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Low-frequency magnetoimpedance: domain wall magnetization processes

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Abstract

A systematic study of the magnetization processes underpinning the giant magnetoimpedance phenomenon at low frequencies ($f < 10\,\mathrm{MHz}$) is presented. Instead of observing only the total impedance as the main parameter, in this paper we make use of the complex permeability formalism, by calculating permeabilities from complex impedance results. We first investigate the effects of the ac magnetic field amplitude (as produced by the ac current flowing through the sample). Results point to domain wall bulging as the dominant magnetization process for low ac field amplitude. As this amplitude increases, domain walls are unpinned and displaced, leading to hysteresis. As frequency increases, a clear relaxation behavior is observed. The effects of the dc field are then studied. This parameter produces a damping of domain wall processes, leading to a serious decrease in permeability. Very high frequencies are also considered (f in the GHz range) from results recently published, which lead to a complete image of all the magnetization processes, since these results clearly show spin rotation and resonance. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Low-frequency magnetoimpedance; Domain wall magnetization

1. Introduction

Giant magnetoimpedance (GMI) can be considered as the large variations in impedance response of a ferromagnetic conductor (submitted to an ac electric current of small amplitude), as a result of a dc magnetic field. GMI has raised a large technological interest, since it is the basis of many magnetic field and electric current sensors [1,2]. From the basic point of view, it has been explained in terms of classic electromagnetism [3,4], as due to the coupling between the ac magnetic field generated inside the material and its magnetic structure; since ferromagnetic alloys are good conductors with high magnetic permeability, a magnetic field of high frequency (in the range of MHz), cannot penetrate through the alloy because of the skin depth effect. When a dc magnetic field is applied, the magnetic permeability is considerably decreased, the ac field can penetrate more easily and the impedance decreases.

At low frequencies, however, the skin depth effect is not the dominant process and magnetoimpedance has to be explained on a different basis. In this paper, a systematic analysis of the low frequency behavior of magnetoimpedance in some amorphous materials (mainly on as-cast amorphous CoFeBSi wires) is presented. Unlike most of the GMI studies published in scientific literature,

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we use both the real and the imaginary parts of impedance, and transform them into imaginary and real permeabilities, which have a more direct magnetic significance than impedance. The obtained results can be consistently interpreted in terms of domain wall dynamics, as a result of the ac magnetic field produced by the ac current. Domain walls exhibit a relaxation behavior as a function of frequency (typical relaxation frequencies are in the 50–500 kHz). At low frequencies and low ac fields the dominant magnetization process is domain wall bulging (domain walls are pinned to the external surface of the wire); for high ac fields, domain walls are unpinned and displaced, showing also a relaxation behavior as the ac field frequency increases. In the whole frequency range, spin rotation occurs, but it is only significant at frequencies above the wall bulging relaxation frequency (typically above 1 MHz).

2. Experimental techniques

Most of the following results have been obtained by means of an impedance analyzer (typically the HP 4192 A impedance analyzer for the 100–13 MHz frequency range), controlled by a PC system, allowing fast frequency scans. The dc magnetic field is commonly applied by using a Helmholtz system of electromagnets, or a solenoid powered by a dc current source. GMI is a very sensitive phenomenon, since magnetic fields of a tens of A/m (i.e., a few tenths of oersteds) produce a significant change of impedance response.

In wires, complex impedance results are transformed into complex permeability by means of the relationship [5]

$$\mu = -2\mathrm{j}\times 10^7 (Z - R_{\mathrm{dc}})/\omega, \tag{1}$$

where is the complex magnetic permeability ($\mu = \mu' - \mathrm{j}\mu''$, with μ' = real part, and μ'' = imaginary part of permeability), j the basis of complex numbers ($\mathrm{j} = \sqrt{-1}$), Z is the complex impedance ($Z = Z' + jZ''$), R_{dc} is the dc electric resistance of the material, ω is the angular frequency and l the length. Note that due to the presence of j, there is a cross-over of terms, since the real impedance leads to the imaginary part of permeability, and conversely, the real part of permeability depends on the imaginary part of impedance.

GMI is considerably large in low negative magnetostrictive CoFeBSi wires (nominally $(\mathrm{Co}_{94}\mathrm{Fe}_6)_{72.5}\mathrm{B}_{15}\mathrm{Si}_{12.5}$ and typically of 125 μm in diameter), obtained by the fast cooling in the in-water rotating technique [6], but has been observed in a wide variety of soft ferromagnetic materials, such as ribbons, thin tubes and thin films, for instance. In a wire of radius a, the ac magnetic field produced by the ac electric current is on a point r is

$$h_{\mathrm{ac}} = i_{\mathrm{ac}} r / 2\pi a^2, \tag{2}$$

where i_{ac} is the ac current amplitude. The maximum ac field is therefore on the surface of the wire. If the impedances in the system are known, the ac current amplitude can easily be transformed into maximum magnetic field values on the surface of the wire. By taking the (RMS) representation, the ac magnetic fields that can be applied by means of an HP 4192 A system vary roughly between 0.1 and 20 A/m (RMS).

3. Experimental results and discussion

3.1. Effects of ac magnetic field amplitude

We first examine the effect of the ac current amplitude (and therefore ac magnetic field amplitude) on spectroscopic plots (100 to 13 MHz) of the complex permeability response of the material. For small h_{ac}, the real permeability, μ', shows a low frequency plateau which is independent of h_{ac} (between 0.10 and 0.72 A/m (RMS)); as frequency increases, μ' exhibits a relaxation dispersion toward very low values, Fig. 1. For higher values of the ac field, the low frequency part of the permeability is no longer a constant, and strongly depends on h_{ac}. The imaginary part of permeability, μ'', see Fig. 2, shows a small, single maximum for the low values of h_{ac} included in the plateau of the real part. As the field amplitude increases, a new maximum appears and grows at lower frequencies, as shown in Fig. 2.

The low field results are very close to a magnetization process with a simple relaxation behavior. A direct way to verify it is to construct a

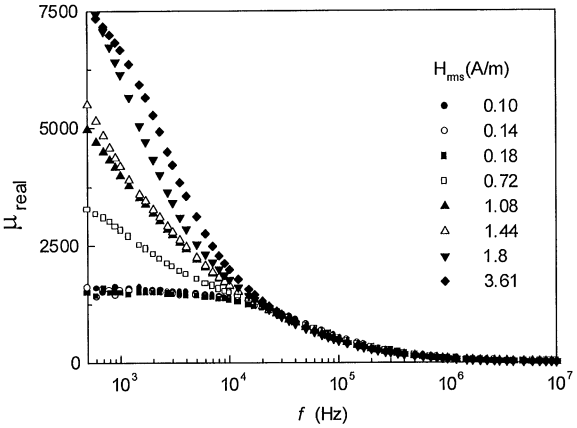

Fig. 1. Real part of permeability as a function of frequency. The ac field amplitude (on the surface of the wire) appears as a parameter.

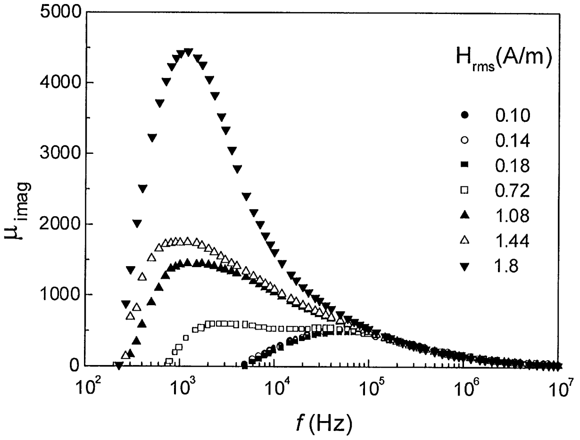

Fig. 2. Imaginary part of permeability as a function of frequency. The ac field amplitude (on the surface of the wire) appears as a parameter.

complex permeability plot (also known as a Cole–Cole plot). The locus of the points (each point obtained at a different frequency) for a relaxation behavior leads to a semicircle on such plot, as shown in Fig. 3.

The high field results point to the presence of a second magnetization process which, unlike the preceding one, is field-dependent. It also seems to possess a relaxation behavior as appears in the Cole–Cole plot even if it exhibits some more distortion than the low-field process.

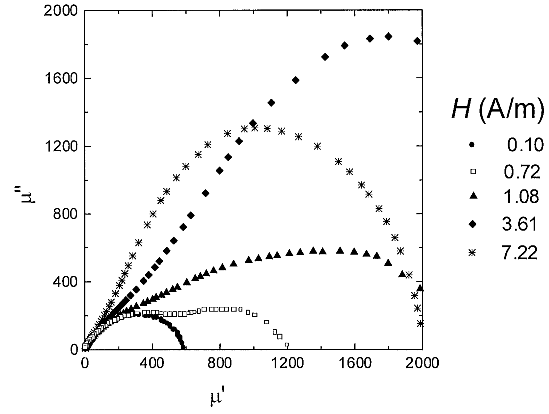

Fig. 3. Complex plot (Cole–Cole plot) of permeability for selected ac field amplitudes.

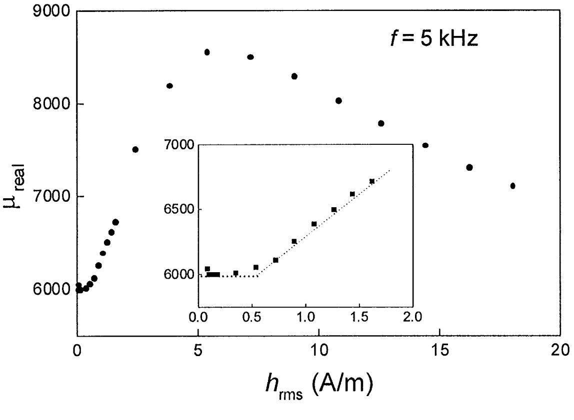

Fig. 4. Behavior of the real permeability as a function of ac field amplitude, at a constant frequency of 5 kHz.

It is also interesting to make a plot of the real part of permeability as a function of ac applied field, at a constant frequency; such a plot appears in Fig. 4. To avoid an additional complexity due to the relaxation process, we chose a frequency lower by a decade, i.e., 5 kHz. A small plateau is then obtained at low fields (see inset), followed by a strong increase, passage through a maximum and then a decrease.

All these results can be interpreted in terms of the dynamics of the circumferential magnetic domain walls in the wire. The real part of permeability at low ac fields and frequencies, and its insensitivity at the field, Fig. 1, indicate that domain walls are pinned (most probably to the external surface of the wire), and the magnetization process is associated with the bulging of the wall. Since such a bulging is reversible (it can be thought of as the elastic deformation of the pinned wall under the "pressure" of the ac field), the permeability value is constant (independent of the field amplitude) and is generally known as the initial permeability.

Domain wall bulging shows a clear relaxation behavior, as confirmed by the semicircles in the Cole–Cole plots. If we consider that an equation of motion can be applied to the wall dynamics,

$$m\mathrm{d}^2x/\mathrm{d}t^2 + \beta\mathrm{d}x/\mathrm{d}t + \alpha x = H(t) \qquad (3)$$

(where m is the effective mass of the domain wall, x is its displacement, β is the damping term, α is the restoring term and $H(t)$ is the excitation field), the inertia term $m\mathrm{d}^2x/\mathrm{d}t^2$ is much smaller than the damping term $\beta\mathrm{d}x/\mathrm{d}t$ and can be neglected, and therefore the solution to this equation for the relaxation frequency is $\omega_x = \alpha/\beta$ ($\omega = 2\pi f$ is the angular frequency).

A detailed analysis of Fig. 4 reveals that this plot is similar to the typical behavior of permeability as a function of applied field. At low fields, there is a small region (inset if Fig. 4) where permeability is a constant: the initial permeability range, where domain walls remain pinned to any defect or discontinuity of the structure. In the case of amorphous samples, the pinning site is expected to be the surface of the sample. After a strong increase in permeability, a maximum appears, and then, a hyperbolic decrease. The latter is due to the simple fact that permeability depends on the ratio of inductance to field.

3.2. Effects of the dc magnetic field

We now consider the effects of the dc magnetic field, which as widely reported, leads to an decrease in the total impedance response. In our case, we observe the changes produced by H_{dc} on spectroscopic plots of the real part of permeability, as shown in Fig. 5. As H_{dc} increases, the whole curve decreases; the dc field produces a decrease in the magnetization process. A similar result is observed in the imaginary part of permeability, Fig. 6. Note that in contrast with the effects of the ac field amplitude (Fig. 2), here there is a simple decrease of the whole curve, with no sensible change in the frequency maximum. These results are summarized in the Cole–Cole plot, Fig. 7, where the dc field leads to a series of decreasing semicircles as H_{dc} increases.

The main effect of the dc field is therefore to produce a damping in domain wall movements: bulging and/or displacement. In this sense, the

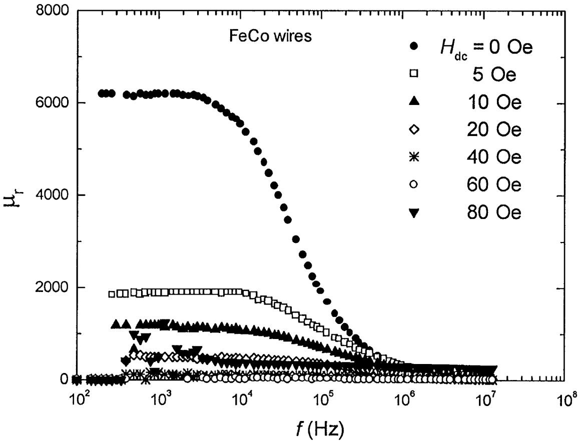

Fig. 5. Real part of permeability as a function of frequency. The dc magnetic field appears as a parameter.

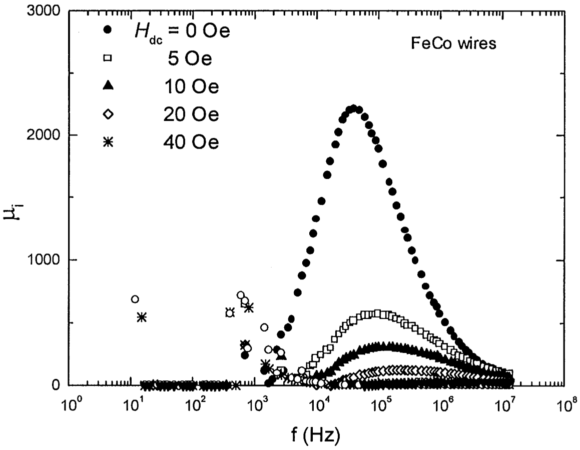

Fig. 6. Imaginary part of permeability as a function of frequency. The dc magnetic field appears as a parameter.

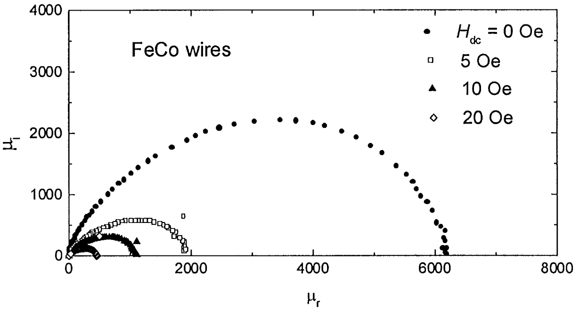

Fig. 7. Complex plot (Cole–Cole plot) of permeability for selected dc magnetic field values.

applied field plays the role of a kind of an induced anisotropy.

3.3. High frequencies

In order to complete the magnetization processes, it is instructive to consider also recent results obtained by other authors at very high frequencies in the GHz range [7]. At these frequencies, a behavior has been observed with all the characteristics of spin resonance: a maximum in the imaginary part of permeability which increases in frequency and absolute value with the dc applied field. In the real part of permeability, an increase in its value with frequency is observed, followed by a fall through the axis down to negative permeability values at the antiresonance section, as shown in Fig. 7. Instead of a semicircle, a whole circle is observed in the Cole–Cole representation. These results are consistent with the previously presented ones, since at such high frequencies, spin rotation is the only active magnetization process.

In a schematic way, all the results we have reviewed can be assembled into one single plot, as shown in Fig. 8. The real part of permeability appears in the upper plot, while the imaginary part is placed in the lower section. We show the results for two extreme values of dc field: solid line for $H_{dc}=0$, broken line for saturation field. At low frequencies and for $H_{dc}=0$, a high value of μ′ appears, which exhibits a relaxation as f increases; at higher frequencies, the spin resonance is extremely small. This latter feature is due to the fact that at $H_{dc}=0$, the material is divided into domains, and the resonance phenomenon cannot take place in a collective way. In the imaginary plot, a strong maximum is observed for the relaxation dispersion, and a very small maximum is obtained for the resonance frequency. When the sample is submitted to a saturating field, the low frequency on both plots is eliminated, as far as obviously, a saturated material possesses no domain walls at all. The spin resonance, on the other hand, is enhanced by the fact that saturation leads to a collective response of all the oriented spins.

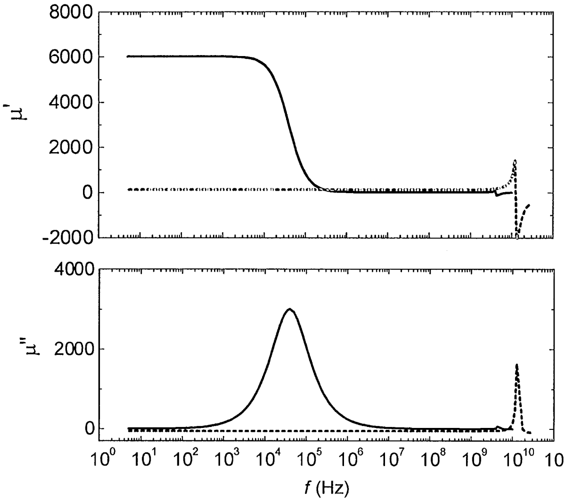

Fig. 8. Schematic representation of the whole frequency range: real permeability in the upper part, and imaginary permeability in the lower section.

4. Conclusions

Magnetization processes underpinning the impedance response have been analyzed. For the low frequency range ($f<1$ MHz) in as-cast CoFeBSi wires, the observed results are consistent with a simple model: at low ac field amplitudes, the bulging of pinned domain walls dominate the permeability response. For high ac field amplitudes, domain walls are unpinned and displaced, leading to an increase in permeability values. Both magnetization processes show a relaxation dispersion. At very high frequencies (in the GHz range), the only active magnetization process is spin rotation, which exhibits a resonance character The dc applied field produces a strong damping of walls, and therefore a strong a decrease in permeability. The described magnetization processes encompass the whole frequency range.

Acknowledgements

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