DIFFERENT MAGNETIC-ANISOTROPY FIELDS IN THE EPITAXIAL COO/CO(HCP) BILAYER INVESTIGATED BY MEANS OF LIGHT SCATTERING ON SPIN WAVES

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The magnetocrystalline and magnetoelastic anisotropies of epitaxial CoO/Co(hcp) bilayers with dominating (100) crystallographic in-plane orientation have been investigated by means of light scattering from spin waves. Analysis of spin-wave frequencies measured in different sample orientations enabled distinction of several anisotropy contribution to the sample energy density. The role of a demagnetizing factor, possible out-of-plane anisotropies and their influence on the in-plane anisotropies, including the magnetoelastic contribution, were discussed.

Keywords: Magnetic anisotropies, Brillouin light scattering

1. INTRODUCTION

One of the most important magnetic-materials parameters, influencing the magnetoelectronic device performance, are magnetic anisotropies of different physical origin [1-6]. Especially, in a case of low-dimensional magnetic structures, built from elementary ferromagnetic/antiferromagnetic (FM/AFM) bilayers, there is a need for information about magnetocrystalline-volume anisotropies, surface-like anisotropies at the FM/AFM interface, and about magnetoelastic anisotropies contributed to this bilayered system-energy. These three mentioned types of anisotropies have their physical origin, respectively, in crystallographic symmetry of the FM layer, in a lattice mismatch between FM and AFM materials, and finally, in a reduced dimensionality of the ferromagnetic region.

One of the most important experimental method suitable for a selective distinction between different anisotropy contributions is the Brillouin Light Scattering (BLS), that measures a spin-wave frequency in a given in-plane direction of a sample [7]. BLS, in the case

of magnetic thin-layered structures, measures a frequency of so-called Damon-Eshbach (DE) mode [8]. This mode possesses a surface-like character – the wave propagates in one direction only, around a whole magnetic layer including the FM/AFM interface, and significantly, this wave is sensitive to both surface and bulk anisotropies.

The analytical formula for the DE mode frequency equals

$$\omega_{DE}^2 = \gamma\left(\left[\frac{1}{M_s}\frac{\partial^2 E_{ani}}{\partial\theta^2} + \frac{2A}{M_s}q^2 + 2\pi M_s f\left(2 - q_{II}d\right) + H\cos\left(\phi - \phi_H\right)\right]\times\right.$$
$$\left.\times\left[\frac{1}{M_s}\frac{\partial^2 E_{ani}}{\partial\phi^2} + \frac{2A}{M_s}q^2 + 2\pi M_s f\, q_{II} d\sin^2\left(\phi - \phi_H\right) + H\cos\left(\phi - \phi_H\right)\right] - \left(\frac{1}{M_s}\frac{\partial^2 E_{ani}}{\partial\theta\,\partial\phi}\right)^2\right) \quad (1)$$

where in the first square bracket (also in the second square bracket) the four terms represent, respectively, the anisotropy-energy field, the exchange-energy field, the demagnetization energy field, and the Zeeman energy field. These four components form an effective magnetic field acting on the magnetization vector M. Next, 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 demagnetization field and other anisotropy fields, including magnetoelastic anisotropies of the out-of-plane or in-plane character. Next, q_{II} is the in-plane component of a spin-wave wave-vector derived from a BLS scattering geometry, H is the externally applied magnetic field intensity, $(\phi - \phi_H)$ is the angle between external magnetic field vector H and the magnetization M, and $(\phi - \phi_q)$ is the angle between the q wave-vector and the magnetization M. The following constant values in Eq.1 were also assumed: $\gamma = (1/2)\cdot\gamma_e \cdot g$, where the γ_e=-1.759·10^{7}Hz/Oe is the free electron gyromagnetic ratio, and g=2.2 is the spectroscopic splitting factor, A=3·10^{-11}J/m, and $4\pi M_s$=17.8 kOe. Below, there is a discussion of results obtained in the standard BLS measurements using a Sandercock tandem spectrometer [9-10], an Ar$^+$-ion laser (514.5 nm, 60mW), and the external DC magnetic field of 0.4T. The measurements were done at room temperatures. The sample was rotated in-plane in the range of 0°-360° with a step of 10°.

2. CORRELATIONS BETWEEN ENERGY DENSITY, STRUCTURAL PARAMETERS AND MAGNETIC ANISOTROPIES

For the MgO(100)/CoO/Co, cobalt was grown in the *hcp* structure in the [2 -1 -1 0] direction. It means that the hexagon-prism c-axis was oriented in the sample plane. Also, the c-axis edge of the hexagon, built from Co atoms, was placed at the Co/CoO interface, in the last layer of CoO, between oxygen atoms (Fig. 1). This contributed to the 2-fold anisotropy symmetry. Additionally, the analysis of structure indicated on the existence of two types of the Co-domains oriented perpendicularly in a sample plane - this resulted in a 4-fold anisotropy symmetry. Also, the values of the c-axis length and the length of the line perpendicular to the c-axis, both lying in the sample plane, were equal to 0.434nm, and 0.407nm, respectively. Thus, the c/a ratio was equal to 1.066.

All this provided a hint for using the typical expression for the bulk anisotropy energy for the hexagonal (*hcp*) structure, using the K_1^{hcp} and the K_2^{hcp} anisotropy constants, and additionally, using the $K_{me}^{(2)}$ magnetoelastic anisotropy contribution [11], namely:

$$E_{ani}^{(100)} = K_1^{hcp}\sin^2\left(\phi-\phi_{hcp}\right)+K_2^{hcp}\sin^4\left(\phi-\phi_{hcp}\right)-K_1^{me}\cos^2\theta+K_2^{me}\cos^2\left(\phi-\phi_{hcp}\right)\sin^2\theta, \quad (2)$$

where ϕ is the in-plane rotation angle of the sample relative to the magnetic easy axis directions ϕ_{hcp} of the volume anisotropy, ϕ_{ref} is the crystallographic reference direction, here $\phi_{ref}\approx 0$, K_1^{hcp} and K_2^{hcp} are the hexagonal volume anisotropy constants, and $K_{me}^{(1)}$ and $K_{me}^{(2)}$ are the magnetoelastic anisotropy constants of the first and second order, respectively. For the fitting procedure only terms with the in-plane anisotropy contributions, assuming θ=90° were used. However, this point requires a careful analysis. Namely, the exclusion of the $K_1^{me}\cos^2\theta$ term before subsequent derivations, needed in Eq. 1, can cause errors in proper estimation of the DE frequency. In a next chapter details about different anisotropy contributions, derived from Eqs. 1-2, are provided.

3. MAGNETIC IN-PLANE AND OUT-OF-PLANE ANISOTROPIES

In order to obtain the proper match between experimental results and a theory we have to derive anisotropy energy fields from Eqs.1-2. These fields are equal to (formulas are written in pairs assuming general condition of $\theta\neq 90^{\circ}$, and $\theta=90^{\circ}$, respectively)

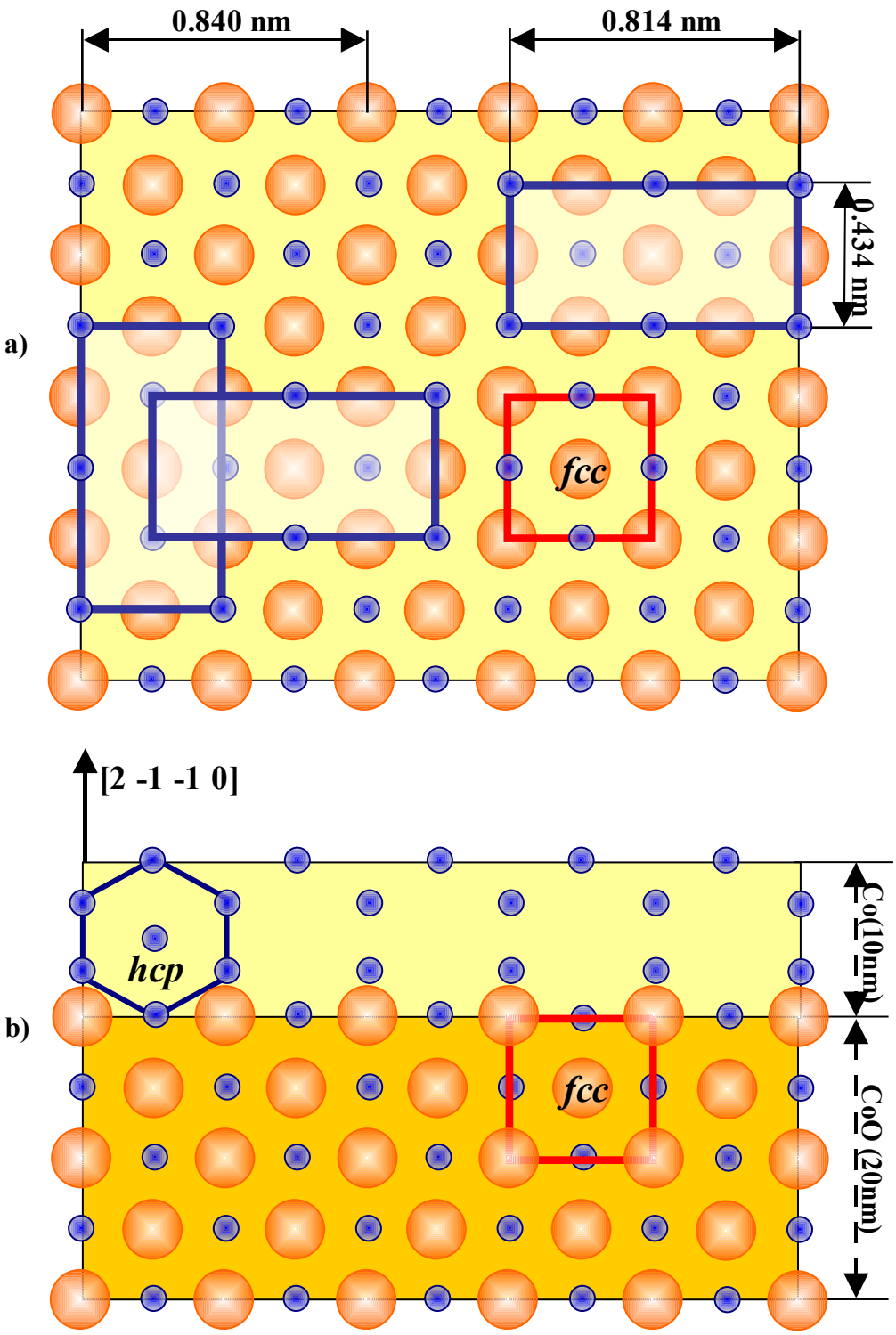

Fig. 1. A top view (a) where the perpendicular elementary Co-domains contributing to a 4-fold symmetry are seen, and a side view (b) of the CoO/Co bilayered system where the structure dimensions are provided. Descriptions: *hcp* – the hexagonal phase, *fcc* – the face centered cubic phase. The lattice mismatch between CoO and Co atoms (840nm vs. 814nm) contributes to the in-plane 2-fold magnetoelastic behavior (K_2^{me}). There are no hints to the magnetoelastic K_1^{me} out-of-plane contribution.

$$\frac{\partial^2 E_{ani}}{\partial\theta^2} = 2\left[K_1^{me} + 2K_2^{me}\cos^2\left(\phi - \phi_{ref}\right)\right]\cos\left(2\theta\right), \tag{3a}$$

$$\frac{\partial^2 E_{ani}}{\partial\theta^2} = -2\left[K_1^{me} + 2K_2^{me}\cos^2\left(\phi - \phi_{ref}\right)\right], \tag{3b}$$

$$\begin{aligned}\frac{\partial^2 E_{ani}}{\partial\phi^2} = {} & 2\cos\left[2\left(\phi - \phi_{hcp}\right)\right]\left[K_1^{hcp} + 2K_2^{hcp}\sin^2\left(\phi - \phi_{hcp}\right)\right] + 2K_2^{hcp}\sin^2\left[2\left(\phi - \phi_{hcp}\right)\right] - \\ & - 2K_2^{me}\cos\left[2\left(\phi - \phi_{ref}\right)\right]\sin^2\theta,\end{aligned} \tag{4a}$$

$$\begin{aligned}\frac{\partial^2 E_{ani}}{\partial\phi^2} = {} & 2\cos\left[2\left(\phi - \phi_{hcp}\right)\right]\left[K_1^{hcp} + 2K_2^{hcp}\sin^2\left(\phi - \phi_{hcp}\right)\right] + 2K_2^{hcp}\sin^2\left[2\left(\phi - \phi_{hcp}\right)\right] - \\ & - 2K_2^{me}\cos\left[2\left(\phi - \phi_{ref}\right)\right],\end{aligned} \tag{4b}$$

$$\frac{\partial^2 E_{ani}}{\partial\theta\partial\phi} = -2K_2^{me}\sin\left[2\left(\phi - \phi_{ref}\right)\right]\cos\left(2\theta\right), \tag{5a}$$

$$\frac{\partial^2 E_{ani}}{\partial\theta\partial\phi} = 2K_2^{me}\sin\left[2\left(\phi - \phi_{ref}\right)\right]. \tag{5b}$$

From the above formulas, especially from Eq. 3b, results that the K_1^{me} and K_2^{me} should be taken into account during a fitting procedure, despite these contributions come from out-of-plane anisotropy fields. A physical interpretation of this effect is as follows: in an intense enough, externally-applied magnetic field, the out-of-plane magnetization component is enforced into the in-plane orientation contributing to the easy-axes of other in-plane anisotropy fields.

Noteworthy, as a role of magnetoelastic contributions to a system energy grows, then the demagnetization energy $2\pi M_S$ falls down. This relation is controlled quantitatively by the demagnetization factor f. If this factor equals 1 – this is a maximum physically-possible value, then there is no mechanism responsible for the out-of-plane anisotropy fields. Tab. I provides values of fitted parameters. In Fig. 2 all anisotropy contributions are shown separately. It is seen that the sum of these contribution fits very well with the experimental data within the experimental uncertainties. Obtained

demagnetization factor $f < 1$ points to the existence of magnetoelastic anisotropies, here, of the 2-fold symmetry. It is evident that the magnetoelastic anisotropy contribution is a dominating factor.

Table I. Anisotropy constants of the CoO/Co (hcp) bilayered system obtained from the BLS measurements at room temperatures.

K_1^{hcp} ($\cdot 10^4$ J/m^3)	K_2^{hcp} ($\cdot 10^4$ J/m^3)	$K_{me}^{(2)}$ ($\cdot 10^4$ J/m^3)	f
-9.0±0.7	11.3±0.3	16.4±3.3	0.6259±0.0103

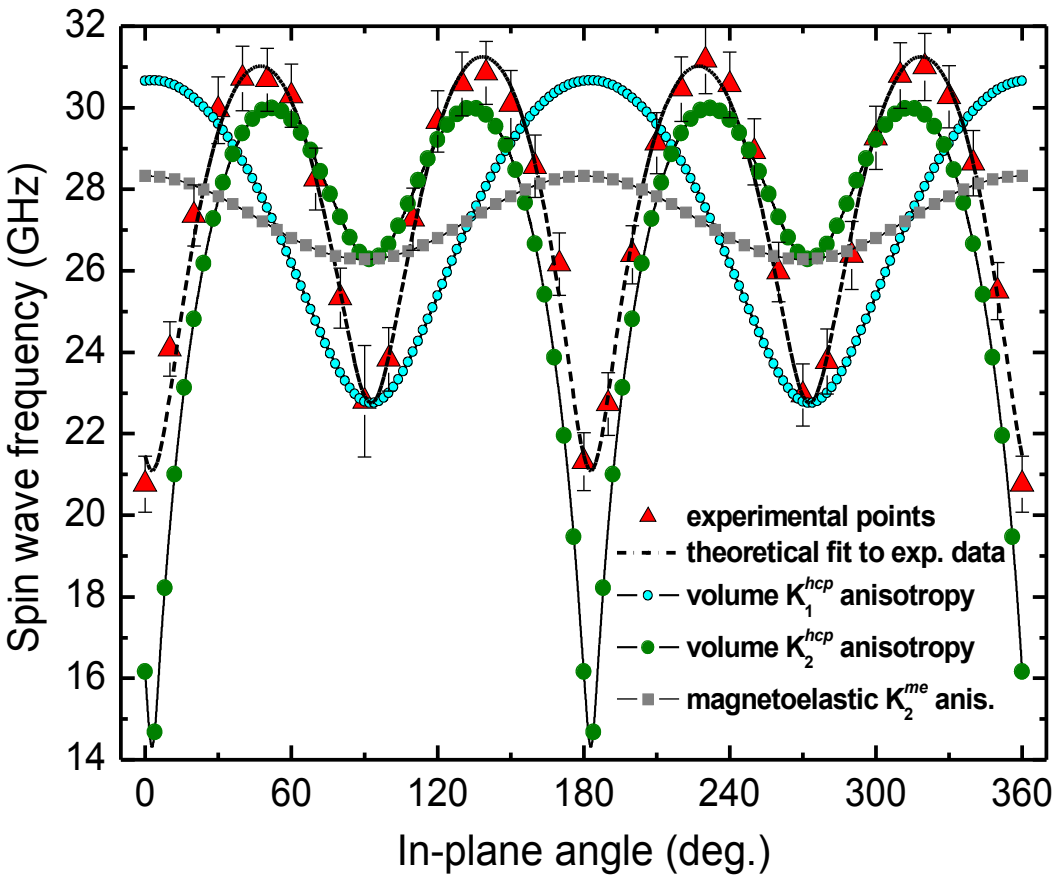

Fig. 2. Brillouin light scattering measurements in the CoO(20nm)/Co(10nm)(hcp) bilayered system. During fitting there was no need to use the magnetoelastic K_1^{me} out-of-plane contribution (this contribution did not correlate with the demagnetization factor f).

4. CONCLUSIONS

It was shown that fitting procedure to experimental Brillouin light scattering (BLS) data enabled distinction between different anisotropy contributions in an epitaxial CoO/Co bilayer from measurements of spin wave frequencies carried out in different in-plane directions. From the fitting it was possible to estimate a balance between the volume-anisotropy and the magnetoelastic anisotropy. Importantly, it was also possible to recognize out-of-plane anisotropies transformed into the in-plane anisotropy fields under the influence of the intense (0.4 T) magnetic in-plane field. In general, BLS occurred especially useful for probing nondestructively anisotropies confined within the CoO/Co thin layers.

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REFERENCES

1. R. Hu, V. F. Mitrović, and C. Petrovic, Anisotropy in the magnetic and transport properties of $Fe_{1-x}Co_xSb_2$, *Phys. Rev. B* **74**, 195130-195136, (2006).
2. H. Schneider, G. Jakob, M. Kallmayer, H. J. Elmers, M. Cinchetti, B. Balke, S. Wurmehl, C. Felser, M. Aeschlimann, and H. Adrian, Epitaxial film growth and magnetic properties of Co_2FeSi, *Phys. Rev. B* 74, 174426-174435, (2006).
3. P. Orgiani, A. Yu. Petrov, C. Adamo, C. Aruta, C. Barone, G. M. De Luca, A. Galdi, M. Polichetti, D. Zola, and L. Maritato, In-plane anisotropy in the magnetic and transport properties of manganite ultrathin films, *Phys. Rev. B* 74, 134419-134426, (2006).
4. G. N. Kakazei, Yu. G. Pogorelov, M. D. Costa, T. Mewes, P. E. Wigen, P. C. Hammel, V. O. Golub, T. Okuno, and V. Novosad, Origin of fourfold anisotropy in square lattices of circular ferromagnetic dots, *Phys. Rev. B* 74, 060406-06410, (2006).
5. B. Dieny, V. S. Speriosu, S. Metin, S. S. Parkin, B. A. Gurney, P. Baumgart, and D. R. Wilhoit, Magnetotransport properties of magnetically soft spin-valve structures, *J. Appl. Phys.* 69, 4774-4779, (1991).
6. S. Kaka, J. P. Nibarger, and S. E. Russek, N. A. Stutzke, and S. L. Burkett, High-frequency measurements of spin-valve films and devices, *J. Appl. Phys.* 93, 7539-7544, (2003).
7. T. Błachowicz and M. H. Grimsditch, *Inelastic scattering technique – Brillouin,* in Encyclopedia of Condensed Matter Physics, G. Bassani, G. Liedl, P. Wyder, Eds., Elsevier Ltd UK, 2005, 199-205.
8. B. Hillebrands, P. Baumgart, and G. Güntherodt, *In situ* Brillouin scattering from surface-anisotropy-dominated Damon-Eshbach modes in ultrathin epitaxial Fe(110) layers, *Phys. Rev. B* 36, 2450-2453 (1987).
9. R. Mock, B. Hillebrands, and R. Sandercock, Construction and performance of a Brillouin scattering set-up using a triple-pass tandem Fabry-Perot interferometer, *J. Phys.E: Sci. Instrum.* 20, 656-659, (1987).

10. T. Błachowicz, *Brillouin Spectroscopy in Crystal Lattices. Acoustic and Spin* Waves, Silesian University of Technology Press, Gliwice 2003, 102-109.

11. H. Fritzsche, J. Kohlhepp, and U. Gradmann, Epitaxial strain and magnetic anisotropy in ultrathin Co films on W(110), *Phys. Rev. B* 51, 15933-15941 (1995).