Wide frequency range magnetoimpedance in tri-layered thin NiFe/Ag/NiFe films: Experiment and numerical calculation

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Given that the magnetoinductive effect (MI), skin effect and ferromagnetic resonance influence magnetic permeability behavior at different frequency ranges, the description of the magnetoimpedance effect over a wide range of frequency becomes a difficult task. To that end, we perform an experimental investigation of the magnetoimpedance effect in a tri-layered thin film over a wide frequency range. We compare the experimental results for a tri-layered thin film with numerical calculus performed using an approach that considers a magnetic transverse susceptibility model for planar systems and an appropriate magnetoimpedance model for a tri-layered system together. The results show remarkably good agreement between numerical calculus and experimental measurements. Thus, we discuss the experimental results in terms of different mechanisms that govern the MI changes observed in distinct frequency ranges and provide experimental support to confirm the validity of the theoretical approach. © 2011 American Institute of Physics. [doi:10.1063/1.3658262]

I. INTRODUCTION

The magnetoimpedance effect (MI) corresponds to the change in complex impedance \( Z = R + iX \) of a ferromagnetic sample submitted to an external magnetic field \( H \).

Since it was first observed, MI has attracted considerable interest not only for its contribution to understanding fundamental physics associated to magnetization dynamics but also due to potential technological applications in magnetic sensors and integrated devices based on the magnetoimpedance effect, even in more complex integrated circuit architectures, such as microprocessors. For this reason, experimental studies on MI have been widely performed in magnetic ribbons, microwires, and, in recent decades, in magnetic films with several structures, such as single layered, multilayered, and structured multilayered samples.

Although the magnetoimpedance effect has been extensively investigated, many questions still remain unclear. For example, a difficult task consists of explaining experimentally measured MI curves, such as impedance \( Z \) as a function of the magnetic field for a given frequency value, as well as curves of the real \( R(Ω) \) and imaginary \( X(Ω) \) parts of impedance as a function of magnetic field or current frequency, in terms of the magnetization processes and mechanisms responsible for MI variations. Traditionally, magnetic permeability, and consequently impedance, changes with magnetic field at different frequency ranges and is interpreted considering three mechanisms: magnetoinductive effect, skin effect, and ferromagnetic resonance. However, their different relevance with frequency is generally very complicated and not easily predictable, since it depends on material properties, such as magnetic anisotropy, as well as sample dimensions and geometry.

The general theoretical approach to the MI problem focuses on its determination as a function of magnetic field for a range of frequencies. Thus, MI can generally be classified into three frequency regimes. For the low-frequency range, MI schematization was proposed by Mohri et al., considering changes in the inductive part of impedance and this is known as the magnetoinductive effect. At the intermediate frequency range, Beach et al. considered that the skin effect was responsible for transverse magnetic permeability changes and consequently, for variations in the magnetoimpedance effect. Finally, at high frequencies, Yelon et al. demonstrated that field configurations favor the appearance of ferromagnetic resonance, the main mechanism responsible for magnetic permeability changes and MI variations.

Since system geometry also has an important effect on MI results, theoretical studies have been performed to obtain further information on this dependence. Considerable attention has been given to the case of planar systems. For example, Kraus performed calculus of the MI for a single planar conductor, studying the influence of the Gilbert damping parameter, as well as the angle between the easy magnetization axis and the applied magnetic field direction, on MI. In addition, Panina et al. and Sukstanskii et al. investigated MI behavior in a tri-layered system (ferromagnet/non-magnetic metal/ferromagnet), analyzing the influence of width, length, and conductivity on MI, while Antonov et al. showed the effect of non-magnetic metal thickness on the MI curves.

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It is well known that the key to understanding and controlling MI lies in the knowledge of transverse magnetic permeability behavior in a given material. However, although the MI results obtained by the abovementioned models are consistent and seem to reproduce experimental data, the main question concerns knowledge of transverse permeability behavior over a wide frequency range. This restricts the results to a limited frequency range or hinders identification of which permeability model must be chosen for that limited range.

Since experimental measurements have been taken over a wide range of frequencies, it is important for MI interpretation to have a single permeability model which enables MI calculus, considering frequency dependent magnetic permeability.

With this spirit, a different approach to the study of magnetization dynamics was undertaken by Spinu et al., who investigated transverse susceptibility and its dependence on both frequency and magnetic field, using knowledge of appropriate magnetic free energy density. It is therefore possible to obtain transverse magnetic permeability from susceptibility and in turn describe MI behavior by using different models, according to system geometry, for a wide range of frequencies and external magnetic fields.

In this paper, we present an experimental investigation of the magnetoimpedance effect in a tri-layered thin film over a wide range of frequencies. In order to interpret the experimental results, we study the MI problem by considering two single models together: the model proposed by Spinu et al. to calculate transverse magnetic permeability, and the approach for MI in tri-layered systems, reported by Panina et al. Experimentally, we produce a tri-layered thin film by magnetron sputtering, with the same structure and geometry considered for the theoretical model, and compare theoretical predictions with experimental MI measurements over a frequency range between 10 MHz and 1.8 GHz. Thus, we discuss the experimental results in terms of different mechanisms that govern the MI changes observed in distinct frequency ranges and provide experimental support to confirm the validity of the theoretical approach.

The paper is organized as follows: in Sec. II, we present the main experimental procedure used during sample preparation, magnetic characterization, as well as the MI setup. In Sec. III, we briefly present the theoretical model, based on energy minimization, used to calculate transverse magnetic permeability, as well as the MI model. To check the models, we show some numerical results for permeability and MI obtained with a tri-layered system. In Sec. IV, we compare and discuss the results obtained by the theoretical numerical calculation of a tri-layered system with those experimentally measured in our tri-layered thin film. Finally, Sec. V presents conclusions.

II. EXPERIMENT

For the study, we produce a tri-layered thin film of NiFe/Ag/NiFe with 150 nm-thick ferromagnetic layers and 100 nm-thick Ag layer and dimensions of $12 \times 4 \times 2$ mm$^2$. The sample was deposited by magnetron sputtering from commercial Ni$_{81}$Fe$_{19}$ and pure Ag targets onto a glass substrate previously covered by a 5 nm-thick Ta buffer. Deposition was done with the substrate moving at constant speed through the plasma to improve film uniformity. The substrate was submitted to a 100 Oe axial magnetic field to induce in-plane uniaxial magnetic anisotropy. The procedure was carried out using the following parameters: base pressure of $4.0 \times 10^{-7}$ Torr, 99.99% pure Ar pressure during deposition of $5.0 \times 10^{-3}$ Torr, 65 W RF power for NiFe, and 25 mA dc current for the Ag layer. The deposition rates for NiFe and Ag were 0.210 nm/s and 0.149 nm/s, respectively, calibrated with x-ray diffraction.

Magnetization measurements were taken using a vibrating sample magnetometer with maximum applied magnetic field of $\pm 300$ Oe, at room temperature. In-plane magnetic behavior was determined by obtaining magnetization curves in two different directions: the first along the direction defined by the magnetic field applied during deposition and the second along the direction perpendicular to the first.

Magnetoimpedance measurements were taken using an HP4396B spectrum-impedance-network analyzer equipped with an HP43961A impedance measuring fixture and a microstrip-line microwave cavity, similar to the one used in Ref. 25. However, in this case, the sample is the central stripe conductor, which is separated from the ground plane by the glass substrate. The probe current was fed directly to one side of the sample, while the other side was in short circuit with the ground plane. To eliminate the propagative effects and acquire only the sample contribution to MI, the analyzer is calibrated at the end of the connection cable by performing open, short, and load (50 $\Omega$) measurements using reference standards, as achieved by other groups. MI measurements were taken over a wide frequency range, between 10 MHz and 1.8 GHz, with magnetic field varying from $-300$ Oe to $+ 300$ Oe. For all measurements, a 0 dBm (1 mW) constant power was applied to the sample, while the external magnetic field was swept. At a given field value, the frequency sweep was made and the real and imaginary parts of line impedance were simultaneously acquired. The curves exhibited hysteretic behavior, associated with the coercive field. However, in order to clarify the general behavior, only curves depicting the field going from negative to positive values are presented.

In our analysis, the MI ratio is defined as

$$MI\% = \frac{Z(H) - Z(H_{\text{max}})}{Z(H_{\text{max}})} \times 100, \quad (1)$$

where $Z(H)$ is the impedance value at a given magnetic field $H$ and $Z(H_{\text{max}})$, the impedance value at the maximum applied magnetic field, given by $H_{\text{max}} = 300$ Oe, where the magnetic state of the sample is saturated. $MI_{\text{max}}$ is defined as the maximum $MI\%$ value for a given frequency. It is important to point out that the $MI\%$ defined here is different from that used, for example, in Ref. 21 where impedance in zero magnetic field is considered the reference.

III. NUMERICAL CALCULATION

In order to investigate and obtain further information on the experimental MI measurements, we performed numerical
calculations of the magnetic properties for a tri-layered system, such as static magnetization curves, magnetic permeability, magnetoimpedance, and MI%.

To that end, we consider two single models together: for a tri-layered thin film, we employed the magnetic susceptibility model proposed by Spinu et al. and the approach to magnetoimpedance behavior in a multilayered system reported by Panina et al.

A. Magnetic permeability

In planar systems, such as thin films, surface impedance depends on alternating electrical current \( I_{ac} \) frequency and transverse magnetic permeability \( \mu(I_{ac}, f, H) \) through the skin depth,

\[
\delta_f = \frac{1}{\sqrt{\sigma f \mu(I_{ac}, f, H)}},
\]

where \( \sigma \) is the conductivity of the ferromagnetic material, \( f \) is the current frequency, and \( H \) is the external magnetic field.

As mentioned earlier, it is possible to understand MI from a ratio and to approach the reader refer to Appendix A of Ref. 24.

In the magnetic susceptibility model proposed by Spinu et al., magnetization dynamics is governed by the Landau-Lifshitz-Gilbert equation, given by

\[
\frac{d\vec{M}}{dt} = \gamma (\vec{H} \times \vec{M}) - \frac{\gamma}{\hbar} \frac{2}{M} [\vec{M} \times (\vec{M} \times \vec{H})],
\]

where \( \vec{M} \) is the magnetization vector, \( \vec{H} \) is the magnetic field vector, and \( \gamma = |\gamma_G|/(1 + x^2) \), where \( \gamma_G \) is the gyromagnetic ratio and \( x \) is the phenomenological damping constant. The magnetic field presents two contributions: \( \vec{H} = \vec{H}_E + \vec{h}_ac \).

The first term contains the static component of the field and corresponds to internal magnetic field \( \vec{H}_E \), determined by different contributions in magnetic free energy density \( E \) and given by \( \vec{H}_E = -\frac{\partial E}{\partial \vec{M}} \), while the second contains alternating magnetic field \( \vec{h}_ac \) generated by \( I_{ac} \). This is a general expression that can be applied to express magnetization dynamics in any system, with any symmetry. Thus, by writing the magnetic field in this manner, it is possible to determine transverse magnetic susceptibility \( \chi \) for any magnetic system, since an adequate magnetic free energy density is considered. For a complete description of this model, we suggest the reader refer to Appendix A of Ref. 24.

In the present investigation, we focus on the study of ferromagnetic films, which can be modeled as a planar system. Figure 1 shows a theoretical system and the definitions of the relevant vectors considered to perform all the numerical calculations. Thus, in this case, considering \( \theta_H = \phi_M = 90^\circ \), according to the angles defined in Fig. 1, the appropriate diagonal terms of the transverse susceptibility tensor, in Cartesians, obtained by Spinu et al. can be written as

\[
\text{Re}(\chi_t) = \text{Re}(\chi_{xx}) = \left( \frac{1}{\xi} \right) \times \left[ (\gamma^2 + \gamma^2 x^2) \times (\varphi_M^2 - \varphi_M^2) \right]
\]

\[
\times \left( E_{\varphi_M} \cos^2 \varphi_M \cos^2 \theta_M \sin^2 \theta_M \right)
\]

\[
+ \left( \frac{1}{\xi} \right) \times \gamma M_s \omega^2 \Delta \omega (\sin^2 \varphi_M + \cos^2 \varphi_M \cos^2 \theta_M)
\]

\[
\text{Im}(\chi_t) = \text{Im}(\chi_{xx}) = \left( \frac{\omega}{\xi} \right) \times \left[ (-\gamma^2 - \gamma^2 x^2) \times \Delta \omega \right]
\]

\[
\times \left( E_{\varphi_M} \cos^2 \varphi_M \cos^2 \theta_M \sin^2 \theta_M \right)
\]

\[
+ \left( \frac{\omega}{\xi} \right) \times \gamma M_s (\varphi_M^2 - \varphi_M^2)
\]

\[
\times (\sin^2 \varphi_M + \cos^2 \varphi_M \cos^2 \theta_M).
\]

In both expressions, \( \xi = \left( \omega_M^2 - \omega^2 \right)^2 + \omega^2 \Delta \omega^2 \), \( \omega \) is the angular frequency, \( \omega_M \) is the widely known resonance frequency in FMR theory, \( M_s \) is the saturation magnetization, \( E_{\varphi_M} = \partial E/\partial \varphi \).
$E_{\phi\phi}$ and $E_{\theta\theta}$ are the second derivatives of the magnetic free energy density at the equilibrium position of magnetization, and $\theta_M$ and $\phi_M$ are the equilibrium angles of magnetization obtained by minimizing the energy density for a given magnetic field value. Transverse magnetic permeability is obtained from susceptibility through

$$\mu = 1 + 4\pi\chi.$$  

For a tri-layered planar system, we used a modified Stoner-Wohlfarth model\cite{28} to write the magnetic free energy density. In this case, where the expression must present contributions from the two ferromagnetic layers, energy density is given by

$$E = -\sum_{i=1}^2 \vec{H} \cdot \vec{M}_i - \sum_{i=1}^2 \left( \frac{H_k}{2M_S} \right) (\vec{M}_i \cdot \hat{u}_{i3})^2$$

$$+ \sum_{i=1}^2 4\pi M^2_S (\vec{M}_i \cdot \hat{u})$$,  

(7)

where the first term is the Zeeman interaction, the second term describes uniaxial magnetic anisotropy and the third corresponds to demagnetizing energy density for a thin planar system, such as a thin film. In this case, $\vec{M}_i$ and $M_S$ are the magnetization vector and saturation magnetization for each ferromagnetic layer, respectively, and $H_k = 2K_M/M_S$ is the anisotropy field for each layer, where $K_M$ is the uniaxial anisotropy constant, directed along unit vector $\hat{u}_3$, with $\hat{u}_{13} = \hat{u}_{23} = \hat{u}$, as well as $M_{81} = M_{82} = M_S$, because there are two similar ferromagnetic layers in the sample.

In this study, we grew a tri-layered sample with a thick non-magnetic metallic layer. Therefore, it is not necessary to include exchange terms between the ferromagnetic layers, such as bilinear and biquadratic exchange couplings. Although, it is known that magnetoelastic anisotropy plays an important role in MI values,\cite{29} it was not included since the ferromagnetic alloy (NiFe) employed for growth contains a saturation magnetostriiction constant of $\lambda \sim 10^{-8}$.

Finally, it is important to point out that domain walls were not considered for two reasons. The first is related to the orientation of the applied magnetic field with respect to the easy magnetization axis of the sample. In the magnetization and MI measurements performed here, the static magnetic field was applied perpendicularly to the easy magnetization axis, where the magnetization rotation is the main magnetization mechanism responsible for the magnetization changes. The second reason lies in the mechanism responsible for the MI changes. At frequencies above $\sim 10$–$100$ MHz, domain walls are strongly damped by eddy currents and only magnetization rotations contributes to the MI changes.\cite{16}

Once the energy density term was written, to verify the permeability model and confirm the validity of the procedures, we present, as a preliminary test, some of the results obtained from the expressions described above. Thus, Fig. 2 shows magnetic permeability vs. magnetic field for different frequency values obtained for a theoretical tri-layered system, using the following parameters: $M_S = 780$ emu/cm$^3$, $H_k = 12$ Oe, $\theta_k = 90^\circ$, $\phi_k = 20^\circ$, $\alpha = 0.018$, and $\gamma = 2.9 \times 10^5$ Oe·Hz. At lower frequencies, represented by the curves for $80, 500,$ and $800$ MHz in the figure, maximum magnetic permeability is located at similar magnetic field values, while at the higher frequencies of $1000, 1400,$ and $1800$ MHz, there is displacement of maximum values in the imaginary permeability part, simultaneously to a zero crossing of the real part. This behavior is usually observed, as verified in Ref. 30.

**B. Magnetoimpedance effect**

Approaches to magnetoimpedance behavior in a tri-layered system have been reported in Refs. 21–23. In particular, Panina et al.\cite{21} studied the magnetoimpedance effect in a tri-layered system, with finite width $2b$ and length $l$ for all layers, thickness, $t_1$ and $t_2$, and conductivity, $\sigma_1$ and $\sigma_2$, for metallic and ferromagnetic layers, respectively, and variable flux leaks across the inner conductor. When $b$ is sufficiently large and the edge effect is neglected, impedance is dependent on thickness films $t$. Therefore, for a tri-layered system, impedance can be written as\cite{21}

$$\frac{Z}{R_{dc}} = \left( \frac{\eta_m}{\eta_F} \right) \left[ \frac{\coth \left( \frac{\eta_m \sigma_2 \sigma_1 \mu}{k_1 t_1} \right)}{\coth \left( \frac{\eta_F \sigma_2 \sigma_1 \mu}{k_1 t_1} \right)} + \frac{2\eta_m}{k_1 t_1} \coth \left( \frac{\eta_F}{k_1 t_1} \right) \right],$$  

(8)

where in Eq. (8),

$$\eta_m = \frac{k_1 t_1}{2} \left( \frac{\sigma_1 \mu}{\sigma_2} \right), \quad \eta_F = k_2 t_2, \quad k_1 = \frac{(1 - i)}{\delta_1}, \quad k_2 = \frac{(1 - i)}{\delta_2}, \quad \delta_1 = [2\pi\sigma_1 \omega]^{-1/2}, \quad \delta_2 = [2\pi\sigma_2 \omega\mu]^{-1/2}$$

when the limit of $t_1 \to 0$ in Eq. (8) is taken, it becomes exactly equal to the classical impedance solution, as shown in our previous work.\cite{31}
Using the model proposed by Spinu et al.\textsuperscript{24} to obtain magnetic permeability, presented Sec. III A, with the magnetoimpedance approach for a tri-layered system, for example, the one studied by Panina et al.,\textsuperscript{21} it is possible to calculate the MI for this system, starting from an appropriate magnetic free energy density. To that end, a routine for energy minimization is necessary to determine $\theta_M$ and $\phi_M$ values for each $H$ external magnetic field value.

Figure 3 shows the real and imaginary parts of the magnetoimpedance as a function of the angle between $\vec{u}_k$ and $\vec{H}$ for selected frequency values, calculated for the same tri-layered system considered in Figure 2, with with $\sigma_1 = 6 \times 10^7$ (Om)\textsuperscript{-1}, $\sigma_2 = \sigma_1/4$, $t_1 = 100$ nm, and $t_2 = 150$ nm. In this case, as expected, magnetoimpedance behavior exhibits distinctive features at different frequency ranges. At 80 MHz, peak structure changed from single peak to double peak behavior.\textsuperscript{8,19} For 1000 MHz, the evolution from a single to a double peak structure was not observed, since the FMR effect was present. This effect leads to double peak behavior, irrespective of the angle between $\vec{u}_k$ and $\vec{H}$, although single peak displacement as the angle varies can be observed.

Finally, since the $M_{I_{max}}$ of a tri-layered system is strongly dependent on the $\sigma_1/\sigma_2$ ratio, Fig. 4 shows the $M_{I_{max}}$ vs. $f$ behavior obtained with the same system, but varying the $\sigma_1/\sigma_2$ ratio value. In this case, there is a decrease in $M_{I_{max}}$ peak followed by peak displacement when $\sigma_1/\sigma_2 \rightarrow 1$. This behavior is similar to that reported in Ref. 32; however, it is important to point out that our numerical calculation was performed for higher frequency values, since the peak occurs at high frequencies, a fact related to smaller layer thicknesses.

**IV. RESULTS AND DISCUSSION**

In this section, we present experimental results, magnetic properties and MI obtained for our tri-layered thin film, and compare them with the numerical findings calculated for a tri-layered system using magnetic permeability and MI models described and tested in Sec. III.

With respect to numerical calculations, the following parameters must be defined to simulate the magnetization and MI curves: saturation magnetization $M_S$, uniaxial anisotropy field $H_k$, uniaxial anisotropy direction unit vector $\vec{u}_k$, thickness, $t_1$ and $t_2$, conductivity, $\sigma_1$ and $\sigma_2$, for metallic and ferromagnetic layers, respectively, damping parameter $\alpha$, gyromagnetic factor $\gamma$, and external magnetic field vector $\vec{H}$.

Thus, since the simulated magnetization curve validates experimental magnetization behavior, the aforementioned parameters are fixed to perform the numerical calculations of MI behavior. However, since there is an offset increase in the real and imaginary parts of measured impedance as a function of frequency, a feature of the metallic contribution to MI that is not taken into account in theoretical models, a procedure was performed to include it manually when calculating MI.

FIG. 3. (Color online) Real and imaginary parts of impedance vs. magnetic field as a function of the angle between $\vec{u}_k$ and $\vec{H}$ for selected frequency values, calculated for the same tri-layered system considered in Figure 2, with with $\sigma_1 = 6 \times 10^7$ (Om)\textsuperscript{-1}, $\sigma_2 = \sigma_1/4$, $t_1 = 100$ nm, and $t_2 = 150$ nm.

FIG. 4. $M_{I_{max}}$ vs. $f$ behavior obtained with our approach for the same system, but for different $\sigma_1/\sigma_2$ ratio, where $\sigma_1$ and $\sigma_2$ are the electric conductivity of the metallic and ferromagnetic layers, respectively. For purposes of comparison, note that $\sigma_1/\sigma_2 = 4$ for our tri-layered thin film.
presented in Sec. IV B. It is important to remember that the netic layer thickness increases.

During deposition, a small misalignment between them is close to the direction defined by the magnetic field applied growth, confirming an easy magnetization axis oriented very possible to observe magnetic anisotropy induced during film production, in order to induce in-plane uniaxial anisotropy. As a matter of fact, by comparing experimental curves, it is possible to observe magnetic anisotropy induced during film growth, confirming an easy magnetization axis oriented very close to the direction defined by the magnetic field applied during deposition. A small misalignment between them is a feature associated to stress stored in the film as ferromagnetic layer thickness increases.

This is confirmed through numerical calculation of the magnetization curves, where the best fit for \( \theta_{HA} = 90^\circ \) and \( \phi_{HA} = 0^\circ \) (not shown here) is obtained considering \( M_s = 780 \) emu/cm\(^3\), \( H_k = 12 \) Oe, \( \theta_k = 90^\circ \), \( \phi_k = 20^\circ \), rather than \( \phi_{HA} = 0^\circ \).

In MI measurements, the external magnetic field and alternating electrical current are applied along the same direction, in order to guarantee field configuration, where \( H_{ext} \) is perpendicular to \( H \). Thus, the best results for impedance are obtained when the alternate field is along the EA or, in other words, the external field and current are applied along HA. Figure 5(b) shows the experimental magnetization curve, obtained in the HA, and the numerical calculation using the abovementioned parameters and \( \theta_{HA} = 90^\circ \) and \( \phi_{HA} = 90^\circ \).

Thus, although the gyromagnetic factor, damping parameter, layer thicknesses and conductivities are not used to calculate the magnetization curve, the parameter list used to perform all the numerical calculations for the tri-layered system is \( M_s = 780 \) emu/cm\(^3\), \( H_k = 12 \) Oe, \( \theta_k = 90^\circ \), \( \phi_k = 20^\circ \), \( \alpha = 0.018 \), \( \gamma = 2.9 \times 10^{4} \) Oe Hz, \( \sigma_1 = 6 \times 10^{-7} \) (\( \Omega m \))\(^{-1} \), \( \sigma_2 = \sigma_1/4 \), \( t_1 = 100 \) nm, \( t_2 = 150 \) nm, \( \theta_{HA} = 90^\circ \), and \( \phi_{HA} = 90^\circ \). Notice that all preliminary tests to validate magnetic permeability and MI models and confirm the procedures have been performed with the same parameter values used up to this point, indicating they correspond to results that would be obtained with our tri-layered thin film.

As mentioned above, parameters are fixed from the calculation of magnetization curves and used to simulate MI behavior.

Figure 5 shows the normalized in-plane magnetization curves of our tri-layered thin film. Figure 5(a) illustrates the experimental magnetization curves obtained along two different directions, i.e., along (EA) and perpendicular (HA) to the direction defined by the magnetic field applied during deposition. For these cases, the coercive field is \( 0.6 \) Oe and \( 3.1 \) Oe for EA and HA, respectively, and the saturation field for both is \( 12 \) Oe. In particular, saturation and anisotropy fields are important for MI measurements, because they represent the estimated position of the MI peak in low frequency regime, as verified in \( Z \) vs. \( H \) plots that will be presented in Sec. IV B. It is important to remember that the substrate was submitted to a magnetic field during sample production in order to induce in-plane uniaxial anisotropy. As a matter of fact, by comparing experimental curves, it is possible to observe magnetic anisotropy induced during film growth, confirming an easy magnetization axis oriented very close to the direction defined by the magnetic field applied during deposition. A small misalignment between them is a feature associated to stress stored in the film as ferromagnetic layer thickness increases.

B. Magnetooimpedance

For this system structure, the approach considered can be used to perform a numerical calculation of the magnetooimpedance effect for a wide range of frequency. However, due to reduced layer thickness, impedance response only becomes measurable at frequencies above hundreds of MHz, when compared to ribbons, wires, or thick films. Figure 6 shows experimental data and numerical calculations of MI as a function of the external magnetic field, for selected frequencies above 480 MHz.

For all cases, it is clear that our numerical calculations, obtained using magnetic permeability and MI models discussed in Sec. III, with parameters fixed by simulating the magnetization curves, are in very good agreement with the experimental results. Even the main features of each impedance component, \( R \) and \( X \), and consequently of impedance \( Z \) itself, are well described.

When traditionally analyzed, such as in Refs. 35 and 36, \( Z \) curves as a function of frequency could be split into frequency regimes, according to the main mechanism responsible for

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**FIG. 5.** (Color online) Normalized magnetization curve for our tri-layered sample. In (a), the experimental magnetization data curves obtained along two different directions, i.e., along (EA) and perpendicular (HA) to the direction defined by the magnetic field applied during deposition. For these cases, the coercive field is \( 0.6 \) Oe and \( 3.1 \) Oe for EA and HA, respectively, and the saturation field for both is \( 12 \) Oe. In (b), the HA experimental magnetization curve (open circles) and numerical calculation (solid line), obtained for the tri-layered system, with \( M_s = 780 \) emu/cm\(^3\), \( H_k = 12 \) Oe, \( \theta_k = 90^\circ \), \( \phi_k = 20^\circ \), \( \theta_{HA} = 90^\circ \) and \( \phi_{HA} = 90^\circ \).
impedance variations. In our case, two regimes can be identified. In the first regime, at frequencies between ~300 MHz and ~900 MHz, represented by the curves for 480 and 700 MHz in the figure, the position of maximum $Z$ remains invariable, at the same magnetic field value. At this frequency range, the skin effect changes the transverse magnetic permeability and induces variations in MI. On the other hand, in the second regime, for frequencies above ~900 MHz, given by the curves for 1270 and 1710 MHz in the figure, the FMR effect becomes the main mechanism responsible for variations in MI, a fact confirmed by $Z$ peak displacement as a function of applied magnetic field.

However, it must be emphasized that it is very difficult to determine the precise frequency limits between regimes, since overlap of contributions to MI of distinct mechanisms, such as the skin and FMR effects, is very likely to occur.

Thus, the use of distinct models for magnetic permeability and their use in calculating MI become restricted, since it is not possible to determine when to leave one model and start using another one as the frequency is changing.

Although there are distinct mechanisms controlling MI variations at different frequency ranges, all of our experimental findings could be described by the theoretical results calculated using the aforementioned magnetic permeability and MI models. This is due to the fact that the distinct mechanism contributions at different frequency ranges are included naturally in the numerical calculation through magnetic permeability.

Given that the theoretical results describe $Z$ and its components as a function of magnetic field and frequency, an estimation of $M_{\text{max}}$ can be easily calculated, as defined in Eq. (1). Figure 7 gives the experimental results of $M_{\text{max}}$ and numerical calculations as a function of frequency. In this case, one of the main properties that alters the amplitude of MI is the $\sigma_1/\sigma_2$ ratio and here, $\sigma_2 = \sigma_1/4$, where $\sigma_1 = 6 \times 10^7$ (Ωm)$^{-1}$. With respect to peak $M_{\text{max}}$, the maximum value obtained for our tri-layered thin film is lower, when compared to that previously reported by our group for multilayered samples with the same composition. This is due to the higher stress stored on the film, associated to larger ferromagnetic layer thickness. The numerical calculation shows remarkably good agreement with the experimental data, thereby correctly describing the MI.

**V. CONCLUSION**

In this paper, we experimentally investigated the magnetoimpedance effect in a tri-layered thin film in a frequency range between 10 MHz and 1.8 GHz. In particular, for this sample, we identify two frequency regimes in the MI curves, according to the mechanism responsible for MI variations. For frequencies between ~300 MHz and ~900 MHz, MI
changes are associated to skin effect, while above \( \sim 900 \) MHz, the FMR contribution is observed, with \( M_{\text{I}} \text{max} \) around 1000 MHz.

Usually, theoretical models that describe magnetization dynamical properties and the MI of a given system consider more than one approach to magnetic permeability. This is due to the fact that these permeability approaches reflect distinct mechanisms responsible for MI changes, applicable only for a restricted range of frequencies where the mechanism is observed. Thus, the difficult task of choosing the correct magnetic permeability model to use at a certain frequency range explains the reduced number of reports comparing MI experimental results and theoretical predictions for a wide frequency range.

At the same time we performed the experimental measurements in a tri-layered thin film. To interpret them, we considered the transverse magnetic susceptibility model proposed by Spini et al.\(^ {24} \) and the approach to magnetoimpedance behavior reported by Panina et al.\(^ {21} \), applying them to a tri-layered system. Consider both models together allowed us to perform numerical calculus over a wide frequency range and compare it with experimental MI results, between 10 MHz and 1.8 GHz, obtained for a tri-layered thin film. All numerical calculation results are in accordance with experimental data obtained for a real tri-layered system, i.e., for a tri-layered thin film. MI is well described for the wide considered frequency range, regardless of the main mechanism responsible for MI variations. Thus, we provide experimental support to confirm the validity of the theoretical approach.

Although we performed here all the analysis just for a tri-layered thin film, since a general model was used to describe magnetic permeability, it can be considered in the study of samples with any planar geometry, such as multilayer with exchange bias, as we previously reported,\(^ {11} \) as well as in ribbons and films, given that an appropriate magnetic free energy density and adequate MI model are considered.

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