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Experimental and theoretical correlation between low-field power absorption and magnetoimpedance in amorphous materials

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Abstract

We present measurements of low-field power absorption (LFA) at 9.45 GHz on an amorphous ribbon of nominal composition $(Fe_{0.06}Co_{0.94})_{75}Si_{15}B_{10}$, at room temperature. These results show an anti-symmetrical shape around zero magnetic field that peaks at ±34 Oe. We also present measurements of magnetoimpedance (MI) at 60 MHz and 3 GHz. In order to make a proper comparison between these experiments, the real part of magnetoimpedance, $\mathrm{Re}(Z_s)$, was numerically derived to obtain $\mathrm{dRe}(Z_s)/\mathrm{d}H$; leading also to an anti-symmetrical plot that peaks at the same fields that LFA. By using the complex Poynting vector, we show that LFA and MI are very similar processes and conclude that both measurements are a manifestation of the same response to electromagnetic absorption, in which the same physical processes take place.

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1. Introduction

Low-field power absorption (LFA) centered at zero magnetic field has been observed in a wide variety of materials: high-temperature superconductors [1], ferrites [2], silicate glasses [3], and amorphous ribbons [4]. In these materials this signal can be caused mainly by three sources: (1) the reflecting dissipative dynamics of the fluxoid tubes characteristic of the mixed state [1]; (2) the interaction of the microwaves with the magnetic or electric dipoles [2,3]; and (3) the magnetization process strongly depending on the anisotropy field, such as in magnetoimpedance [4].

We have recently implemented this experimental technique [5], whose results are clearly different from ferromagnetic/paramagnetic resonance. The results have been used to establish a correlation between LFA and low-frequency magnetoimpedance (MI) measurements [4] in amorphous ribbons. We have also implemented measurements of MI in a wide range of frequencies (up to 3 GHz) as a function of the applied magnetic field, in ferromagnetic amorphous ribbons, using a microstrip transmission line [6].

In this work, we present measurements of MI and LFA on a Co-rich amorphous ribbon, at room temperature. As LFA signal is obtained as an electronic derivative of the microwave power absorption ($\mathrm{d}P_s/\mathrm{d}H$), to make a proper comparison, we must use the field derivative of the real part of MI, $\mathrm{dRe}(Z_s)/\mathrm{d}H$. An analytical relation between LFA

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and this derivative is obtained to explain the common features observed between both measurements.

2. Experimental procedure

The amorphous ribbon used in this study, of nominal composition $(Fe_{0.06}Co_{0.94})_{75}Si_{15}B_{10}$, was obtained by melt spinning. A 2 mm long sample, 0.65 mm wide and 20 μm thick was used in the experiments. Its amorphous state was checked by X-ray diffraction.

The microwave investigation used a JEOL JES-RES 3X spectrometer operating at 9.45 GHz (X-band) adequately modified [5]. A JEOL ES-ZCS2 zero-cross sweep unit compensates digitally any remanence in the electromagnet, allowing measurements to be carried out by cycling the dc magnetic field about its zero value.

High-frequency MI was measured by inserting the sample in a microstrip transmission line and using microwave-adapted data reduction [6]. The impedance is measured as a function of the magnetic field, provided by a pair of Helmholtz coils.

In both experiments the sample is oriented longitudinally with the applied magnetic field.

3. LFA signal and MI

Let us consider an electromagnetic wave with both electric (**E**) and magnetic (**H**) fields. The time-average density of the power absorption (P_s), for a ferromagnetic conductor at high frequencies, can be expressed by the complex Poynting vector as [7]: $P_s = 1/2\text{Re}[\mathbf{E}\times\mathbf{H}^*]$ or $P_s = 1/2\text{Re}[E\times H^*]$, where $\mathbf{H}^*$ is the complex conjugate of **H**, and Re[x] the real part of the operator. Additionally, the ac surface impedance for a ferromagnetic conductor material is defined as the ratio of the fields at the surface: $Z_s = E_s/H_s$. Then the time-average density of the microwave power absorption can be written as $P_s = 1/2H_s^2\text{Re}(Z_s)$. The ac magnetic field H_s, in a ferromagnetic conductor at high frequency, is generated by a uniform current $j = \sigma E_s$ (with σ the electrical conductivity) induced by the ac electric field E_s; and therefore H_s is constant to changes of an applied static magnetic field.

Therefore, we can establish a relation between the field derivative ($\text{d}P_s/\text{d}H$) of the microwave power absorption and the rate of change of Re(Z_s) with an applied static magnetic field H, given as:

$$\frac{\text{d}P_s}{\text{d}H} = \frac{H_s^2}{2}\frac{\text{dRe}(Z_s)}{\text{d}H} \tag{1}$$

For a good magnetic conductor $Z_s = (1 + \text{j})/\sigma\delta$, with the classical skin depth $1/\delta = (\omega\mu\sigma/2)^{1/2}$, where $\omega = 2\pi f$, f is the frequency and μ the permeability.

The magnetoimpedance is defined as the change of the impedance of a magnetic conductor subjected to an ac excitation current, under the application of a static magnetic field H_{DC}; it is a very similar phenomenon to the one involved in the microwave power absorption. At high-frequencies (microwaves) and due to the skin depth effect, only the surface impedance is involved.

Besides, different phenomena contribute to MI depending on the dynamics of the magnetization. In the quasistatic regime, MI is controlled by low frequency magnetization processes, whereas in the dynamic one (at higher frequencies) the ferromagnetic resonance dominates the MI behavior [8]. However, we have recently observed that high frequency MI at low fields, where the resonance conditions are not fulfilled, presents a behavior that resembles the quasistatic one. Here we present the comparison between LFA and MI in both regimes.

4. Results and discussion

Fig. 1 compares both MI curves at (b) 60 MHz and (c) 3 GHz, with (d) the LFA spectrum. The magnetization curve, Fig. 1(a), is also included as a reference. Note that according to the previous paragraph, MI is shown as $\text{dRe}(Z)/\text{d}H$, calculated numerically.

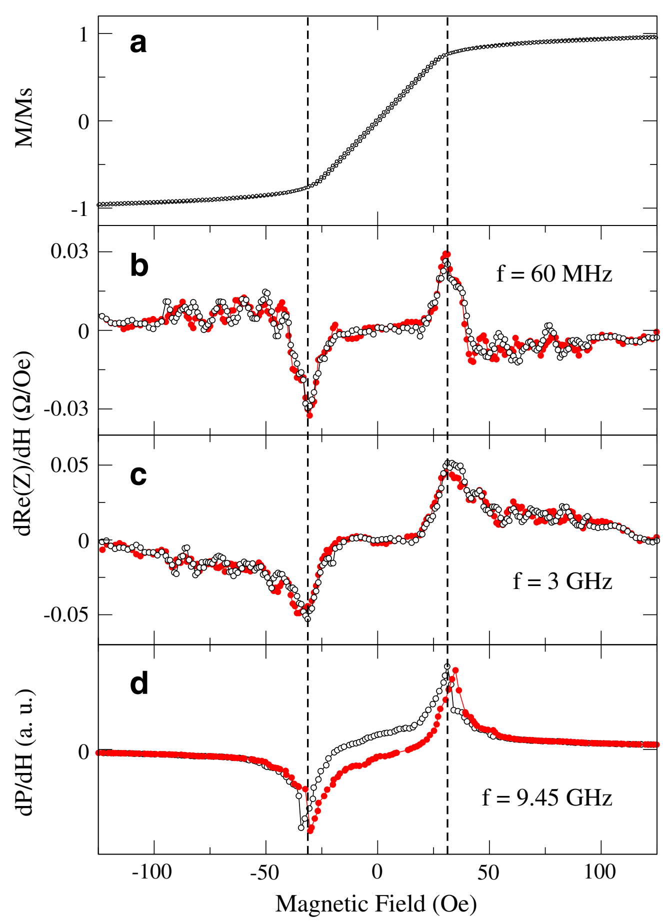

Fig. 1. (a) Longitudinal hysteresis loop; (b) numerical derivative of the real part of MI at 60 MHz; (c) same at 3 GHz; and (d) LFA spectrum at 9.45 GHz for the $(Fe_{0.06}Co_{0.94})_{75}Si_{15}B_{10}$ alloy.

The LFA spectrum, Fig. 1(d), shows an anti-symmetrical shape around zero that peaks at about ±34 Oe, displaying a clear hysteresis upon cycling the field. These peaks coincide with the ones obtained in the dRe(Zs)/dH curves both at low (b) and high (c) frequencies.

Besides, the hysteresis loop presented in Fig. 1(a) indicates that the phenomena involved in both the MI and LFA curves are dominated by the anisotropy field. For the above-mentioned, this supports a correlation for the curves, establishing an empirical proportionality of the type:

$$\frac{\mathrm{d}P_\mathrm{s}}{\mathrm{d}H} \alpha \frac{\mathrm{dRe}(Z_\mathrm{s})}{\mathrm{d}H} \quad (2)$$

which (except by the H_s^2 term which is a constant) is identical to Eq. (1). This is an evidence that $\mathrm{dRe}(Z_\mathrm{s})/\mathrm{d}H$ (at both low and high frequency) and LFA represent a similar response, essentially controlled by the anisotropy field, generated by the same electromagnetic phenomenon.

It is worth mentioning the close resemblance of both (b) and (c) curves despite of the huge frequency difference. As mentioned before, it demonstrates that the dynamic effects that dominate at high frequency only take place when the sample is magnetically saturated, once the resonance conditions are fulfilled.

Finally, we must insist that the low field processes shown in Fig. 1(c) and (d) are clearly distinguished from the FMR peaks that take place at higher fields, both in MI [9] and microwave power absorption experiments [4].

5. Conclusion

Experimental results of low-field microwave power absorption and magnetoimpedance on the same Co-rich ribbon are presented. The LFA shows features similar to the derivative of the real part of the impedance measured at low and high frequencies: all of them display peaks at the same magnetic fields, which in fact are essentially equal to the anisotropy field. We conclude that both experiments are therefore a manifestation of the sample response to electromagnetic excitation, in which the same fundamental physical processes take place.

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