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Magnetization dynamics as derived from magneto impedance measurements

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In this work, the magnetization dynamics of soft magnetic materials is studied with the aid of transverse differential permeability $\mu(I_{ac},f,H_{dc})$ spectra. Contributions to the magnetization processes from domain wall motion and rotation of the magnetization can be extracted from the transverse differential permeability data which are in turn obtained from impedance $Z(I_{ac},f,H_{dc})$ spectra. In particular, an iteration method is used to extract $\mu(I_{ac},f,H_{dc})$ from $Z(I_{ac},f,H_{dc})$ data. The approach is tested in samples with a very well known domain structure, namely $(110)[001]\mathrm{FeSi}_{3\%}$. Permeability spectra $\mu(I_{ac},f,H_{dc})$ were obtained in the frequency range $(100\,\mathrm{Hz}\leqslant f\leqslant 100\,\mathrm{kHz})$, probe current range $(0.1\leqslant I_{ac}\leqslant 50\,\mathrm{mA})$ and dc magnetizing field range $(0\leqslant H_{dc}\leqslant 500\,\mathrm{Oe})$. It is shown that the method developed in this article can be efficiently used to identify and study different dynamic processes driven by the probe current and controlled by the external dc field. In particular, it is shown that the method provides the tools to separate the reversible and irreversible parts of these processes.
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I. INTRODUCTION

The study of the dynamic magnetization processes is an important subject because many applications involve the use of ac magnetic fields of high frequencies or short switching times, e.g., in thin film inductive or even magnetoresistive recording heads. These magnetization processes depend on the particular domain structures as well as on the frequency and amplitude of the ac exciting (or switching) magnetic fields.

Besides the characterization of the devices themselves (e.g., in a recording head), several techniques have been used to study dynamic magnetization processes, namely Kerr and Faraday effects (which are not adequate to apply at high frequencies), and permeability spectra. On the other hand, some studies on the dynamics of magnetization using the complex impedance $(Z=R+iX)$ spectra as a probing tool can be found in the literature. In these techniques, usually applied to amorphous wires,[1,2] the $\mathrm{Re}\{Z\}$ and $\mathrm{Im}\{Z\}$ are associated with the imaginary and real parts of the circumferential permeability, respectively. Few measurements are reported in other geometries. In a previous work,[3] we have obtained permeability spectra from impedance curves of $\mathrm{FeSi}_{3\%}(110)[001]$ laminations. However, in that article no considerations on the basic dynamical magnetization processes involved were made. In the present article, we show that useful information about dynamic magnetization processes can be obtained from impedance measurements, even in a noncylindrical geometry.

Based on the skin effect, the complex impedance is a well established result of classical electrodynamics,[4] although in general there are inherent difficulties in solving simultaneously the Maxwell and Landau–Lifshitz–Gilbert equations for a magnetic conductor.[5,6] Furthermore, it is well known that the effective transversal permeability plays a very important role in describing the whole phenomena.[7,8] In this work we study the magnetization dynamics of electrical laminations using the $Z(I_{ac},f,H_{dc})$ and transverse complex permeability $\mu(I_{ac},f,H_{dc})=\mu'+i\mu''$ spectra, which are connected through the skin-depth $\delta_m=(2\rho/\pi f\mu)^{1/2}$. One of the advantages of studies based on impedance measurements is the fact that the magnetization processes excited by the probe current occur in a closed magnetic circuit contained in the cross sectional area of the sample. In other words, no demagnetizing factors affect the measurements.

In order to test the impedance method as a tool to get information on the magnetization processes in slabs of ferromagnetic materials, it is important to have samples with very well established domain structures. Besides that, it is important to know the evolution of these structures under slow varying magnetic fields. One material exhibiting such properties is the $\mathrm{FeSi}_{3\%}$ with (110)[001] texture. This material is used as the core of high power transformers and electrical machines. In a previous work[3] we have shown that by changing the angle between the [001] axis and the main sample axis, interesting Z vs H behavior was obtained. For example, magneto impedance (MI) values as high as 150% can be obtained for a sample cut at 55° to the easy axis, measured at 100 kHz and 4 mA probe current. In particular, the features observed in the Z vs H curves could be associated with the magnetization process, more precisely to the specific mecha-

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nisms of domain wall (DW) evolution which have taken place in the studied samples. In the present article the domain wall dynamics and its relaxation are studied with the help of the impedance spectra and a phenomenological model for the DW motion.[9,10] The approach consists in analyzing the motion of a plane 180° DW as one-dimensional system, subjected to the ac external magnetic field produced by the probe current and to a restoring force associated with the random potential $V(x)$, plus the damping of the DW motion inherent to a conducting sample. Although $\mathrm{FeSi}_{3\%}$ is not adequate for very high frequency applications because of the low permeability (~500 at these frequencies) and relaxation frequency (~50 kHz), it is an excellent system to understand the physical principles involved in the study of the magnetization dynamics through the impedance approach. In particular, $\mathrm{FeSi}_{3\%}$ has a well known domain structure and domain evolution under dc applied fields with the additional advantage of having δ_m comparable to the sample's thickness at low frequencies. It must be mentioned that this approach differs from that presented if Ref. 11, where the mutual inductance method which is based on the longitudinal permeability and open magnetic circuit has been used.

II. EXPERIMENT

The $\mathrm{FeSi}_{3\%}$ samples were spark cut from an ANSI M5 commercial sheet (produced by Nippon Steel) in rectangular shapes $(10\times1\times0.3\,\mathrm{mm}^3)$ at angles 0°, 50° and 90° between the [001] and the sample's length. Due to the sharp texture and large grain size (5 mm) the magnetic domains are extended to the whole sample. At zero applied field the domains are mainly oriented parallels to the easy axis, which means longitudinal and transverse to the sample's length for 0° and 90°, respectively, for example.

MI measurements were carried out using a standard four-probe ac method, with all cables carefully 50 Ω matched. A dual phase lock-in amplifier was used to detect the voltage proportional to Z in the $100\,\mathrm{Hz}\leqslant f\leqslant 100\,\mathrm{kHz}$ frequency range with a probe current amplitude in the range $0.1\leqslant I_{\mathrm{ac}}\leqslant 50\,\mathrm{mA}$ (resulting in a surface ac magnetic field in the range $0.05\leqslant H_{\mathrm{ac}}\leqslant 25\,\mathrm{A/m}$). Electric contacts were spark welded, giving ultra-low contact resistance and thus avoiding possible effects from stray capacitance at the higher frequencies. The resistance of the samples was about 0.020 Ω. The magnetizing field (H_{dc}) was provided by a long solenoid and always applied parallel to the I_{ac} and sample's length.

III. DW DYNAMICS AND MI: A PHENOMENOLOGICAL APPROACH

A. DW motion versus permeability

The motion of a 180° Bloch wall under the influence of a small amplitude time dependent external magnetic field $H_{\mathrm{ac}}(t)$, can be described by the equation of motion[9]

$$m\frac{d^2x}{dt^2}+\beta\frac{dx}{dt}+\alpha x=2M_S H_{\mathrm{ac}}(t). \tag{1}$$

In this equation, αx is the restoring force, which is a consequence of the parabolic approximation for $V(x)$, β accounts the damping of the DW motion and m is the effective DW mass. It must be noted that, within this approximation, the one-dimensional equation of motion for a DW becomes similar to the equation for a driven damped harmonic oscillator. In fact, β accounts mostly for the induced eddy current opposing the DW motion[12] and α for the increase in wall energy considering that the walls are distorted by the ac magnetic field.[13]

On the other hand, it is well known that the position of a DW is related to the initial susceptibility (χ) of the material and can be written as[9]

$$x(t)=\frac{\chi H(t)d}{2M_s}, \tag{2}$$

where d is the domain width. By introducing Eq. (2) in Eq. (1), the equation of motion can be solved for the susceptibility. In the case of a driving field oscillating with a frequency f, we find the following expressions for χ' and χ'', the real and imaginary component of the complex susceptibility ($\chi=\chi'+i\chi''$), respectively[9]

$$\chi'=\chi_0\frac{1-(f/f_r)^2}{(1-f^2/f_r^2)^2+(f/f_x)^2}, \tag{3a}$$

$$\chi'''=\chi_0\frac{f/f_x}{(1-f^2/f_r^2)^2+(f/f_x)^2}. \tag{3b}$$

In the above expressions χ_0 is the low frequency limit of the susceptibility, $f_r=\sqrt{\alpha/m}/2\pi$ and $f_x=\alpha/2\pi\beta$ are the resonant and relaxation frequencies for the DW motion, respectively. It can be seen from Eqs. (3a) and (3b) that the frequencies f_r and f_x, or equivalently m and β, will define whether the system exhibits a resonance, or if the relaxation processes dominate. The frequency response in each case is different: if $f_r<f_x$ the χ'' component has a sign inversion, which does not occur for $f_r>f_x$. In our particular case, only relaxation is expected because of the small effective wall mass, typical of metallic systems. On the other hand, as the studied materials have large susceptibilities, hereafter we will assume the approximation: $\mu\approx\chi$. Thus, all the results for the susceptibility apply directly for the permeability.

B. Complex permeability from the Z vs f measurements

The expressions for Z are obtained from the model proposed by Landau,[4] which can be modified to describe for a slab of infinite area, thickness $2b$ in which flows an alternating current $I_{\mathrm{ac}}=I_0\exp(2\pi ift)$. This approximation is valid at high frequencies, when $\delta_m\ll b$. The energy flow rate entering the slab (ϵI) is dissipated partially as Joule heat and partially spent to promote the magnetic field changes within the material. This energy must equal the rate of electromagnetic energy crossing the sample's surface, as described by the Poynting vector ($\mathbf{S}=\mathbf{E}\times\mathbf{H}$). In order to find $Z(f)$, the distributions of $\mathbf{E}$ and $\mathbf{H}$ inside the sample must be calculated from Maxwell's equations. The final expression for Z can be written as[7,14]

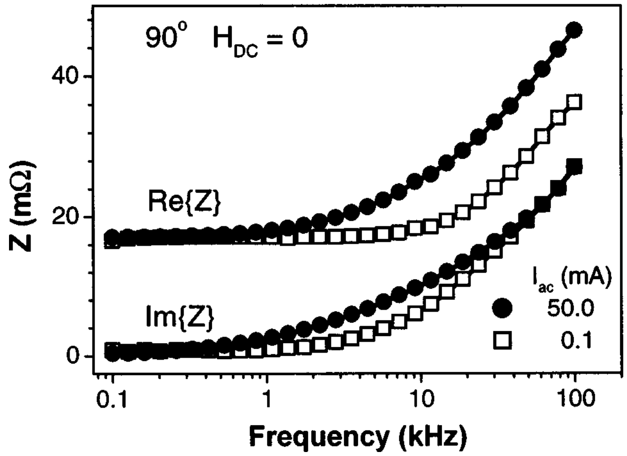

FIG. 1. Typical impedance measurement for the $FeSi_{3\%}$ 90° sample showing the difference on the impedance spectra for two values of ac measuring current. $H_{dc}=0$. The solid lines are guides to the eyes.

$$Z=\frac{\epsilon}{I_{ac}}=kbR_{dc}\coth(kb), \tag{4}$$

where R_{dc} is the dc resistance of the sample and $k^2\equiv 2\pi i f\mu\sigma=i/\delta_m^2,\delta_m$ is the skin depth, $\mu=\mu'+i\mu''$ is the transversal complex permeability and $\sigma(=1/\rho)$ is the sample's conductivity. As can be seen from expression (4), the relation between Z and μ is fairly complicated. As a consequence, it is very difficult to get μ from the Z vs f measurements analytically, with exception made to the high frequency limit. To overcome this difficulty we have made use of an iterative numerical method which allows us to obtain the μ vs f curves from the measured Z vs f ones. A built-in routine of MathCad® software for solving the real and imaginary parts of Eq. (4) has been used. It is important to note that both μ' and μ'' contribute to Re$\{Z\}$ and Im$\{Z\}$ simultaneously. The input parameters are ρ, b and f. For each measured value of the normalized complex impedance $Z(f)/R_{dc}$, the program searches for the corresponding Re$\{\mu(f)\}$ and Im$\{\mu(f)\}$ values. The resulting curves are analyzed in terms of the above mentioned domain dynamics.

IV. RESULTS

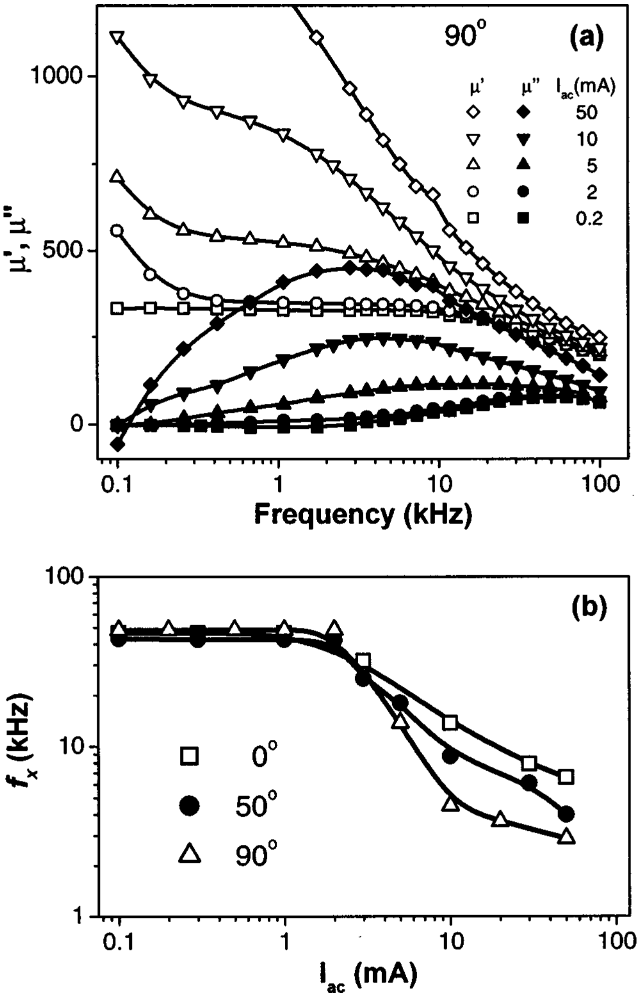

FIG. 2. (a) Real and imaginary components of the permeability vs frequency curves for the $FeSi_{3\%}$ 90° sample for several probe current values. The data were obtained from impedance measurements. (b) Relaxation frequencies for the $FeSi_{3\%}$ 0°, 50° and 90° samples as function of the ac current. In both figures the solid lines are guides to the eyes.

In order to evaluate the different dynamic processes in $FeSi_{3\%}$, impedance measurements as function of frequency were carried out at several amplitudes of I_{ac} and several H_{dc} values. Figure 1 shows two extreme I_{ac} conditions for a Z vs f measurement performed in the 90° sample without external magnetic field. From Fig. 1 it is clear that some dynamic effect driven by the probe current is taking place in this sample. Figure 2(a) shows a representative set of μ vs f curves obtained from the corresponding impedance measurements made in the same 90° sample. It can be seen from Fig. 2 that the relaxation of the DW motion is always present independent of the probe current magnitude, as seen from the peaks in μ'' and the associated decrease in μ'. Note also that these peak positions evolve with the magnitude of I_{ac}. From the same figure, it can be seen that μ increases with the amplitude of I_{ac} indicating a larger amplitude of wall motion. On the other hand, the relaxation frequency (f_x), as indicated by the position of the peak in the μ'' vs f curves, decreases with the increase of I_{ac}. As seen in Fig. 2(b), the behavior of f_x vs I_{ac} plots is almost the same for all samples, showing a range of probe current magnitudes $(I_{ac}<2\text{ mA})$ where f_x is essentially constant. The increase of the probe current above this limit decreases f_x for all samples. Relaxation frequencies are in the range 50 kHz (at 0.1 mA) to 5 kHz (at 50 mA).

Figure 3 presents the Cole plot[15] of the calculated permeability for the 0° and 90° samples. A semicircle in these plots indicates that a single dynamic magnetic process, excited by the probing current, is taking place.[15] This feature is particularly well observed for low current measurements $(I_{ac}<2\text{ mA})$. For higher currents the curves become strongly distorted, indicating a departure from the parabolic approximation for the potential $V(x)$.

When a dc magnetic field is applied to the sample, the magnitudes of μ are reduced due to the proximity to the saturated state, as seen in Fig. 4. From the same figure, a striking feature can be observed: for 0.5 mA the relaxation

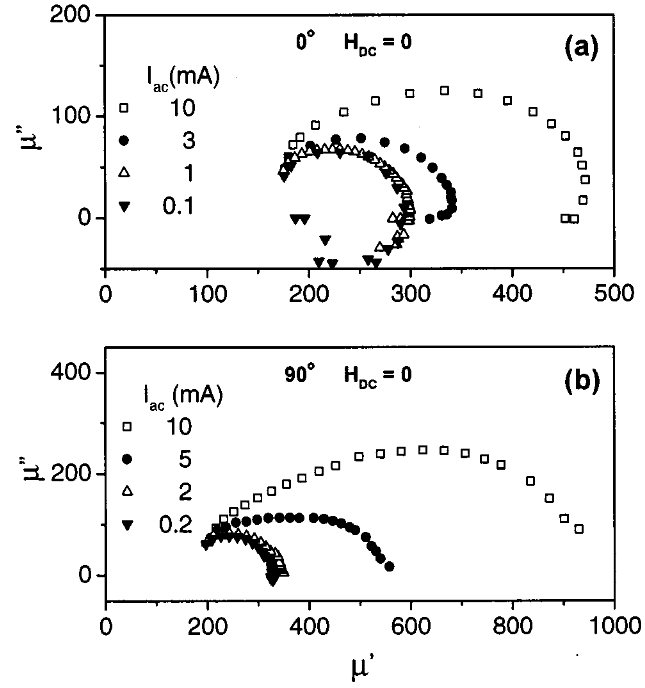

FIG. 3. Cole plots of the permeability spectra for the $FeSi_{3\%}$ 0° and 90° samples. Data were obtained at several ac current values and zero applied field. For currents up to 2 mA, the curves are very similar.

frequency remains almost unchanged by the magnetic field [see Fig. 4(a)], while it is strongly modified for $I_{ac}>2$ mA. In the case of $I_{ac}=50$ mA [shown in Fig. 4(b)], f_x has values of 2.7 and 50 kHz for fields of 0 and 150 Oe, respectively. Furthermore, the half height width of the μ'' vs f plots for the $I_{ac}=50$ mA encompasses 2 decades of frequency, while for 0.5 mA it encompasses less than 1 decade. Above 150 Oe, the sample is close to saturation, the permeability is strongly reduced and a constant value is attained. Figure 4(a) also shows the fitting of Eqs. (3a) and (3b) (solid lines) to the permeability data. In fact, the fitting was made with an additional constant term to the Eq. (3a), relative to the moment rotation (μ_{rot}) as discussed later. It must be noticed that the curves are very well fitted to the experimental data as shown in Fig. 4(a) (using the same three parameters for both, μ' and μ''), indicating the validity of the approach for the low current regime.

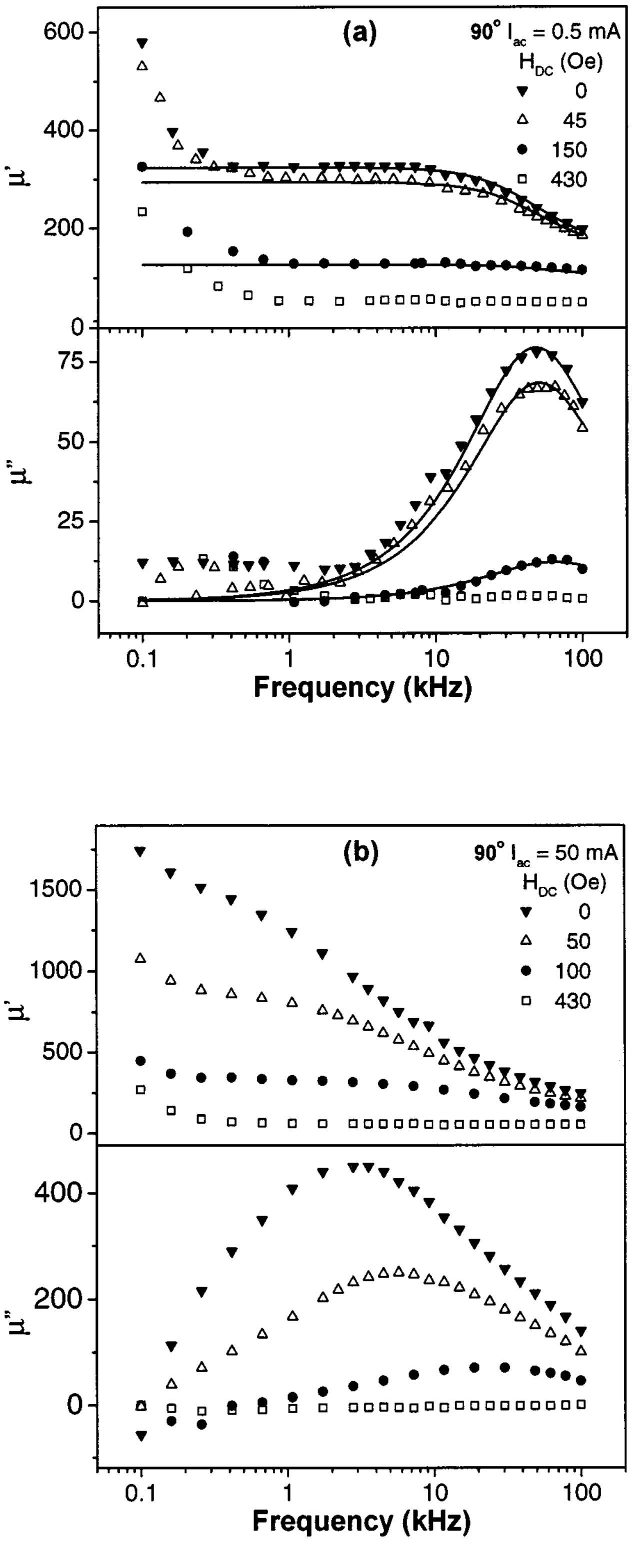

FIG. 4. Permeability spectra for the $FeSi_{3\%}$ 90° sample at different dc applied fields. Spectra obtained from impedance measurements performed with $I_{ac}=0.5$ mA. Solid lines are the fittings made with Eqs. (3a) and (3b) using the same set of parameters (f_x, μ_{dw} and μ_{rot}) for μ' and μ''. (b) Spectra obtained from impedance measurements performed with $I_{ac}=50$ mA.

V. DISCUSSION

The details of the μ vs f curves must be analyzed bearing in mind the static magnetization process of the (110) ×[001]$FeSi_{3\%}$ samples and their respective domain configuration. The main magnetic domains on the studied samples are aligned with the easy axis [001]. However, it must be remembered that this particular material is characterized by an average spread angle, between the (110) plane and the sample's surface (tilt angle), of about 4°. This misalignment gives rise to the formation of a superficial closure domain structure in order to minimize the appearance of free magnetic poles on the surface. These closure domains are known as ''lancet domains'' in view of their shape.[16,17] When a magnetizing field is applied to the samples, the lancet structure has its relative volume increased, this increase being larger for the higher angles between the easy axis and the sample length. This feature is associated with the better orientation of the closure domains relative to the applied field as the angle is increased. The closure domain structure has a major role on the dynamic behavior of the samples. Its evolution has been extensively studied due to the well known connection to power losses in $\mathrm{FeSi}_{3\%}$. The link of this structure to the magneto impedance has been analyzed in a previously published work.[3]

The shape of the μ vs f curves (Figs. 2 and 4) shows that this set of samples obeys the relation $f_r \gg f_x$. This is expected in view of the small domain mass when compared to the damping term for metallic systems. The maximum on μ'' together with the decay of μ', are typical features of a system where a strong damping process is taking place. This allows one to analyze them using the dynamic model for DW motion introduced in Sec. III.

The permeability is usually described in terms of two components: DW motion and rotation of the magnetization. The Cole plot of Fig. 3 shows that, for high frequencies, μ' does not go to zero as expected from the domain dynamic model proposed. This is an indication that, at these frequencies, the rotation of the magnetization has a major contribution to the transverse permeability, which is mainly reflected in μ'. The behavior can be observed from Fig. 4(a), where μ'' was fitted with the Eq. (3b) and μ' with the Eq. (3a) plus an additional term relative to the rotational contribution to the complex permeability. It is again worth mentioning that the parameters used in both fittings are the same, i.e., the values of f_x and $\mu_{\mathrm{dw}}(\sim\chi_0)$ were first adjusted to fit μ'' and then used to adjust μ'. In this fitting, the contribution of the magnetization rotation to the permeability (μ_{rot}) is the free parameter. A comparison of this value with the one obtained from the Cole plot of Fig. 3 shows that both values are very close to each other.

A closer look to Fig. 2(a) reveals that, for I_{ac} below 2 mA, the permeability values are almost the same over the whole frequency range. The reason for this behavior is that, up to 2 mA, the walls are pinned and the ac field associated with the probe current is able to produce only reversible wall movement. Above 2 mA, although larger values of μ are attained, relaxation frequencies are strongly reduced and the peaks of the μ'' vs f curves become wider [see Fig. 2(a)]. These facts are a consequence that the domain walls have overcome the pinning forces and irreversible wall motion is the main dynamic process active in the sample giving rise to dynamic hysteresis. This regime is associated with a higher level of eddy currents around the DW and to a departure of the linear restoring force regime, which holds only for small wall displacements. Possibly, this is the origin of the decrease of the relaxation frequency, as the current is increased. These features can also be observed on the Fig. 3, through the distortion from the semicircle.

For dc fields higher than 50 Oe, relatively far from saturation, the permeability exhibits a strong decrease, possibly associated with the nucleation of the lancet domains.[16,17] On the other hand, for the 90° sample H_{dc} dislocates f_x to higher values. This behavior can be accounted by an increase in the number of domains (due to the nucleation of the lancet ones) which, in turn, cause an increase of the restoring force (αx), since α depends on the DW energy.[13]

VI. CONCLUSIONS

We have shown that relevant information on the magnetization dynamics of soft magnetic materials can be obtained from impedance measurements without the use of any inductive coupling. For the studied $\mathrm{FeSi}_{3\%}$ (110)[001] samples the DW resonance has not been activated by the probe current, as expected, due to the relaxation of the DW motion by eddy currents. On the other hand, the relaxation frequency is extremely sensitive to probe current magnitude and external applied dc fields. From the proposed approach, the rotation and DW contributions for the total transverse permeability have been separated. This allows one to make detailed studies of the magnetization dynamics in this kind of material as a function of field, an issue that will be addressed in a forthcoming article.

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