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Correlation between magnetization processes and giant magnetoimpedance response in CoFeBSi amorphous CoFeBSi wires

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Abstract

Giant magnetoimpedance (GMI) in amorphous $(Fe_{0.06}Co_{0.94})_{72.5}B_{15}Si_{12.5}$ wires (submitted to an alternative current, i_{ac}) has a dependence of the impedance response, Z, on direct current magnetic field, H_{dc}. In as-cast wires, the ac current frequency changes the GMI: for frequencies of a few kHz, the impedance response is a function of H_{dc}, having a single maximum at $H_{dc} = 0$; for frequencies >1 MHz, however, two maxima (with a minimum at $H_{dc} = 0$) are observed. By analyzing the frequency dependence of real, L_r, and imaginary inductance, L_i (proportional to real and imaginary permeability, respectively), we show that these results can be explained in terms of the dominant magnetization process: domain wall bulging for low frequencies, and magnetization rotation for high frequencies. Plots of both L_r and L_i as a function of frequency indicate relaxation processes at about 45 kHz, due to a change from domain wall to spin rotation as the dominant magnetization process.

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1. Introduction

Giant magnetoimpedance (GMI) is characterized by large variations in the impedance response of a ferromagnetic conductor (submitted to an alternating current with an amplitude of a few milliamperes) when a magnetic field is applied. It has been shown that GMI is an classic electromagnetic phenomenon [1] depending on the inductive coupling between the ac magnetic field generated by the ac current and the material's magnetic structure. It is usually interpreted [1] on the basis of a skin-depth effect, which provides an additional contribution to the total impedance. As the direct current magnetic field increases, the magnetic permeability decreases as well as its contribution to the skin effect [2], causing to a decrease in this additional contribution. GMI has an interest for applications in magnetic sensors [2,3].

GMI is usually investigated by using the variations in total impedance, Z, measured at frequencies >1 MHz [4], as a function of the dc magnetic field [4]. While this methodology shows directly the GMI potential of a given material, in our opinion it provides no information about the magnetization processes which are responsible for GMI. On the other hand, experiments using complex inductance (instead of total impedance) are evidence [5,6] of the contribution of domain walls and their dynamics to GMI.

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The goal of this paper is to combine both types of measurements in order to find an agreement between them, and more specifically, to investigate a possible correlation between magnetization processes and GMI response.

2. Experimental

Amorphous wires with the nominal composition $(Fe_{0.06}Co_{0.94})_{72.5}B_{15}Si_{12.5}$ and 125 μm in diameter [7], prepared by an in-water-rotating technique [7] and kindly provided by Unitika, Japan, were used as samples. Pieces about 8 cm long were measured in the 5 Hz to 13 MHz frequency range, in a system that includes an impedance analyzer (Hewlett-Packard, HP 4192A), controlled by a personal computer, PC. The ac current amplitude was fixed at 1 mA (root-mean-square, RMS), which was an ac field amplitude of 0.013 A/m (RMS). Additionally, a dc magnetic field was applied in the axial direction by means of a solenoid powered by a dc current source, with a maximum field $H_{dc} = 6400$ A/m (80 Oe).

3. Experimental results and discussion

The total Z as a function of H_{dc}, at frequencies > 1 MHz has been used to measure GMI [4]. At frequencies <1 MHz, Z's are smaller than Zs at 1 MHz, and are not relevant for applications. Fig. 1 shows results of total impedance at 5 MHz as a function of dc magnetic field, applied in the axial direction of the samples. The ac current amplitude is $i_{ac} = 1$ mA (RMS). A plot with respect to the dc applied field (a 'two-maxima' plot) is shown in Fig. 1.

Measurements of real and imaginary parts of Z were made at frequencies < 5 MHz; Fig. 2 shows the results for $f = 10$ kHz. As expected, Zs are smaller than those shown in the previous figure, and also, only one maximum is observed. A change in magnetization occurs between these frequencies, as previously shown by other authors [8].

To assess such a change, measurements of permeability as a function of frequency were made. As we have shown [9], inductance formalisms measurements are more useful than total impedance measurements for insights into the magnetization processes producing GMI. This is because there exists a relationship [10] between complex inductance and complex permeability formalisms [10]. In the simplest case, permeability is proportional to inductance through geometrical factors [10]. Real and imaginary inductances are obtained from impedances by the simple relation [10],

$$L = (-j/\omega)Z, \quad (1)$$

where L is the total (or complex) inductance, j is the imaginary number ($j = \sqrt{-1}$), and ω is the angular frequency ($\omega = 2\pi f$). Note that the j crosses-over the real and imaginary components: real inductance, L_r, depends on imaginary impedance, Z_i, and conversely, imaginary inductance, L_i, is determined by real impedance, Z_r.

Real and imaginary inductances as a function of frequency (in the frequency range 100 Hz to 13 MHz), at zero dc field and an ac current amplitude of 1 mA (RMS), are shown in Fig. 3. Real inductance has a plateau at frequencies <10 kHz, followed by a decrease with frequency increases. At the frequency where L_r decreases, imaginary inductance is a maximum. This relation is characteristic of a relaxation process, and has been related to domain wall bulging of pinned domain walls [11]. The maximum in the $L_i(f)$ plot, as well

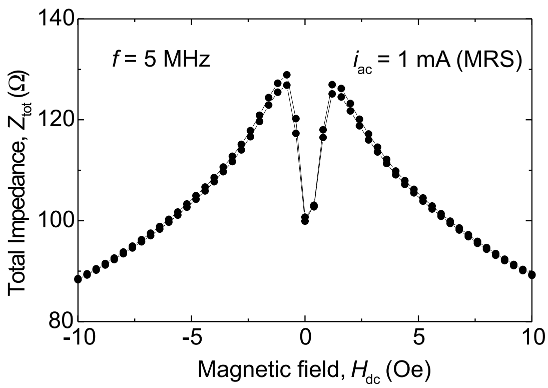

Fig. 1. Total impedance at 5 MHz as a function of dc magnetic field. The ac current amplitude was 1 mA (RMS). Lines were drawn to guide the eye.

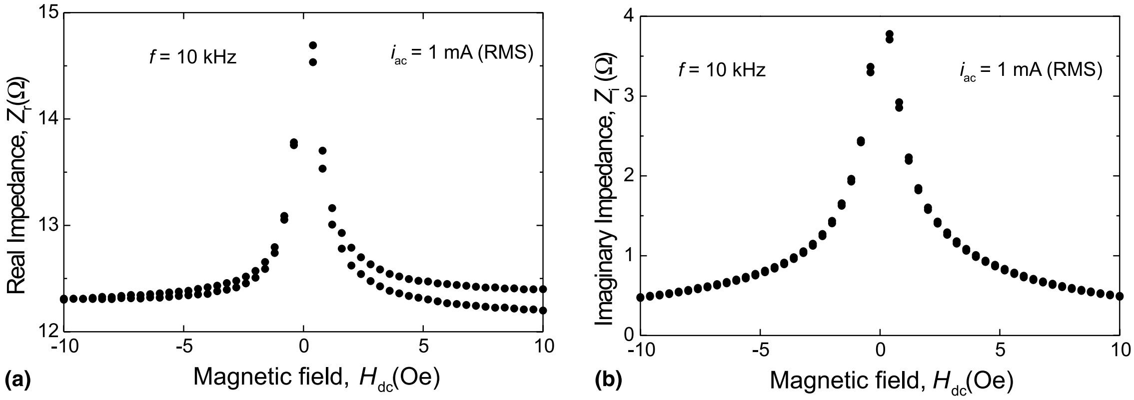

Fig. 2. (a) Real, and (b) imaginary impedances at 10 kHz as a function of dc magnetic field. The ac current amplitude was 1 mA (RMS).

as the frequency where L_r is half the low frequency plateau, indicates the relaxation frequency which is ~50 kHz, but the decrease in the real permeability begins at ~1 kHz, and extends up to ~1 MHz. Another [12] relaxation process is shown by the locus of frequency points in a Cole–Cole plot [12] (in inset of Fig. 3) which is an approximate semicircle.

The dynamics of many processes can be described by an equation of motion [13]

$$m\,d^2x/dt^2 + \beta\,dx/dt + \alpha x = F(t), \quad (2)$$

where $m\,d^2x/dt^2$ is the inertia term with an effective mass m, $\beta\,dx/dt$ is the damping term with a viscous damping coefficient β, αx is the restoring term with a restoring constant α, and the system is excited by a time-dependent force, $F(t)$. As the excitation frequency increases, a resonant process occurs when the inertia term is larger or similar to the damping term; a relaxation process, on the other hand, takes place when the damping term is larger than the inertia term. Since the data shown in Fig. 3 is a relaxation, we conclude that the effective mass of domain walls in amorphous wires is smaller than the damping term.

Eq. (2) can be solved [14] for the relaxation condition (with a sinusoidal excitation field) for which the (angular) relaxation frequency is

$$\omega_r = 2\pi f_r = \alpha/\beta. \quad (3)$$

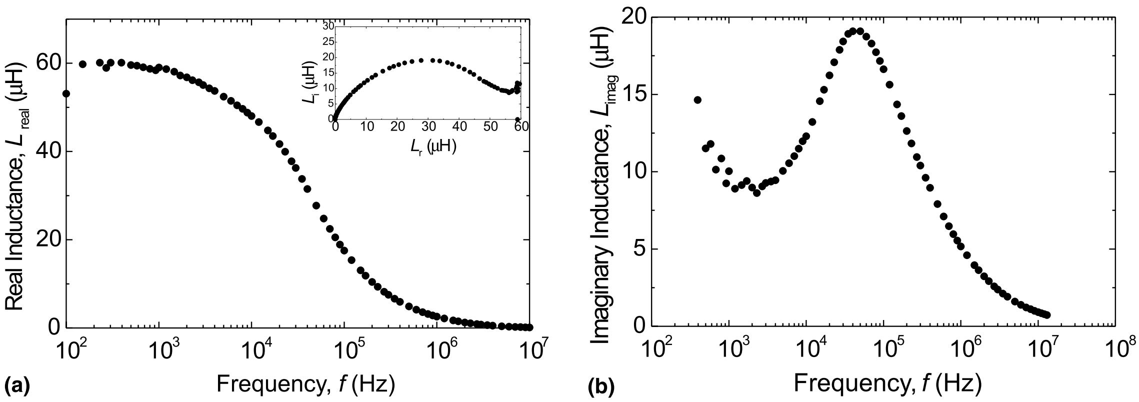

Fig. 3. (a) Real, and (b) imaginary inductances as a function of frequency at zero dc magnetic field and an ac current amplitude of 1 mA (RMS).

The relaxation frequency therefore depends on the restoring force, and on the inverse of the damping coefficient. A domain wall with a damping term less than its effective mass, and/or a stiff wall lead to a greater relaxation frequency. The origin of the viscous damping coefficient is not known to us. By assuming that domain wall movements involve an inversion of the spins within the wall, we deduce that β should depend on magnetic anisotropy. More research, however, is needed in this subject to determine the effect of the various parameters involved.

At frequencies < 10 kHz both domain wall bulging and spin rotation are active. The effects of dc magnetic field on GMI at frequencies less than the relaxation frequency (Fig. 2) are interpreted as follows: spin rotation has a real inductance (and hence [15] real permeability) less [15] than domain wall bulging, and therefore the latter dominates the GMI response. The presence of a dc magnetic field dampens domain wall bulging [16], and this damping explains the strong decrease of both Z_i and Z_r as H_{dc} increases, as long as explained in this same paragraph, domain wall bulging dominates the GMI response.

As frequency increases above the relaxation frequency, domain wall bowing is unable to follow the field, and the only remaining magnetization process is spin rotation. Spins are affected by the anisotropy field, and are less sensitive to H_{dc} than domain wall processes. At zero dc magnetic field, spins are oriented essentially in the circumferential direction, and the ac field (resulting from the ac current) is parallel to spins. Since this orientation is an unfavorable geometry, the contribution from spin rotation to permeability (and hence to impedance and/or inductance) is small as compared with that produced by the interaction between spins and a perpendicular field. As H_{dc} increases, spins are reoriented from their circumferential direction towards the axial direction, and the spin rotation contribution increases. When H_{dc} is comparable to the anisotropy field, H_k, spins rotation is a maximum as is the rotation permeability. For larger values of H_{dc}, however, spins are affected by a larger anisotropy field (since $H_{dc} > H_k$) and spin rotation decreases. These effects explain the presence of the two-maxima in Fig. 1.

4. Conclusions

By a combination of dc magnetic field of impedances and frequency measurements of inductances, we proposed an explanation of the different shapes of impedance plots at 10 kHz and 5 MHz on the basis of the dominant magnetization processes: domain wall bulging and magnetization rotation, respectively. In particular, results indicate that the relaxation frequency of domain walls is 50 kHz, but the decrease in real permeability extends from a few kHz to about 1 MHz. The analysis of domain wall dynamics by means of an equation of motion seems a promising start to determine the microscopic origin of the damping term.

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References

[1] R.S. Beach, A.E. Berkowitz, Appl. Phys. Lett. 64 (1994) 3652.
[2] M. Vázquez, M. Knobel, M.L. Sánchez, R. Valenzuela, A.P. Zhukov, Sensors Actuators A 59 (1997) 20.
[3] K. Mohri, T. Uchiyama, L.V. Panina, Sensors Actuators A 59 (1997) 1.
[4] J.M. García-Beneytez, F. Vinai, L. Brunetti, H. García-Miquel, M. Vázquez, Sensors Actuators A 81 (1997) 78.
[5] R. Valenzuela, M. Knobel, M. Vázquez, A. Hernando, J. Phys. D 28 (1995) 2404.
[6] M.L. Sánchez, R. Valenzuela, M. Vázquez, A. Hernando, J. Mater. Res. 11 (1996) 2486.
[7] Y. Waseda, S. Ueno, M. Hagiwara, K.T. Aust, Prog. Mater. Sci. 34 (1990) 149.
[8] L.G.C. Melo, A.D. Santos, Mater. Sci. Forum 302&303 (1999) 219.
[9] R. Valenzuela, M. Knobel, M. Vázquez, A. Hernando, J. Appl. Phys. 78 (1995) 5189.

[10] J.T.S. Irvine, A.R. West, E. Amano, A. Huanosta, R. Valenzuela, Solid State Ionics 40&41 (1990) 220.
[11] K.L. García, R. Valenzuela, Mater. Lett. 34 (1998) 10.
[12] K.L. García, R. Valenzuela, J. Appl. Phys. 87 (2000) 5257.
[13] R.C. O'Handley, in: Modern Magnetic Materials: Principles and Applications, Wiley, New York, 2000, p. 343.
[14] G. Aguilar-Sahagún, P. Quintana, E. Amano, J.T.S. Irvine, R. Valenzuela, J. Appl. Phys. 75 (1994) 7000.
[15] R.C. O'Handley, in: Modern Magnetic Materials: Principles and Applications, Wiley, New York, 2000, p. 318.
[16] K.L. García, R. Valenzuela, IEEE Trans. Magn. 34 (1998) 1162.