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Statics and Dynamics in Giant Magnetostrictive $Tb_xFe_{1-x}/Fe_{0.6}Co_{0.4}$ Multilayers for MEMS

J. Ben Youssef¹, N. Tiercelin², F. Petit¹, H. Le Gall¹, V. Preobrazhensky², P. Pernod²

Abstract— In the present paper, giant magnetostrictive thin films have been investigated for future microelectromechanical systems (MEMS) purposes. For this goal, flexural and torsional motions have been studied in low field anisotropic giant magnetostrictive (GMS) single domain state (SDS) exchange-coupled TbFe/FeCo multilayers (ECML). The magnetoelastic (ME) coefficient $b^{\gamma,2}$ depend strongly on the ECML structures, compositions, and sputtering deposition parameters. Giant magnetostrictive Multilayers with a high $b^{\gamma,2}$ (18MPa for $TbFe_2/Fe_{0.6}Co_{0.4}$ compared to 11MPa for $TbFe_2/Fe$) were obtained with or without an in-plane easy axis with a controlled direction, and *without* any annealing post-process. Dynamical excitations of the actuators have been investigated under various conditions. An enhancement up to a factor 5 of the oscillations compared to the TbFe/Fe multilayers is observed with the possibility to tune the flexural/torsional dynamical behavior of these cantilevers. The corresponding very large dynamical ME susceptibility of these improved uniaxial ECML gives the possibility to control GMS MEMS with further reduction of the excitation field down to a few oersteds.

Keywords— giant magnetostriction, thin films, multilayer, spin reorientation transition, dynamics, actuators

I. INTRODUCTION

THE development of microsystems and in particular the needs of new ways of actuation motivate the works on active materials and especially active thin films. One of the most promising alternatives is the use of giant magnetostrictive materials as already pointed out by Quandt *et al.*[1] and Honda *et al.*[2]. Many improvements have been achieved on the active thin films from Terfenol single layers to the recent TbFe/FeCo nanostructured multilayers[3]. In [4], E. Orsier *et al.* showed the possibility of tuning flexion versus torsion motion in cantilevers by adjusting the direction of a magnetic easy axis in TbCo magnetostrictive layers. More recently, the works by Tiercelin *et al.* demonstrated the possibility of using a field-induced Spin Reorientation Transition (SRT) in TbFe/Fe multilayers which offers new perspectives for the development of contactless, lowfield driven actuators[5]. In the present work, we first verified the most effective Tb_xFe_{1-x} composition, then we studied the possibility to induce an easy axis along different directions in TbFe/FeCo systems in order to be able to control the dynamic properties. Then we observed the dynamical torsional and flexural behaviour of the cantilevers in the vicinity of the field induced SRT.

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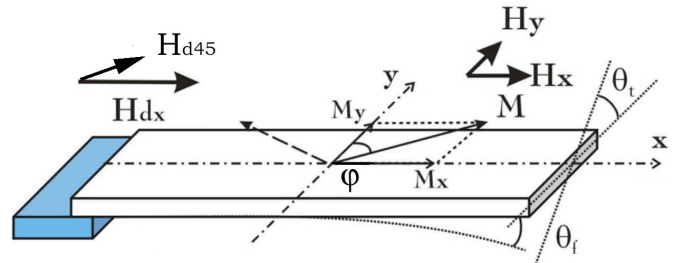


Fig. 1. Magnetostrictive unimorph geometry : The active layer is deposited onto the cantilever.

II. SAMPLE PREPARATION & CHARACTERIZATION

Artificially nanostructured uniaxial giant magnetostrictive ($Tb_xFe_{1-x}(5nm)/Fe_{0.6}Co_{0.4}(6nm)$) * 25 ECML were deposited for different Tb contents and under a bias magnetic field H_{dx} along the x direction, H_{d45} along the $y = x$ direction (45° samples), or without $H_d = 0$, onto unheated $4 \times 24 \times 0.05mm^3$ rectangular silicon₁₀₀ substrates from a commercially available RF diode sputter deposition system, Leybold Z550. The multilayer structures were adjusted from a rotary turn-table substrate holder in a continuous rotation mode. The composition and magnetization were determined from Electronic Probe Micro Analysis (EPMA) and Vibrating Sample Magnetometer (VSM). The magnetostriction was deduced from optical deflectometry by the measurement of the flexion Θ_f angle of the ECML/substrate unimorphs induced by an external dc field applied along either the large (H_x) or the small (H_y) side of the rectangular unimorph (Fig. 1).

III. STATICS IN TbFe/FeCo ECMLS

The magnetoelastic coefficient $b^{\gamma,2}$ was measured for different ratios of Tb content and as for the $(TbFe/Fe) * n$ multilayers, the best value of $b^{\gamma,2}$ in $(TbFe/FeCo)$ is obtained for a Terbium content approximately equal to 34%. This result is consistent with previous studies [3]: the best composition for Tb_xFe_{1-x} is close to the terfenol $TbFe_2$ one. Our measurements showed that it is still the case when a bias field is applied during the deposition.

Fig. 2 shows the increase of $b^{\gamma,2}$ in the $(TbFe/FeCo) * n$ multilayers compared to $(TbFe/Fe) * n$. As expected and already discussed in [3], the soft $FeCo$ layer replacing the Fe layer exhibits a quite large saturation magnetisation ($4\pi M_S \approx 24kG$) and a non negligible magnetostriction ($\lambda_S \approx 100 \times 10^{-6}$) which contributes to the enhancement of the magnetoelastic effect in the film almost by a factor 2. As shown on the magnetization loops (Fig. 3), even if

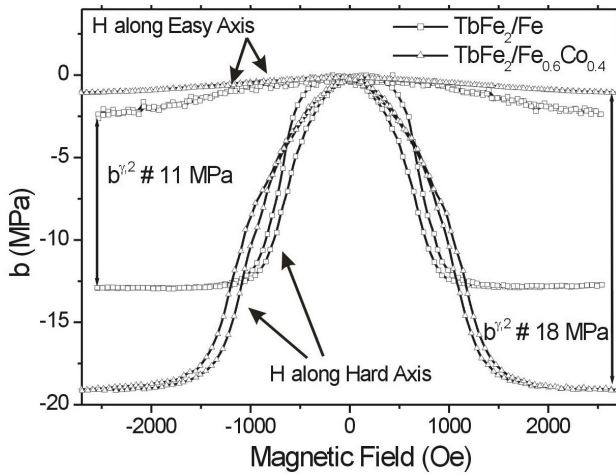


Fig. 2. Flexural ME parameter b versus magnetic field applied along the EA and HA in $TbFe_2/Fe$ and $TbFe_2/FeCo$ multilayers.

the FeCo layer is harder than the Fe layer, the values of the in-plane anisotropy field are comparable for both kind of films, when trying to obtain uniaxial samples with RF-sputtering under a bias field. This means that the SRT can be induced with a polarizing field of the same order of value than in the $(TbFe/Fe) \times n$ multilayers: the former must indeed be equal to the in-plane anisotropy field of the layer. Magnetization loops on Fig. 4 show the uniaxial character of the $TbFe/FeCo$ layers and their monodomain state, which can also be observed on the magnetostriction (Fig. 2). b is maximum for H along the hard axis and weak for H along the easy axis. Fig. 4 also show the possibility to induce an in-plane easy axis in the 45° direction when sputtered under H_{d45} (c.f. Fig. 1). This is also seen on the static magnetostriction measurements (Fig. 5): when the magnetic field is applied along the hard axis direction for 45° samples, the shape of the flexion and torsion displacements are swapped compared to those of the samples with the anisotropy in the x direction. It is to be noted that these in-plane anisotropies along the different directions were obtained *without* post deposition annealing to avoid intermixing between the hard ($TbFe_2$) and soft ($Fe_{0.6}Co_{0.4}$) layers.

IV. DYNAMICS

Dynamical excitation of the cantilever at SRT for the flexural and torsional resonance as described on $(TbFe_2/Fe)$ films in [5] and [6] has also been investigated on $(TbFe_2/Fe_{0.6}Co_{0.4})$ layers. In order to take advantage of the SRT, the excitation field h is applied along the easy axis direction, while the dc field H_S is directed along the hard axis. Fig. 6 shows the evolution of the torsion amplitudes as a function of H_S . As expected, the excitation field sensitivity is strongly increased when $H_S \approx H_A$. For $(TbFe_2/Fe_{0.6}Co_{0.4}) \times n$ ECML, this figure shows a strong enhancement of the amplitudes versus the excitation field compared to those obtained in the previous works: several milliradians of angular torsion amplitude were obtained on centimeter cantilever with 3 Oersteds excitation field am-

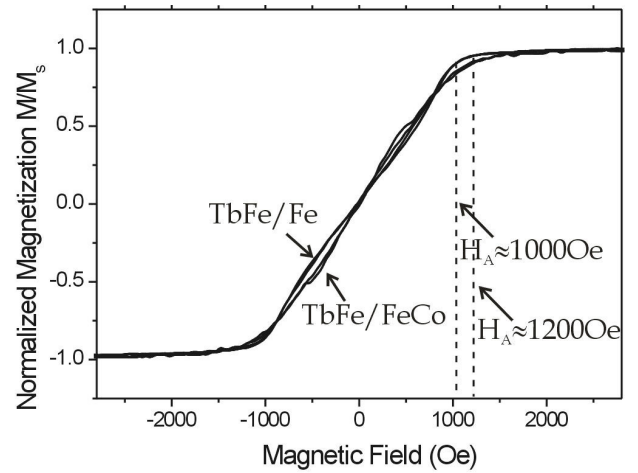


Fig. 3. M-H loops along the in-plane hard axis in $TbFe/FeCo$ and $TbFe/Fe$.

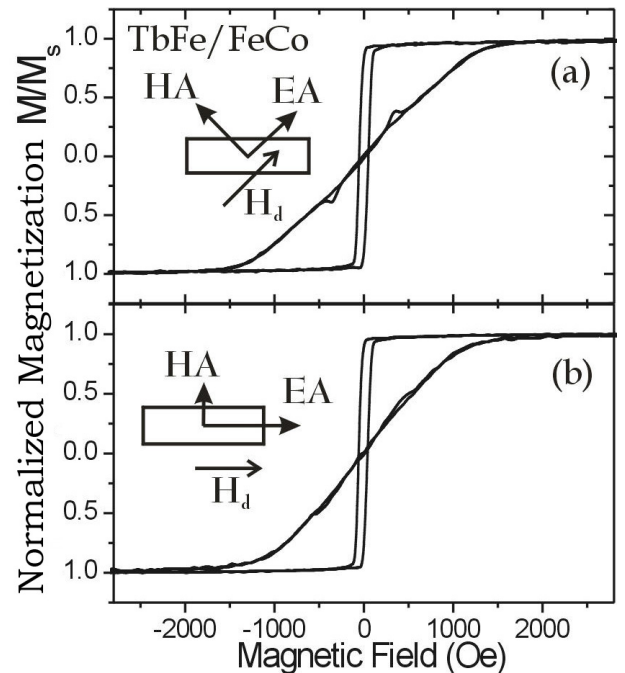


Fig. 4. M-H loops along the in-plane easy and hard axis: $TbFe/FeCo$ with uni-axial anisotropy in the 45° direction (a) compared with those with anisotropy in the x direction (b).

plitudes. This represents an increase in the torsion mode sensitivity by a factor 5 compared to $(TbFe_2/Fe)$.

In the case of an easy axis along the x direction, amplitude of the torsion motion is much larger than the flexion one. This is due to the fact that with the notation we use (Fig. 1), the shear stresses generated in the film are proportional to $\sin(2\varphi)$ while the compression stresses are proportional to $\cos^2 \varphi$. The symmetry of the system explains the difference of amplitudes: near the SRT, φ oscillates around zero and this generates a maximum amplitude of the $\sin(2\varphi)$ component while the $\cos^2 \varphi$ one is weak. This phenomenon is the opposite when the easy axis is along a 45° direction in the plane: then, still when applying

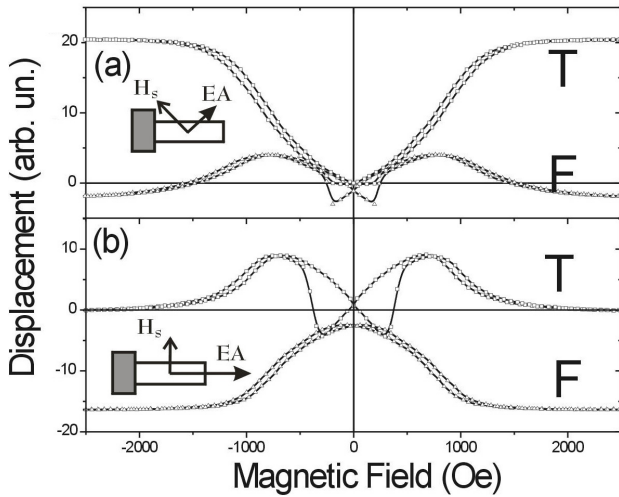


Fig. 5. Static flexion and torsion displacements in TbFe/FeCo with easy axis along the x direction (b) and at 45° from the x direction (a).

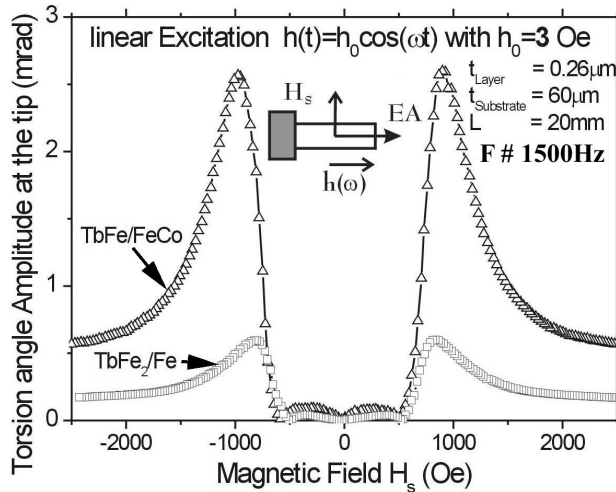


Fig. 6. Torsion (Θ_t) amplitude versus H_S for the excitation field $h_0 = 3\text{Oe}$ in TbFe_2/Fe and $\text{TbFe}_2/\text{Fe}_{0.6}\text{Co}_{0.4}$.

H_S along the hard axis direction and $h(t)$ along the easy axis, φ oscillates around the 45° direction, which favors the flexural motion versus the torsion. This phenomenon was correctly observed with our samples and shown on Fig. 7. Flexion oscillations are very weak compared to torsion ones when the easy axis is along the x direction, and stronger with the EA along the 45° direction.

This result shows that it is possible to “tune” the torsion and flexion dynamical amplitudes, by choosing the direction of the bias field during the sputtering process. A theoretical approach of such phenomena will be soon submitted for publication.

V. CONCLUSIONS

This work shows the possibility of a further improvement of the giant magnetostrictive nanostructured multilayer systems by using SRT associated with a well defined easy axis induced by a dc field during deposition.

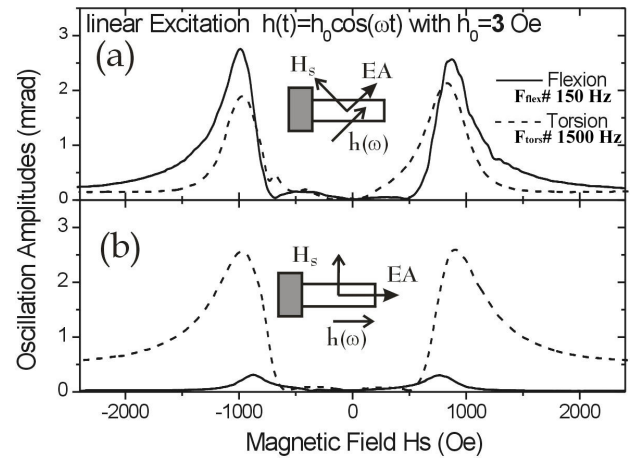


Fig. 7. Torsion (Θ_t) and flexion (Θ_f) oscillation amplitude for samples with EA along the x direction (b) and at 45° from the x direction (a).

We demonstrated the possibility of obtaining strong magnetostriction ($b\gamma^{,2} \approx 18\text{MPa}$) and an in-plane uniaxial anisotropy in any direction and *without* an annealing post process which avoids any intermixing between the layers of the film. This allows to control the behaviour of the actuators by using the SRT phenomenon with driving fields down to a few oersteds only. This represents an improvement by a factor 5 compared to TbFe/Fe layers. The different easy axis directions also have shown the possibility of “tuning” the dynamical behaviour of the actuators.

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