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Correlations between low-field microwave absorption and magnetoimpedance in Co-based amorphous ribbons

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Microwave power absorption measurements at 9.4 GHz were carried out on as-cast amorphous ribbons of nominal composition $Co_{66}Fe_4B_{12}Si_{13}Nb_4Cu$. Two absorptions were observed: a small signal at a low dc field (<0.01 T) and another one at a high dc field (~ 0.1682 T). The high-field signal shows all the features corresponding to ferromagnetic resonance. The low-field absorption (LFA) signal exhibits different characteristics such as hysteresis and a minimum in power absorption at zero magnetic field. A correlation between this LFA signal and magnetoimpedance measurements showed that both electromagnetic processes are associated with the same phenomenon. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1861959]

Ferromagnetic materials exhibit a wide variety of behaviors when subjected to ac magnetic fields, including domain wall relaxation (DWR), magnetoimpedance (MI), and ferromagnetic resonance (FMR). For instance, DWR is generally found at relatively low frequencies—below 1 MHz in most metals.[1] FMR must satisfy the Larmor equation, usually in the GHz range.[2] In contrast, MI measurements have shown to encompass a large frequency range.[3] MI can be measured in three different frequency ranges, as follows. (1) A low-frequency range, where domain wall motion contributes significantly to transverse permeability.[4] (2) An intermediate frequency interval for which MI is explained in terms of the classical skin effect in magnetic conductors with large permeability. A strong dependence of MI with the static magnetic field has been observed.[5] (3) A high-frequency range, where MI measurements can be associated with the FMR process. The relationships and similarities between FMR and MI have recently raised interest as MI phenomena are investigated at increasingly higher frequencies.[6–10] Microwave power absorption (MPA) centered at zero magnetic field has been observed in a wide variety of materials: high-temperature superconductors,[11] ferrites,[12] and semiconductors.[13]

Here we present MPA measurements obtained on Co-rich amorphous ribbons, where in addition to the typical FMR absorption, a low-field absorption (LFA) is observed. This LFA signal exhibits hysteresis. A comparison is made between the LFA signal and MI measurements, which exhibit common features.

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. MPA measurements were carried out on samples 2 mm long, using a JEOL JES-RES3X spectrometer operating at 9.4 GHz (X band). 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.

Magnetization measurements were carried out in a LDJ 9600 vibrating sample magnetometer (VSM) at room temperature. Measurements of LFA and VSM were carried out by applying the dc field on the ribbon's plane and oriented perpendicular to its longitudinal axis. MI measurements were carried out on samples 2.8 cm long, by means of a system controlled by a PC which includes an Agilent 8753ES Network Analyzer, and a 800-turn solenoid coil powered by a dc source affording dc magnetic fields up to 0.01 T.[14] The MI ratio was defined as $\Delta Z/Z = 100([Z(H)-Z(H_{max})]/Z[(H_{max})]$, where H_{max}($\sim$0.01 T) is the maximum magnetic field value.

The inset of Fig. 1 shows the derivative of the MPA spectrum. We carried out forward and backward H_{dc} scans in order to detect reversible/irreversible absorption processes. Two signals were observed, which can be associated with two different processes: a strong absorption at $H_{dc} = 1682$ Oe and a LFA signal at fields smaller than 100 Oe.

The high-field absorption can be straightforwardly associated with FMR, satisfying the condition for a hollow conductor, as applied to the case of a thin sheet with both negligible anisotropy field and demagnetizing fields:[15]

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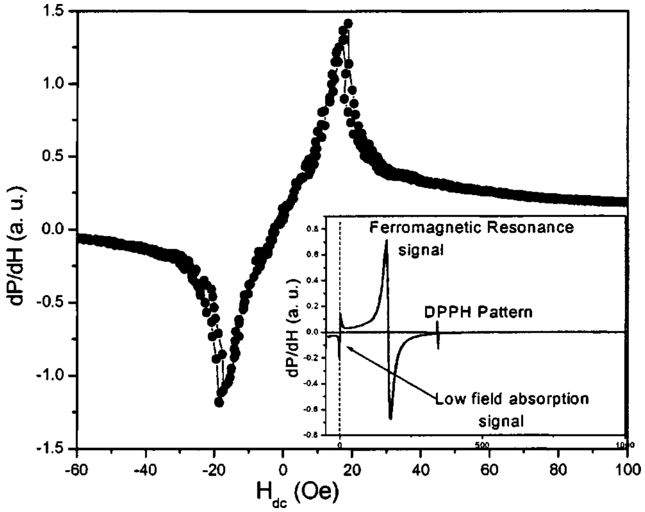

FIG. 1. The low-field absorption signal. The inset shows the derivative of MPA.

$$\omega_0 = \gamma[(4\pi M + H_{dc})H_{dc}]^{1/2}, \tag{1}$$

where ω_0 is the microwave angular frequency (with $\omega_0 = 2\pi f_0$ and $f_0 = 9.4$ GHz, γ is the gyromagnetic ratio, H_{dc} is the static magnetic field, and M is the magnetization. At the resonance condition, $M = M_s$ and $H_{dc} = H_{res}$. By assuming a free-electron behavior (Landé factor $g = 2.0023$), the saturation magnetization of the surface of the sample can be calculated from the resonance conditions as $4\pi M_s = 4741$ G, which is close to the bulk saturation magnetization $4\pi M_s = 5250$ G, as measured by VSM. The difference can be attributed to the fact that FMR is probing only the surface of the sample, while the VSM is a bulk measurement. This absorption shows no hysteresis between the up- and down-field sweeps.

We turn now to the LFA signal, shown with more detail in Fig. 1. This signal is centered at zero magnetic field and shows a phase opposite to the FMR signal. The opposite phase is indicating that the MPA has a minimum value at zero magnetic field, in contrast to the maximum value for FMR line, both registered in the measuring run. A clear hysteresis of this signal appears on cycling the field. The existence of a LFA signal has been reported previously in other soft magnetic materials as wires and thin films,[5,8] and have been interpreted as due to low-field spin magnetization processes. Figure 2(b) shows the MI results; the maximum value reached in the experiment is ~8% at a frequency of 50 MHz. The double peak clearly indicates low field surface magnetization processes[5] originated by the change in transversal permeability. The peak-to-peak width in MI exhibits a very good agreement with the anisotropy field. Figure 2(a) shows also VSM hysteresis measurements. The hysteresis loop is characterized by axial anistropy, and a correlation between both experiments is observed on the basis of this anisotropy field.

We compare measurements of LFA and MI in Figs. 2(b) and 2(c), respectively. A significant decrease of MPA (from $H = 16$ Oe down to zero) is observed in LFA measurements, whereas at the same fields, the MI measurements show that the MI response is approaching saturation at a field lower than 20 Oe. As the field decreases, a maximum is reached by MI, which corresponds to the anisotropy field ($H = 15.6$ Oe). A further decrease of impedance is observed at zero field. As is well known, MI is due to changes in the skin depth as a consequence of changes in the transversal permeability under the influence of the external H_{dc}. The change in domain structure, and therefore in spin dynamics, is also produced by H_{dc}, in direct interaction with the material axial anisotropy. Experimentally, the maxima in the MI curve coincide with the minimum and maximum of the LFA curve. This clearly points to a common origin for both processes, essentially controlled by the anisotropy field.

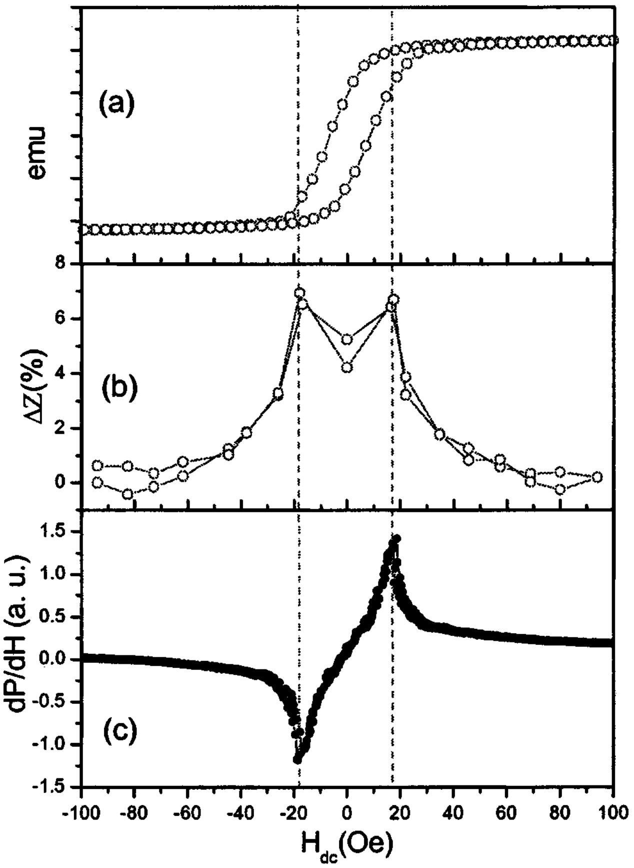

FIG. 2. (a) VSM hysteresis loop, (b) magnetoimpedance curves at a frequency of 50 MHz, and (c) LFA results.

The hysteresis effect of LFA signal appears to be due to nonuniform surface magnetization processes. A ferromagnetic conducting system can absorb electromagnetic radiation with an efficiency that depends on the particular conditions such as the magnetic domain structure, magnetic anisotropy, the orientation of the incident propagation vector radiation, its conductivity, its frequency, and amplitude. This absorption can easily be modified by H_{dc}, which changes the magnetic susceptibility, the penetration depth, the magnetization vector, the domain structure, and spin dynamics. Such changes can show hysteresis, as normally occurs in a domain structure subjected to dc fields lower than the saturating field. By cycling the dc field, different irreversible domain configurations occur, and therefore a hysteresis effect can occur.

The change in phase between the two absorption is correctly explained by the minimum of the MI signal at zero field, compared to the maximum of the FMR signal at the resonance field. This is additional evidence that MI and LFA represent the same response, generated by the same electromagnetic phenomenon. MI and LFA can therefore be understood as the absorption of electromagnetic radiation by spin systems that are modified by domain configuration and strongly depend on anisotropy field (H_K). Moreover MI and LFA can be explained with classical electromagnetic processes, without quantum processes involved.

[1] R. Valenzuela and I. Betancourt, IEEE Trans. Magn. **38**, 3081 (2002).
[2] R. C. O'Handley, *Modern Magnetic Materials: Principles and Applications*, (Wiley and Sons, New York, 2000), pp. 347–353.
[3] A. Yelon, L. G. C. Melo, P. Ciureanu, and D. Ménard, J. Magn. Magn. Mater. **249**, 257 (2002).
[4] L. V. Panina, K. Mohri, T. Ushiyama, M. Noda, and K. Bushida, IEEE Trans. Magn. **31**, 1249 (1995).
[5] R. S. Beach and A. E. Berkowitz, J. Appl. Phys. **76**, 6209 (1994).
[6] L. Kraus, J. Magn. Magn. Mater. **195**, 764 (1999).
[7] D. P. Makhnovskiy, L. V. Panina, and D. J. Mapps, Phys. Rev. B **63**, 144424 (2001).
[8] M. Domínguez, J. M. García-Beneytez, M. Vázquez, S. E. Lofland, and S. M. Baghat, J. Magn. Magn. Mater. **249**, 117 (2002).
[9] T. A. Ovari, H. Chiriac, and M. Vázquez, IEEE Trans. Magn. **36**, 3445 (2000).
[10] J. M. García-Beneytez, F. Vinai, L. Brunetti, H. García-Miquel, and M. Vázquez, Sens. Actuators **81**, 78 (2000).
[11] G. Alvarez and R. Zamorano, J. Alloys Compd. **369**, 231 (2004).
[12] H. Montiel. G. Alvarez, M. P. Gutiérrez, R. Zamorano, and R. Valenzuela, J. Alloys Compd. **369**, 141 (2004).
[13] A. I. Veinger, A. G. Zabrodskii, and T. V. Tisnek, Phys. Status Solidi B **218**, 189 (2000).
[14] K. L. García and R. Valenzuela, J. Appl. Phys. **87**, 5257 (2000).
[15] F. Yildiz, B. Z. Rameev, S. I. Tarapov, L. R. Tagirov, and B. Aktas, J. Magn. Magn. Mater. **247**, 222 (2002).