Physica B 506 (2017) 133–137

Contents lists available at ScienceDirect

Physica B

journal homepage: www.elsevier.com/locate/physb

Invariance of the magnetic behavior and AMI in ferromagnetic biphase films with distinct non-magnetic metallic spacers

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ARTICLE INFO

Keywords:
Magnetic systems
Magnetization dynamics
Magnetoimpedance effect
Ferromagnetic films

ABSTRACT

We investigate the quasi-static magnetic, magnetotransport, and dynamic magnetic properties in ferromagnetic biphase films with distinct non-magnetic metallic spacer layers. We observe that the nature of the non-magnetic metallic spacer material does not have significant influence on the overall biphase magnetic behavior, and, consequently, on the magnetotransport and dynamic magnetic responses. We focus on the magnetoimpedance effect and verify that the films present asymmetric magnetoimpedance effect. Moreover, we explore the possibility of tuning the linear region of the magnetoimpedance curves around zero magnetic field by varying the probe current frequency in order to achieve higher sensitivity values. The invariance of the magnetic behavior and the asymmetric magnetoimpedance effect in ferromagnetic biphase films with distinct non-magnetic metallic spacers place them as promising candidates for probe element and open possibilities to the development of lower-cost high sensitivity linear magnetic field sensor devices.

1. Introduction

Advances in the field of the magnetization dynamics during the last decades have contributed to the comprehension in the context of fundamental physics on how the magnetization responds to external magnetic fields and electric currents, and also have led to enormous progress in the development of sophisticated technological devices [1,2]. In this direction, the magnetoimpedance effect (MI) appears an important tool to investigate nanostructured magnetic materials, revealing the magnetic properties at different frequency ranges and magnetic field values, at saturated and unsaturated states, as well as at resonant and non-resonant regimes [3]. Moreover, the effect is of technological interest due to the potential of application of materials exhibiting magnetoimpedance as probe element in magnetic sensor devices for low-field detection [4].

The magnetoimpedance effect corresponds to the change of the real and imaginary components of electrical impedance $Z = R + iX$ of a ferromagnetic material caused by the action of an external static magnetic field. In recent years, the interest on materials exhibiting MI to act as probe element in technological sensor devices has grown significantly [5–8], justifying the increasing number of reports addressing different magnetic structures [9–15]. The sensitivity and linearity as a function of the magnetic field are the most important parameters for practical applications of the magnetoimpedance effect. However, although most of the soft magnetic materials are highly sensitive to small field variations at low magnetic fields, they use to show a nonlinear MI behavior around zero field [16].

For this reason, the design of novel magnetic materials with optimized properties and specific dynamic magnetic response is fundamental, making possible the observation of new phenomena and their use to the development of a next generation of technological devices. In this sense, several studies have been carried out to improve the linear features of the MI. This explains the recent interest in materials with asymmetric magnetoimpedance (AMI), which can present linear response around zero magnetic field. These materials are obtained by inducing an asymmetric magnetic configuration, usually done by magnetostatic interactions or exchange bias. The primary AMI results have been measured in wires [17–19], amorphous ribbons [20,21], and exchange biased multilayered films [16,22,23], opening possibilities for the use of this kind of material for the development of auto-biased linear magnetic field sensors [22].

Beyond the aforementioned magnetic systems, recently, it has been shown that AMI can be obtained in NiFe/Cu/Co films presenting biphase magnetic behavior and which consist of hard and soft

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http://dx.doi.org/10.1016/j.physb.2016.11.009
Received 31 August 2016; Received in revised form 3 November 2016; Accepted 4 November 2016
Available online 15 November 2016
0921-4526/

ferromagnetic phases intermediated by a non-magnetic metallic layer acting together [24]. In this case, the linear region of the AMI curves has been tuned by varying the thickness of the Cu spacer layer, and probe current frequency. Moreover, as an improvement with respect to this structure, it has been already verified that the AMI sensitivity at low fields can be amplified if ferromagnetic multilayered biphase films are considered [25].

In this work, we investigate the quasi-static magnetic, magnetotransport, and dynamic magnetic properties in ferromagnetic biphase films with distinct non-magnetic metallic spacers. By analyzing the magnetization dynamics through the magnetoimpedance effect, we verify that the films present asymmetric magnetoimpedance. We confirm that the linear region of the AMI curves around zero magnetic field can be tuned by the probe current frequency. We show that the nature of the non-magnetic metallic spacer material does not have significant influence on the overall biphase magnetic behavior and, consequently, on the magnetotransport and dynamic magnetic responses. The invariance of the magnetic behavior and the AMI in ferromagnetic biphase films with distinct non-magnetic metallic spacers place them as promising candidates for probe element and represent an important step to the development of lower-cost high sensitivity linear magnetic field sensor devices.

2. Experiment

For this study, we produce a set of ferromagnetic biphase films with distinct non-magnetic metallic spacers, i.e. $Ni_{81}Fe_{19}$(25 nm)/NM(7 nm)/Co(50 nm) films, where NM=Cu, Ta, and Au. The films are deposited by magnetron sputtering onto glass substrates, with dimensions of 8×4 mm^2. For all, a 10 nm-thick Ta buffer layer is considered in order to reduce irregularities of the substrate and enhance the adherence of the magnetic film, as well as a cap layer with similar thickness is employed to avoid oxidation. The deposition process is carried out with the parameters presented in Table 1. During the deposition, a constant 2 kOe magnetic field is applied perpendicularly to the main axis of the substrate in order to induce magnetic anisotropy.

The deposition rates, also presented in Table 1, are obtained through low angle X-ray diffractometry, while the structural properties of the films are investigated by high-angle X-ray diffraction measurements. The latter, not shown here, reveals the crystalline structural character of the ferromagnetic layers and indicates the fcc cubic Co (111) and NiFe (111) preferential growth for all films [24,25], irrespective on the non-magnetic metallic spacer material.

The quasi-static magnetic properties are investigated through magnetization curves obtained using a vibrating sample magnetometer. The curves are acquired at room temperature, with in-plane magnetic field of maximum amplitude of ±300 Oe applied in two directions, along ($\phi = 0°$) and perpendicular ($\phi = 90°$) to the main axis of the film.

Magnetotransport properties are obtained through magnetoresistance (MR) measurements performed using the four probe method. The experiments are carried out for the $\phi = 90°$ configuration, with in-plane magnetic field of maximum amplitude of ±300 Oe, and *dc* electric current of 0.2 mA applied along the main axis of the film. The MR results are presented in terms of the magnetoresistance ratio, defined by

$$\frac{\Delta R}{R}(\%) = \frac{[R(H) - R(H_{max})]}{R(H_{max})} \times 100\%, \quad (1)$$

where $R(H)$ is the electric resistance at a given magnetic field value and $R(H_{max})$ is the resistance at the maximum applied magnetic field, in which the film is magnetically saturated.

The magnetization dynamics is investigated through longitudinal MI effect, where magnetic field and current are applied along the direction of the main axis of the film, $\phi = 0°$. The measurements are 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. 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. The curves are taken by acquiring the real R and imaginary X components of the impedance Z in a wide range of frequencies from 0.1 GHz up to 3.0 GHz, in a linear regime with 1 mW (0 dBm) constant power, and with in-plane magnetic field varying between ±300 Oe. To quantify the sensitivity as a function of the frequency, we calculate the magnitude of the impedance change at low fields through [24,25]

$$\frac{|\Delta Z|}{|\Delta H|} = \frac{|Z(H = 6\text{ Oe}) - Z(H = -6\text{ Oe})|}{12}. \quad (2)$$

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

Table 1
Parameters employed for the deposition of the films.

Parameters	NiFe	Co	Cu	Ta	Au
Base pressure (Torr)	10^{-8}	10^{-8}	10^{-8}	10^{-8}	10^{-8}
Deposition pressure (mTorr)	2.0	2.0	2.0	2.0	2.0
Ar flow (sccm)	32	32	32	32	20
Power (W)	150	150	100	200	60
Source	DC	DC	RF	DCP	RF
Deposition rate (Å/s)	1.04	0.97	1.4	1.32	0.8

3. Results and discussion

First all, we address the experimental results associated to the quasi-static magnetic and magnetotransport properties, which provide us information on the magnetic anisotropy, the orientation of the magnetization in each ferromagnetic layer, and the magnetization reversal process.

Fig. 1 shows the normalized magnetization curves and MR ones for the NiFe/NM/Co films with NM = Cu, Ta and Au.

The angular dependence of the magnetization curves, Fig. 1(a,c,e), indicates the existence of a magnetic anisotropy, with the easy magnetization axis oriented perpendicularly to the main axis, induced by the magnetic field applied during deposition. The films exhibit a biphase magnetic behavior, as clearly verified from the magnetization curves obtained for $\phi = 90°$. The two-stage magnetization process is characterized by magnetization reversal of the soft NiFe layer at low magnetic field, followed by the reversal of the hard Co layer at higher field.

The orientations between the magnetizations of the ferromagnetic layers at different magnetic field values, as well as the magnetization reversal process, previously discussed can also be identified through the MR curves. The largest MR ratio values are found when an antiparallel alignment between the magnetizations of the soft and hard ferromagnetic layers is established, while the smaller MR ratios occur in the case of the parallel alignment [26–29]. Thus, from the MR curves, Fig. 1(b,d,f), starting from the maximum negative field value, as the magnetic field increases, the abrupt rise in the MR curve occurs at the switching field of the soft NiFe layer. As the magnetic field continuously increases, the sudden drop in the MR curve in located at the switching field of the hard Co layer. Similar behavior is verified in the MR curves along the other branch of the hysteresis loop, with decreasing field starting from the maximum positive field value. These features correspond to a clear signature that the shape of the MR curve is directly related to the magnetization reversal process and to the biphase magnetic behavior observed through the magnetization curves.

The biphase magnetic behavior verified through both the magne-