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Mirroring the dynamic magnetic behavior of magnetostrictive Co/(Ag,Cu,Ta) multilayers grown onto *rigid* and *flexible* substrates

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ABSTRACT

We investigate the magnetoimpedance effect in a wide frequency range in magnetostrictive Co/(Ag,Cu, Ta) multilayers grown onto *rigid* and *flexible* substrates. We observe a direct correlation between structural and quasi-static magnetic properties and the magnetoimpedance effect, since they are directly dependent on the nature of the spacer material. Moreover, we verify that all these properties are insensitive to the kind of employed substrate. We compare the magnetoimpedance results measured for multilayers in rigid and flexible substrates and discuss them in terms of different mechanisms that govern the impedances changes, magnetic anisotropy, structural character, and of numerical calculation results found in the literature. The fact that magnetostrictive multilayers can be reproduced in distinct kinds of substrates corresponds to an important advance for their applicability. The results place multilayers grown onto flexible substrates as attractive candidates for application as probe element in the development of MI-based sensor devices.

1. Introduction

The magnetization dynamics in magnetic thin films has been extensively studied in the recent past not just due to the importance in the context of fundamental physics, but also due to its technological relevance in a wide variety of magnetic devices. For instance, ferromagnetic films may be employed in a large variety of magnetic sensors for different purposes [1–3]. Thus, the knowledge of the magnetization behavior under *rf* magnetic fields in these systems, its correlation with the structural and magnetic properties, as well as the role of the substrate on this behavior, is crucial to their applicability.

Several experiments may provide relevant information on the magnetization dynamics in thin films. For instance, the *ac* susceptibility technique reveals features of the magnetization at low frequencies, in a wide range of temperature [4], while the ferromagnetic resonance experiment reports on the magnetization dynamics at high frequencies, informing issues on magnetic anisotropy and damping parameter [5]. On the other hand, the magnetoimpedance (MI) effect appears as a valuable tool to investigate the magnetization dynamics due to its probe in a wide range of frequencies and magnetic field values, giving insights on saturated and non-saturated states, resonant and non-resonant regimes, as well as magnetic anisotropy and uniformity of the magnetization.

The magnetoimpedance effect corresponds to the change of the real and imaginary components of the electrical impedance $Z = R + iX$ of a ferromagnetic conductor caused by the action of an external magnetic field H_{dc}. For a general review on the effect, we suggest Ref. [6]. The key to understanding the MI effect in planar systems lies on the transverse magnetic permeability μ_t. The changes of the magnetic permeability and impedance are caused by mechanisms as magnetoinductive effect, skin effect, and ferromagnetic resonance (FMR) effect. However, the contribution of each one with frequency is generally complicated and not easily predictable, since it depends on the magnetic properties and geometry of the sample.

The magnetoimpedance behavior, as well as the structural and magnetic properties of ferromagnetic films, may be strongly influenced by the geometry and kind of substrate in which the samples are grown. Several works are found in the literature reporting on the effect in single layered films, sandwiches and multilayers deposited onto rigid substrates [7–11]. Besides, most of them does indicate that the geometry has great impact in the MI performance [12]. Generally, FM/NM multilayers, where NM is a non-magnetic metal and FM is a ferromagnetic material, with higher magnetic permeability, well-defined magnetic permeability and lower electric resistivity, use to present higher MI effect

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[9–11,13,14], when compared to single layered films.

At the same time, flexible substrates have attracted great attention due to the potential of application in a wide variety of flexible electronic systems. Recently, fundamental experiments have been carried out to verify the influence of the magnetron configuration on ferromagnetic thin films on flexible substrates [15], high frequency applications [16], and magnetotransport properties, such as magnetic tunnel junctions in flexible organic substrate [17]. On the other hand, studies on the magnetization dynamics and MI effect in ferromagnetic single layered films and multilayers deposited onto flexible substrates are still very limited.

Although the results found in the literature for non-magnetostrictive films [12,18,19] provide important information on the dynamic magnetic behavior, the MI response of magnetostrictive multilayers grown onto flexible substrates is an open question, and a complete comprehension of the MI effect of films grown onto flexible substrates is still lacking.

In this paper, we report an experimental investigation of the magnetoimpedance effect in a wide frequency range in magnetostrictive multilayers produced with different non-magnetic metallic spacers and grown onto *rigid* and *flexible* substrates. In order to interpret the results, we perform a systematic study of the structural and quasi-static magnetic properties of the samples. We observe a correlation between them and MI effect, since they are directly dependent on the nature of the spacer material. We also verify these properties are insensitive to the kind of employed substrate. We show that the magnetoimpedance effect reflects structural and magnetic properties, as well as the dependence with the spacer and substrate. We compare the MI results obtained for the multilayers produced with distinct substrates and discuss them in terms of different mechanisms that govern the MI changes at distinct frequency ranges, magnetic anisotropy, structural character, as well as based on numerical calculation results previously reported. Thus, the results place multilayers grown onto flexible substrates as attractive candidates for application as probe element in the development of MI-based sensor devices.

2. Experiment

For this study, we produce a set of magnetostrictive [Co/(Ag,Cu, Ta)] $\times$ 50 multilayers, with $\lambda \approx -10^{-6}$, grown onto rigid (R) glass and flexible (F) Kapton® substrates. The deposition is performed by magnetron sputtering using the parameters presented in Table 1. In particular, we consider $t_{Co} = 10$ nm and $t_{NM} = 2$ nm as the thicknesses of the Co magnetic and Ag, Cu or Ta non-magnetic metallic spacers, respectively. A 1 nm-thick Ta buffer layer is deposited before the Co layer to reduce the roughness of the substrate, as well as a 2 nm-thick Ta cap layer is inserted after the multilayer in order to avoid oxidation of the sample. The films have dimensions of 12×4 mm^2. A 1.0 kOe constant magnetic field H_d is applied perpendicular to the main axis of the substrate during the deposition, in order to induce anisotropy and define an easy magnetization axis. Fig. 1 shows a schematic representation of the structure of the samples.

Table 1
Parameters employed for the deposition by magnetron sputtering of the multilayers and the deposition rates, obtained through x-ray reflectometry.

Parameter	Co	Ag	Cu	Ta
Base pressure (Torr)	3×10^{-6}			
Deposition pressure (Torr)	2×10^{-3}			
Ar flow (sccm)	32			
DC source power (W)	20	10	20	20
Deposition rates (nm/s)	0.20	0.44	0.58	0.19

While low-angle x-ray reflectometry (XRR) results calibrate the sample thicknesses and provide information on the quality of the multilayers, high-angle diffraction (XRD) measurements verify the structural character of all films. Both experiments are performed with a Bruker model D8 Advance diffractometer, in a Bragg–Brentano geometry with Cu – K_α radiation.

The quasi-static magnetic behavior at room temperature is verified through magnetization curves measured with a LakeShore model 7404 vibrating sample magnetometer, with maximum in-plane magnetic field of ± 350 Oe applied along and perpendicular to the main axis of the films.

Magnetization dynamics is investigated through MI measurements obtained using a RF-impedance analyzer Agilent model *E*4991, with *E*4991*A* test head connected to a stripline, in which the sample is the central conductor, as shown in Fig. 1, following the procedures traditionally employed by our group [10,20–22]. The experiment is performed by acquiring the real R and imaginary X components of the impedance Z in a wide range of frequencies from 0.5 GHz up to 3.0 GHz, with 0 dBm (1 mW) constant power, and with external magnetic field applied along the main axis of the films varying between ± 350 Oe.

3. Results and discussion

We first characterize the multilayers from the structural and quasi-static magnetic point of view. Both reveal significant changes with the spacer material and seem to be insensitive to the kind of used substrate. Then, we investigate the magnetoimpedance effect in a wide range of frequencies. The latter reflects the structural and magnetic characteristics, as well as evidences of an interesting dynamic magnetic behavior.

3.1. Structural properties

Fig. 2 shows the x-ray diffraction patterns for the multilayers produced with different spacers and grown onto rigid and flexible substrates. The XRD results indicate the hexagonal Co structure for all multilayers, although the patterns present a clear dependence with the metallic non-magnetic spacer. The Co/Ag and Co/Cu multilayers have a (002) Co texture in the *c* crystallographic direction, assigned by the peak at $2\theta \sim 44.49°$. In particular, when the spacer of Ag is used, the Co texture is more evident, although the multilayers do not present high crystallinity, since the Co peaks have considerable linewidth [23]. For the Co/Ta multilayers, the pattern indicates the polycrystalline state, depicted from the (100), (002) and (101) Co peaks identified at $2\theta \sim 41.55°$, $2\theta \sim 44.49°$, and $2\theta \sim 47.41°$, respectively.

A semi-quantitative analysis can be performed in order to evaluate the texture characteristics of the polycrystalline Co/Ta multilayers, as well as the cell parameters for the multilayers. Similar analysis has already been performed by our group for NiFe/Ag and NiFe/Ta multilayers [19]. In this case, for the texture analysis, we consider the intensity of the (100), (002), and (101) Co peaks, respectively called I_{100}, I_{002} and I_{101}, and calculate the texture factors, given by [24]

$$T_{hkl} = \frac{I_{hkl}}{\sum_{hkl} I_{hkl}}, \qquad (1)$$

where I_{hkl} is the respective peak intensity. Based on the powder texture values obtained from the Powder Diffraction File JCPDS 01-089-7094 to Co, the texture percentage for the Co lattice direction in each samples can be obtained through