Resonant and non-resonant phenomena in measurements of microwave absorption in Co-based amorphous ribbons

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Microwave absorption measurements in X band (9.4 GHz,), were carried out as a function of the transverse dc magnetic field, on as-cast amorphous ribbons of composition $Co_{66}Fe_4B_{12}Si_{13}Nb_4Cu$ prepared by melt spinning. Two different absorptions were observed: one at low dc fields (> 200 Oe) and the other one at high dc fields (< 1800 Oe). The high-field absorption has a resonant character and is associated with ferromagnetic resonance (FMR). The low-field absorption showed non-resonant features (hysteresis, non-Larmor dependence on the dc field) and can be associated with giant magnetoimpedance (GMI); it showed a good agreement when directly compared with GMI measurements. Some additional measurements were performed by rotating the sample's plane with respect to the dc field.

Keywords: Ferromagnetic resonance; Giant magnetoimpedance; Alloys amorphous.

1. Introduction

Ferromagnetic materials exhibit a wide variety of behaviors when subjected to ac magnetic fields, ranging from domain wall relaxation (DWR), to giant magnetoimpedance (GMI), to ferromagnetic resonance (FMR). While DWR is limited to low frequencies where domain walls are able to follow the frequency of the excitation field (usually lower than 1 MHz [1]), and FMR phenomena must satisfy an exact equation (the Larmor equation, usually for frequencies in the GHz range, [2]). GMI has shown to extend on an extremely wide frequency range [3].

On the other hand, in others studies, microwave absorption centered at zero magnetic field has been observed in a wide variety of materials. For high-temperature superconductors the appearance of this absorption has been widely accepted as a signature of the transition to the superconductive state [4,5]. This signal is reflecting the dissipative dynamics of fluxons. For ferrites, this low-field absorption signal is due to microwave absorption processes closely related to the low-field magnetization of the sample [6]. For semiconductors this signal is due to magnetoresistive effects that are responsible for most of the magnetic field dependence of the microwave absorption [7]. For manganites the appearance of the microwave absorption centered at zero magnetic field is used to indicate the onset of the ferromagnetic phase and provides a sensitive detector of ferromagnetism [8]. Recently, the microwave response near zero magnetic field was observed in doped silicate glasses [9]. The authors in the above mentioned work argue that such response can be described as magneto-induced microwave conductivity in the dielectric glass, which derives from spin-dependent charge migration within the first coordination sphere of the paramagnetic ion.

In this paper, we investigated the absorption behavior of Co-based as-cast amorphous ferromagnetic ribbons when subjected to high frequency fields at 9.4 GHz (X band), in the usual FMR geometry (ac field perpendicular to dc field). Two different absorptions were observed: the typical FMR absorption and a low-field absorption (LFA). Additionally, a comparison is made between the LFA signal and GMI measurements, exhibiting a good correlation. We also performed experiments by varying the angle between the dc field and the ribbon's plane; similar effects of shape anisotropy on both absorptions were observed.

2. Experimental Techniques

We studied as-cast, amorphous ribbons 2 mm wide and 22 μm thick of nominal composition $Co_{66}Fe_4B_{12}Si_{13}Nb_4Cu$, prepared by melt-spinning. Their amorphous state was checked by X-ray diffraction. Microwave power absorption measurements were made on samples 2 mm long, using a JEOL JES-RES3X spectrometer operating at 9.4 GHz (X-band). The power of the ac signal was 1 mW. The absorption curves were obtained by the dc magnetic field modulation technique, with a modulation frequency of 100

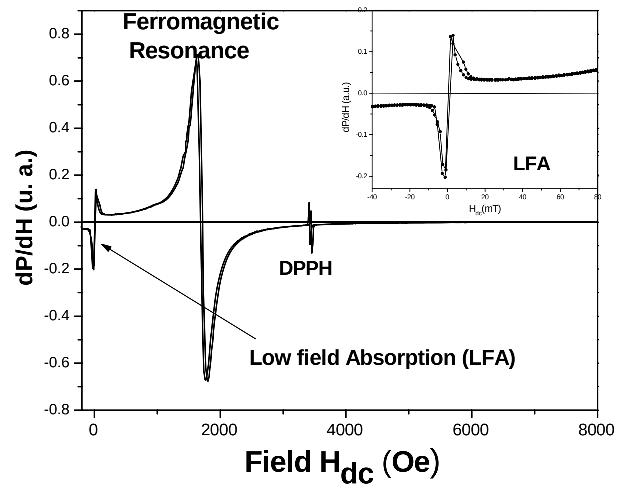

Figure 1. Microwave absorption of Co-based amorphous ribbons in X-band at θ=0°. The inset shows the low field range absorption.

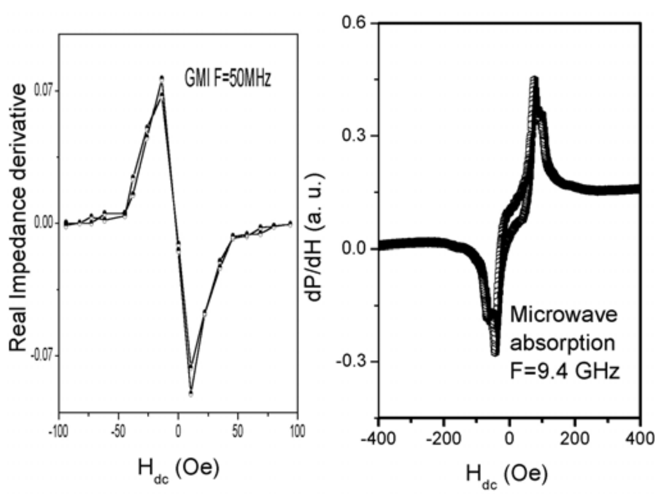

Figure 2. Comparison of a) GMI (f = 50 MHz) and b) FMR (low-field absorption at 9.4 GHz) experiments. GMI results are based on the derivative of the real part of impedance, Z'.

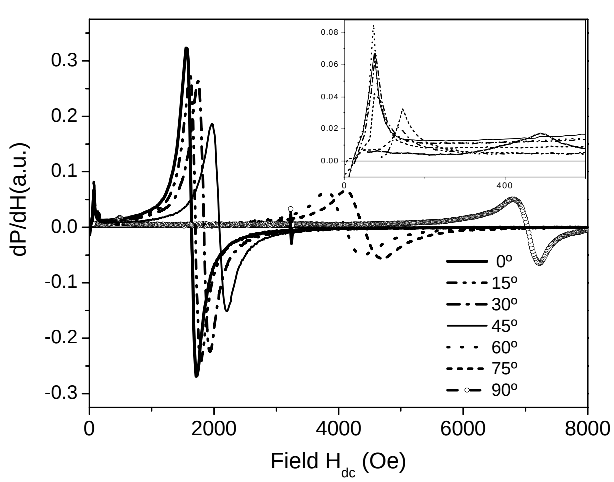

Figure 3. Microwave absorption as a function of angle θ. The ribbon's plane turns from θ = 0° for parallel orientation, to 90° for dc field normal to the ribbon. In inset, the low field range.

KHz. All spectra were obtained at room temperature (300 K). A JEOL ES-ZCS2 Zero-Cross Sweep unit compensates digitally for any remanence in the electromagnet, with a standard deviation of the measured field of less than 2×10^{-5} T, allowing measurements to be carried out by cycling the dc magnetic field (H_{dc}) about its zero value continuously from –0.1 to 0.8 T.

Some experiments were carried out by changing the orientation angle, θ, of the sample with respect to the dc field. For this, the sample was rotated about a vertical axis that coincided with its longitudinal axis. For θ = 0°, the dc field is parallel, and for θ = 90°, H_{dc} is normal to the ribbon's plane. We also carried out GMI measurements on longer ribbons (2.8 cm) of the same composition in the MHz range, by using an Agilent 8753 ES network analyzer.

3. Experimental Results and Discussion

We first address the results obtained at θ = 0°. Fig. 1 shows the spectrum obtained at f=9.4 GHz (a DPPH marker was used to ensure the accuracy of results, showing the expected resonance at H_{dc} = 3357 Oe). A strong absorption is observed at H_{dc} = 1817 Oe, which can be associated with ferromagnetic resonance (FMR), satisfying the Larmor relationship, as derived for the case of a thin sheet with negligible anisotropy field within the sheet plane [10],

$$\omega_0 = \gamma[BH_{dc}]^{1/2} \qquad (1)$$

where ω_0 is the microwave angular frequency (9.4 GHz), γ is the gyromagnetic ratio, H_{dc} the static magnetic field and B is the magnetic induction of the sample ($B = H_{dc} + 4\pi M_s$; M_s is the saturation magnetization). By assuming a spin-only behavior (Lande factor g=2.0023), the saturation magnetization can be calculated from the resonance conditions as $4\pi M_s \approx 4385$ G.

This value is about 20% smaller than the one measured from magnetometry (VSM) experiments. An explanation proposed [11] to account for this difference is that at such high frequencies in a conductive material, the penetration of the microwave field is severely limited by the skin effect, and it is only a small layer in the sample's surface that effectively shows a response to the ac field.

Fig. 1 also exhibits an additional absorption process at low dc fields (in the range + 200 Oe); this section is enlarged in inset. This phenomenon obviously does not satisfy the Larmor relationship. By cycling the dc field, it clearly shows a hysteresis character, centered on zero dc field. These characteristics indicate a non-resonant classical process that can be explained in terms of the non-resonant absorption of the microwave signal by a process essentially similar to giant magnetoimpedance (GMI); similar phenomena have been recently reported [11-14], albeit, to our knowledge, the irreversibility had not been observed directly through FMR experiments. These results can be interpreted on the basis of the changes in magnetic permeability that occur in presence of the dc field, which

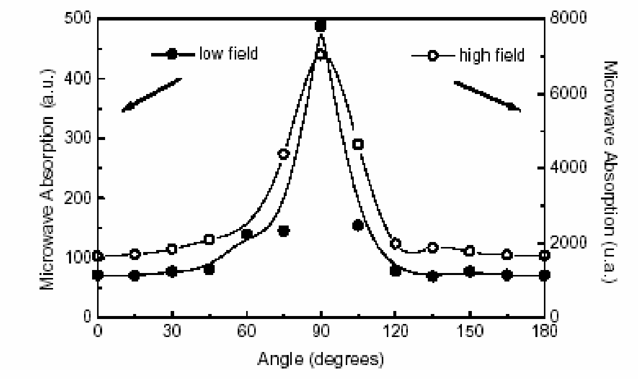

Figure 4. Comparison of effect of angle on the low-field, and high-field absorptions.

modify the ac field penetration depth, thereby changing the impedance response of the sample.

In order to confirm this origin of the low dc field absorption, we carried out GMI measurements on ribbons of the same composition, at $f = 50$ MHz. In order to make a comparison with the microwave results, we have to take into account two points: first, we have to use the real part of impedance, Z', (instead of the usual total impedance $|Z| = [Z'^2 + Z''^2]^{1/2}$, with Z'' = imaginary part), since all measurements in magnetic resonance systems show only the dissipative component of impedance, and second, we have transformed the GMI results into the same form of FMR spectra, by calculating their derivative. The results are shown in Fig. 2. A change in phase is shown; in Co-rich wires $Co_{66}Fe_4B_{12}Si_{13}Nb_4Cu$, an inversion in GMI behavior has been observed at $f \approx 1$-2 GHz [13]. Otherwise, the main features, i.e., two maxima and hysteresis are found on both curves.

It is important to note that in addition to the skin depth effect, there is an important contribution of the rotation magnetization process into this phenomenon, as shown by transverse susceptibility experiments in non-conductive materials, where plots quite similar to GMI have been observed [15].

We turn now to experiments carried out by rotating the sample by an angle θ about its longitudinal axis, which coincides with the microwave signal direction. As θ increases from 0° to 90°, the sample's plane turns from the parallel orientation, to the perpendicular orientation to the dc field. As shown by Fig. 3, the dc field increases strongly from 1817 Oe for θ= 0°, to H_{dc} = 7045 Oe for θ = 90°. This behavior can be easily explained because shape anisotropy, which is negligible at 0° and becomes maximum at 90°. For the dc field normal to the ribbon's plane, the Larmor FMR condition is written as [16]:

$$\omega_0 = \gamma (H_{dc} - 4\pi M_s) \qquad (2)$$

A calculation of saturation magnetization by using this relationship leads to $4\pi M_s$ = 3687 G, which is about 32% lower than the dc value obtained by classical magnetometry. Clearly, the saturation condition is more difficult to achieve for this orientation.

The low field absorption, inset of Fig. 3, showed also an increase in H_{dc} as a function of θ. This is also the effect of shape anisotropy on the GMI-like absorption, since the dc field needs larger values in order to produce changes in domain configuration which, in turn, provide the right conditions for the absorption to take place. A comparison between both absorptions is shown in Fig. 4, to confirm that the main effect is produced by the shape anisotropy.

4. Conclusions

We carried out measurements of microwave absorption in Co-based amorphous ribbons which showed two dc field range: low-field (> 200 Oe) and high-field absorption. The high-field absorption can be clearly associated with the well-known ferromagnetic resonance. The saturation magnetization calculated from these experiments showed values lower than the ones obtained from magnetometry measurements, which can be explained by the skin effect. The low-field absorptions observed can be associated with the coupling of the ac magnetic field with the ferromagnetic structure, with most of features exhibited by GMI. To our knowledge, their hysteretical nature was observed for the first time from FMR experiments. In order to make a sound comparison, we have to use the real part of impedance from GMI experiments, and have to transform GMI results into the appropriate form of FMR experiments.

References

[1] R. Valenzuela and I. Betancourt, IEEE Trans. Magn., **38**, 3081 (2002).
[2] R.C. O'Handley, "*Modern Magnetic Materials Principles and Applications*", John Wiley & Sons, New York, 347, 2000.
[3] A. Yelon, L.G.C. Melo, P. Ciureanu and D. Menard, J. Magn. Magn. Mater. **249**, 257 (2002).
[4] G. K. Padam, S. N. Ekbote, Malay Rajan Tripathy, G. P. Srivastava and B. K. Das, Physica C **315**, 45 (1999).
[5] G. Alvarez and R. Zamorano, J. Alloys Comp. **369,** 231 (2004).
[6] H. Montiel. G. Alvarez, M. P. Gutiérrez, R. Zamorano and R. Valenzuela, J. Alloys Comp. **369,** 141 (2004).
[7] A. I. Veinger, A. G. Zabrodskii and T. V. Tisnek, Phys. Stat. Sol. (b) **218,** 189 (2000).
[8] F. J. Owens, J. Phys. Chem. Solids **58,** 1311 (1997).
[9] R. R. Rakhimov, H. R. Ries, D. E. Jones, L. B. Glebov and L. N. Glebova, Appl. Phys. Lett. **76,** 751 (2000).
[10] C. Kittel, Phys. Rev. **73**, 155 (1948).
[11] M. Domínguez, J.M. García-Beneytez, M. Vázquez, S.E. Lofland and S.M. Bhagat, J. Magn. Magn. Mater. **249**, 117 (2002).
[12] H. Hoffmann, Thin Sol. Films, **373**, 107 (2000).
[13] C. Tannous, J. Gieraltowski, J. Mat. Sci. Mat. Elec.,. **15**, 125 (2004).
[14] T.A. Ovari, H. Chiriac and M. Vazquez, IEEE Trans. Magn., **36**, 3445 (2000).
[15] J.M. García-Beneytez, F. Vinai, L. Brunetti, H. García-Miquel and M. Vazquez, Sensors & Act., **81**, 78 (2000).
[16] A. H. Morrish, *The Physical Principles of Magnetism,* (John Wiley & Sons Inc., New York, 1965)