TOPS - Metrology for topological spin structures

Joint Research Project
Newsletter December 2021

Metrology for topological spin structures

Introduction

We are pleased to welcome you to the fourth and final newsletter for the "TOPS" Joint Research Project. The project started in June 2018 and just ended in November 2021. The underlying goal of TOPS was to develop and establish metrological and scientific tools for the characterization of topological spin structures.

The project was divided into four technical work packages: (i) Towards reliable measurements of key parameters in topological spin structures, (ii) Distinct detection and manipulation of multiple and individual topological spin structures, (iii) Novel dynamical and quantization effects in topological spin structures, and (iv) Materials and simulations.

The aim of this newsletter is to summarize selected work that has been performed across this project over the previous year. More details will be available on our webpage.

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(1) Key points in the determination of the interfacial Dzyaloshinskii-Moriya interaction

The interfacial Dzyaloshinskii-Moriya interaction (DMI) plays an important role in stabilizing chiral spin textures as well as in attaining extremely efficient domain wall motion for future spintronic applications as sensors or memories. A classification of heavy metal (HM)/ferromagnet (FM) material combinations for their DMI strength (constant D) is therefore highly desirable, but requires the accurate measurement of the magnitude and sign of the DMI. Our recent review [1.1] shows that there are still discrepancies in the measurement results obtained on similar systems. We therefore performed an international round robin comparison [1.2] of two of the most popular techniques asymmetric bubble expansion method using the magneto-optic Kerr effect (MOKE) and the determination of spin wave non-reciprocity exploiting Brillouin light scattering (BLS). We analysed in detail the measurement process and evaluation of D, in order to provide recommendations to the community for the reliable and accurate measurement of the DMI. We find that the MOKE method can be applied to a wide variety of heterostructures with magnetic bubble domains, but its applicability depends strongly on the interface quality and the applied theoretical model for the evaluation. The BLS method appears to be more versatile, having a more straightforward evaluation of the DMI and being less sensitive to defects and inhomogeneities of the sample. However, we find in some cases large differences in the measured value, with BLS resulting in a higher DMI (see Fig. 1.1). In the literature, e.g. [1.3], it was shown that for certain samples using more sophisticated models for the evaluation of the MOKE data a better agreement between the techniques can be obtained. However, it remains to be investigated in the future if there are intrinsic differences between the techniques.

References

[1.1] M. Kuepferling, A. Casiraghi, G. Soares, G. Durin, F. Garcia-Sanchez, L. Chen, C. H. Back, C. H. Marrows, S. Tacchi, G. Carlotti, arxiv.org/abs/2009.11830.

[1.2] A. Magni, G. Durin, A. Casiraghi, Chanyong Hwang, G. Jakob, M. Kläui, E. Darwin, A. Huxtable, C. H. Marrows, B. J. Hickey, S. Tacchi, G. Carlotti, H. T. Nembach, G. A. Riley, J. M. Shaw, V. Sokalski, L. Herrera-Diez, D. Ravelosona, J. Langer, M. Kuepferling, paper in preparation.

[1.3] K. Shahbazi, Joo-Von Kim, H. T. Nembach, J. M. Shaw, A. Bischof, M. D. Rossell, V. Jeudy, T. A. Moore, C. H. Marrows, PRB 99, 094409 (2019).

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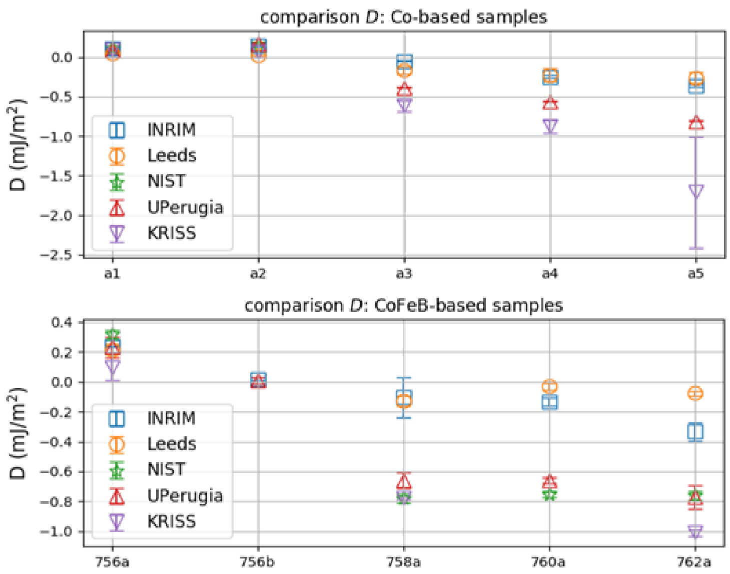

Fig. 1.1 D measured by MOKE at INRIM and Univ. Leeds and by BLS at NIST, Univ. Perugia, and KRISS. Upper panel: Ta(5)/Pt(3)/Co(0.8) with top layers a1 Pt(3)/Ta(3), a2 Pt(1)/Ta(3), a3 Ir(3)/Ta(3), a4 Ir(1)/Ta(3), a5 Ta(3). Lower panel: W(5)/$Fe_{60}Co_{20}B_{20}$(0.6)/MgO(2)/Ta(5): 756a (annealed at 400°C) and 756b (as grown); Pt(3.4)/$Co_{60}Fe_{20}B_{20}$(0.8)/MgO(1.4)/Ta(5) at different sputter power: 758a (200W), 760a (700W), 762a (1200W). All nominal thicknesses in nm.

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovations programme and the EMPIR participating states.

(2) Manipulation of magnetic skyrmion density in continuous Ir/Co/Pt multilayers

In a recent paper [2.1], we have shown that magnetic skyrmions can be stabilized at room temperature in continuous $[Ir/Co/Pt]_5$ multilayers on SiO_2/Si substrate without prior application of electric current or magnetic field. While decreasing the Co thickness, tuning of the magnetic anisotropy gives rise to a transition from worm-like domain patterns to long and separate stripes. The skyrmions are clearly imaged in both states using Magnetic Force Microscopy, see Fig. 2.1. The density of skyrmions can be significantly enhanced after applying the “in-plane field procedure”. In addition, we have investigated the phase diagram of a sample deposited in the same run, but onto a SiN_x membrane using Lorentz transmission electron microscopy. Interestingly, this sample shows a different behaviour as function of magnetic field hinting to the influence of strain on the phase diagram of skyrmions in thin film multilayers, see Fig. 2.1. Our results provide means to manipulate magnetic skyrmion density, further allowing for optimized engineering of skyrmion-based devices [2.1].

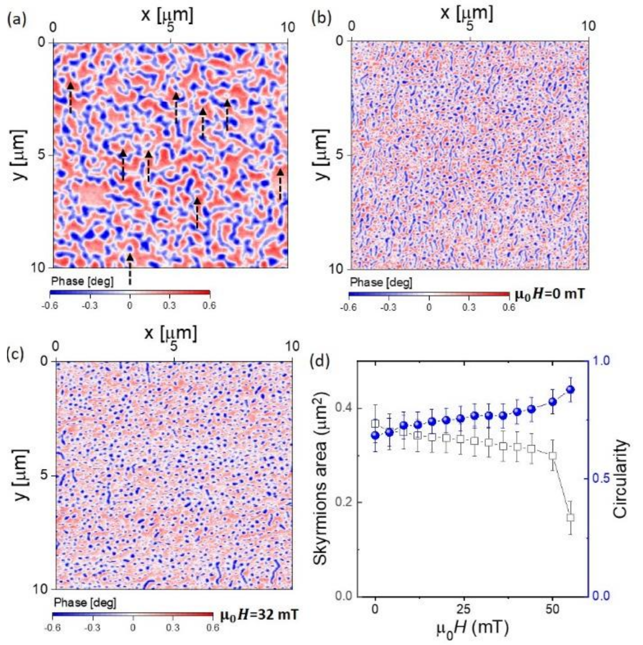

Fig. 2.1 MFM measurements on $[Ir/Co/Pt]_5$ multilayers for t_{Co}=0.8nm at room temperature. (a) The MFM images were acquired in the as-grown state. Red and blue contrasts represent the out-of-plane magnetizations of opposite direction. Some skyrmions are indicated by dashed black arrows. (b) As grown-state modified by the “in-plane field procedure”. (c) An example of the evolution of skyrmions vs the perpendicular applied magnetic field for $\mu_0 H = 32 mT$. (d) A plot showing the area of the skyrmions (open square) and circularity (blue spheres) vs $\mu_0 H$. From Ref. 2.1.

References

[2.1] M. Cubukcu, S. Pollath, S. Tacchi, C. Barton, A. Stacey, E. Darwin, C.W.F. Freeman, C. Barton, B.J. Hickey, C.H. Marrows, G. Carlotti, C.H. Back, O. Kazakova, *"Manipulation of magnetic skyrmions in continuous Ir/Co/Pt multilayers"*, arXiv:2111.12634 (2021).

Contact & further information

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(3) From propagative to stationary spin waves: suppression of the DMI-induced non-reciprocity by lateral confinement in magnetic dots

Brillouin Light Scattering (BLS) experiments have been performed at Perugia University on samples consisting of CoFeB/Pt films grown at University of Mainz and patterned by e-beam lithography at PTB, in the framework of the TOPS project. In particular, the samples consist of bidimensional arrays of circular dots, patterned starting from a Pt/Co bilayer, with a diameter d ranging from 100 to 400 nm, i.e., comparable with the wavelength of the thermal spin waves detected in BLS experiments. The aim of the experiments was to determine how the lateral confinement influences the spin-wave non-reciprocity induced by the presence of a sizeable interfacial Dzyaloshinskii-Moriya interaction (DMI) supplied by the heavy-metal substrate (Pt) on the ferromagnetic film (CoFeB). As illustrated in Fig. 3.1, the experimental results provide evidence for a strong suppression of the frequency asymmetry Δf between counter-propagating spin waves (corresponding to either Stokes or anti-Stokes peaks in BLS spectra), when the dot diameter is reduced from 400 nm to 100 nm, i.e., when it becomes lower that the wavelength of spin waves. Such an evolution reflects the modification of the spin-waves character from propagating to stationary and indicates that the method of quantifying the DMI strength from the frequency difference of counter-propagating spin waves is not applicable in the case of sufficiently small magnetic elements. Micromagnetic simulations are in progress at INRIM, using the $MuMax^3$ software package, to quantitatively reproduce the experimental results [3.1].

References

[3.1] S. Tacchi, R. Silvani, M. Kuepferling, A. Fernandez-Scarioni, S. Sievers, H.W. Schumacher, G. Jakob, M. Klaui and G. Carlotti, paper in preparation.

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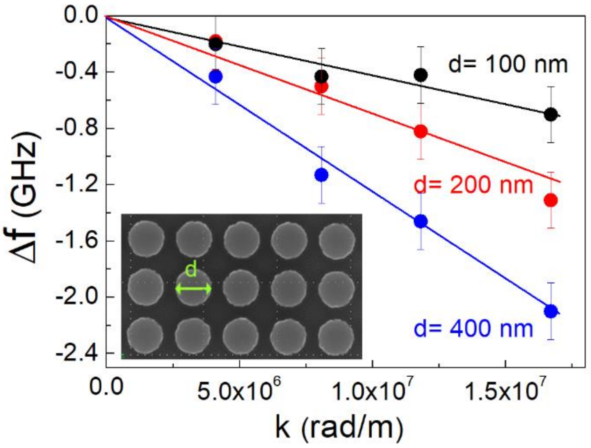

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Fig. 3.1 Measured values of the frequency asymmetry Δf between Stokes and anti-Stokes peaks in Brillouin Light Scattering spectra measured on patterned arrays of circular magnetic Pt/CoFeB dots of diameter d=100 nm, 200 nm and 400 nm. It can be seen that the frequency asymmetry is strongly suppressed for d=100 nm, if compared to the case of d=400 nm.

(4) Influence of the interfacial Dzyaloshinskii-Moriya interaction on the band structure of one-dimensional magnonic crystals

In the framework of the TOPS project, researchers operating at Perugia University have investigated the effect of periodic interfacial Dzyaloshinskii-Moriya interaction on the spin wave (SW) dispersion relation of one-dimensional magnonic crystals (MCs). MCs consist of an extended CoFeB film, 1 nm thick, sitting over an array of Pt stripes having a thickness of 7 nm. Two set of samples having a periodicity of the Pt stripes p=400 nm (with a stripe width w=200 nm) and p=200 nm (with a stripe width in the range between 150 and 170 nm) have been studied. SW dispersion was measured by Brillouin light scattering in the Damon-Eshbach geometry, applying the external magnetic field along the stripe axis and sweeping the in-plane transferred wave-vector (k_z) along the perpendicular direction. The experimental results have been compared to the band diagram calculated by means of the plane wave method. In agreement with theoretical calculations, in all the investigated samples we observe the presence of low-frequency flat bands, due to appearance of SW modes localized in the areas where the Pt stripes are present. The frequency position of the flat band is found to strongly depend on the stripes period. Moreover, for the samples having smaller periodicity the dispersion curves are characterized by a marked qualitative change. In particular, we find SWs modes, featuring a strong non-reciprocal intensity, which are present in the SW dispersion only for positive wavevectors [4.1].

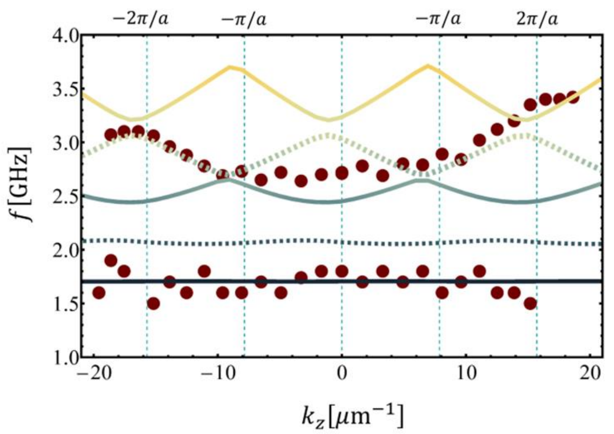

Fig. 4.1 Measured (points) and calculated (lines) SW dispersion relation of the sample having a periodicity of the Pt stripes p=400 nm and a stripe width w=200 nm.

References

[4.1] S. Tacchi, R. A. Gallardo, D. Petti, A. Cattoni, J. Flores-Farías, E. Albisetti, G. Carlotti, P. Landeros, paper in preparation

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(5) Dynamical eigenmodes of Néel Skyrmions: from isolated elements to a one-dimensional magnonic crystal

In the framework of the TOPS project, researcher operating at Perugia University, in collaboration with colleagues at INRIM-Torino, exploited the micromagnetic software MuMax[3] to calculate the ground state and the dynamics of Néel skyrmions (SKs) in the range between 1 and 30 GHz, in systems with three different levels of complexity, considering first the eigenmodes of an isolated SK, then the case of two interacting SKs and finally a linear chain of 71 units. For each simulation, the sample was discretized in cubic cells of side 1 nm and the spin-wave eigenmodes, excited by a pulse of external magnetic field, have been studied as a function of the intensity of the Dzyaloshinskii-Moriya (DMI) constant D and the exchange constant A. It has been shown that the band structure of one-dimensional magnonic crystals consisting of interacting Néel SKs can be interpreted in terms of magnonic bands that derive from the main eigenmodes of isolated SK, separated by forbidden band gaps. However, this simple picture is a good approximation only for either relatively small values of the DMI constant D or for relatively large values of the exchange constant A. In general, instead, the magnonic band structure is characterized by hybrid collective excitations, with anticrossing and band repulsion phenomena, caused by the dipolar interaction among the elemental constituents of the chain. Consequently, the amplitude of the permitted frequency bands and of the forbidden gaps are remarkably sensitive to variations of both D and A in the range of values typical of current ferromagnetic materials. This suggests that both parameters could be in principle exploited for fine-tuning the permitted and forbidden operation frequencies of future devices based on such kind of skyrmionics magnonic crystals [5.1].

References

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