Experimental Evidence of Ferromagnetic Resonance in Magnetoimpedance Measurements

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Detailed impedance measurements as a function of the applied magnetic field in an amorphous ribbon are presented for frequencies up to 3 GHz. The shape of the impedance versus field curves is greatly modified by the appearance of a contribution whose maximum is displaced toward higher fields as frequency increases. The analysis of the data reveals that the origin of this contribution is the ferromagnetic resonance induced by the alternating magnetic field associated with the flow of the electrical current employed in the impedance measurements.

***Index Terms*—Giant magneto-impedance (GMI), high frequency impedance measurement, magnetic resonance.**

I. INTRODUCTION

THE change of impedance experienced by a magnetic material when an external magnetic field is applied is known as magneto-impedance (MI). Depending on the permeability of the magnetic material and on the frequency of the alternating current flowing through it, the skin effect (limited penetration of the electromagnetic fields) determines the impedance of the material. The external magnetic field modifies the permeability thus producing the mentioned change in the impedance. Although this effect is completely classical and has been known for a very long time, it has attracted great attention in the last years, due to the huge impedance changes (up to several hundreds percent) observed in well suited samples and optimum experimental configurations. This giant MI (GMI) effect is very promising for constructing high sensitivity magnetic sensors and has been the subject of a large amount of theoretical and experimental work.

In the quasistatic regime (typically up to tens of MHz) the permeability dependence on the applied field can be modeled from classical methods as arising from domain wall movements or magnetization rotation. Considering it to be constant as function of the frequency, the impedance can be calculated from Maxwell equations. For a sheet of infinite width and length, with a thickness $2a$, when an ac current of angular frequency $\omega = 2\pi f$ flows through it, the impedance is given by [1]

$$Z = R_{\rm dc}\sqrt{j}\theta\coth(\sqrt{j}\theta) \tag{1}$$

where $R_{\rm dc}$ is the dc resistance and $\theta = \sqrt{2}(a/\delta)$ is an adimensional "frequency," with $\delta = (\omega\sigma\mu/2)^{-1/2}$ the skin depth, σ being the conductivity and μ the low frequency transverse permeability. A similar expression holds for wires, where Bessel functions are involved. The external magnetic field H changes the permeability and therefore, the impedance of the sample. The impedance is maximum at $H = 0$ (single peak MI curves) for longitudinal anisotropy or at $H = \pm H^k$ (double peak curves) for transverse anisotropy (H^k is the anisotropy field). The minimum value of the impedance is obtained when the sample is magnetically saturated and $\mu \approx \mu_0$. The experimental set-up for GMI measurements at these frequencies is usually based on a simple four-contacts method.

In the search for smaller GMI devices and fabrication procedures that can be integrated into electronic systems, thin film samples have been considered. In this situation, higher frequencies, beyond the quasistatic regimen, are necessary to make the skin depth comparable to the thickness. At these frequencies (of the order of gigahertz) both theory and experiment become much more complicated. The behavior of the magnetization in the alternating magnetic field created by the current used to determine the impedance must be described in the framework of the Landau–Lifshitz (LL), Gilbert or similar dynamical equations [2]. According to the phenomelogical LL equation, the motion of the magnetization is governed by

$$\dot{\mathbf{M}} = -\gamma(\mathbf{M}\times\mathbf{H}) - (\lambda/M^2)[\mathbf{M}\times(\mathbf{M}\times\mathbf{H})] \tag{2}$$

where γ is the gyromagnetic ratio and λ is a damping parameter (also called relaxation frequency) that takes into account different phenomena as dipole-dipole interactions and exchange conductivity. This equation establishes the existence of large permeability peaks when the ferromagnetic resonance (FMR) takes place for certain values of the applied field and the frequency of the alternating current. The magnitude of the maxima and the width of the resonance are determined by λ. The impedance is concomitantly modified by the permeability changes induced by the ferromagnetic resonance. This situation has been examined by several authors [3], [4] but the interpretation of the data is quite controversial. Besides, the experimental measurements at high frequency are largely affected by the measurement set-up and propagative effects that must be taken into account to obtain accurate impedance results.

In this paper, we have performed a study of the magneto-impedance behavior at frequencies up to 3 GHz in a 20-μm thick amorphous ribbon, in order to clarify the role of the FMR and how it modifies the GMI response as the frequency is increased.

It is to be noted that, as the field H in (2) is the effective internal field, $H_{\rm eff}$, shape effects should be considered. For ribbon samples, as the one in this work, with the field applied along the longitudinal axis, the resonance condition (not taking into account the damping) is [5]

$$\omega_{\rm res} = 2\pi f_{\rm res} = \gamma\mu_0\sqrt{H_{\rm eff}(H_{\rm eff}+M_s)}. \tag{3}$$

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II. Experiment

A soft, zero magnetostrictive Fe-Co-Si-B amorphous ribbon was used for the experiments. Its dimensions were 20-mm long, 1-mm wide and 20-μm thick. To measure the impedance, the sample was included in a microstrip transmission line. The complex reflection coefficient (S_{11}) of the fixture including the sample was measured by a RF Network Analyzer (Agilent 8714ET) for frequencies ranging from 300 kHz up to 3 GHz (801 frequencies in total, logarithmically spaced). When the frequency is high enough for the associated wavelength to be comparable to the dimensions of the transmission line, the propagation effects introduce an undesired contribution to the impedance. This contribution is eliminated by a calibration procedure that is explained in depth in [6]. The applied field H was provided by means of Helmholtz coils.

III. Results and Disccusion

The absolute value of the impedance measured as a function of the applied field for selected values of the frequency is shown in Fig. 1. For frequencies up to 500 MHz, the low field range is displayed so the main low field features can be distinguished. For the curves measured at 1 and 2 GHz, an extended field range has been chosen. For these two frequencies, the real and imaginary parts of the impedance are also displayed. At the lowest frequency (300 kHz), a typical GMI curve is obtained, showing a maximum (vaguely double peaked) at low fields and a steady decrease of impedance for fields larger than H^k, as the sample is being magnetically saturated and the transversal permeability decreases. (The longitudinal hysteresis loop measured in this sample shows that H^k is about 100 A/m and it can be considered magnetically saturated for fields higher than about 300 A/m). When the frequency increases, a contribution to the impedance appears for applied fields higher than the anisotropy field that progressively "pushes" that region of the curve upwards, in such a way that, for 10 MHz, the central (low field) part is depressed. In the curve obtained at 100 MHz the impedance shows a distinct maximum (in fact there are two maxima, one for positive and one for negative fields). The position of this maximum shifts toward larger field values with increasing frequency. The analysis of the real and imaginary components of the impedance provides further information about the main origin of the observed phenomena: a maximum in the real part occurs for applied magnetic fields where the imaginary part displays a change in slope (the typical behavior of the imaginary part at resonance is a change of sign. It is not observed in our data due to the external impedance of the measuring set-up. In particular, the external inductance L_{ext}, gives a contribution $j\omega L_{\text{ext}}$ to the impedance that prevents the zero crossing of the imaginary part). To clarify, Fig. 2 shows the field dependence of the real part of the impedance for some selected frequencies. The estimated resonance frequency (frequency at which the real part displays a maximum value) is plotted in Fig. 3 as a function of the magnetic field H. The solid line in Fig. 3 represents the estimated curve considering (3) where H_{eff} is taken as $H_{\text{eff}} = H - H^k$, to account for the small perpendicular anisotropy that the sample displays. The parameters used in this estimation are $(\gamma/2\pi) = 28$ GHz/T, $\mu_0 M_s = 0.7$ T, and $H^k = 263$ A/m.

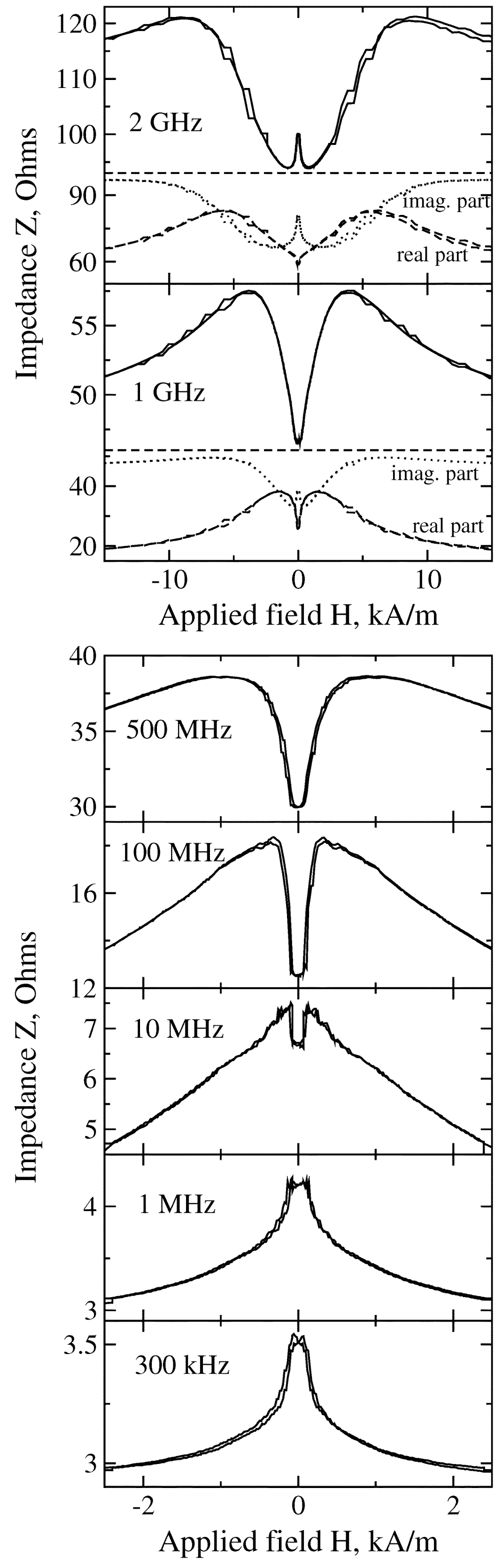

Fig. 1. Impedance as a function of the applied magnetic field H for selected frequencies. For the measurements at 1 and 2 GHz, the real and imaginary parts of the impedance are also displayed.

The value of the gyromagnetic ratio γ used corresponds to a splitting factor $g = 2.00 (\gamma = g\mu_B/\hbar)$ which is slightly lower than the reported values for pure Fe and Co at room temperature (2.10 and 2.18, respectively, [5]), while the measured value of saturation magnetization $\mu_0 M_s$ for this sample is 0.8 T. Both

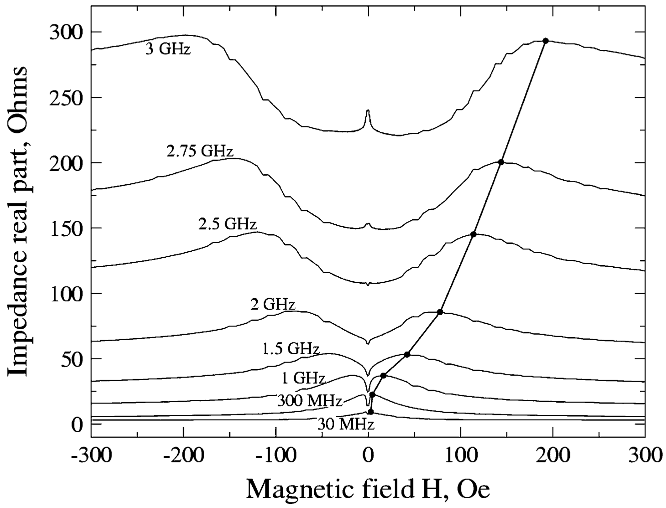

Fig. 2. Real part of the impedance as a function of the applied magnetic field for selected frequencies. The maxima for positive fields are marked with a circle and joined by a continuous line.

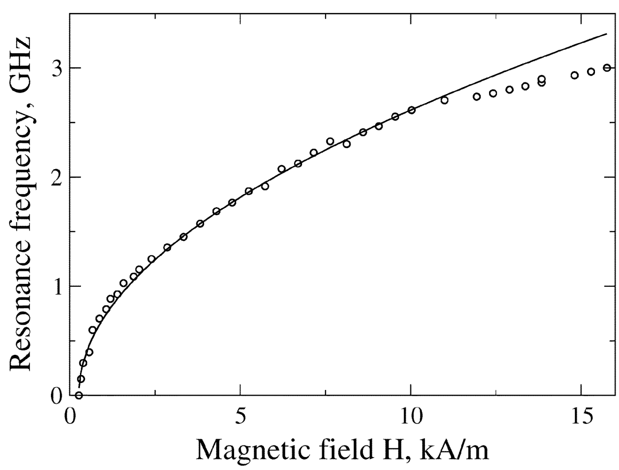

Fig. 3. For each measured frequency, the field at which the maximum of the impedance is reached is considered the resonance field for FMR. The circles are experimental points taken from curves like the ones shown in Fig. 2. The line is the evaluation of (3) with values of the parameters given in the text.

parameters, γ and M_s, affect the shape of the curve in a similar way: higher values of any of them move the curve upwards. In any case, the description of the data by the FMR equation is exceptional up to a frequency of about 2.5 GHz. For higher frequencies, we suspect that the propagation effects are important enough to make the impedance subtraction procedure inaccurate. Besides, there are some impedance contributions from the transmission line that worsen the results (coming from the external self-inductance and capacitance). An improved data reduction procedure (based in the one proposed in [7] for wires) can probably improve the results. Work on it is in progress and will be published elsewhere.

Another important feature of the impedance spectra presented in Fig. 1, is the small peak that appears at low field in the curve obtained at 2 GHz (also visible at higher frequencies). Its shape is identical to the single peak obtained at low frequency (300 kHz) and, despite the different magnitude of the impedance in both cases, their relative variations are very close (about 15%). Although further clarification is needed, in our opinion, the origin of both peaks at low and high frequencies is the same: the magneto-impedance produced by the magnetization processes at low fields. At high frequency this low field peak is only visible when the FMR contribution has gone sufficiently apart form the center of the graph.

IV. Conclusion

The detailed evolution of the magneto-impedance behavior with increasing frequencies unequivocally demonstrates the existence and importance of ferromagnetic resonance processes, al least for fields where the sample is magnetically saturated. The contribution of FMR completely modifies the behavior observed at low frequency that is governed by magnetization processes. However, the low frequency behavior re-appears when the low field contribution of FMR weakens at the highest frequencies.

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