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Angular dependence of microwave absorption in multilayer films

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ABSTRACT

Microwave absorption measurements on a NiFe/Au/NiFe multilayer film were carried out at X-band (8.8–9.8 GHz). The angular dependence of microwave absorption, both in ferromagnetic resonance (FMR) and low-field microwave absorption (LFA), is investigated in two orientations. In both cases the film plane is orientated parallel to the AC field. In the longitudinal orientation, the film axis makes angles between 0° and 90° with the DC magnetic field (H_{dc}). In the transverse orientation, the film axis is always perpendicular to H_{dc}, marking angles between 0° to 90° with the axis of the induced transverse anisotropy. For the longitudinal orientation, FMR spectra suggested a compound absorption mode that can be interpreted as the combination of two different magnetic phases. Additionally, these measurements showed an increase in the resonance field as a function of the angle, which can be explained in terms of a contribution of shape anisotropy field (SAF). For this same orientation, the LFA spectra exhibited a compound antisymmetric shape around zero field with double peaks, which we associated with each one of the magnetic phases. The separation of these peaks increased as a function of the angle between the DC field and the multilayer film axis, suggesting also a contribution from SAF. In the transverse orientation, we observed an additional contribution of induced transverse anisotropy field (ITAF) in FMR measurements. The LFA measurements exhibited differences with the longitudinal orientation which are also associated with ITAF.

1. Introduction

The existence of the low-field microwave absorption (LFA) has been reported in soft magnetic materials such as amorphous ribbons [1], glass-coated microwires [2] and multilayers [3]. The results of this experimental technique are clearly different from ferromagnetic resonance (FMR), since LFA shows hysteresis and is very far from the Larmor conditions. Recently, we have shown that LFA signal is caused mainly by magnetization processes, which strongly depend on the anisotropy field (H_K), as in magnetoimpedance [1–3]. Additionally, we also have shown that the angular dependence of LFA and FMR, in amorphous ribbons, are sensitive methods which allow the determination of the different contributions to the total H_K [4].

In this paper, we investigated the angular dependence of LFA and FMR on a NiFe/Au/NiFe multilayer film when it is subjected to a high frequency field of 9.4 GHz (X-band).

2. Experimental

The sample studied in this work is a NiFe/Au/NiFe film system. The film width is 50 μm and the length is 5 mm. The multilayered structure was prepared by sputtering the materials onto a glass substrate, which was placed inside a magnetic field in order to induce a transverse anisotropy during the deposition. The grown thicknesses were 500 nm for both NiFe and Au layers. A thermal treatment was applied to the samples in order to relax internal stresses and enhance the induced transverse anisotropy.

The microwave investigations used a JEOL JES-RES 3X spectrometer operating at X-band (8.8–9.8 GHz). All measurements were carried out at room temperature. In FMR spectra, the applied DC magnetic field (H_{dc}) is varied from 0 to 5000 Oe. LFA measurements were performed using a JEOL ES-ZCS2 zero-cross sweep unit that digitally compensates any remanence in the electromagnet, thus allowing measurements to be carried out by cycling H_{dc} about its zero value continuously from −500 to 500 Oe with a standard deviation of less than 0.2 Oe for the measured field. For longitudinal and transversal orientation, the film plane is always orientated parallel to the AC field, and both define an in-plane configuration. In the longitudinal orientation, the film axis generates an angle

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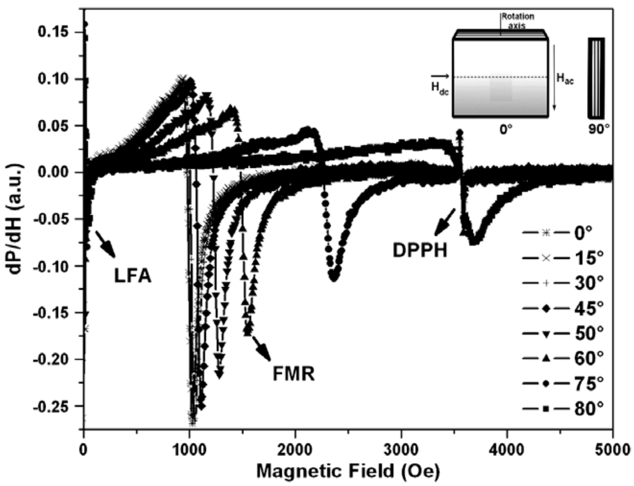

Fig. 1. Angular dependence of FMR for longitudinal orientation; for clarity, only results from 0° to 80° are shown. The inset shows the geometry between the film axis and the field H_{dc} for 0° and 90°.

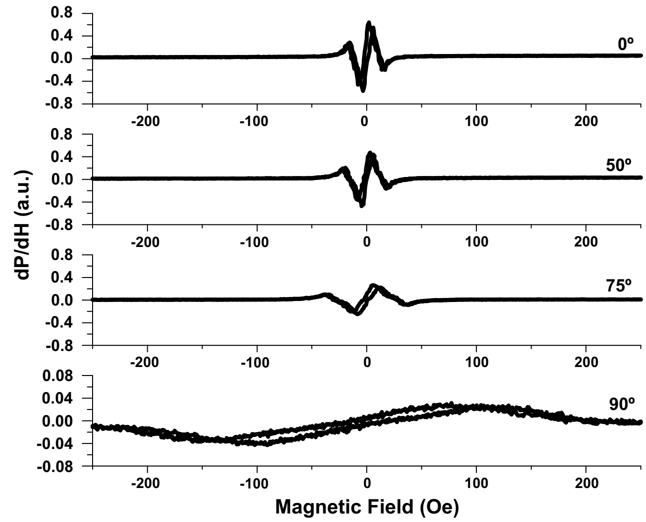

Fig. 2. Angular dependence of low-field microwave absorption in longitudinal orientation for selected angles.

between 0° and 90° with H_{dc}. For 0°, H_{dc} coincides with the easy direction of magnetization, as shown in inset of Fig. 1. For transversal orientation, the film axis is always perpendicular to H_{dc}, and it makes angles of 0–90° with the axis of induced transverse anisotropy. For 90°, H_{dc} coincides with the hard direction of magnetization.

3. Results and discussion

Fig. 1 shows the angular dependence of FMR spectra for the longitudinal orientation. For clarity, we show variations in FMR spectra only from 0° to 80°; the FMR spectrum for 90° has a resonant field larger than 5000 Oe.

Two features are significant: the shape of the FMR spectra in this multilayer film, and the fact that the resonant field (H_{res}) shifts towards higher values. The first point suggests a compound absorption mode, which can be resolved into two signals with a deconvolution process [5]. This compound absorption mode can be interpreted as the combination of two magnetic phases, which we associate with to the presence of each NiFe layer with different interfaces (glass substrate–NiFe–Au and Au–NiFe–air). These different environments originate a different magnetoelastic contribution that modifies the parameters of FMR lineshape. A comparison with measurements on a single layer sample with similar thickness, clearly suggests that spectra in Fig. 1 correspond to a compound absorption mode. A complete analysis will be published soon [6]. Concerning the angular dependence of H_{res}, this behavior is explained by means of the shape anisotropy field (SAF). It corresponds to the energy needed to orientated the magnetic moment in the hardest direction, out of the plane. For 0°, SAF is a minimum because the magnetization remains within the plane, corresponding therefore to the smallest H_{res} value.

Fig. 2 shows the angular dependence of LFA signal for the longitudinal orientation for variations from 0° to 90°. LFA shows an antisymmetrical compound shape around zero field that have double peaks, displaying a clear hysteresis upon cycling the field, and among them they exhibit an opposite phase; these opposite phases indicate that the absorption modes have a minimum and maximum value at zero magnetic field, suggesting a different absorption nature. We have shown that the sign of the phase is associated with the kind of magnetic order [7,8].

This LFA compound spectrum can also be explained in terms of a superposition of signals, due to a complex distribution of anisotropy (in contrast with the single signal for a single amorphous ribbon with axial anisotropy [8]). In a similar way, we associate this compound signal with each of the NiFe layers, in a very good agreement with FMR spectra. LFA compound spectra show an increase in the width ΔH_{LFA}, for angle variations of 0–90°, where ΔH_{LFA} is the separation between their maxima and minima. In addition, the intensity of this compound mode decreases when increasing the angle up to 90°; it becomes roughly an order of magnitude smaller for 90°. Both the increase in ΔH_{LFA} and its variations in intensity can be explained by the SAF contribution to the total H_K [4].

We turn now to measurements in the transversal geometry. Fig. 3 shows the angular dependence of FMR spectra for the transversal orientation for variations from 0° to 75°. The angular variation of H_{res} is similar to the longitudinal orientation, and which suggests that this behavior also is induced by SAF; but now the different rate of growth for H_{res}, and it is associated with a contribution of the induced transverse anisotropy field (ITAF). This ITAF can be associated to the induced anisotropy during the deposition and thermal treatment, that it is confirmed with Kerr effect measurements [3]; where are shown that the films present the typical hysteresis loop of transverse anisotropy samples.

LFA measurements were also carried out in the same geometries as a function of H_{dc} orientation. The inset of Fig. 3 shows

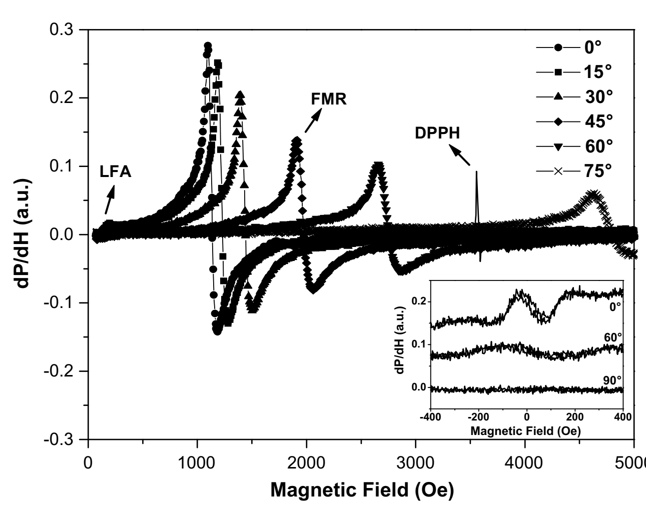

Fig. 3. Angular dependence of FMR for transversal orientation; for clarity, only results from 0° to 75° are shown. The inset shows LFA spectra for 0°, 60° and 90°.

the LFA spectra for the transversal orientation at 0°, 60° and 90°. This LFA signal is also centered at zero magnetic field, but it exhibits a phase opposite to that of longitudinal signal; i.e. there is a sign change in the absorption modes, from maximum to minimum and to the inverse one. This phase change can be related with a change in the relative orientation of magnetic moments, indicating a different contribution of the absorption processes, and where we suggest a strong contribution from ITAF. The intensity of this signal decreases while ΔH_{LFA} increases for angle variations of 0–90°, this last confirms a small contribution from SAF. For 0°, ITAF is a maximal because the magnetization remains within the plane on the axis of induced transverse anisotropy. But at 90° this signal disappears, in a good correspondence with the hardest direction of magnetization.

LFA signal is originated by absorption during the saturation process of magnetization and is very similar to MI [1–4,8], while FMR signal is due to absorption in the full saturation state and corresponds to the quantum-mechanical resonant phenomenon. Both signals, however, are modulated by total anisotropy field, including SAF and ITAF. As we have shown, under the appropriate geometrical conditions, it is possible to separate these contributions. It is interesting to note that for the in-plane configurations, FMR becomes especially sensitive to the induced transverse anisotropy.

4. Conclusions

The angular dependence of the magnetic anisotropy field can be correlated with the angular dependence of the LFA and FMR signal. LFA and FMR experiments are proposed as sensitive methods to determine different contributions to the total anisotropy field in multilayers.

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