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# Low-field non-resonant microwave absorption in glass-coated Co-rich microwires

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A study of low-field non-resonant microwave absorption (LFA) at 9.8 GHz, on as-cast amorphous Co-rich CoFeBSi microwires under different measuring geometries is presented. Results confirm that LFA is associated with the magnetization processes from the unmagnetized state ($H_{DC} = 0$) to the saturated condition, in many aspects similar to Giant Magnetoimpedance (GMI), and clearly different from ferromagnetic resonance (FMR). LFA signal showed large variations in its maximum–minimum separation as a function of the measuring geometry, which is interpreted in terms of the total anisotropy in the process.



**1 Introduction** The frequency response of magnetically-ordered materials in the microwave range is a complex phenomenon; in the homogeneous spin precession (no phase shift between spins) it corresponds to the ferromagnetic resonance, FMR, expressed essentially by the Larmor relationship, $\omega = \gamma H$, where $\omega$ is the resonance frequency, $\gamma$ the gyromagnetic ratio, and $H$ the total internal field upon spins. Several authors have recently shown, however, that ferro and ferrimagnetic materials can absorb microwave fields at low applied fields, i.e., magnetic fields well below $H_K$ [1–9].

**2 Experimental techniques** Glass-coated amorphous microwires of nominal composition $Co_{69.4}Fe_{3.7}B_{15.9}Si_{11}$, prepared by fast cooling with the Taylor–Ulitovski technique [10], were kindly provided by Professor Vázquez, Spain. The metal core diameter was 24 µm, with a total (metal + glass) diameter of 30 µm.

The microwave absorption measurements were carried out using a JEOL JES-RES 3X spectrometer operating at X-band frequencies (8.8–9.8 GHz). The microwave response is measured with modulation of a superimposed magnetic field. The modulation field at a frequency of 100 kHz, is applied parallel to the dc field and the microwave signal is detected synchronously with the modulation using a phase-sensitive detector. 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. The complete scheme and details concerning the experimental set-up for the LFA measurements can be found in [11].

**3 Experimental results and discussion** We first measured the microwires by applying the DC field, $H_{DC}$, parallel to the microwire axis, and the AC field ($h_{AC}$) perpendicular to this axis, as shown Fig. 1. The $dP/dH$ vs. $H_{DC}$ plot, Fig. 2, exhibited two clearly distinct absorptions: one centered about $H_{DC} = 0$, and the other with a resonance field of 1129 Oe. The former corresponds to the low-field

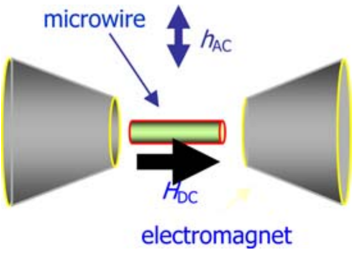


**Figure 1** (online colour at: www.pss-a.com) First geometry used for measuring the microwires. The DC magnetic field is parallel to the microwire axis, while the AC field is perpendicular to the axis.

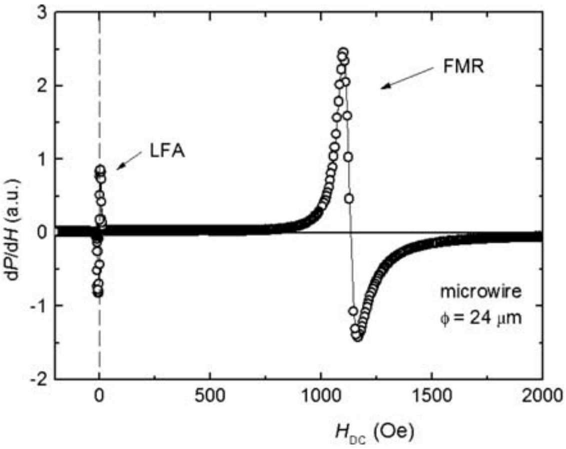


**Figure 2** Microwave absorption in the geometry of Fig. 1. FMR and LFA signals are clearly shown.

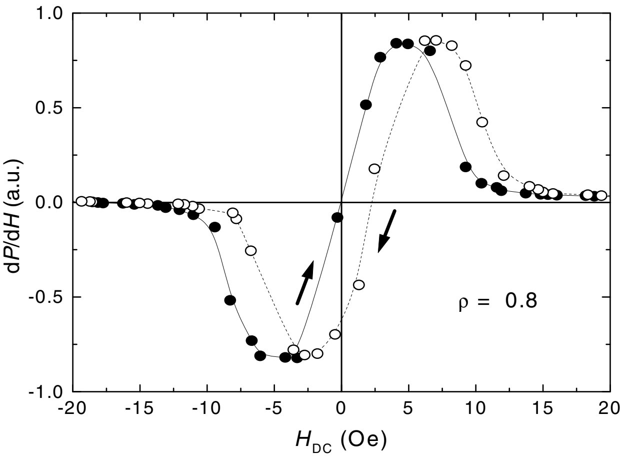


**Figure 3** Enlargement of the LFA section of Fig. 2.

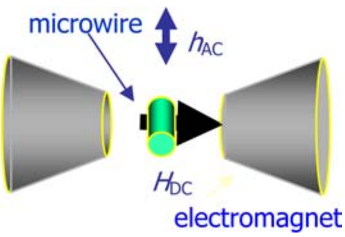


**Figure 4** (online colour at: www.pss-a.com) Second geometry used for measuring the microwires. Both the DC and the AC magnetic fields are perpendicular to the microwire axis.

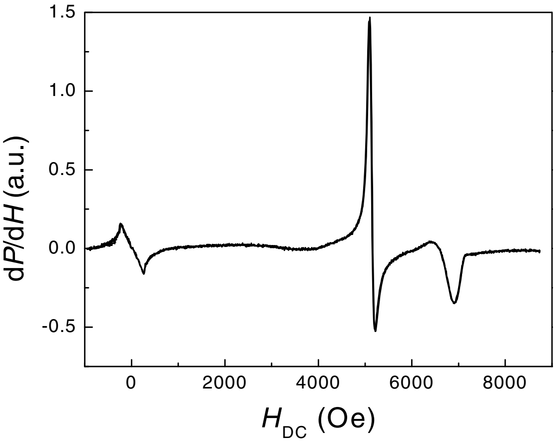


**Figure 5** Microwave absorption resulting from the geometry of Fig. 4. Two resonance signals are observed, in addition to the LFA signal.

absorption LFA, while the second is the ferromagnetic resonance, FMR. We will focus on LFA results in this paper.

By cycling the magnetic field (enlargement of the plot close to $H_{DC} = 0$, Fig. 3), LFA signal shows magnetic hysteresis and a separation $\Delta H_{LFA} \sim 12$ Oe between the maximum and the minimum. The presence of hysteresis, as well as the $H_{DC}$ values involved (very far from Larmor resonance conditions) clearly shows that this is a non-resonant phenomenon. Low-field microwave absorption (LFA) is effectively a non-resonant phenomenon physically similar to giant magnetoimpedance (GMI) [12, 13]. $\Delta H_{LFA}$ is associated in fact with twice the anisotropy field, $H_K$. For this microwires, the reported value of $H_K$, measured by magnetoimpedance is ~18 Oe [14].

We carried out measurements by changing the geometry as shown in Fig. 4. Here, both the DC and the AC magnetic fields are applied perpendicular to the microwire axis. The microwave absorption plot, Fig. 5, exhibits again a

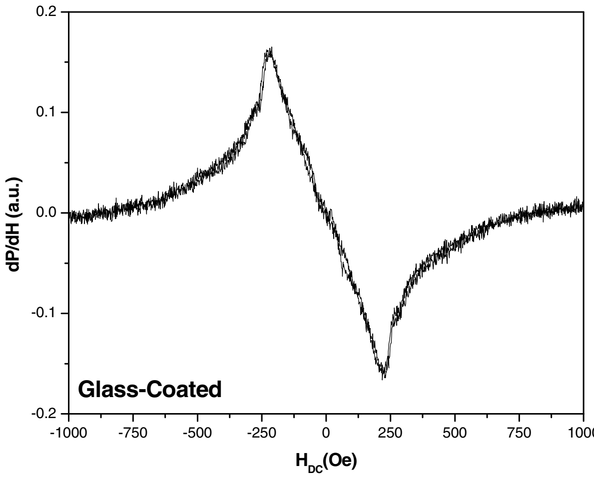


**Figure 6** LFA signal for the measuring geometry of Fig. 4.

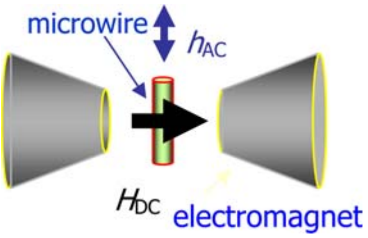


**Figure 7** (online colour at: www.pss-a.com) Third geometry used for measuring the microwires. The DC magnetic field is perpendicular to the microwire axis, while the AC field is parallel.

low-field signal, and two resonance peaks. An enlargement of the LFA section, Fig. 6, shows the maximum and minimum characteristic of LFA, but $\Delta H_{LFA}$ is now ~480 Oe.

To complete the measured geometries, we obtained results also by placing the microwire axis perpendicular to the HDC field, and parallel to the AC field, as shown in Fig. 7.

The observed behavior appears in Fig. 8. As in the former experiment, two resonance signals are obtained; also, the separation between the maximum and the minimum in the LFA section is large, Fig. 9.

LFA has shown to be directly related with the microwave absorption of the magnetization processes from the unmagnetized state to the saturation. Co-rich microwires with a Co/Fe ratio close to the compensation of the respective contributions of Fe and Co to the magnetostriction (positive from Fe, negative from Co), are known to possess a core/shell magnetic structure, where the magnetization has an axial arrangement in the core, and spins adopt a circumferential orientation in the shell. In the first geometry, the $H_{DC}$ field produces a reorientation of the spins in the shell from circumferential towards axial arrangement. Since shell spins become parallel to the microwire surface, no contribution is expected from the shape anisotropy. This reorientation needs a relatively small applied field, as shown by GMI experiments, and mentioned above.

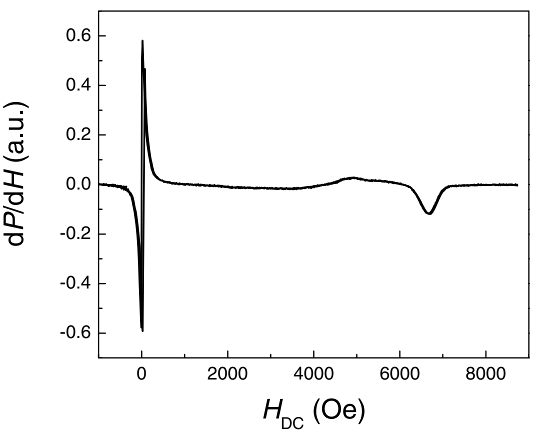


**Figure 8** Microwave absorption for the measuring geometry of Fig. 7. LFA signal amplitude is considerably larger than FMR signals.

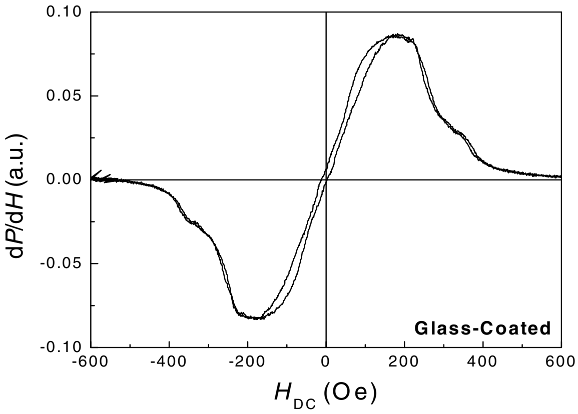


**Figure 9** LFA section for the third measuring geometry (Fig. 7).

For the second and third measuring geometries, Figs. 4 and 7, respectively, the applied field has to overcome not only the circumferential anisotropy, but also the shape anisotropy, since a substantial part of spins will be oriented out of the microwire surface in the saturated state. This process needs a much higher applied field, as shown by the high value in the $\Delta H_{LFA}$, ~40 times larger than in the first geometry.

An interesting point is the relative amplitudes between LFA and FMR signals. FMR exhibits a significant decrease in amplitude in the third geometry. This can be understood simply in terms of the total number of absorbing centers interacting with the AC field. Since at these frequencies the skin depth limits the field penetration to a very thin layer, the number of absorbing centers is roughly proportional to the microwire surface exposed to the AC field. In both the first and the second geometries, this surface is the side of the microwire (2 mm), while the third geometry involves only the circular cross-section (24 µm). In contrast, LFA shows an amplitude with smaller variations for all the geometries, and does not follow the same pattern as FMR. It seems as if the magnetization processes (with which LFA is associated) would allow a larger penetration of the AC field, leading to an absorption by the whole sample and not only by the surface exposed to the AC field.

Finally, there is the presence of two resonance signals for high DC fields. This point, which we think is related to the inner core in the microwires, will be addressed in our next paper.

**4 Conclusions** We have confirmed that LFA is associated with magnetization processes in Co-rich microwires, and by varying the measuring geometries, we have shown the effects of induced anisotropy, as well as those of shape anisotropy.

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