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Giant magnetoimpedance in Co-based microwires at low frequencies (100 Hz–13 MHz)

I. Betancourt[a] and R. Valenzuela
Instituto de Investigaciones en Materiales, UNAM, México, P.O. Box 70-360, Mexico DF 04510, Mexico

M. Vazquez
Instituto de Ciencia de Materiales, CSIC, Campus de Cantoblanco, 28049 Cantoblanco Madrid, Spain

A systematic study of the complex inductance response and the giant magnetoimpedance effect of as-cast CoFeBSiMoNi microwires (30 μm diameter) as a function of frequency (100 Hz–13 MHz) and circular field amplitude (21–212 A/m rms on the wire's surface) is presented. The microwire magnetization mechanisms are discussed in terms of complex inductance plots (in both real and imaginary parts). The analysis of the experimental results showed evidence of pinning, bulging, and displacement of circumferential domain walls. Higher relaxation frequencies together with a larger unpinning field ($3-5\times10^6$ Hz and 127 A/m, respectively), compared with conventional amorphous wires, were explained in terms of the reduced dimension of the microwire. Total impedance plots as a function of a bias H_{dc} field showed an asymmetric character associated with an induced anisotropy during the wire fabrication. [DOI: 10.1063/1.1447518]

I. INTRODUCTION

Giant magnetoimpedance (GMI) in amorphous materials has raised great interest during the last decade due to the technological applications on sensing magnetic fields and electric currents[1–3] by means of changes in the impedance response of a ferromagnetic material, submitted to a high frequency current of small amplitude when a dc magnetic field (H_{dc}) is applied. In general, GMI is considered as a classic electromagnetic phenomenon based on the inductive coupling between the small ac field h_{ac} generated by the current flowing through the material and its magnetic structure. It has been interpreted in terms of the classical theory of the skin effect in a magnetic conductor,[4] since at high frequencies the penetration depth of h_{ac} decreases by this skin effect, causing an additional contribution to the total impedance.

An alternative approach to GMI in amorphous wires[5,6] proposes the study of the separate components of the complex inductance formalism $L=L_r+jL_i$, where L_r and L_i are the real and imaginary components of inductance, respectively, and $j=(-1)^{1/2}$, through the following transformation: $\mathbf{L}=-j\mathbf{Z}/\omega$ (where $\mathbf{Z}$ is the complex impedance $\mathbf{Z}=Z_r+jZ_i$ and ω the angular frequency). This formalism gives a clearer insight into the magnetization processes in amorphous wires since it allows the complex permeabilities $\mu=\mu_r-j\mu_i$ to be calculated using a simple formula: $\mu=G\mathbf{L}$, where G is a geometrical factor.[5]

In this article, we present a detailed study of the inductance response of as-cast CoFeBSiMoNi microwires (30 μm in diameter) as a function of frequency and as a function of both h_{ac} and H_{dc} field amplitudes at selected frequencies. The results are interpreted in terms of pinning, bulging, and displacement of circumferential domain walls.

II. EXPERIMENTAL TECHNIQUE

As-cast amorphous microwires (30 μm in diameter) of nominal composition $Co_{69.7}Fe_{3.8}B_{13}Si_{11}Mo_{1.5}Ni_1$ prepared by quenching and drawing method (Taylor–Ulitovsky technique[7]), were used for inductance measurements carried out on 10-cm-long wire pieces at room temperature. To ensure a good electric contact, the wire ends were firmly attached to the measurement clamps using a low-melt point welding paste. A HP4192A impedance analyzer system, controlled by a PC, was used for the inductance measurements. The frequency range was 100 Hz–13 MHz together with the root mean square (rms) voltage varying between 0.1 and 1.0 V, which led to ac currents through the sample within the range $i=2-22\,\text{mA}$ (rms). The rms field amplitude on the wire surface was calculated as $h_{ac}=i/2\pi a$ with $a=15\,\mu$m (wire radius), resulting in h_{ac} range of 21–212 A/m.

III. EXPERIMENTAL RESULTS AND DISCUSSION

Spectroscopic plots of L_r at selected amplitudes of h_{ac} are shown in Fig. 1. At low fields ($h_{ac}<127\,\text{A/m}$) and low frequencies (<1 MHz), L_r exhibits the same constant trend even for different h_{ac} amplitudes, followed by a dispersion with a relaxation character. This relaxation frequency (f_x) is about 2.5 MHz (f_x determined at the corresponding L_i maximum[5]), which is much higher than the corresponding f_x of its conventional 120 μm (or above) diameter amorphous wire counterpart ($f_x\sim13.5\,\text{kHz}$[5]). The substantial increase of f_x for these microwires is a consequence of their reduced diameter, since the wall lengths are smaller than those in conventional amorphous wires, and, therefore, the expected relaxation occurs at higher frequencies. For $h_{ac}>127\,\text{A/m}$, L_r is no longer independent of h_{ac} amplitude (at $f<f_x$). For $f>f_x$, all the plots converge into the low field plot exhibiting the same relaxation dispersion. Assuming a domain structure consisting of circumferential walls for these Co-based microwires,[3] the magnetization process for h_{ac}

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[a] Electronic mail: israelb@correo.unam.mx

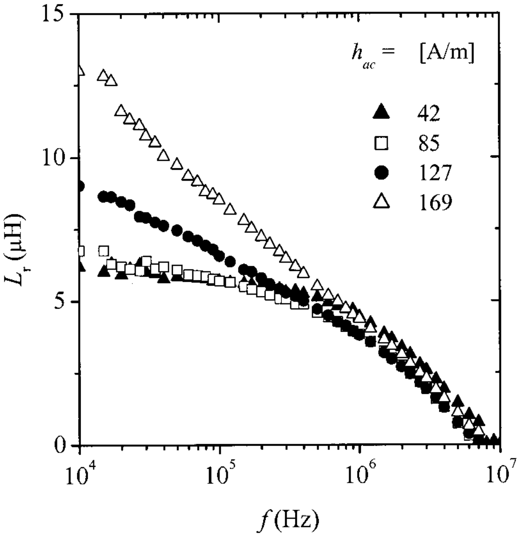

FIG. 1. Real part of inductance L_r, as a function of frequency f with h_{ac} amplitude as a parameter.

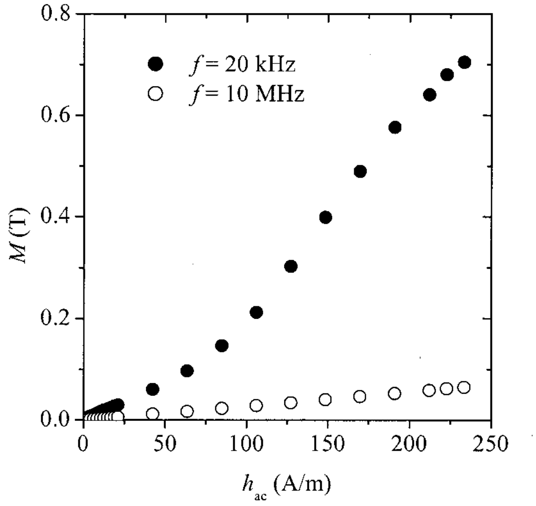

FIG. 3. Circumferential magnetization curves, for low- ($f \ll f_x$) and high- ($f > f_x$) frequency values.

<127 A/m is associated with reversible bulging of domain walls since these domain walls are considered to be pinned to defects (such as the external surface of the wire). The corresponding circumferential permeability can be calculated as $\mu = G\mathbf{L}$.[5]

The frequency behavior of L_i for various h_{ac} amplitudes is shown in Fig. 2. For $h_{ac} < 127$ A/m, a single peak is observed, which is ascribed to the energy dissipated during the domain wall bulging process, whereas for increasing h_{ac} such peak remains but an additional low-frequency peak appears. The height of this new peak increases as h_{ac} increases, and the low-frequency peak should be associated with a hysteretic mechanism, since the processes involved (bulging, unpinning, displacement, etc.) are characterized by time constants larger than the bulging process alone. In addition, the larger energy dissipation of this hysteretic mechanism (compared with domain bulging) results in a higher peak height.

Circumferential magnetization curves at two selected frequencies are shown in Fig. 3. They were derived from L_r and h_{ac}, as discussed elsewhere.[8] The low-frequency ($f = 20$ kHz) curve exhibits the expected features of domain wall magnetization, such as a finite initial susceptibility (for h_{ac} below 100 A/m) followed by a marked increase in slope at about $h_{ac} = 100$ A/m and a trend to saturation above 200 A/m. In contrast, the curve obtained at 10 MHz (high frequency) shows a linear tendency, in agreement with a pure rotational magnetization process.[8]

L_r as a function of H_{dc} at $f = 10$ MHz is plotted in Fig. 4. The initial increase of L_r can be ascribed to an additional component (axially oriented) to the circumferential permeability exerted by H_{dc}, which results in larger permeability

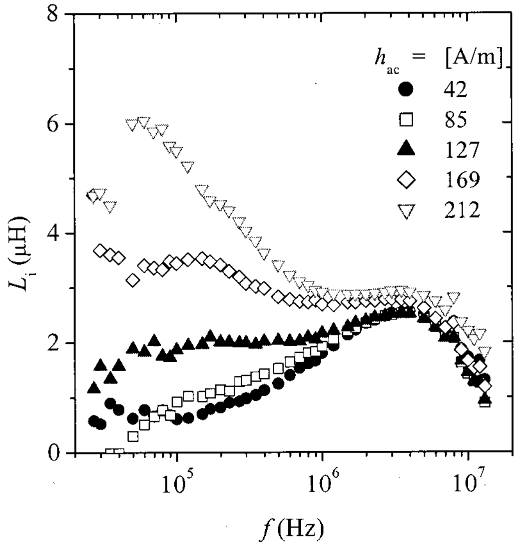

FIG. 2. Imaginary part of inductance L_i, as a function of frequency f for various h_{ac} field values.

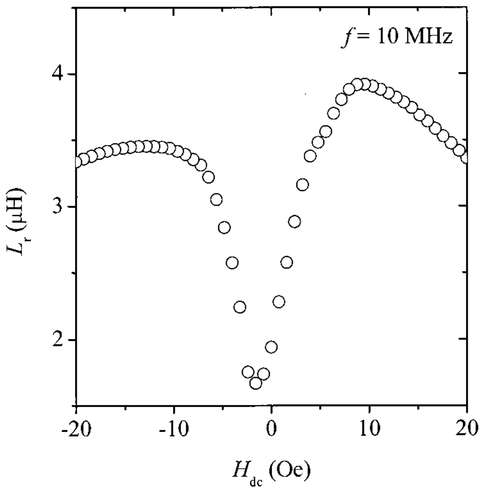

FIG. 4. Real part of inductance L_r as a function of H_{dc} for $f = 10$ MHz.

values and therefore larger L_r values. For increasing H_{dc} ($\geqslant 10$ Oe), the circumferential permeability decreases since the magnetic spins are mostly axially oriented. The asymmetric curve form (minimum for a negative H_{dc} value) might be related to an induced anisotropy during the wire fabrication,[9] which facilitates spin rotation along positive H_{dc} values while a damping effect occurs for negative H_{dc} amplitudes. L_r as a function of H_{dc} exhibited similar features compared with previous reports on amorphous wires.[6]

IV. CONCLUSIONS

Magnetoimpedance effect was observed in Co-based microwires for which magnetization processes were resolved through spectroscopic plots of L_r, L_i vs f. In addition, circumferential magnetization curves showed, for various frequency values, domain wall magnetization process (at $f \ll f_x$) and rotational magnetization mechanism ($f > f_x$).

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