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Handling magnetic anisotropy and magnetoimpedance effect in flexible multilayers under external stress

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ABSTRACT

We investigate the dynamic magnetic response though magnetoimpedance effect of ferromagnetic flexible NiFe/Ta and FeCuNbSiB/Ta multilayers under external stress. We explore the possibility of handling magnetic anisotropy, and consequently the magnetoimpedance effect, of magnetostrictive multilayers deposited onto flexible substrates. We quantify the sensitivity of the multilayers under external stress by calculating the ratio between impedance variations and external stress changes, and show that considerable values can be reached by tuning the magnetic field, frequency, magnetostriction constant, and external stress. The results extend possibilities of application of magnetostrictive multilayers deposited onto flexible substrates when under external stress and place them as very attractive candidates as element sensor for the development of sensitive smart touch sensors.

1. Introduction

In the recent years, as a consequence of an increasing number of works exploring the integration between magnetic properties and flexible systems [1–5], many applications have been proposed using the fascinating characteristics of ferromagnetic flexible nanostructures. Experiments have been carried out in numerous samples, including ribbons and films. However, although the ribbons may present very interesting properties for flexible applications [6], they are limited to the electronic integration due to the difficulty in the miniaturization and integralization with lithography techniques. In contrast, thin films, multilayers and flexible substrates overcome these issues and appear as key elements, having striking potential of application in distinct smart devices. For instance, they have been investigated to be applied in electronic skin to mimic the nature with respect to functionality and appearance [7–10], as well as have been widely explored as ground for spintronics devices mainly due to their magnetic and mechanical properties [11,1,12,2,5], in a sense that magnetic properties can enable/disable the film applicability in a specific magnetic devices. This explains the recent interest in controlling and handling of properties as magnetic anisotropy, dynamic magnetic response, magnetostrictive properties and stress in ferromagnetic flexible nanostructures.

In this context, the magnetoimpedance effect (MI) corresponds to a powerful tool to investigate magnetic materials and the dynamic response, as well as it is of technological interest due to the application of materials exhibiting MI in sensor devices [13]. The MI corresponds to the change of the real and imaginary components of electrical impedance of a ferromagnetic sample caused by the action of an external static magnetic field. In a typical MI experiment, the studied sample is also submitted to an alternate magnetic field associated to the electric current $I_{ac} = I_o \exp(i2\pi ft)$, with f being the probe current frequency. Irrespective to the sample geometry, the overall effect of these magnetic fields is to induce strong modifications of the effective magnetic permeability [14].

With regard to MI in multilayers deposited onto flexible substrates, in the recent past, distinct groups have reported very interesting results [15–20], opening the possibilities for the use of flexible substrates in the development of MI based sensors devices for field detection. In particular, our group has shown that non-magnetostrictive NiFe/(Ag,Ta) multilayers with similar magnetic properties and dynamic magnetic response can be obtained in distinct substrates [15]. For magnetostrictive multilayers, we have performed similar study in Co/(Ag,Cu,Ta) structure [16], and the mirroring of the magnetic features considering rigid and flexible substrates has been also verified [16]. This corresponds to a fundamental issue, since the optimized response obtained for films in ordinary rigid substrates can be reproducible in flexible ones [15,16]. However, considering both aforementioned reports, it is important to emphasize that, up to now, we have investigated the

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magnetic properties just in multilayers without external stress.

In this work, we report on the magnetoimpedance effect in ferromagnetic flexible NiFe/Ta and FeCuNbSiB/Ta multilayers under external stress. We handle magnetic anisotropy and magnetoimpedance effect of the flexible magnetostrictive nanostructures and verify that the sensitivity of the multilayers under external stress, calculated by the ratio between impedance changes and external stress variations, reaches considerable values and is experimentally tunable by the magnetic field, frequency, magnetostriction constant, and external stress. The results extend possibilities of application of magnetostrictive multilayers deposited onto flexible substrates when under external stress and place them as very attractive candidates as element sensor for the development of sensitive smart touch sensors.

2. Experimental procedure

For this study, we produce ferromagnetic multilayers, deposited onto flexible substrates, with distinct magnetostrictive properties. We select ferromagnetic alloys (FM) with nominal composition of $Ni_{81}Fe_{19}$, the well-known Permalloy which has vanishing magnetostriction [21], and $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$, the precursor of the so-called nanocrystalline Finemet [22] that presents high positive saturation magnetostriction constant [23], $\lambda_s \approx +26 \times 10^{-6}$, and soft magnetic properties even in the amorphous state [24]. The [FM(10 nm)/Ta(2 nm)] × 50 multilayers are deposited by magnetron sputtering onto flexible Kapton® substrate, covered with a 2 nm-thick Ta buffer layer, with dimensions of around $10 \times 4\ \text{mm}^2$, using the following parameters: base pressure of 7×10^{-7} Torr, deposition pressure of 2×10^{-3} Torr with Ar at 32 sccm constant flow, and using a DC source with 20 W. Under these conditions, the deposition rates for the NiFe, FeCuNbSiB and Ta layers are 0.52 nm/s, 0.33 nm/s and 0.18 nm/s, respectively. During the film deposition, the substrate moves at constant speed through the plasma to improve the film uniformity, and a constant 1 kOe magnetic field is applied perpendicular to the main axis of the substrate to induce magnetic anisotropy and define an easy magnetization axis. For comparison, multilayers deposited onto rigid glass substrate are also produced in the same batch. In particular, these multilayers are used just for the structural characterization (not shown).

The structural characterization of the multilayers is performed through x-ray reflectometry (XRR) and x-ray diffraction (XRD) performed with a Rigaku-Miniflex diffractometer in a Bragg–Brentano geometry and using CuK_α radiation.

The magnetic properties and magnetization dynamics are investigated in ferromagnetic multilayers with distinct magnetostrictive properties under external stress. Experimentally, the multilayers are submitted to external stress by bending the substrate with predefined curvatures.

The external stress in the multilayer may be estimated following the approach described in Refs. [25,26], which is based on the Stoney Model and considers the bending of the sample. To this end, some assumptions are taken into account: (i) the film must be planar, homogeneous and isotropic; (ii) the thicknesses of the film (t_{FM}) and of the substrate (t_S) must be uniform; and (iii) $t_{FM} \ll t_S$. For the multilayers studied here, $t_{FM} \approx 0.0046 t_S$. From Hooke's Law, where Young's modulus Y and Poisson ratio ν_s are considered, the average stress $\bar{\sigma}$ along the main axis of the sample can be written as

$$\bar{\sigma} = \frac{Y}{6(1-\nu_s)r}\frac{t_S^2}{t_{FM}}, \tag{1}$$

where r is the curvature radius that has a dependence with the sample's dimensions. Fig. 1 presents the experimental parameters considered for the estimation of the external stress. Thus, considering that our samples present small differences of size, the estimated average stress is distinct for each induced bending. At the same time, the multilayers present a natural curvature, leading to a compressive stress when the curvature is reduced, a fact primarily evidenced for the FeCuNbSiB/Ta multilayers. Here, we consider the selected $\bar{\sigma}$ values of 32.1, 64.7, 92.0, and 124.2 MPa for the NiFe/Ta multilayer and −1.5, 44.1, 82.4, and 127.3 MPa for the FeCuNbSiB/Ta one.

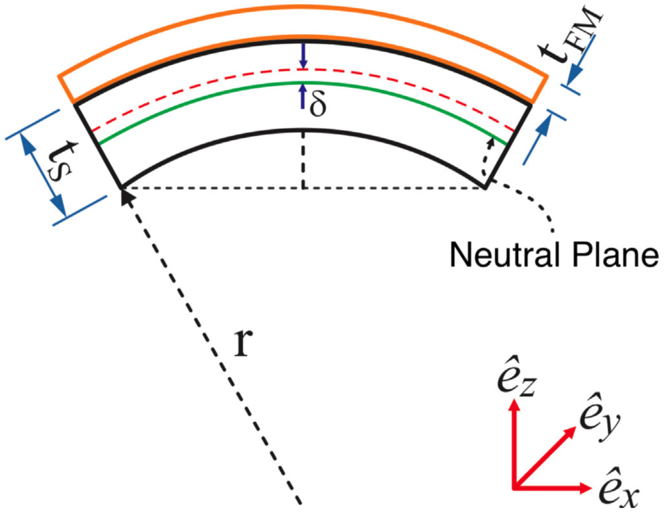

Fig. 1. Experimental parameters considered for the estimation of the external stress. In this case, δ is the displacement of the neutral plane, r the curvature radius in which the multilayer is submitted, and t_{FM} and t_S are the thicknesses of the film and of the substrate, respectively.

The in-plane magnetic properties are obtained through magnetization curves measured along and perpendicularly the main axis of the samples with a Lakeshore 7400 Vibrating Sample Magnetometer. All the curves are obtained with maximum applied magnetic field of ±350 Oe at room temperature.

The magnetoimpedance effect is measured using a RF-impedance analyzer Agilent model $E4991$, with $E4991A$ test head connected to a microstrip in which the sample is the central conductor,[1] which is separated from the ground plane by the substrate. 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 RF impedance analyzer is calibrated at the end of the connection cable by performing open, short, and load (50 Ω) measurements using reference standards. The probe current is fed directly to one side of the sample, while the other side is in short circuit with the ground plane. The *ac* current and external magnetic field are applied along the length of the sample. MI measurement is taken over a wide frequency range, between 0.5 GHz and 3.0 GHz, with maximum applied magnetic fields of ±350 Oe. While the external magnetic field is swept, a 0 dBm (1 mW) constant power is applied to the sample characterizing a linear regime of driving signal. Thus, at a given field value, the frequency sweep is made and the real R and imaginary X parts of the impedance Z are simultaneously acquired.

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[1] See supplementary material for a movie showing an illustration of the MI experiment for a magnetostrictive multilayer deposited onto flexible substrate when under external stress.