High frequency [1-500 MHz] measurements of the Magneto-Impedance (MI) of glass-covered CoFeBSi microwires are carried out with various metal-to-wire diameter ratios. A twin-peak, anhysteretic behaviour is observed as a function of magnetic field. A maximum in \( \Delta Z/Z \) appears at different values of the frequency \( f \), 125, 140 and 85 MHz with the corresponding diameter ratio \( p = 0.80, 0.55 \) and 0.32. We describe the measurement technique and interpret our results with a thermodynamic model that leads to a clearer view of the effects of \( p \) on the maximum value of MI and the anisotropy field.

I. INTRODUCTION

When a ferromagnetic conductor is traversed by a current of low amplitude and high frequency, its impedance or rather its Magnetoimpedance (MI) can be altered by applying a dc magnetic field. This phenomenon, first described in the 1930’s, has been receiving special attention over the last 15 years due to its potential technological applications in sensors, devices and instruments. Its fundamental physics is also being deeply examined.

MI has been observed in a wide variety of materials, geometries and structures, particularly in amorphous wires having typically diameters of a few hundred microns. Wires with smaller diameters (a few microns) covered with a glass sheath show an increase of the working frequency, and introduce an additional structural feature that alter the physical parameters. Since glass exerts some mechanical stress on the metallic wire, a change in the magnetic response is expected. Therefore it is of interest to finely tune the physical properties through the control of the thickness and nature of the glass sheath.

In this paper, we report on MI measurements of Co-rich amorphous microwires with various ratios of the metal-to-glass diameter, in the [1-500 MHz] frequency range, carried out with a novel broadband technique. This technique allows a complete determination of MI as a function of both frequency and magnetic field. The effects of the thickness of the glass sheath are clearly illustrated and the variation of the anisotropy field \( H_K \) is evaluated directly as a function of stress.

II. EXPERIMENTAL RESULTS

Glass-covered amorphous microwires of nominal composition Co\(_{69.4}\)Fe\(_{3.7}\)B\(_{15.9}\)Si\(_{11}\) were prepared by fast cooling with the glass-coated melt-spinning technique also known as Taylor-Ulitovski technique. Several metal-to-wire ratio values, \( p = \phi_m/\phi_w \), with \( \phi_m \) the metallic core diameter and \( \phi_w \) the total wire diameter, were produced and characterized. For values of metal core diameters of 24, 12 and 7 \( \mu \)m, with corresponding total diameters of 30, 21.8 and 21.9 \( \mu \)m we get \( p = 0.80, 0.55 \) and 0.32, respectively. In order to make electrical contacts, the glass sheath was etched away over a few mm on both microwire ends, with a solution of hydrochloric acid. Silver paste contacts were then made in order to proceed with the electrical measurements.

MI measurements were carried out in the [1-500 MHz] range, on pieces of microwires \( \sim 12 \) mm in length, with an HP 8753C Network Analyzer using a novel broadband measurement technique described in. Helmholtz coils served as source of axial dc magnetic fields ranging from -80 Oe to 80 Oe.

The results obtained are typically plotted in a 3D representation of \( \Delta Z/Z \):

\[
\Delta Z/Z = \left( Z_{H_{dc}=0 \text{ Oe}} - Z_{H_{dc}=80 \text{ Oe}} \right) / Z_{H_{dc}=80 \text{ Oe}}
\]

where \( Z \) is the total impedance modulus \( Z = \sqrt{(Z' + Z''^2)} \); with \( Z' \) the real part and \( Z'' \) the imaginary part of impedance, as a function of dc field, \( H_{dc} \), and frequency, \( f \). The results are shown for \( p = 0.8 \) in Fig. 1. The
expected symmetrical double peak MI plot is obtained as a function of \( H_{dc} \); the peaks are associated with \( \pm H_K \), the anisotropy field. We obtain \( H_K \approx 3.5 \) Oe and no hysteresis was observed by cycling the dc field \( H_{dc} \). Regarding frequency \( f \), MI shows a maximum of \( \sim 250 \% \) at about 100 MHz. Similar plots were obtained with the other \( p \) ratios, albeit with significant differences in the values of the anisotropy field and peak frequency values. This allows us to make a detailed comparison, for a fixed frequency (as is typically presented), of the effect of the magnetic field. For instance, Fig. 2. displays the results we obtain at 10 MHz. The diameter ratio seems to produce a strong damping effect on the MI response.

Since our measurement method provides information over the full [1-500 MHz] range, we can use a deeper physical basis to make such a comparison. We choose the frequency at which the maximum in \( \Delta Z/Z \) appears and compare results as a function of \( H_{dc} \), as shown in Fig. 3. In addition to the absolute differences in MI values, important changes in the relative values are observed, as compared with Fig. 2. Now the \( p = 0.55 \) microwire shows a MI maximum close to that of \( p = 0.80 \). The anisotropy field, however, is three times larger. Note that the sample with \( p = 0.32 \) exhibits, as a function of field, several peaks that can be associated with a distribution of the anisotropy axis orientation. This introduces a large uncertainty in the numerical value of the anisotropy field \( H_K \) that will be discussed further below.

The effect of \( p \) on the MI response and anisotropy field is roughly indicated in Fig. 4. This is consistent with what has been previously observed: MI response increases as \( p \) increases, while the anisotropy field decreases. \( p \) indicates
the importance of the metal core with respect to the total diameter of the wire and the stress increases as the thickness of the glass sheath increases.

The result is consistent with the following fact. During fabrication, glass-covered microwires are subjected to strong stresses, generally proportional to the thickness of the glass coating that varies inversely proportional to \( p \). The origin of such stresses can be somehow, readily understood, since glass possesses a smaller thermal contraction coefficient than metals. In the cooling process, the metallic core tends to contract faster and more substantially than the surrounding glass sheath, however glass hampers such contraction. The overall consequences and the nature of the stresses are highlighted in the next section.

III. INTERPRETATION OF THE RESULTS AND CONCLUSIONS

Torcunov et al. modeled the thermoelastic and quenching stresses that occur in glass-coated wires and evaluated with a thermodynamic model the stress components in terms of their axial \( \sigma_{zz} \), radial \( \sigma_{rr} \) and azimuthal \( \sigma_{\phi\phi} \) components (in a cylindrical system of coordinates \((r, \phi, z)\) with the \( z \) axis along the wire). The following expressions (providing the Poisson’s coefficients of the glass and metal are equivalent \( \nu_g \sim \nu_m \sim \frac{1}{3} \)) are obtained and adapted to our case:

\[
\sigma_{rr} = \frac{\epsilon E_g(1 - p^2)}{(k + 1)(1 - p^2) + \frac{3p^2}{4}} \tag{2}
\]

\[
\sigma_{\phi\phi} = \sigma_{rr} \tag{3}
\]

\[
\sigma_{zz} = \sigma_{rr} \frac{(k + 1)(1 - p^2) + 2p^2}{k(1 - p^2) + p^2} \tag{4}
\]

where \( E_g \) is the glass Young modulus, \( k = E_g/E_m \) and \( E_m \) is the metallic wire Young modulus.

The term \( \epsilon \) is given by the difference of the glass and metal expansion coefficients \( \alpha_g, \alpha_m \) (respectively) times the difference of the minimum glass solidification temperature \( T^* \) and room temperature \( T \), \( \epsilon = (\alpha_m - \alpha_g)(T^* - T) \).

Using the numerical values \( 3.2 \times 10^{-6} \text{ K}^{-1} \) and \( 1.2 \times 10^{-5} \text{ K}^{-1} \) for the expansion coefficients \( \alpha_g, \alpha_m \), \( T^* = 550\text{C} \), \( 64 \text{ GPa} \) and \( 110 \text{ GPa} \) for the Young modulus of glass and metal \( E_g, E_m \) we get the variation of all stress components versus \( p \) as depicted in Fig. 5. The variation shows that all stresses decrease steadily with the increase of \( p \) as one might expect, since the origin of stress is associated with the increase of glass thickness.

Applying this variation to the anisotropy field \( H_K = 2K_\sigma/\mu_0 M_s \) with \( K_\sigma \) the anisotropy constant of the wire under stress \( \sigma \) and adopting the change of the anisotropy constant according to with the additional assumption of no extra applied stress (\( \mu_0 \) and \( M_s \) are vacuum permeability and saturation magnetization respectively):
FIG. 4: Overall indication of the effect of diameter ratio, $p$, on the MI maximum value and on the anisotropy field $H_K$. In the following figures, we show that the $H_K$ value is overestimated at small $p$.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig4}
\caption{Overall indication of the effect of diameter ratio, $p$, on the MI maximum value and on the anisotropy field $H_K$. In the following figures, we show that the $H_K$ value is overestimated at small $p$.}
\end{figure}

FIG. 5: Effect of diameter ratio, $p$, on the axial $\sigma_{zz}$, radial $\sigma_{rr}$ and azimuthal $\sigma_{\phi\phi}$ stress components. Parameters used are taken from Adenot et al.\cite{Adenot2020}. All stress components decrease with $p$ as predicted.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig5}
\caption{Effect of diameter ratio, $p$, on the axial $\sigma_{zz}$, radial $\sigma_{rr}$ and azimuthal $\sigma_{\phi\phi}$ stress components. Parameters used are taken from Adenot et al.\cite{Adenot2020}. All stress components decrease with $p$ as predicted.}
\end{figure}

\begin{equation}
K_S = K_{(\sigma=0)} - \frac{3}{2} \lambda_s (\sigma_{zz} - \sigma_{\phi\phi})
\end{equation}

Using physical parameters of wires\cite{Wang2019} with a composition (Co$_{0.94}$ Fe$_{0.06}$)$_{72.5}$ B$_{15}$ Si$_{12.5}$ similar to ours, we get in Fig.6, a reasonable agreement with the experimental behaviour depicted in Fig.4, despite a faster tapering off of $H_K$ at low values of $p$ where we observe experimentally a large uncertainty in the value of $H_K$ due to a broad distribution of anisotropy axis orientation (see Figs.2 and 3). From Fig.6, we infer that when $p = 0.32$, the value of $H_K$ has been overestimated and should be about 20 Oe and not 25 Oe as obtained in Figs.2 and 3.

In conclusion, the measurement of the MI response of microwires with a novel broadband technique provides a satisfactory view of the interplay between different physical phenomena operating on the glass or metal side. It is observed that when the metal core is small ($p$ small) a larger distribution of $H_K$ is observed. One possible cure to that problem is to perform the Taylor-Ulitovsky process under the application of a magnetic field in order to control magnetic orientation during growth or to perform post-annealing with/out external stress. Several applications of the present results are possible. One of them is the ability to select or tune the physical properties such as a better microwire might be produced and suited for a specific application. A simple description of the desired property might be given by a $\Delta Z/Z$ percentage value, static field or frequency operation range and finally a sensitivity, bandwidth or signal to noise figure of merit.

Acknowledgements
FIG. 6: Effect of diameter ratio, $p$, on the anisotropy field $H_K$. The parameters taken from Mohri et al.\textsuperscript{10} are $\mu_0M_s=0.8$ T, zero stress anisotropy constant $K_{s=0}=40$ J/m$^3$ and $\lambda_s=-0.1\times10^{-6}$. All the other parameters are the same as in Figure 5. As $p$ decreases, the tapering off of $H_K$ is faster than expected, nevertheless an increase in experimental uncertainty should be accounted for as well. For large values of $p$ good agreement between theory and experiment is obtained.

The authors acknowledge Prof. M. Vazquez (Spain) for providing the microwires samples; R.V. thanks DGAPA-UNAM, Mexico, for partial support through grant PAPIIT IN119603-3.

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