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Dynamic magnetic behavior in non-magnetostrictive multilayered films grown on glass and flexible substrates

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ABSTRACT

Dynamic magnetic behavior, through magnetoimpedance effect, is investigated in non-magnetostrictive multilayered films of $Ni_{81}Fe_{19}$/(Ag,Ta) grown on glass and flexible substrates. The magnetoimpedance measurements are performed in a wide range of frequencies (from 0.01 GHz up to 3.0 GHz) and are interpreted in terms of the structural and quasi-static magnetic properties of the films. In particular, $Ni_{81}Fe_{19}$/Ag multilayered films grown on glass and flexible substrates present very similar results, with MI_{max} values of 40% at around 0.5 GHz. For the $Ni_{81}Fe_{19}$/Ta multilayered film on glass substrate, higher MI_{max} value is observed, 60% at around 0.45 GHz, whereas for the one produced on flexible substrate, 28% at around 0.3 GHz. Thus, the fact that the produced multilayered films present good MI performance, irrespective of the employed substrate, opens new possibilities for technological applications, making easier the integration of these samples as a sensor element in MI based electronic devices, where flexible substrates can be used with the same efficiency.

1. Introduction

The magnetoimpedance (MI) effect is the name given to the changes in the electrical impedance of a metallic magnetic sample when submitted to an external magnetic field. In the last few years, the MI effect has been widely studied due to distinct motivations and with different goals. Several works have presented the great potential of application of the MI effect in sensors and integrated devices [1–7]. On the other hand, the effect has also been investigated in the context of fundamental physics as an interesting tool to study the dynamic magnetic behavior in ferromagnetic samples [8]. Considering the frequency range of the electrical current employed in a traditional MI experiment, for some decades of MHz, the main mechanism responsible for the MI variations is the skin effect, where the electrical current density changes the transverse magnetic permeability of the sample. At moderate and high frequencies, above hundreds of MHz, the modifications of the impedance can be associated to the strong skin effect, and, due to the magnetic fields configuration, to the Ferromagnetic Resonance (FMR) effect [9]. Therefore, since the impedance changes are related to the modifications in transverse magnetic permeability of the sample, the MI effect becomes a promising method to provide further information on the magnetic dynamic behavior of ferromagnetic samples with reduced dimensions [10].

Several works found in the literature report the MI effect in ferromagnetic thin films and nanostructures, such as, single layers [11], sandwiched samples [12], and multilayers [13,14], usually deposited by sputtering on non-flexible substrates. In general, multilayers with F/NM structure, where F is a ferromagnetic material and NM is a non-ferromagnetic metal, have soft magnetic properties and low electric resistivity, leading to a high MI effect [10,13,15]. This structure, in comparison with a single layer, has low stored stress, enabling, in some cases, the control of magnetic anisotropies. At the same time, flexible substrates have been employed recently in fundamental experiments to verify the influence of the magnetron configuration on ferromagnetic thin films on flexible substrates [16], high frequency applications [17], and magnetotransport properties, such as, magnetic tunnel junctions in flexible organic substrates [18], and magnetoimpedance in trilayer structures [19,20]. At this moment, the knowledge about the MI effect enables us to tune some fundamental parameters in order to obtain better MI results. In this sense, studies considering different sample structures and substrates are of interest, to make easier the integration of these samples as a sensor element in MI based electronic devices. Particularly, the use of alloys with low magnetostriction constant (λ), such as, $Ni_{81}Fe_{19}$ with $\lambda \approx 10^{-8}$ [21], and high λ, e.g., $Co_{40}Fe_{40}B_{20}$ alloy where $\lambda \approx +10^{-6}$ [22], for

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films grown on flexible substrates opens new possibilities for the MI effect in technological applications.

In this paper, we present MI effect results for multilayered films of $Ni_{81}Fe_{19}$/(Ag,Ta) grown on glass and flexible substrates, in which the employed alloy presents low magnetostriction constant and high saturation magnetization. The structural characterization and quasi-static magnetic properties of the studied samples provide us information to understand the magnetic dynamic behavior. We investigate the magnetic dynamic behavior in a wide range of frequencies and compare the dynamical response obtained in multilayered films produced on distinct substrates. Thus, we verify good MI response for all the produced samples, irrespective of the employed substrate, although similar MI maximum values are not observed for the films produced with Ta as a spacer material. The paper is organized as follows: In Section 2, we indicate the experimental procedure employed for the growth of the multilayered films, structural and magnetic characterization, as well as to the MI measurements. In Section 3, we present and discuss the experimental results obtained for the multilayered films. Finally, the last section is devoted to the conclusion and indication of new possibilities opened with this study.

2. Experimental procedure

In this work, multilayered films [Py/NM] $\times$ 50, where Py with 10 nm-thick is an alloy with composition of $Ni_{81}Fe_{19}$ and NM is Ta or Ag with 2 nm-thick, were produced. Fig. 1 shows the structure of the studied samples. They were deposited by magnetron sputtering on glass (G) and Kapton® flexible (F) substrates with dimensions of 12 mm $\times$ 4 mm, covered by a 2 nm-thick Ta buffer layer. The deposition process was carried out with the following parameters: a base pressure of 5.0×10^{-7} Torr, Ar pressure during the deposition of 2.5×10^{-3} Torr, 50 W DC source for deposition of the Py layers, 20 W DC source for Ta and, finally, 10 W DC source for Ag layers. Using these parameters, the deposition rates were 0.52 nm/s, 0.18 nm/s and 0.44 nm/s for Py, Ta and Ag, respectively. The thicknesses values chosen to produce the samples (Py[10 nm]/NM[2 nm]) are based on previous papers published by our group [13,15], in which samples grown with F[10 nm]/NM[2.5 nm] and F [10 nm]/NM[1 nm], respectively, where F is the ferromagnetic layer and NM the non-ferromagnetic layer. These thickness ratios between ferromagnetic and non-ferromagnetic metal lead to soft magnetic behavior and low electrical resistivity, as already cited in the introduction.

The structural characterization was performed through high angle X-ray diffractometry using a Rigaku MiniFlex system. To induce an uniaxial in-plane magnetic anisotropy, the substrates were submitted to a 1 kOe magnetic field during the deposition, applied perpendicularly to the long axis of the substrates, as indicated by the arrows in Fig. 1. The quasi-static magnetic behavior was verified using a Vibrating Sample Magnetometer, with maximum magnetic field of $\pm$300 Oe. Measurements were performed along two different directions in order to verify the induced magnetic anisotropy in the samples: along and perpendicular to the main axis of the samples.

The dynamic magnetic behavior was obtained through magnetoimpedance measurements performed using an Agilent (E4991A-RF) Impedance Analyzer with a head kit (E4991A-010 probe station connection kit) in a frequency range of 0.01–3.0 GHz. A special microstrip was developed for these samples, where the film is the central stripe conductor, which is separated from the ground plane by the glass or flexible substrate. The probe current was fed directly to one side of the film, while the other side was in short circuit with the ground plane. The films were fixed to the microstrip sample holder using low resistance silver paint, in which all contacts were cured for 24 h. For the measurements, a 0 dBm (1 mW) constant power was applied to the sample, characterizing a linear regime of driving signal. Thus, at a given field value, the frequency sweep was made and the impedance results were acquired. From this, the MI% is given as

$$MI\% = \frac{Z(H) - Z(H_{max})}{Z(H_{max})} \times 100 \quad (1)$$

where $Z(H_{max})$ is the impedance at maximum applied magnetic field, where the sample is saturated magnetically, and $Z(H)$ is the impedance at a given magnetic field value. Finally, MI_{max} is defined as the maximum MI% value for a given frequency.

3. Results

In order to investigate and obtain further information on the experimental MI measurements, the results are discussed in distinct subsection: structural characterization, quasi-static magnetic properties and, finally, magnetoimpedance effect results.

3.1. Structural characterization

The structural characterization of the produced multilayered films was obtained by analyzing the *intensity* vs. 2θ X-ray diffractograms, presented in Fig. 2. Here, a semi-quantitative analysis can be performed to evaluate the texture characteristics of the polycrystalline Py layers. For this purpose, considering the intensity of the (110), (111), and (200) Py peaks, respectively, called I_{110}, I_{111} and I_{200}, it is possible to calculate the texture factors, given by [23]

$$T_{hkl} = \frac{I_{hkl}}{\sum_{hkl} I_{hkl}}, \quad (2)$$

where I_{hkl} is the respective peak intensity. Based on the powder texture values obtained from the International Center Diffraction Data (ICPDS) pattern file 03-065-3244 to a $FeNi_3$-like cubic lattice, then a texture percentage for a Py lattice direction in each sample can be obtained through

$$T\%_{hkl} = \frac{T_{hkl} - T_{hkl}^{ICPDS}}{1 - T_{hkl}^{ICPDS}} \times 100. \quad (3)$$

In this context, $T\%_{hkl}$ indicates the degree of occurrence of a texture relative to a random value. Thus, $T\%_{hkl} = 0$ indicates a random texture, $T\%_{hkl} = 100$ infers a completely preferential growth, while orientations that occur less often than for a random arrangement lead to negative values of $T\%_{hkl}$. Table 1 presents the results obtained for each produced sample, including the texture percentages evaluated from the three Py peaks previously mentioned, and the d_{111} cell parameters calculated for the (111) peak position through the Bragg law.

In this case, both Py/Ag multilayered films present similar compressible stress, irrespective of the substrate. In particular,

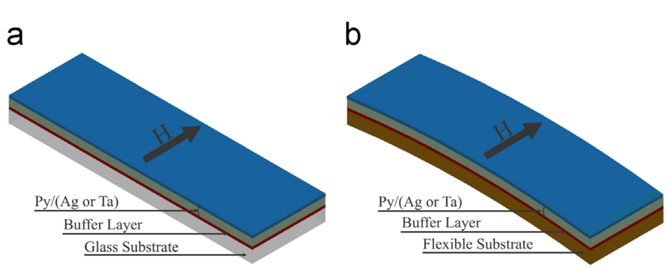

Fig. 1. Structure of the multilayered films deposited on (a) glass and (b) flexible substrates. The Py/(Ag or Ta) structures represent a multilayer with 50 bilayers, as described in the text. The arrows indicate the direction of the H applied during the deposition to induce an uniaxial in-plane magnetic anisotropy.