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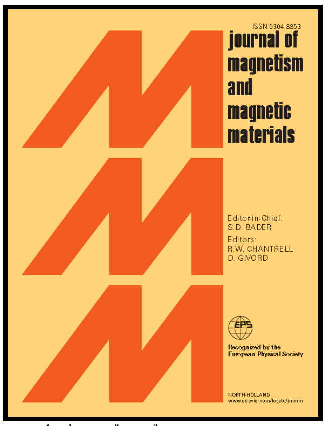

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Asymmetric magnetoimpedance effect in ferromagnetic multilayered biphase films

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We investigate the magnetoimpedance effect in ferromagnetic multilayered biphase films. We verify that the films present asymmetric magnetoimpedance behavior and, by playing with the number of the repetitions of the base structure of the multilayer and the probe current frequency, we explore the possibility of tailoring the linear region around zero magnetic field in order to achieve higher sensitivity values. The highest sensitivity is observed for the thicker film, reaching ~ 15 mΩ/Oe at ~ 0.52 GHz. Thus, the results open the possibilities for application of ferromagnetic multilayered biphase films with asymmetric magnetoimpedance effect in sensors devices.

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I. INTRODUCTION

The magnetoimpedance effect (MI) corresponds to the change of the real and imaginary components of electrical impedance $Z = R + iX$ of a ferromagnetic conductor caused by the action of an external static magnetic field. In a typical MI experiment, the sample is also submitted to an alternate magnetic field associated to the probe electric current $I_{ac} = I_o exp(i2\pi f t)$, f being the current frequency [1]. The overall effect of these magnetic fields can induce strong modifications of the effective magnetic permeability even when a rather small field is applied, leading to strong variations of the sample's impedance [2].

The MI effect has been widely employed as a versatile tool to investigate ferromagnetic materials. In recent years, the interest for this phenomenon has grown considerably, not only for its contribution to the understanding of fundamental physics associated to magnetization dynamics [3], but also due to the possibility of application of materials exhibiting magnetoimpedance as probe element in sensor devices for low-field detection with fast response under rf magnetic fields [4].

It is well-known that quasi-static magnetic properties play a fundamental role in the dynamic magnetic response and are reflected in the MI behavior [5]. Although soft magnetic materials are highly sensitive to small field variations, they present a nonlinear MI behavior around zero field. This makes difficult the derivation of an appropriate signal for sensor applications [5, 6].

From the practical point of view, MI sensitivity and linearity are the main parameters to be controlled [7]. In this sense, to improve the linear features of the MI response, studies have been carried out considering different magnetic systems, including wires [6, 8], amorphous ribbons [7, 9], and exchange biased multilayers [5, 10]. All of them exhibit asymmetric magnetoimpedance (AMI), characterized by a linear response around zero magnetic field, opening possibilities for the use of this kind of materials for the development of auto-biased linear magnetic field sensors.

Recently, it has been shown that AMI can be obtained in ferromagnetic NiFe/Cu/Co films [11]. For these samples, the linear region of the AMI curves can be tuned by varying the thickness of the spacer and probe current frequency. The films present a biphase magnetic behavior, with hard and soft ferromagnetic phases intermediated by a non-magnetic layer acting together, a fact associated to the kind of the magnetic interaction between the ferromagnetic layers.

In this work, we investigate the magnetoimpedance effect in ferromagnetic multilayered biphase films and play with the number of the repetitions of the base structure of the multilayer and the probe current frequency. We verify that the ferromagnetic multilayered biphase films present asymmetric magnetoimpedance behavior, and explore the possibility of tailoring the linear region around zero magnetic field in order to achieve higher sensitivity values. The results open the possibilities for application of ferromagnetic multilayered biphase films with AMI in auto-based sensors devices.

II. EXPERIMENT

For this study, we produce ferromagnetic multilayered $[Ni_{81}Fe_{19}$(25 nm)/Cu(7 nm)/Co(50 nm)/Ta(10 nm)$]\times n$ films, with $n = 1$, 3 and 5. Figure 1 shows a representative structure of the films. The samples are deposited by magnetron sputtering onto glass substrates, with dimensions of 8×4 mm^2. A buffer Ta layer is deposited before the NiFe layer to reduce the roughness of the substrate,

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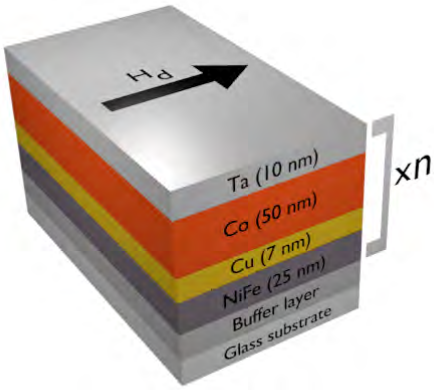

FIG. 1: Schematic structure of the ferromagnetic multilayered films, in which $n = 1$, 3 and 5. The arrow indicates the direction of the magnetic field H_d applied perpendicularly to the main axis and in the plane of the substrate during the deposition.

as well as a cap Ta layer is inserted after the Co layer in order to avoid oxidation of the sample. The deposition process is carried out using the following parameters: base vacuum of 10^{-8} Torr, deposition pressure of 2.0 mTorr with a 99.99% pure Ar at 32 sccm constant flow, dc source with power of 150 W for the deposition of the NiFe and Co layers, while 100 W set in the rf power supply for the Cu, and 200 W dcp for the Ta layers.

While low angle x-ray reflectometry results calibrate the sample thicknesses, high angle diffraction measurements verify the structural character of all films. In particular, the diffraction patterns, not shown here, suggest the fcc cubic Co(111) and NiFe(111) preferential growth for all samples.

During the deposition, a 2 kOe constant magnetic field H_d is applied perpendicularly to the main axis and in the plane of the substrate to induce a magnetic anisotropy and define an easy magnetization axis. The quasi-static magnetic behavior at room temperature is obtained through magnetization curves, acquired along and perpendicular to the main axis of the films, measured using a vibrating sample magnetometer, with maximum external in-plane magnetic field of ±300 Oe.

The MI measurements obtained using a RF-impedance analyzer Agilent model $E4991$, with $E4991A$ test head connected to a microstrip in which the sample is the central conductor. The electric contacts between the sample and the sample holder are made with 24 h cured low resistance silver paint. To avoid propagative effects and acquire just the sample contribution to MI, the analyzer is calibrated at the end of the test head connector by performing open, short, and load (50 Ω) measurements using reference standards. Longitudinal MI measurements are performed by acquiring simultaneously the real R and imaginary X parts of the impedance Z over a wide range of frequencies, from 0.1 GHz up to 3.0 GHz, with 0 dBm (1 mW) constant power applied to the sample, characterizing the linear regime of driving signal, and magnetic field varying between ±300 Oe, applied along the main axis of the sample. Detailed information on the MI experiment is found in Refs. [12, 13].

In order to quantify the sensitivity and MI performance as a function of the frequency, we calculate the magnitude of the impedance change at the low field range ±6 Oe using the expression [11]

$$\frac{|\Delta Z|}{|\Delta H|} = \frac{|Z(H = 6\,\mathrm{Oe}) - Z(H = -6\,\mathrm{Oe})|}{12}. \qquad (1)$$

Here, we consider the absolute value of ΔZ, since the impedance around zero field can present positive or negative slopes, depending on the sample and measurement frequency. In particular, we verify that $|\Delta Z|/|\Delta H|$ is roughly constant at least for a reasonable low field range.

III. RESULTS AND DISCUSSION

Figure 2 shows the normalized quasi-static magnetization curves, obtained with the in-plane magnetic field applied both along and perpendicular to the main axis of the films. The angular dependence of the magnetization curves indicates the existence of a magnetic anisotropy for all films, induced by the field applied during the deposition.

By considering the curves acquired with the magnetic field along the main axis, the higher hysteretic losses verfied with the raise of n are consistent with the stress stored in the film, roughness of the interfaces and lack of homogeneity of the Cu layer arisen as the total thickness of the sample increases [13, 14], as well as related to orange peel and similar effects.

The easy magnetization axis remains perpendicular to the main axis of the substrate, as expected. Along this direction, the films exhibit a biphase magnetic behavior. The two-stage magnetization process is characterized by the magnetization reversion of the soft NiFe layer at low magnetic field, followed by the reversion of the hard Co layer at higher field.

For the films with $n = 3$ and 5, one extra step, during the NiFe reversion, in the magnetization curve is verified. This fact is related to the different magnetic properties between the inner ferromagnetic NiFe layers with respect to deposited first one. In this case, the first NiFe layer deposited on the Ta buffer layer interacts only with one Co layer, while the other NiFe layers are sandwiched between two Co layers. Similar behavior is verified for exchange biased NiFe/IrMn multilayers [15].

In principle, the biphase magnetic behavior could suggests that the ferromagnetic layers are uncoupled. However, in our case, even there is a spacer material between the ferromagnetic layers, we interpret the extra steps as a first indication that the ferromagnetic layers interacts [15].

Regarding the dynamical magnetic behavior, the MI curves reveal important information on the main mechanisms acting at different frequency ranges, such as skin

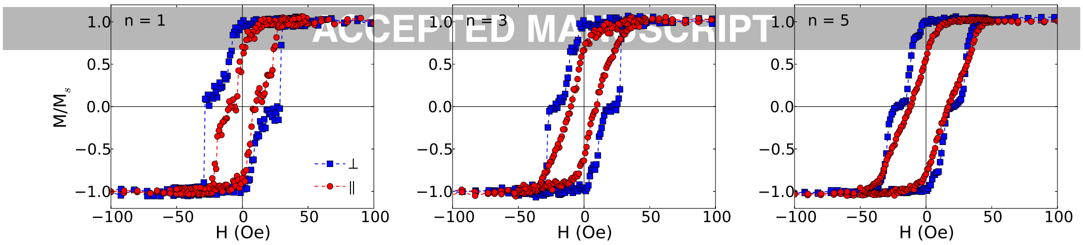

FIG. 2: Normalized magnetization curves for multilayered films, with n = 1, 3, and 5, measured with external in-plane magnetic field applied along (∥) and perpendicular (⊥) to the main axis.

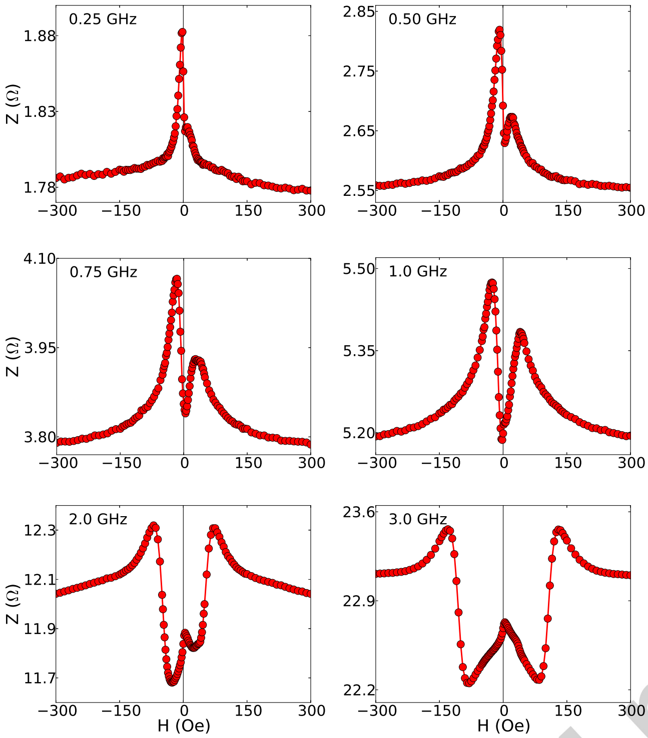

FIG. 3: The MI curves for selected frequencies for the multilayered film with n = 5. Similar behavior is obtained for the multilayered films with distinct n values. The curves are acquired over a complete magnetization loop and present hysteretic behavior. Here, we show just part of the curve, when the field goes from negative to positive values, to make easier the visualization of the whole MI behavior.

effect and ferromagnetic resonance (FMR) effect at saturated and even unsaturated samples, as well as provide further insights on the energy terms affecting the transverse magnetic permeability and nature of the interactions governing the magnetization dynamics.

Figure 3 shows the evolution of the MI curves as a function of magnetic field, at selected frequencies, for the multilayered film with $n = 5$. Similar behavior is verified the other studied multilayered films.

The MI measurements present a frequency dependent shift, a feature related to the electrical/metallic contributions of the sample and of the microwave cavity or microstrip employed in the experiment [16].

The MI curves present a double peak structure for the whole frequency range, as expected, since the external field and *ac* current are perpendicularl to the easy magnetization axis [17].

It is worth to point out that for a traditional multilayered film, composed by similar ferromagnetic layers separated by a metallic non-magnetic layer, symmetric peaks around zero field are usually verified. This behavior is not observed here. Our films consist of ferromagnetic layers, with distinct anisotropy fields, intermediated by a non-magnetic spacer. If the ferromagnetic layers were completely uncoupled, one could expect multiple peaks MI behavior, associated to the anisotropy fields of the layers. However, the sample structure affects in different ways the dynamical response, resulting in asymmetric magnetoimpedance effect. Thus, the asymmetry arises as a result of the magnetostatic coupling between the ferromagnetic layers [6, 7, 11, 18].

The asymmetry is assigned in the MI curves by two characteristic features: asymmetric position of the peaks and difference of their amplitude. The difference of amplitude at low and intermediate frequencies is understood in terms of the orientation of the magnetization of the soft NiFe and hard Co layers [6, 7, 11, 18]. On the other hand, regarging the position of the peaks, for frequencies below ∼ 0.45 GHz, their position remains unchanged, a fact indicating that the skin effect as the main responsible for the magnetization dynamics and MI variations at this frequency range. In the case of the multilayered film with $n = 5$, the peak at negative field is located at ~ -4 Oe, while the peak at positive field is at $\sim +10$ Oe. Similar behavior is verified for the multilayered with $n = 3$. For $n = 1$, the respective peaks are located at ~ -4 Oe and $\sim +30$ Oe. For frequencies above ∼ 0.45 GHz, besides the skin effect, the FMR effect starts appearing and also contributes for the MI variations, a feature evidenced by the displacement in the position of the peaks toward higher fields as the frequency is increased, following the behavior predicted for the FMR dispersion relation [2, 19, 20]. Above ∼ 1.5 GHz, the FMR effects is the main responsible by the MI variations. At this high frequency range, the asymmetry still remains in the central part of the impedance curve. The displacement of the peaks toward higher fields suppress the peak asymmetry resulting in symmetric peaks around zero field with same amplitude.

Thus, it is important to emphasize that the MI curves

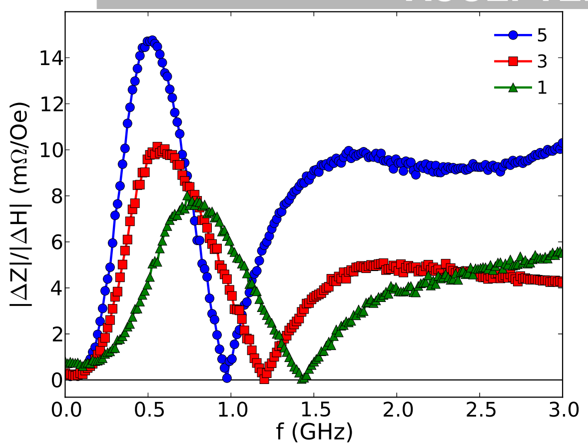

FIG. 4: Frequency spectrum of impedance variations between ±6 Oe for the multilayered films, with $n = 1$, 3 and 5, indicating the sensitivity around zero field.

are not strongly affected by the number of repetitions of the base structure. In particular, the general MI behavior for the studied multilayered films seems to strictly depend on the probe current frequency, irrespectively on the n value. The most striking finding in the asymmetry in the MI curves measured for the multilayered films resides in the nearly linear behavior around zero field.

Figure 4 shows the frequency spectrum of impedance variations, defined by Eq. 1, for the multilayered films, indicating the sensitivity at low fields. The highest sensitivity values are verified at ~ 0.75 GHz, ~ 0.55 GHz, and 0.52 GHz for the films with $n = 1$, 3, and 5, respectively. The change in the peak position is related to the structure of the samples [21], and to the increasing thickness of the whole system. This frequency dependence of the sensitivity peak position is in concordance with previously reported experimental results [22]. For all of them, the sensitivity peak is found to be at frequencies just after the FMR effect starts appearing. The sensitivity is reaised with the total sample thickness, as expected. In particular, the highest sensitivity is observed for $n = 5$, reaching ~ 15 mΩ/Oe. Thus, ferromagnetic multilayered biphase films become an attractive candidate for developing auto-biased linear magnetic field sensors for high performance devices.

At the same time, at higher frequencies, after a minumum of sensitivity, a roughly contant sensitivity frequency range is verified. These values are related to the presence of the FMR effect modifying the shape of the MI curves in the field range selected for analysis. Although at this frequency range the MI curves do not present a linear MI behavior at low field, since the imaginary part becomes relevant and increases its contribution to the impedance, changing the peak structure and giving rise to a new impedance peak at around, considerable sensitivity values are still observed. This new feature may be interesting for some technological applications, such as MI based magnetic field sensors that demand the similar efficiency for a wide frequency range.

IV. CONCLUSION

In summary, we have investigated the MI effect in ferromagnetic multilayered biphase films and observed the influence of the number of repetitions of the multilayer base structure and the probe current frequency on the MI curves. The MI curves are not strongly affected by the n value, and the general MI behavior for the studied multilayered films seems to strictly depend on the probe current frequency. We have verified the films present asymmetric magnetoimpedance behavior and have tailored the linear region around zero magnetic field by tuning the frequency of the experiment in order to achieve higher sensitivity values. We have estimated the MI sensitivity at low field and it is raised with the total sample thickness. The highest sensitivity is observed for the thicker film, reaching ~ 15 mΩ/Oe at ~ 0.52 GHz. Thus, the results place the ferromagnetic multilayered biphase films as promising candidates to optimize the MI sensitivity and extend the possibilities for the application of films with particular magnetic properties and AMI in MI-based sensors devices.

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