Domain model for the magnetoimpedance of metallic ferromagnetic wires

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Complex inductance formalism (L) is used to calculate the complex circular permeability ($\mu_{\rm circ}$) in a domain model for the magnetoimpedance (MI) of soft ferromagnetic wires. An excellent agreement between calculated and experimental values of $\mu_{\rm circ}$ as a function of frequency is observed. In addition, a very good agreement is also exhibited between experimental and calculated plots of $\mu_{\rm circ}$ as a function of an applied dc magnetic field before and above the relaxation frequency (also known as single- and double-peak MI effect). These results confirm the validity of L as an alternative approach to MI phenomena in soft ferromagnetic wires. [DOI: 10.1063/1.1558239]

I. INTRODUCTION

The study of magnetoimpedance (MI) in soft magnetic materials has attracted great interest during the last decade due to its technological applications on sensing magnetic fields and electric currents.[1,2] MI leads to significant changes in the impedance response of a ferromagnetic material submitted to a high frequency current of small amplitude, when a dc magnetic field is applied. In contrast with magnetoresistance, MI is a classical electromagnetic effect due to the skin depth phenomenon.[3,4] At low frequencies (where the skin depth is larger than the pertinent dimension of the sample) the variations in the impedance response are originated by the coupling between the ac magnetic field produced by the ac current and the ferromagnetic domain structure of the sample.[5]

A domain model was reported recently,[6,7] proposing exact analytical expressions for the real and imaginary components of the complex impedance (Z), for the case of soft ferromagnetic wires. Based on these Z equations, a fluxmetric definition of circular permeability (i.e., the ratio of the cross-sectionally averaged circular induction flux density to the circular field) allows the calculation of the complex circular permeability ($\mu_{\rm circ}$) expressions. However, while Z calculations are fairly consistent with experimental results, a poor agreement is observed when comparing with experimental results of $\mu_{\rm circ}$. In this article, an alternative transformation for obtaining $\mu_{\rm circ}$, based on the complex inductance formalism,[8,9] is used and compared with experimental measurements.

II. EXPERIMENTAL TECHNIQUE

As-cast amorphous $(Co_{94}Fe_6)_{72.5}B_{15}Si_{12.5}$ wires, 10 cm length and 125 μm diameter, prepared by the in-rotating-water spinning method[10] and kindly provided by Unitika Ltd, Japan, were used for spectroscopic measurements. The measuring system[11] includes an HP 4192 A impedance analyzer controlled by a computer, having a frequency range of 5 Hz–13 MHz.

III. RESULTS AND DISCUSSIONS

The domain model assumes a long straight wire of radius a and conductivity σ, placed along the z axis. The magnetization (M_s) has a circular easy direction within each domain of width $2c$ and radius a. Circular domains are directed alternatively along the $\pm$ azimuth direction. A transport current $Ie^{j\omega t}$ is applied in the z direction, corresponding to a superficial circular field $H_0 e^{j\omega t}$, with $H_0 = I/2\pi a$. At low frequencies, the magnetization process is carried out by domain wall displacements (DWD). The DWD mechanism depends on the local magnetic fields acting on the domain wall, according to the wire constant scalar dc permeability $\mu_{\rm dc}$. After solving the corresponding electrodynamic Maxwell equations, the following expressions are obtained for the complex impedance $Z=R+jX$:[6]

$$\frac{R}{R_{\rm dc}} = 1 + \frac{\theta^4 c}{a} \sum_{n=1}^{\infty} \frac{1}{\lambda_n} \left[\lambda_n^2 \tanh \frac{\lambda_n c}{c} + \frac{\theta^4 c^2}{a^2} \coth \frac{\lambda_n c}{c} \right]^{-1}, \tag{1}$$

$$\frac{X}{R_{\rm dc}} = \theta^2 \sum_{n=1}^{\infty} \left[\lambda_n^2 + \frac{\theta^4 c^2}{a^2} \coth^2 \frac{\lambda_n c}{c} \right]^{-1}, \tag{2}$$

where $R_{\rm dc}$ is the wire dc resistance, λ_n corresponds to nth root of the first-order Bessel function [i.e., $J_1(\lambda_n)=0$], and $\theta^2 = a^2 \sigma \mu_{\rm dc} \omega$ is a convenient dimensionless parameter.

According to the complex inductance formalism,[8] complex inductance $L = L_r + jL_i$ can be directly obtained from complex impedance Z (at low frequencies, where the skin effect can be neglected), via the following transformation:

$$L = -jZ/\omega. \tag{3}$$

Hence, the circular complex permeability ($\mu_{\rm circ} = \mu_r - j\mu_i$) can be derived as follows:

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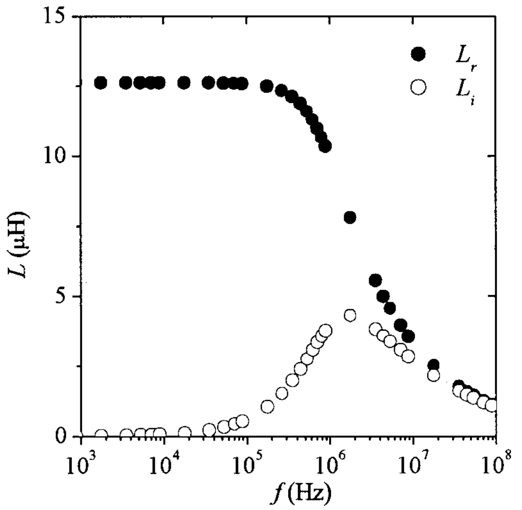

FIG. 1. Calculated spectroscopic L_r, L_i plots.

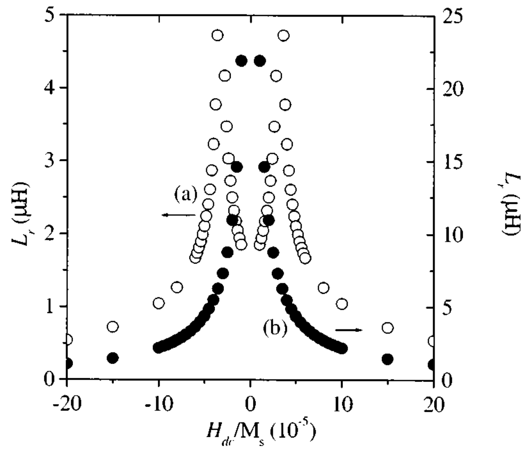

FIG. 3. Calculated L_r plots as a function of H_{dc} for (a) $\omega \gg \omega_x$ and (b) $\omega \ll \omega_x$.

$$\mu_{\mathrm{circ}} = GL, \tag{4}$$

where G is the geometrical constant.[9]

This transformation leads to an exchange in real-imaginary components, since L_r depends on the imaginary component of impedance; conversely, L_i is obtained from the real component of Z. Therefore, phenomena corresponding to magnetization (permeabilities) are associated with L_r, while dissipative effects should be related with L_i.

Since θ^2 is proportional to ω, the transformation (3) can be applied to Eqs. (1) and (2) to obtain L_r, L_i (and thus μ_r, μ_i), leading to

$$L_r = \frac{X/R_{\mathrm{dc}}}{\theta^2} \tag{5}$$

$$L_i = \frac{R/R_{\mathrm{dc}}}{\theta^2}. \tag{6}$$

Once L_r and L_i are calculated following Eqs. (5) and (6), further substitution of θ^2 by ω (by using experimental a, σ, and μ_{dc} values) allows comparison of L_r and L_i with their experimental counterparts. Calculated $L_r(\omega)$ and $L_i(\omega)$ are shown in Fig. 1. L_r exhibits a plateau for frequencies below 10^5 Hz; further increase in ω results in an L_r relaxation dispersion. On the other hand, L_i shows a small single maximum at a particular frequency ω_x for which L_r reduces roughly to half its initial vale. This particular frequency value corresponds to the domain wall relaxation frequency. On the other hand, for higher frequencies, the DWD mechanism is no longer active since domain wall becomes unable to follow the excitation field. Thus, this interpretation corresponds to a magnetization process with a simple relaxation behavior. Experimental spectroscopic plots for the CoFeSiB wire are shown in Fig. 2. An excellent agreement between calculated and measured data is observed, giving support to the validity of transformation (3).

It is now instructive to consider the effects of the dc magnetic field on the impedance as is typically represented

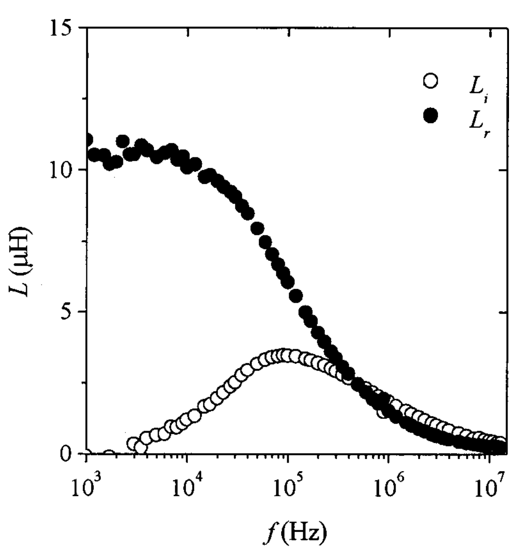

FIG. 2. Experimental spectroscopic L_r, L_i plots corresponding to an amorphous CoFeSiB wire.

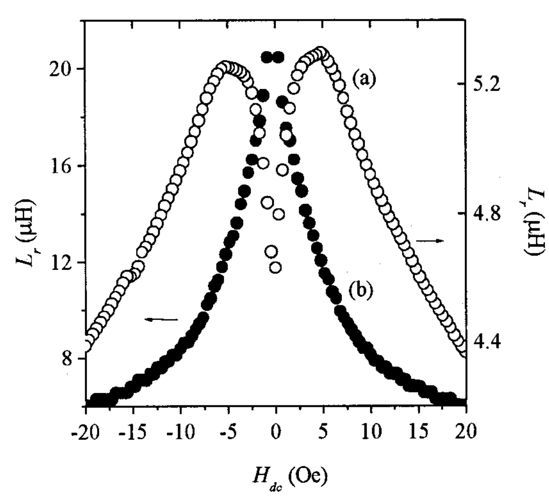

FIG. 4. CoFeSiB wire experimental L_r plots for (a) $\omega = 1$ MHz, (b) $\omega = 1$ kHz. Relaxation frequency is $\omega_x = 100$ kHz (see Fig. 2).

in the MI literature. We use the inductance, but note that at fixed frequency, impedance and inductance are proportional, as shown by transformation in Eq. (3). At a fixed frequency $\omega<\omega_x$ the active magnetization process is DWD, and μ_{dc} is proportional to M_s/H_{dc}, owing to the uniaxial magnetostatic anisotropy. θ^2 becomes a function of $1/H_{dc}$. Figure 3 shows the calculated L_r [obtained by means of Eq. (5) at constant θ^2] as a function of H_{dc}/M_s. Figure 3 exhibits the so-called single-peak MI.

For higher frequencies (i.e., $\omega>\omega_x$), spin rotation is the active magnetization mechanism[5,11] and μ_{dc} is proportional to $M_s/(H_{dc}-H_k)$, where H_k is the anisotropy field (due to the circular anisotropy). The increase in H_{dc} leads to an initial increase in L_r up to a maximum at $H_{dc}=H_k$, where M_s is partially reoriented toward the axial direction and the effective anisotropy field $H_{dc}-H_k$ becomes negligible. Beyond this point, the hyperbolic decreasing behavior of L_r reflects further increment of H_{dc}, which brings the spins into the axial direction with an increasing coupling. A plot of L_r (H_{dc}/M_s) is also included in Fig. 3, showing the high-frequency double-peak MI. Finally, Fig. 4 exhibits the corresponding experimental measurements for the CoFeSiB wire, with a remarkable agreement in both the single- and the double-peak MIs.

IV. CONCLUSIONS

We have shown that the use of the complex inductance formalism in combination with the domain model proposed for MI leads to a very good agreement with experimental results.

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