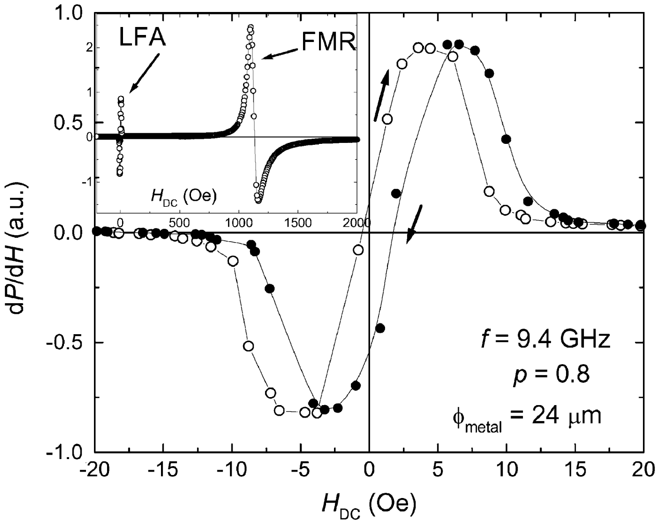

Fig. 1. Microwave power absorption in the low field range (LFA) for the $p = 0.8$ sample. In inset, a run in the -500 to 2000 Oe range is shown, with FMR at 1129 Oe.

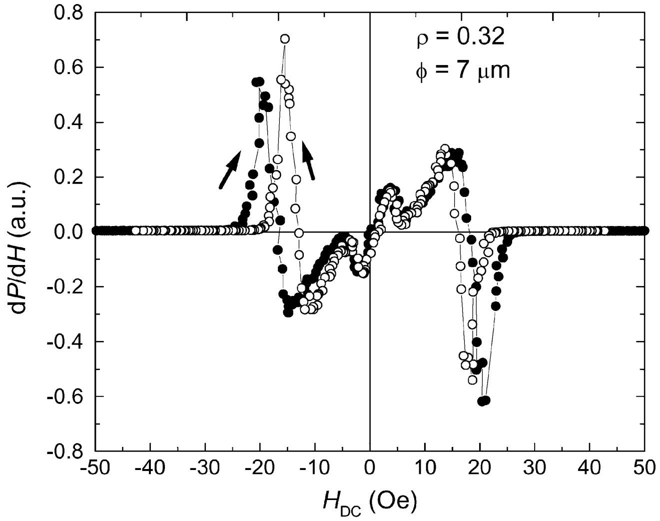

Fig. 2. LFA for the $p = 0.32$ sample.

LFA results from wires with the glass removed exhibited a significant decrease in anisotropy field. The three samples showed very similar H_{K} values in the 0.9–1.7 Oe range. Finally, a good agreement was observed with H_{K} values obtained from GMI experiments at 13 MHz on samples 15 mm long.

During preparation, microwires are fast-cooled to retain the amorphous state. Since glasses have a smaller thermal contraction coefficient than metals, a tensile stress develops in the latter at room temperature. This effect is expected to increase as the metal diameter decreases as compared to the glass thickness. Co-rich microwires possess a small, negative saturation magnetostriction constant leading to a transverse anisotropy. A "bamboo"-like magnetic structure, formed by circumferential domains with alternate magnetization direction has been reported in microwires [7]. A tensile stress therefore has the effect of increasing the tendency of spins to adopt a transverse (circumferential) direction. The axial DC field needed to rotate spins toward the axial orientation increases as does the anisotropy field.

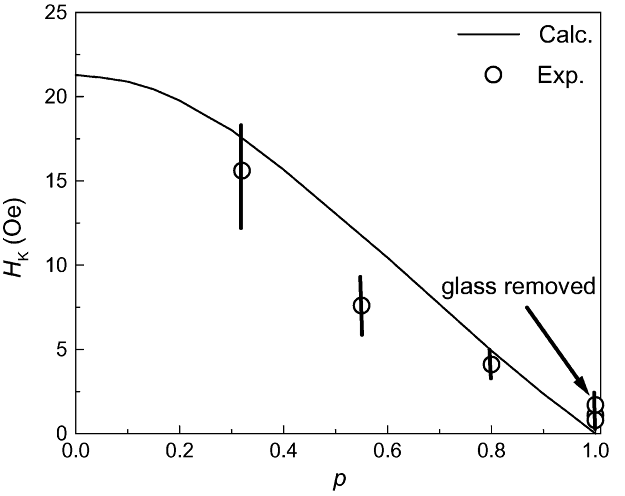

Fig. 3. Estimation of H_{K} as a function of p. Experimental points are also shown, with the corresponding error bars.

Torcunov *et al.* [8] modeled the quenching and thermoelastic stresses occurring during cooling in glass-coated microwires, in a cylindrical coordinate system (r, σ, z) with the z-axis along the wire, in terms of the radial, σ_{rr}, axial, σ_{zz}, and azimuthal, $\sigma_{\phi\phi}$, stresses. The obtained expressions, as adapted to our case, are

$$\sigma_{rr} = \varepsilon E_m k(1-p^2)/[(k/3+1)(1-p^2)+4p^2/3] \quad (1)$$

$$\sigma_{\phi\phi} = \sigma_{rr} \quad (2)$$

$$\sigma_{\mathrm{zz}} = \sigma_{rr}[(k+1)(1-p^2)+2p^2]/[k(1-p^2)+p^2] \quad (3)$$

where $k = E_g/E_m$ is the glass and metal ratio of Young moduli, $\varepsilon = (\alpha_m - \alpha_g)(T* - T)$, with $\alpha_m, \alpha_g = \mathrm{metal}$ and glass thermal expansion coefficients, respectively, $T*$ is the glass solidification temperature, and T is the room temperature. By assuming a uniaxial anisotropy, H_{K} can be expressed in terms of the anisotropy constant, K_σ

$$H_{\mathrm{K}} = 2K_\sigma \mu_0 M_s \quad (4)$$

where μ_0 and M_s are the vacuum permeability and the saturation magnetization, respectively. The magnetoelastic contribution to the anisotropy constant can be written as

$$K_\sigma = K_{(\sigma=0)} - 3\lambda_s(\sigma_{zz} - \sigma_{\phi\phi})/2. \quad (5)$$

We can make an estimation of (5) by using the numerical values for a generic CoFeBSi composition [9]: $T* = 823$ K, $E_g = 64$ GPa, $E_m = 110$ GPa, $\alpha_m = 1.2 \times 10^{-5}$ K^{-1}, $\alpha_g = 3.2 \times 10^{-6}$ K^{-1}, as well as magnetic parameters for a composition very similar to ours [10]. The results are shown in Fig. 3. LFA results have been added, showing values a little smaller, but with the same tendency than the estimated ones. Since the exact $T*, \alpha_m$ and E_m values are not available for our composition, small differences can arise from the calculations.

IV. CONCLUSION

LFA measurements in microwires with different metal-to-total diameter ratios (p) have shown to be controlled by the sample's anisotropy field. As p decreases, the stress exerted by the glass coating on the metal increases, leading to a stronger tendency of spins to adopt a transverse (circumferential) orientation. Therefore, the anisotropy field increases in a similar way as observed in GMI experiments. LFA can become a powerful characterization technique.

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