TOPS - Metrology for topological spin structures

Joint Research Project
Newsletter October 2019

Metrology for topological spin structures

Introduction

We are pleased to welcome you to the first newsletter for the "TOPS" Joint Research Project. The project started in June 2018 and will run for 3 years. The underlying goal of TOPS is to develop and establish metrological and scientific tools for the characterization of topological spin structures. This work is expected to contribute to the development of new magnetic storage, spin-logic, and microwave devices in the future well as new quantum standards.

The project is 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 through further newsletters and on our webpage.

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(1) Measuring Interfacial Dzyaloshinskii-Moriya Interaction: A Review

The Dzyaloshinskii-Moriya Interaction (DMI) is considered today to be responsible for the formation and stabilization of exotic magnetic structures, as e.g.chiral domain walls of Neel type or skyrmions, particle-like excitations of continuous fields predicted by Skyrme. Such magnetic structures, due to their unusual static and dynamic properties are extremely promising for future applications in spintronics, as e.g. novel magnetic memories. The DMI was discovered as an anisotropic exchange interaction, favouring non-collinear spin configurations and being the main mechanism of weak ferromagnetism occuring in some antiferromagnetic compounds. It was forgotten or considered of relative importance for almost 40 years, unless skyrmions were found to be present as magnetic states in materials with certain crystal symmetries. Since then DMI-based phenomena have created an extremely active research field, often referred to as chiral magnetism. Considering the Web of Science database, about 1500 articles on the topic of DMI have been published since 2000, reaching the remarkable record of 7000 citations in 2018 only. Nevertheless, a detailed literature review is not yet available and an established and reliable method to measure DMI is still lacking.

We aim therefore to publish a literature review on the, from applicative point of view, especially interesting interfacial DMI, occurring in systems composed of a heavy metal (HM) layer and an ultrathin ferromagnetic (FM) film with perpendicular magnetic anisotropy (PMA) (e.g., FM: Co, CoFeB; HM: Pt, Ta, Ir, W). We find disagreement in the attempt of reliably quantifying DMI by measuring the related energy coefficient *D*, especially for small DMI ($D < 0.5$ mJ/m^2). Not only different measuring techniques deliver contradictory values for *D*, but results are even controversary when the same method on nominally identical stacks is employed (see Fig.1). Therefore, an accurate comparison within a Round Robin, as it will be undertaken within the TOPS project, is indispensable and will provide useful information for the research community.

Contact & further information

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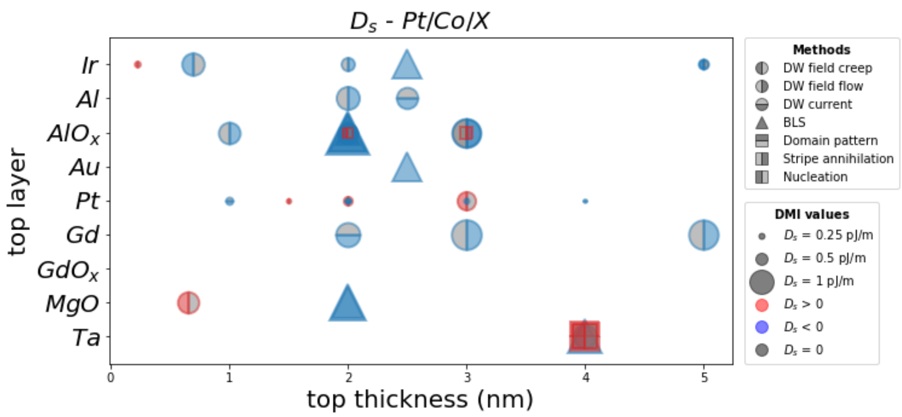

Fig. 1: D_s values (*D* times thickness) found in literature measured by different techniques on Pt/Co/X stacks with different top materials. The Pt thicknesses range between 2 nm and 5 nm. Inset: sample; NM-non magnetic, FM-ferromagnetic layer.

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(2) Manipulation of single skyrmions using local magnetic field gradients

While completing a recent secondment project within a researcher mobility grant at NPL, Arianna Casiraghi (INRIM) together with a team of NPL scientists have been demonstrated controllable manipulation of individual skyrmions using local magnetic field gradients.

The technique implements a localised magnetic field gradient from a magnetic probe in a combination with an external magnetic field to magnetise the samples, see Fig. 2(a). By developing and applying an advanced sequence of MFM scanning, it is possible to nucleate skyrmions and perform MFM imaging without perturbing their magnetization, see Fig. 2(b). We have also demonstrated that individual skyrmions can be controllably moved and imaged using a magnetic probe, Fig. 2(b-h). The manuscript [1] is under review in Physics Communications (NPG).

The technique is highly reproducible and is now available for all types of single skyrmion studies.

References

[1] A. Casiraghi, H. Corte-Leon, M. Vafaee, F. Garcia-Sanchez, G. Durin, M. Pasquale, G. Jakob, M. Kläui, and O. Kazakova, Individual skyrmion manipulation by local magnetic field gradients [to be published].

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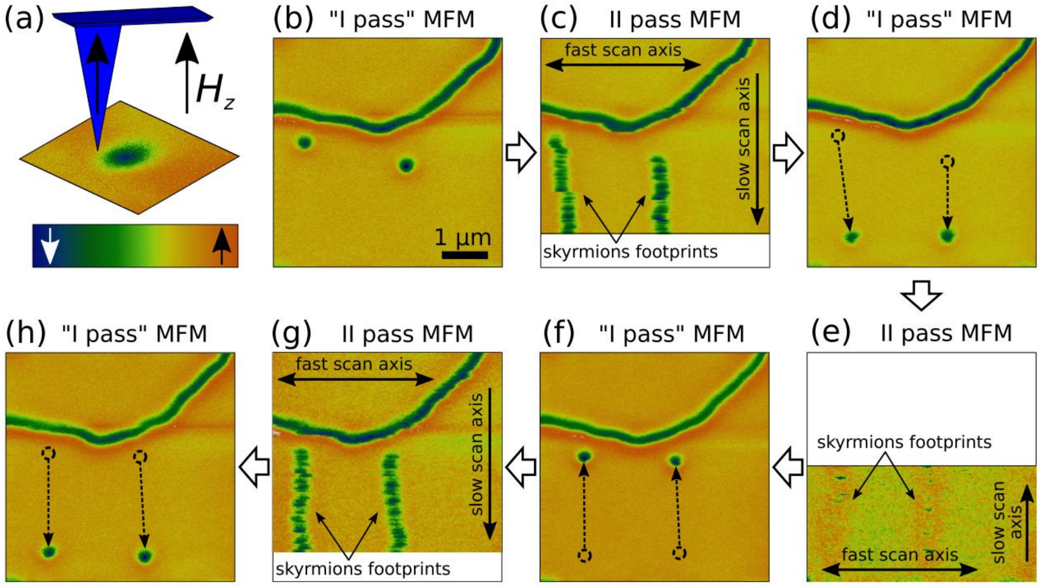

Fig. 2: (a) Combination of probe magnetic field gradient and external field. (b) to (h), sequence of imaging and manipulation to move skyrmions up and down. (b), (d), (f), (h) magnetic force microscopy (MFM) images, (c), (e), and (g), manipulation scans in close proximity to the surface.

(3) Influence of DMI on the spin wave eigenmodes of magnetic nanodots magnetized either in-plane or out-of-plane

In a recent focused review paper, the characteristics of spin waves eigenmodes in magnetic nanodots with sub-200 nm lateral dimension have been discussed, [1] considering both out-of-plane and in-plane magnetization, as well as the effect of the interfacial DMI.

For perpendicular magnetization, Fig. 3(a), the modes can be labeled using a couple of indices *(r,l)*, where the radial number *r* counts the circular nodal lines and the azimuthal number *l* accounts for a phase shift of $l \times 2\pi$ along a circular line. The plus and minus signs of *l* indicate the sense of the spin-wave (SW) propagation in the counter-clockwise and clockwise directions, respectively. Interestingly, the azimuthal eigenmodes undergo a frequency splitting in presence of DMI, associated with lifting in the degeneracy eigenmodes with opposite chirality ($l=\pm l$) [2]. The magnitude of the splitting increases with the DMI constant *D*, so that a measurement of the splitting amplitude enables one to quantify the value of *D*. On the other hand, radial modes experience only a slight decrease in their frequency with increasing

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DMI, accompanied by a minor distortion of their spatial profile.

Similar to the case of the perpendicularly magnetized dots, also for in-plane magnetized dots each spin wave eigenmode can be labeled with two integer indices (n_x,n_y) whose values correspond to the number of nodal lines. In this case, however, the nodal lines are either parallel or perpendicular to the direction of the magnetization (x axis), as illustrated in Fig. 3(b). As for the effect of DMI, it has been shown very recently [3] that, as a consequence of the nonreciprocity of SW propagation along $+k_x$ and $-k_x$, one finds states with well-defined nodes which are inherently phase modulated so that space-inversion symmetry of the mode profile is lost. As a consequence, further spectral features become visible in experiments based on the detection of the spatial average of the dynamical magnetization, such as ferromagnetic resonance, Brillouin light scattering or time-resolved Kerr effect. This means that a careful measurement of the eigenmodes spectrum of magnetic nanodots by the above techniques may provide direct access to a quantification of DMI.

References

[1] G. Carlotti, Appl. Phys. Rev. **6**, 031304 (2019).

[2] F. Garcia-Sanchez, P. Borys, A. Vansteenkiste, J.-V. Kim, and R.L. Stamps, Phys. Rev. **B 89**, 224408 (2014).

[3] B.W. Zingsem, M. Farle, R. L. Stamps and R. E. Camley, Phys. Rev. **B 99**, 214429 (2019)

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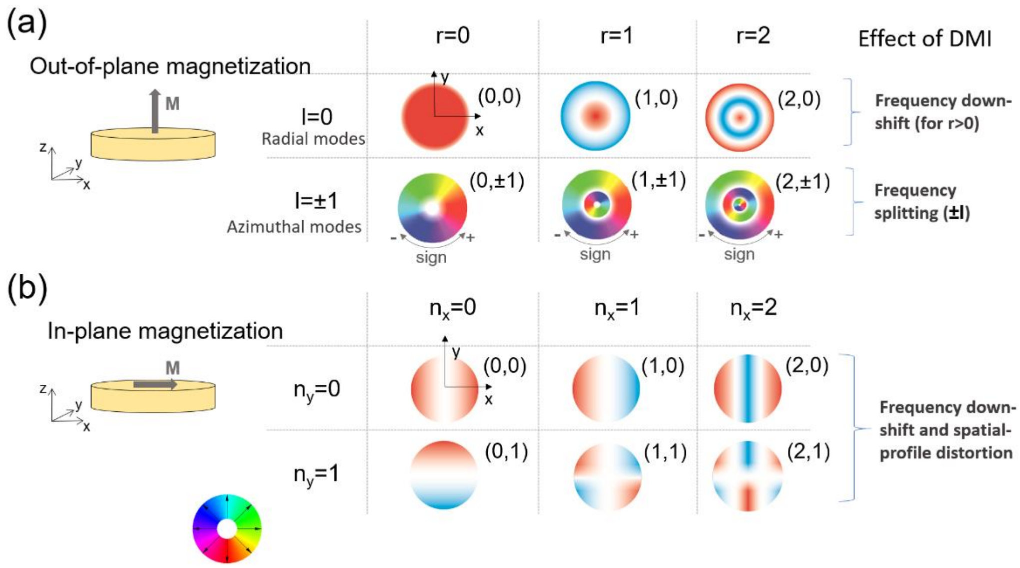

Fig. 3: Schematic diagram showing the spatial characteristics and the labelling scheme for the magnetic eigenmodes of circular magnetic nano-disks with diameter in the range of a few tens of nanometers, magnetized either out-of-plane (a) or in-plane (b). In our coding scheme, the hue indicates the phase of the dynamical magnetization, according to the enclosed color wheel, while the brightness represents its amplitude. The nodal lines are marked in white. The qualitative effect of the presence of a sizeable DMI on the mode frequencies is shown on the right.

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