Giant Magnetoimpedance in CoFeBSi Wires and Polycrystalline Ferrites

E. Carrasco, K.L. García and R. Valenzuela
Institute for Materials Research, National University of Mexico,
P.O. Box 70-360, Mexico D.F., 04510, Mexico.

Abstract—**Measurements of Giant magnetoimpedance (GMI) in Co-rich amorphous wires are compared with magnetic measurements in polycrystalline ZnMn ferrites as a function of frequency (5Hz-13MHz) and a superimposed *dc* magnetic field, aiming to simulate GMI conditions. It is found that, except for the scale differences expected in these two different materials, frequency phenomena are essentially similar. In particular, both properties set can be represented by using the same equivalent-circuit approach. These results point to a domain wall damping effect of the *dc* field, and a reduced role of macroscopic eddy currents.**

I. INTRODUCTION

The giant magnetoimpedance effect (GMI) consists in considerable variations in the impedance of ferromagnetic materials (submitted to a small *ac* current) when a *dc* magnetic field is applied. GMI has been explained [1] in terms of classical electromagnetism, as an increase in impedance as a result of the skin effect. The application of a *dc* magnetic field to the sample reduces its circumferential permeability and increases the field penetration depth, therefore leading to a decrease in impedance.

We have recently proposed [2] an alternative approach to GMI based on modeling by means of an equivalent circuit. An association of the circuit elements with physical parameters of the sample has been established [3]. In this approach, the dominant magnetization mechanisms involve domain wall movements [4,5], and the effects of the *dc* magnetic field responsible for the decrease in impedance (or inductance) are associated with domain wall damping instead of skin effect.

In this paper, we make an attempt to submit a very different type of magnetic material, a polycrystalline ferrite, to the conditions similar to GMI. The effects of the *dc* field, however, are strikingly similar to those typically observed in a low, negative magnetostrictive Co-rich amorphous wire. Results can be interpreted on the basis of an increase in domain wall damping under the *dc* field for both materials, and a reduced importance in the skin effect.

II. EXPERIMENTAL TECHNIQUES

5 cm. long pieces of as-cast, amorphous wires of nominal composition $(Co_{0.94}Fe_{0.06})_{72.5}B_{15}Si_{12.5}$ and 125 μm in diameter kindly provided by Unitika Ltd. Japan, were used. Electrical contacts were prepared as described previously [5].

Polycrystalline ferrites in the system $Zn_xMn_{1-x}Fe_2O_4$ (with $x = 0.4$) were prepared by the usual ceramic method from the mixture of oxides, by sintering in air, typically at temperatures of 1200 °C, for 12 hours, in air [6]. After mixture, they were pressed in the shape of toroids (typically 12 mm OD, 4 mm ID and 5 mm thick) to avoid demagnetization fields. The behavior of their initial permeability as a function of temperature exhibited a very high chemical homogeneity, which is a good quality test [7]. Frequency measurements were carried out by using a low-capacitance coil [8], in order to avoid any spurious resonance.

Frequency measurements were carried out at room temperature in a system including a HP 4192A Impedance Analyzer with a 5Hz-13MHz frequency range, controled by a PC computer. A small *ac* current amplitude (0.9 mA RMS for wires and 5 mA RMS for ferrites) was used.

Axial *dc* magnetic fields for wires up to 6.4 kA/m (80 Oe) were applied by means of a 200-turn, 9 cm long solenoid wound around the sample and powered by a *dc* source. In the case of ferrites, a barium ferrite permanent-magnet system was used to apply higher fields, up to 64 kA/m (800 Oe). For this, two large permanent magnet pieces (toroids with 12 cm OD, 5cm ID and 2.5 cm thick) were fixed in a system that allowed to have relative distance variations. By varying their distance (with their magnetic fields in the same orientation), magnetic fields up to 64 kA/m were easily produced. The field values, as well as the field homogeneity of both the solenoid and the permanent magnet system were measured using a model 410 Lake Shore Gaussmeter. Maximum field inhomogeneity at the solenoid ends was typically

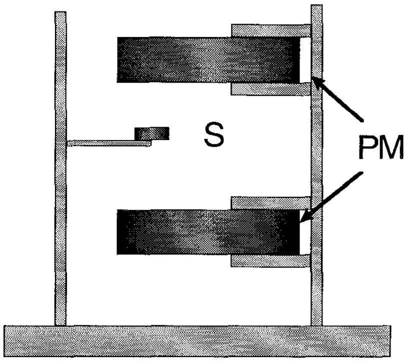

Fig. 1. Permanent-magnet system used to apply dc fields to ferrite samples. PM are the permanent magnets, S the sample.

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K.L. García, +525 622 4641, Fax: +525 616 1371, e-mail: dmmciim@ servidor.unam.mx. R. Valenzuela, +525 622-4653, Fax: +525 555 2071, e-mail: monjaras@ servidor.unam.mx.

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in the 10% range; inside the permanent-magnet system, it was typically within ±15% in an area similar to that of the ferrite samples.

We used the complex inductance formalism, **L**, instead of the complex impedance formalism, **Z**. The transformation is,

$$\mathbf{L} = (-\mathrm{j}/\omega)\,\mathbf{Z}, \qquad (1)$$

where j is the basis of imaginary numbers [$\mathrm{j} = (-1)^{1/2}$] and ω is the angular frequency ($\omega = 2\pi f$).

III. EXPERIMENTAL RESULTS AND DISCUSSION

The behavior of the real part of the inductance (at zero *dc* axial field) of both materials shows the general features of a relaxation dispersion, Fig. 2. In order to compare these different magnetic materials, a "normalization" was made on the y-axis, by dividing the observed values by the L_r value of each sample at low frequencies. The observed absolute values of real inductance, calculated permeability and other pertinent parameters for both materials are collected in Table I.

L_r exhibits a constant value at low frequencies, followed by a drop (a "dispersion") toward a very small value as frequency increases. In the case of the ferrite, a small increase is observed at the onset of the dispersion; also, the drop is steeper than that of the wire.

The imaginary part of inductance of both samples, L_i (f), Fig. 3, at $H_{dc} = 0$, show a maximum associated with dissipative processes. Again, these plots have been normalized in order to be compared, by taking as 1.0 the maximum observed for each sample. This maximum is found at the relaxation frequency, f_x.

The observed behavior on both materials suggested [5,9] that they can be modeled by means of a simple equivalent circuit, a R_pL_p parallel arrangement. Such a circuit leads to a semicircle in the complex plane L_i - L_r, which is shown in Fig. 4. Once again, a normalization has been made to be able to compare these two materials, by taking as 1.0 the semicircle's diameter.

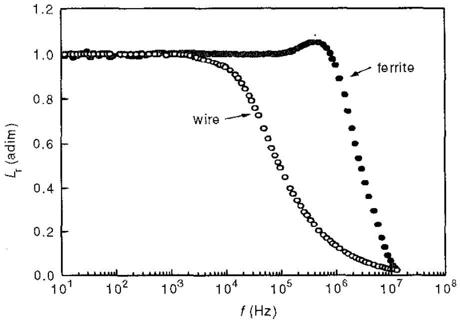

Fig. 2. Spectroscopic plot of real inductances, L_r, for both materials, at zero *dc* field.

TABLE I

	μ	ρ (Ω m)	L_p (μH)	R_p (kΩ)	f_x (MHz)
Ferrite	827	1.05×10^{4}	119.3	2.14	3.39
Wire	5220	1.35×10^{-6}	26.6	0.015	0.07

In this equivalent circuit, the inductive element, L_p, represents the static circumferential permeability of the sample, which can be calculated by means of the pertinent geometrical factor. The resistive element is associated with the inverse of the viscous damping factor [10] of domain walls. Such a circuit exhibits a relaxation frequency, ω_x (= $2\pi f_x$), given by the ratio R_p / L_p. The values of the circuit elements can be extracted from data as follows: L_p is the semicircle's diameter; f_x is obtained from the maxima of L_i (f) plots (Fig. 2), and R_p is calculated as $R_p = \omega_x L_p$.

When the *dc* magnetic field is applied, both the real and the imaginary parts of inductance decrease. To characterize GMI, we consider L_p first, which is independent of frequency, Fig. 5. An attempt has made to normalize this plot, by taking the value of L_p for each sample as 1.0 at $H_{dc} = 0$. Since the main effect of the *dc* field is to produce a rotation of domain spins, we have plotted the values of each sample using H_{dc}/H_K, where H_K is the corresponding anisotropy field.

In spite of the fact that our normalized values do not encompass the same field range, it is possible to observe that the behavior of both samples is similar. This is quite unexpected, as far as sample properties are very different. In particular, the resistivity ratio at room temperature is about 10^{10} (see Table I), which makes it difficult to associate the whole variations in impedance solely to the macroscopic skin effect.

The analysis of R_p can give some insight in the origins of this behavior. This circuit element is associated [10] with the inverse of the domain wall damping factor. As shown in this same issue [11], the effect of the *dc* field on wires is essentially to increase domain wall damping, β. This factor can be thought as dependent on two main contributions,

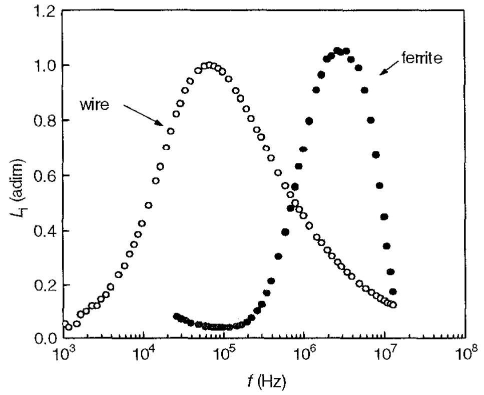

Fig. 3. Dependence of the imaginary inductance, L_r, as a function of frequency, at zero *dc* field.

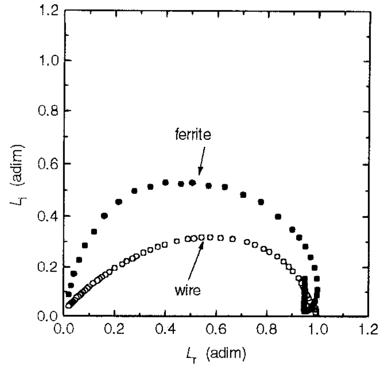

Fig. 4. Complex inductance plot, at zero *dc* field.

$$\beta = \beta_{\mathrm{int}} + \beta_{\mathrm{eddy}}, \tag{2}$$

where β_{int} represents the contribution from intrinsic properties (anisotropy and exchange), and β_{eddy} from eddy microcurrents (associated with domain wall movements), respectively, to the total damping factor. From our results, it appears that β_{int} is considerably larger for ferrites than for wires (the anisotropy is larger), while β_{eddy} is the opposite (the resistivity is much larger). The differences compensate to a certain extent, and the relaxation frequency ratio f_x (ferrite) / f_x (wire) is only about 50.

The application of a *dc* field superimposed to a small *ac* field, as recently shown on a theoretical basis [12], increases domain wall damping and can be assimilated as an increase in anisotropy. The observed results on both ferrite and wire samples are consistent with this interpretation. The differences in behavior (decrease of inductance) are also small. This points also to a mechanism different to the simple (macroscopic) skin effect.

As a conclusion, we have shown that GMI phenomena seems to be general phenomenon, not only observed in amorphous wires and ribbons, but also on non-metalic magnetic materials, and that its general features (once differences in scale have been taken into account) are comparable.

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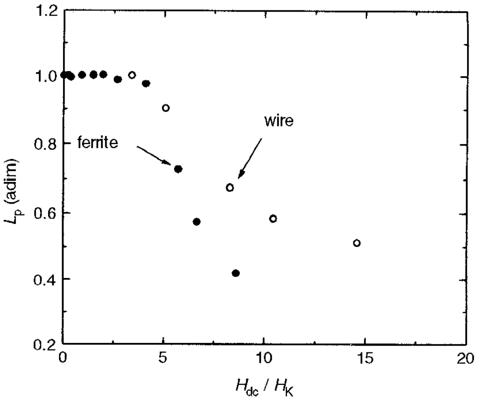

Fig. 5. Normalized complex inductance *Lp*, as a function of (normalized by corresponding anisotropy) *dc* field.

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