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Isotropic effects in exchange-biased ferromagnetic /antiferromagnetic bilayers

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Novel, direction-independent (rotatable) spin-wave frequency modifications in a ferromagnetic layer biased by an antiferromagnetic film, revealed recently with Brillouin light scattering, have been analyzed. Physical conditions needed for the rotatable behaviour observations in epitaxial layers have been presented. The omni-rotatable down-shift, being a function of a spin-wave frequency, was distinguished from the up-shift of spin-wave frequencies induced by the exchange-bias. Additionally, the rotatable anisotropy constant was estimated from the available BLS results.

Key words: magnetoelectronics; exchange bias; rotatable anisotropy; Brillouin light scattering

1. Introduction

Different types of magnetoelectronic devices based on thin-film technology require a proper adjustment of structural, energetic and electronic parameters of materials. A fundamental functionality of these devices results from magnetic anisotropy fields, influencing the static and dynamic behaviour of magnetization. Among many types of magnetic anisotropies employed in magnetoelectronics, magnetocrystalline anisotropies and shape anisotropies are of special, practical importance.

Noteworthy, for the special case of a ferromagnetic (FM) film deposited onto an antiferromagnetic (AFM) layer, two new anisotropy fields can be induced. They may be subdivided into directional (unidirectional) and non-directional (rotatable) ones. In the former case, a ferromagnetic hysteresis loop is shifted along an externally applied magnetic field direction, thus a magnetic response is sensitive to different magnetic fields intensities enabling an adjustment of the ferromagnetic material performance. This effect is nowadays applied in spin-valves [1–3]. In the non-directional case, ferromagnetic spins are disturbed uniformly what results in a drop of the FM spins energy. The rotatable behaviour was discovered by McMichael et al. [4] in polycrystal-

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line exchange-biased materials using a ferromagnetic resonance (FMR), and recently by Błachowicz et al. [5], in epitaxial exchange-biased Co/CoO bilayers with the use of Brillouin light scattering (BLS). Within these BLS studies the up-shift of spin-wave frequencies was observed.

It should be pointed out that while the hysteresis-loop shifts represent a static aspect of the exchange-bias phenomenon, the rotatable effects revealed in the GHz range of frequencies through FMR or BLS experiments represent a dynamical part of the exchange-bias effect [6]. In this sense, a classical definition of the exchange-bias emphasizing the directional FM hysteresis loop shift, provided by Meiklejohn and Bean [7], addresses the static aspect of this phenomenon.

In this paper, BLS experimental conditions needed for rotatable effects observations are reported. Also, the epitaxial CoO(110) 20 nm/Co(110) 6 nm system [5], where there is no evidence for the out-of-plane magnetocrystalline anisotropies, is analyzed from the rotatable anisotropy point of view. Additionally, a rotatable anisotropy constant for this sample has been determined from BLS experimental results.

2. Experimental requirements

Both FMR and BLS methods are similar in principle, being perturbative methods. Samples are measured in the presence of an externally applied magnetic field at saturation and the magnetization vector, kept in a given direction, is disturbed from a local equilibrium state; this gives an access to the measured spin-wave frequencies. In the BLS experiments, a surface spin-wave frequency propagating in a given in-plane direction is measured. This wave is known as the Damon–Eshbach (DE) mode [9]. The DE mode frequency is dependent on all external and internal magnetic fields.

The BLS measurements are usually made using a Sandercock tandem 3-pass spectrometer [10], and an Ar^+ ion single-mode laser in the back-scattering geometry. The external magnetic field ($B < 1$ T) is applied in the sample plane in order to induce spin waves propagating on its surface. Measurements are carried out above and below the Néel temperature of the antiferromagnetic (AFM) layer. In a typical situation, low temperature measurements (~140 K) are easy to perform [5]. Additionally, a series of in-plane measurements for various sample orientations is needed; a sample is usually rotated in-plane, in the range of 0–360º, in order to detect magnetic surface anisotropies. More details about the BLS experiments can be found elsewhere [8].

However, in order to measure rotatable effects using BLS method, the sample has to reveal only in-plane magnetic anisotropies. The reason is that for samples with out-of-plane anisotropies, distinction between perpendicular contributions and rotatable anisotropies is not possible as both the contributions can be angle-independent. A good candidate meeting above criteria is a sample grown epitaxially on the MgO(110) substrate in a UHV MBE chamber. The sequence of layers was MgO(110)/CoO(20 nm)/Co(6 nm). The Co layer had the fcc structure with no evidence for out-of plane contributions. The CoO/Co sample structural details are described in Ref. 5.

3. Analysis of BLS results revealing a rotatable anisotropy

One of the main goals of the BLS experiments with a magnetoelectronic material is to determine anisotropy constants. A numerical fitting procedure is usually applied to the measured spin-wave frequencies ω_{DE} according to the following formula of the DE mode [9]

$$\begin{aligned}\frac{\omega_{DE}^2}{\gamma} = \Bigg(&\left[\frac{1}{M_s}\frac{\partial^2 E_{\text{ani}}}{\partial\theta^2} + \frac{2A}{M_s}q^2 + 4\pi M_s f\left(1-\frac{1}{2}q_{\text{II}}d\right) + H_{\text{ext}}\cos(\phi-\phi_H) + H_{\text{rot}}\right] \\ &\times\left[\frac{1}{M_s}\frac{\partial^2 E_{\text{ani}}}{\partial\phi^2} + \frac{2A}{M_s}q^2 + 4\pi M_s f\frac{1}{2}q_{\text{II}}d\sin^2(\phi-\phi_q) + H_{\text{ext}}\cos(\phi-\phi_H) + H_{\text{rot}}\right] \\ &-\left(\frac{1}{M_s}\frac{\partial^2 E_{\text{ani}}}{\partial\theta\partial\phi}\right)^2\Bigg)\end{aligned} \quad (1)$$

where γ is the gyromagnetic ratio, M_s is the magnetization at saturation, E_{ani} is the free energy density, A is the exchange stiffness constant, q^2 is the squared wave-vector of a spin wave, f is the demagnetization factor which controls the balance between the shape anisotropy and out-of-plane anisotropy contributions, q_{II} is the in-plane component of a spin-wave wave-vector, H is the externally applied magnetic field intensity, H_{rot} is the isotropic (rotatable) field, $(\phi - \phi_H)$ is the angle between external magnetic field vector $\vec{H}$ and the magnetization $\vec{M}$, and $(\phi-\phi_q)$ is the angle between the $\vec{q}$ wave-vector and the magnetization $\vec{M}$. The constant values in Eq. (1) are: $\gamma = (1/2)\gamma_e g$, $\gamma_e = -1.759\times10^7$ Hz/Oe being the free electron gyromagnetic ratio. For the Co case, another set of physical constants can be applied: $g = 2.2$ – the spectroscopic splitting factor, $A = 3\times10^{-11}$ J/m, and $4\pi M_s = 17.8$ kOe ($M_s = 1.42\times10^6$ A/m).

For a simplified case (simplified Eq. (1)), with the lack of the out-of-plane and magnetoelastic anisotropies, the following formula for the spin-wave frequency can be employed (see discussion in [5]):

$$\begin{aligned}\frac{\omega_{DE}^2}{\gamma} = &\left[\frac{2A}{M_s}q^2 + 4\pi M_s\left(1-\frac{1}{2}q_{\text{II}}d\right) + H_{\text{ext}}\cos(\phi-\phi_H) + H_{\text{rot}}\right] \\ &\times\left[\frac{1}{M_s}\frac{\partial^2 E_{\text{ani}}}{\partial\phi^2} + \frac{2A}{M_s}q^2 + 4\pi M_s\frac{1}{2}q_{\text{II}}d\sin^2(\phi-\phi_q) + H_{\text{ext}}\cos(\phi-\phi_H) + H_{\text{rot}}\right]\end{aligned} \quad (2)$$

As results from Eqs. (1), (2), measured spin-wave frequencies depend on several local fields acting on the magnetization. For example, looking at the second main factor in Eq. (2), we can easily recognize the following fields (from left to right): the anisotropy-energy field (the magnetocrystalline energy and the exchange-bias), the quantum effective exchange-energy field, the demagnetization energy field, the Zeeman energy field, and finally the rotatable anisotropy field which can be described by the following angle-independent expression

$$H_{\mathrm{rot}} = \frac{1}{M_s} K_{\mathrm{rot}} \tag{3}$$

where K_{rot} is the rotatable anisotropy constant.

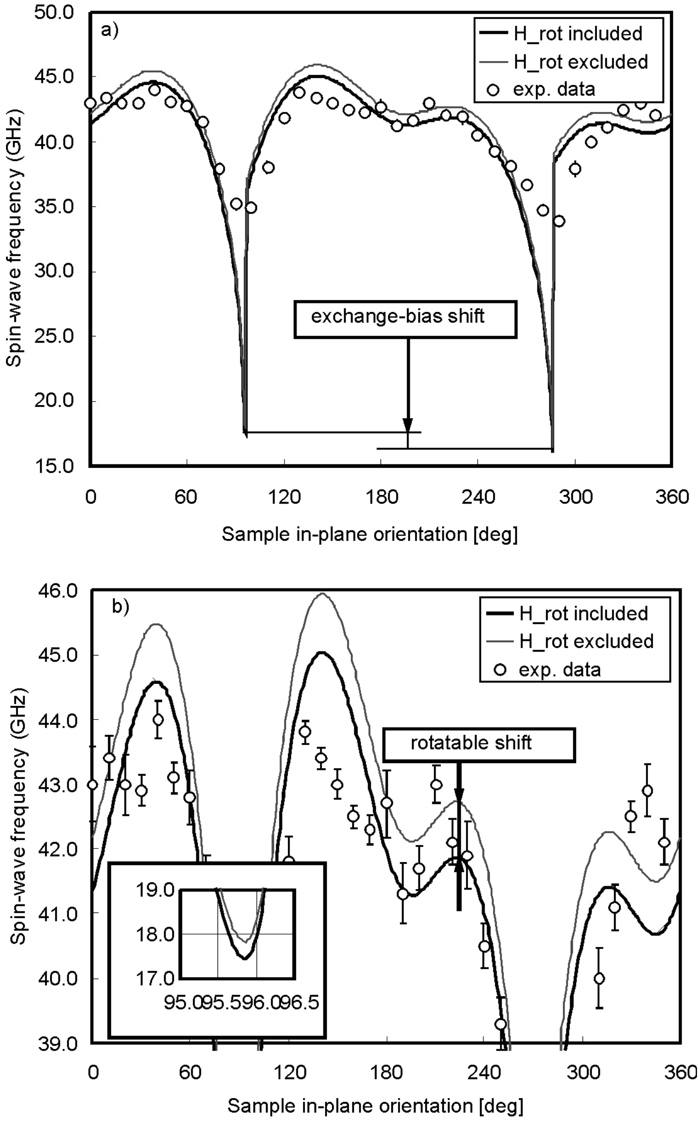

Fig. 1. Spin-wave frequencies as a function of an in-plane sample orientation:
a) general view, b) zoomed view. The overall rotatable frequency shift is negative

In order to calculate the magnetocrystalline and exchange-bias contributions to the observed frequency behaviour (Eqs. (1), (2)), the following expression for the free energy density can be applied

$$F_{ani}(\phi) = K^{(4)} \cos^2(\phi)\sin^2(\phi) + K^{(2)} \cos^2(\phi) + K_{eb} \cos(\phi - \phi_{eb}) \tag{4}$$

where $K^{(4)}$ and $K^{(2)}$ are the effective 4-fold and 2-fold symmetry anisotropy constants, respectively, ϕ is the sample orientation angle measured in respect to the sample edge, and ϕ_{eb} is the easy-direction of the exchange-bias (unidirectional) anisotropy field.

In Figure 1, measured spin-wave frequencies as functions of sample in-plane orientations have been shown with fittings to experimental data using Eqs. (2), (3), with the rotatable contribution (thick line), and without the rotatable contribution H_{rot} (thin line). Fig. 1b shows zoomed details giving some insight into a frequency dependence of the rotatable anisotropy. It is evident that the rotatable shift is larger for higher spin-wave frequencies.

Table 1. Anisotropy constants of the MgO(110)/CoO/Co sample obtained from the BLS measurements at 140 K

$K^{(4)}$(×10^4 J/m^3)	$K^{(2)}$(×10^4 J/m^3)	K_{eb}(×10^4 J/m^3)	K_{rot}(×10^4 J/m^3)
−16.4	−32.5	8.1	−14.1

Values of $K^{(4)}$, $K^{(2)}$, K_{eb} constants taken from [5].

In Table 1, the fitted anisotropy constants are given. The obtained negative value of K_{rot} constant is equivalent to down-shift of frequencies visible in Fig 1. A similar down-shift of frequencies was observed in the FMR experiments [4, 6]. We can also notice that the use of the H_{rot} term improves matching between experimental data and theory.

4. Conclusions

The results of the rotatable effects, obtained for the sample grown epitaxially – revealing in-plane anisotropies only – have shown that the rotatable anisotropy follows spin-wave frequencies for various sample orientations. The rotatable frequency down-shift is maximized (~0.9 GHz) in directions where the largest spin-wave frequencies were obtained (45 GHz at 140º position). On the other hand, a lower value of the rotatable shift (~0.4GHz) was obtained at about 96º position for the 17.5 GHz spin wave frequency (see inset in Fig. 1b).

The overall rotatable spin-wave frequency down-shift is a relatively small quantity, of the order of 2% in comparison to the measured spin-wave frequencies. The observed exchange-bias, readout from the dependences between spin-wave frequencies and the sample in-plane orientations (Fig. 1), was a larger quantity. The difference between the frequencies at 96º and 186º positions equalled to 1.5 GHz. However, it is difficult to claim at this stage of investigations, if it is a rule that the exchange-bias shift dominates over the rotatable shift.

The current results address the issue of time-scales used in BLS and FMR experiments, what was first emphasized by McMichael et al. [6]. They claimed that during a typical BLS data collection, which runs in minutes or hours, the magnetocrystalline anisotropies, exchange-bias, and the shape anisotropies are stable as samples are kept at saturation. However, the precession time-period of the magnetization vector, involved in a wave-like movement (a spin-wave), is of the order of 10^{-10} s (GHz range). Thus at these time scales, the processional movement of magnetization can lose the contact with static, e.g. magnetocrystalline contributions, exerting an additional dynamical torque onto the AFM interface antiferromagnetic spins. Additionally, these antiferromagnetic spins have to overcome energy barriers associated with antiferromagnetic partial domain-walls. This is why we should expect a reduction of the FM spins energy. We also expect that when the precession time-scales are shorter (spin-frequencies are higher), the subsequent angle-independent rotatable-behaviour should be more intense.

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