Low Field Anisotropic Magnetostriction Single Domain Exchange-Coupled (TbFe/Fe) Multilayers : Static And Dynamical Properties

H. Le Gall, J. Ben Youssef, N. Tiercelin*, V. Preobrazhensky* And P. Pernod*.

Laboratoire de Magnetisme de Bretagne (LMB), CNRS/UMR 6135, University, 6 Av. Le Gorgeu, 29285 BREST, France.

*IEMN, Groupe Electronique et Acoustique, Cite Scientifique, BP 65, 59652 VILLENEUVE D'ASCQ, France.

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Abstract- Flexural and torsional motions have been investigated in low field anisotropic giant magnetostrictive (GMS) single domain state (SDS) exchange-coupled Tb/Fe/Fe multilayers (ECML). The magnetoelastic (ME) coefficient $b^{\gamma,2}$ and susceptibility db/dH depend strongly on the ECML structures, compositions, sputtering deposition parameters and post-deposition heat treatments. Due to a well defined but low uniaxial anisotropy associated with the SDS induced by a bias field during the film deposition, a Spin Reorientation Transition (SRT) with quasi-static and resonant bistability properties is clearly achieved near the saturation field along the hard axis. Harmonic and subharmonic excitations of first and higher-orders (linear and non-linear excitations) of flexural and torsional oscillations modes with huge amplitudes have been stimulated from the SRT in agreement with our theoretical model. The corresponding very large dynamical ME susceptibility gives the possibility to control GMS micro-electromechanical systems (MEMS) with a strong reduction of the excitation field.

Key words: Giant magnetoelasticity, thin films, Spin reorientation Transition, Giant non linearity, actuators.

1. Introduction

Transfer from electrical into mechanical energy is of strong interest to realize microactuators and sensor for microelectromechanical systems (MEMS) technology. Microactuators include microvalves, pumps and motors. A big potential application arises for all-optical switching for telecoms technology from either micromirrors or moving optical fibers or waveguides. In that case micro-opto-electromechanical systems (MOEMS) combines MEMS structures and integrated optics [1, 2]. Recently microcantilevers for scanning probe microscopes (STEM, SFM, MFM) have been explored for scanning probe lithography and high density storage [3]. The remote and independent actuation from dynamical giant magnetostriction (GMS) in magnetic bimorphs open the way for individually controlled magnetostrictive operations. Very large magnetoelastic (ME) coefficients $b^{\gamma,2}$ associated with the magnetostriction $\lambda=\Delta l/l$ are

required to produce important mechanical effects in MEMS. However these effects have to be induced under the as possible lowest driving magnetic field to improve the sensitivity $d\lambda/dH$ of the microdevices. In a first part, the procedure to obtain a low field anisotropic GMS in rare earth-transition metal (RE-TM) alloys (TbFe/Fe)_n ECML with single domain state (SDS) is reported. The amplitudes and susceptibilities of the flexural (F) and torsional (T) motions of GMS bimorphs are optimized from their correlations with the ECML structures, compositions, deposition parameters and post-deposition heat treatments. In a second part the investigation of GMS ECML is extended from their static to their dynamical properties. A spin reorientation second-order transition (SRT) [4] is achieved near the saturation field along the hard axis in ECML with SDS [5]. In such materials anomalous huge torsional and flexural ME oscillation modes can be induced from low amplitudes harmonic and subharmonic (linear and non-linear excitations) rf magnetic fields in agreement with a theoretical model we have proposed. Very large dynamical ME susceptibilities are presented with the possibility to control the GMS MEMS with a small rf field.

2. Experiments

[Tb_{0.4}Fe_{0.6} (4.5 nm) / Fe (6.5 nm)] × 40 ECML were deposited under a bias magnetic field H_d (or without $H_d = 0$) onto unheated 5×24×0.16 mm³ rectangular Corning glass substrates from rf diode sputtering in a standard Leybold Z 550 equipment. The multilayer structures were adjusted from a rotary turn-table substrate holder in a continuous rotation mode. The microstructure, elastic stress and magnetization were determined from X-ray diffraction, optical Michelson interferometer and VSM. The magnetostriction was deduced from the measurement of the flexion θ_f and torsion θ_t angles of the ECML/substrate bimorphs induced by an external dc field applied along either the large (H_x) or the small (H_y) side of the rectangular bimorph (Fig. 1) and detected by optical deflectometry.

Fig. 1 Magnetostrictive bimorph geometry.

3. Static GMS in ECML

GMS thin films are primarily based on the RE-TM (RE = Tb, Sm, Dy and TM = Fe, Co) Laves phases such as the Terfenol TbFe₂. The ME devices require GMS reduce the switching field H_{sw} in quasi-static operation mode or to increase the oscillating response in harmonic operation mode. Due to the high uniaxial anisotropy K_u induced by Tb and the low saturation magnetization M_s associated with their ferrimagnetic structure, TbFe₂ mono-layers exhibits large switching field ($H_{sw} \propto K_u/M_s$). If the increase of M_s is limited in RE-TM monolayers, the reduction of K_u and therefore H_{sw} was found by using either amorphous or nanocrystalline binary RFe₂ (R = Tb, Sm) materials⁶⁾ or ternary alloys with anisotropy compensation from an optimal Tb/Dy ratio control such as (Tb_{0.3}Dy_{0.7})Fe₂ (Terfenol-D)⁷⁾. Low field GMS can be obtained from alternative approach based on exchange-spring-magnet type structures which associate in ECML GMS layers such as TbFe₂ with soft high M_s films such as Fe or FeCo⁸⁾.

Fig. 2 Magnetic field dependence of the magnetostriction in (TbFe) mono- and (TbFe/Fe) multilayers.

Compared with a TbFe single layer, the softness and the ME properties of (TbFe/Fe) $\times$ 40 ECML are both improved either before or after post-deposition annealing as shown in Fig. 2 due to the exchange coupling between layers with thickness smaller than the exchange length to avoid interfacial domain wall

Fig. 3 Magnetostriction versus magnetic field in isotropic (TbFe/Fe) multilayers ($H_d = 0$).

When deposited without bias field ($H_d = 0$), ECML present isotropic magnetic (M-H curves) and ME properties as described in Fig. 3. The flexural ME coefficients b_{fx} and b_{fy} present similar amplitudes but with opposite signs associated with opposite flexion of the cantilever under increasing field applied parallel (H_x) or perpendicular (H_y) to the large side of the rectangular bimorph ($H_x \rightarrow b_{fx} > 0$ and ($H_y \rightarrow b_{fy} < 0$). The symmetry of b_f under H_x and H_y , with similar saturation values ($b_{fx} = -b_{fy} \cong 7$ MPa), describes the quasi-isotropic character of the ME properties of the ECML in agreement with the observed M-H curve. The ME coefficient $b^{*2} = b_{fx} - b_{fy} \cong 14$ MPa is shared in such an isotropic ECML between the two orthogonal measurement directions.

Fig. 4 In-plane M-H curves of anisotropic (TbFe/Fe) multilayers deposited under bias field H_{dx} .

Fig. 5 Flexural magnetoelastic parameter b versus magnetic field applied along the EA and HA in anisotropic (TbFe/Fe) multilayers ($H_{dx} \neq 0$).

ECML present original strongly anisotropic magnetic and ME properties after deposition under a bias field H_d applied for instance parallel to the large side of the substrate ($H_{dx} \neq 0$) as shown in Fig. 4 and 5. After saturation along the easy axis (EA) induced by H_{dx} , a single domain state (SDS) is kept by decreasing the field H_x down to zero ($M_r / M_s = 1$) followed by the switching in a short field range of the magnetization from $\phi = +\pi/2$ to $\phi = -\pi/2$ (Fig. 1). Such a behaviour explains why no change is observed for the flexural ME parameter b_{fx} which is proportional $M_y^2 \approx \cos^2 \phi (H_x)$. A different behaviour arises along the hard axis (HA) with a strong increase of the flexural parameter which varies like $\cos^2 \phi (H_y)$ from zero to a maximum value $b_{fy} = -14$ MPa. In anisotropic SDS ECML it is observed like a transfer induced by H_{dx} of the entire ME properties from the EA to the HA with $b_{fx} \approx 0$ and $b_{fy} = -14$ MPa [5]. The ME anisotropy can be described by the ratio b_{fy}/b_{fx} which is near unity for isotropic ECML ($H_d = 0$) but can increase up to very large values near the saturation field for anisotropic SDS multilayers ($H_d \neq 0$) as shown in Fig. 6.

Fig. 6 Flexural magnetoelastic anisotropy versus magnetic field applied along the HA in anisotropic (TbFe/Fe) multilayers.

Large ME effects, associated with high MS coefficients $b^{y,2}$, are required under the lowest applied field for high sensitivity applications as described from the magnetostrictive susceptibility db/dH or $d\lambda/dH$. The evolutions of the flexural susceptibility as a function of the dc field are reported in Fig. 7 in as-sputtered (AS) and annealed (under increasing temperature T_a) SDS ECML. Two ME improvements induced by annealing are observed : first a large increase of the ME coefficient $b^{y,2}$ from 14 MPa (AS) up to 21 MPa at $T_a = 325^\circ\text{C}$ and second a strong decrease of the ME linewidth ΔH by a factor 10. As a result of annealing a strong increase by a factor 6 of the maximum flexural susceptibility $db_f/dH_y)_{\max}$ is obtained under reduced dc field H_y (Fig. 8).

Fig. 7 Flexural magnetostriction susceptibility in anisotropic (TbFe/Fe) multilayers.

Fig. 8 Magnetostriction line-width ΔH and maximum susceptibility $(db/dH)_{\max}$ versus the annealing temperature of anisotropic (TbFe/Fe) multilayers.

Since both compressive and shear strains are induced by magnetization processes in magnetostrictive materials, it is expected in GMS films with EA along the Ox axis, to observe simultaneously flexural and torsional motions proportional respectively to $M_y^2 = M_s^2 \cos^2 \phi$ and $M_y M_x = M_s^2 \cos \phi \sin \phi$. By increasing H_y along the HA, the magnetization is rotating from Ox to Oy axis and the flexion follows a $\cos^2 \phi$ law as reported in Fig. 5. On the other hand, as shown in Fig. 9 the torsion deformation,

described by the torsion angle θ_t on the same sample, does not follow strictly an S-shape field dependence as expected from a simple model associated with a $\sin\phi \cos\phi$ law. A butterfly shape is observed and can be induced not from a simple coherent rotation of the magnetization but by more complex magnetization process in ECML. If the maximum flexion angle is about three times the value obtained for the torsion angle, the torsion susceptibility is higher than the flexion susceptibility near the spin reorientation transition (SRT) as discussed in what follows.

Fig. 9 Torsion angle of the magnetostrictive bimorph versus magnetic field applied along the EA and HA in anisotropic (TbFe/Fe) multilayers.

4. Dynamics of GMS in ECML

Due to a large uniaxial anisotropy ($H_{ku} \approx 750$ Oe) the flexural and torsional oscillating modes associated with the magnetization rotation induced from the EA by an excitation field $h(\omega) = h_0 \cos \omega t$ applied along the HA cannot be detected. The situation is different in a transverse configuration when the ME bimorph is submitted to a rf excitation along the EA and a dc field H_y along the HA ("transverse" susceptibility geometry). By decreasing H_y from the saturation, a spin reorientation transition (SRT) arises near $H_y \approx H_{ku}$ with the possibility of large rotation angle ϕ of the magnetization from the HA. This is induced by two potential wells associated with the two easy magnetization directions $\pm O_x$ in uniaxial anisotropic films⁴⁾⁻⁹⁾. ME bistability and non-linearities are induced under quasi-static or low frequency excitation and high frequencies near the natural F and T mechanical resonances of the cantilever. Higher order ME oscillations can be observed under high amplitude non-linear sub-harmonic excitation.

At low frequency (100 Hz) far from the mechanical resonance only a torsional bi-stability induced by the fast switching over a large angle ϕ of the magnetization between the two potential wells is observed (Fig. 10). The fine oscillating structure at high

frequency corresponds to the first resonant torsional eigen mode at 2.4 kHz excited from the low frequency field by the strong ME non-linearity in the vicinity of the SRT¹⁰⁾.

Fig. 10 Torsional bi-stability associated with magnetization jump under low frequency excitation (100 Hz) near SRT. The high frequency fine structure (2.4 kHz) corresponds to sub-harmonic non-linear excitation of the first-order torsion resonance mode.

Fig. 11 Static θ_{fs} and dynamical $\theta_f(\omega_{f1})$ flexural angles versus the magnetic field applied along the HA of anisotropic (TbFe/Fe) multilayers.

The sensitivity on the rf excitation is strongly increased at the flexion and the torsion mechanical resonance frequencies of the cantilever as shown in Fig. 11 where the static and the first-order dynamical flexion angles θ_{fs} and $\theta_f(\omega_{f1})$ are compared. It is to be noted that first the maximum dynamical flexion angle ($\theta_f(\omega_{f1}) = 0.65$ mrad) is excited by a small 10 Oe amplitude rf field at the resonance frequency $\omega_{f1}/2\pi = 300$ Hz and second is higher than the maximum static flexion angle ($\theta_{fs} = 0.33$ mrad) obtained under a high saturation field ($H_s > 1.5$ kOe). This high dynamical ME sensitivity is strongly stimulated for the torsion modes as reported in Fig. 12 with huge torsion amplitude higher than the flexion amplitudes by a factor 6 in agreement with the angular dependences of the flexural and torsional motions proportional to $\cos^2\phi$ and $\sin 2\phi$ respectively.

Fig. 12 Linear excitation of the first-order flexion F_1 and torsion T_1 modes versus the magnetic field applied along the HA in (TbFe/Fe) multilayers.

Fig. 13 Non-linear second-order sub-harmonic excitation of the flexion F_2 and torsion T_2 modes versus the magnetic field applied along the HA in (TbFe/Fe) multilayers.

In the vicinity of the SRT the free energy of the ME material exhibits non-linear terms at the origin of anharmonic excitation of higher-order F and T modes. This gives also the possibility to stimulate by "sub-harmonic" generation the F and T fundamental modes by lower excitation frequency $\omega_n^{f,t} = \omega_1^{f,t} / n$ ($n = 1, 2, \dots$). Such sub-harmonic excitations of the fundamental F and T modes have been observed up to $n=3$ as shown in Fig. 13 for the second-order F_2 and T_2 oscillations. Compared to the static torsion, the amplitudes of the higher-order T modes are also very large. The high dynamical ME sensitivity of the anisotropic SDS ECML near the SRT gives the possibility to use GMS multilayers for an efficient actuation at a low driving field which is interesting for MEMS applications.

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