Study of skyrmions in ferromagnetic metallic superlattices using in situ Lorentz magnetic methods

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Background incl. aims
Magnetic skyrmions, which consist of local swirls of spins, are a prime example of topologically nontrivial spin textures. Nanoscale isolated skyrmions exist at low temperature in bulk chiral materials, while in thin films and multilayers, room temperature (RT) stable skyrmions exhibit intermediate sizes ranging between 50 nm to a few µm. Ferromagnetic metallic superlattices are materials which are promising for the development of RT nanoscale skyrmions due to the high tunability of their properties. There exist a large number of experimental studies reporting the observation of stripe domains and skyrmion bubbles in metallic multilayers, for example Pt/Fe/Ir[1] and Ta/Co/Pt[2]. It is well understood that these skyrmions and stripes are created by a combined action of the stray field effect and the Dzyaloshinskii-Moria interaction (DMI)[3]. These non-collinear spin structures can also be easily simulated numerically [2]. However, in a system with a high number of degrees of freedom, the quest remains open regarding how to optimize the parameters to obtain the most compact and stable skyrmion and the development of adequate analytical tools could lead to breakthrough and transform this quest from a random walk to a guided tour. Many experimental techniques have been used throughout the years in order to study skyrmions, including Magnetic Force Microscopy[4], soft-x-ray microscopy[1] and Magneto-Optical Kerr Effect (MOKE) microscopy [5] among others. But quantitative nanoscale studies on the conditions of skyrmion nucleation remains of primary importance. In this study we chose to study skyrmions in a classical [Pt/Co/Ta]n metallic superlattices system, n being the number of repetition of the tri-layer.

Methods
Samples were fabricated by magnetron sputtering, and studied using Lorentz Transmission Electron Microscopy (LTEM) in Fresnel mode combined with electron holography (EH). LTEM in Fresnel mode offers an easy and straightforward method for a semi-quantitative study of the local magnetization, well suited to the observation of skyrmions. We aimed to explore the magnetic phase diagrams of our multilayered magnetic system by developing an automatized process to record magnetic images with in situ application of magnetic field through the control of the objective lens and modulation of the temperature using a dedicated sample holder. In parallel, we used electron holography (EH) which allows to reach higher spatial resolution (up to 0.5 nm) and obtain quantitative magnetic measurements. Our approach is combined with MOKE, theoretical models and numerical simulations (using Mumax3).

Results
In this system, RT skyrmionic bubbles as small as 50 nm have been observed when the Co thickness was tuned close to the spin reorientation transition[2]. In our study, we fixed the Co thickness at 0.8 nm and we tuned the thickness of the total system by varying the number of repetitions n of the Pt/Co/Ta tri-layer. This allows us to tune selectively the effect of the stray field while keeping roughly constant the system intrinsic parameters (magneto-crystalline anisotropy, saturation magnetisation, DMI). We were able to image the magnetic micro-structures of [Pt/Co/Ta]n multilayers with various different number of repetitions in LTEM and MOKE (Figure 1a). We conducted an experimental study of the stripe domain structures as a function of the multilayer total thickness, see Figure 1b, and when applying a magnetic field (using the objective lens), we studied the formation process of magnetic skyrmions, the stripe-skyrmion transition, and the presence of skyrmion lattice or isolated skyrmions in certain samples. We could correlate the magnetic contrast observations with applied field to

the magnetic hysteresis obtained from VSM measurements. We also studied the influence of the temperature on the stripe pattern and on the formation of skyrmions, from which we could elaborate experimental phase diagrams coupled to theoretical diagrams, based on skyrmionic bubble model (Figure 2). Finaly, we performed EH experiments at the state-of-the-art, combining high spatial resolution with a dedicated Lorentz stage, direct electron detector with the K3 camera and long exposure time up to 4 mn thanks to the dynamical correction of instabilities. We were able to recover the magnetic phase of the Néel type skyrmions up to few nanometers of spatial resolution, and to observe the detailed stripe-to-skyrmion transition with external applied magnetic field (Figure 3). We will detail the magnetic processes which has been deduced from such observations combined with simulations.

Conclusions

Our experimental study focused on [Pt/Co/Ta]n metallic superlattices, investigating the manipulation of their properties by varying the number of repetitions (n) of the tri-layer. Through spatially resolved magnetic measurements using magneto-optic techniques and transmission electron microscopy methods combined with in situ experiments, we could explore the stripe domain structures and skyrmion formation as a function of total thickness, the applied magnetic field and varying the temperature. Our findings give new insights of the stripe-skyrmion transition and temperature's influence on these phenomena, supported by experimental phase diagrams and theoretical models. Additionally, we studied Néel-type skyrmions structure using advanced EH observations, achieving a very high spatial resolution and observing detailed transitions from stripe to skyrmion configurations under external magnetic fields. Our study provides significant contributions to understanding the magnetic behaviors of skyrmions in metallic superlattices by combining TEM magnetic imaging and MOKE, correlated to micromagnetic simulations, stripe domain and skyrmion models.

Graphic:

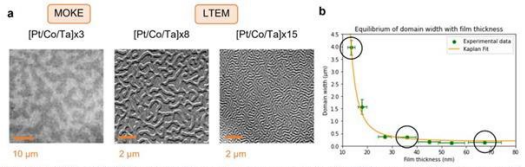

Figure 1 : (a) MOKE and LTEM observations of stripe domains at zero applied field for different numbers of repetition n, and (b) the stripe domain width as a function of the multilayer thickness in [Pt/Co/Ta]$_n$ multilayers with circled points extracted from images of (a), fitted with Kaplan stripe domains model.

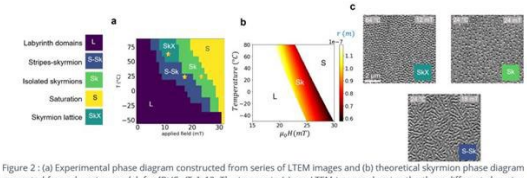

Figure 2 : (a) Experimental phase diagram constructed from series of LTEM images and (b) theoretical skyrmion phase diagram computed from skyrmion model, for [Pt/Co/Ta]x12. The images in (c) are LTEM images showing the three different skyrmion phases observed and identified in the phase diagram (a) by the stars, with the temperature (°C) and applied magnetic field (mT) indicated in the upper corners.

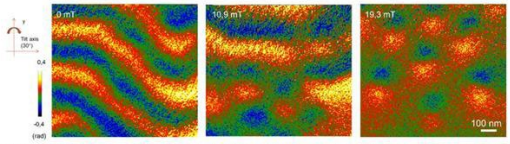

Figure 3 : Magnetic phase images of [Pt/Co/Ta]x10 sample extracted from respective holograms at different *in-situ* applied fields, with the sample tilted by 30°. A circular mask has been applied in Fourier space leading to 7 nm spatial resolution.

Keywords:

LTEM, EH, skyrmion, MOKE, nanomagnetism

Reference:

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