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Angaben zur Veröffentlichung / Publication details:

Moutafis, C., J. Rhensius, A. Bisig, Felix Büttner, C. Barton, C. Morrison, T. Thomson, et al. 2011. "Skyrmions in perpendicular magnetic anisotropy dots: imaging and simulations." *International Conference on Electromagnetics in Advanced Applications, 12-16 September 2011, Turin, Italy*, 1121–23. https://doi.org/10.1109/iceaa.2011.6046506.

Skyrmions in Perpendicular Magnetic Anisotropy Dots: Imaging and Simulations

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Abstract **We present the results of soft X-ray holography imaging of sub-micrometer disc-shaped dots with perpendicular magnetic anisotropy. For particular geometries such dots can sustain magnetic bubbles that have been predicted to exhibit rich spin dynamical behaviour. By applying suitable in-situ magnetic fields to the system we can manipulate the magnetic configuration of the system and create the desired bubble-like state. This is a pre-requisite for imaging of the bubble's dynamical response as well as for pump-and-probe imaging of their dynamics.**

1 INTRODUCTION

Extensive experimental efforts of the research community in the last years have focused largely on magnetic vortices in in-plane magnetised materials. These are topologically non-trivial structures and can be found in abundance in soft magnetic elements (characterised by a small magnetic anisotropy) in wide range of geometries [1-4]. It has been shown in time-resolved experiments that the vortex topological structure effectively dominates its translational dynamics, the so-called magnetic vortex gyrotropic mode [5,6]. The investigation of the statics and dynamics of magnetic Skyrmions in confined geometries (dots) with perpendicular anisotropy has also raised much interest in recent years. Specifically, magnetic bubbles were observed as stable states at remanence in corresponding magnetic elements with a very large perpendicular anisotropy, constituting the so-called monobubble state [7]. This was seen as the analogue of the magnetic vortex in the technologically relevant [8] high magnetic anisotropy materials. Furthermore, such magnetic bubble domains in magnetic elements have been predicted to exhibit rich dynamics [9-11]. Specifically, it was predicted that a magnetic bubble with a Skyrmion number of unity, confined in a magnetic element, can show a gyrotropic motion when displaced by magnetic field gradient pulses [9]. Here we report on soft X-ray holography imaging of sub-micrometer sized dots subject to large in-situ applied magnetic fields. This allows us to manipulate the magnetic states in order to utilise them in subsequent pump-and-probe experiments.

2 IN-SITU IMAGING WITH SOFT X-RAY HOLOGRAPHY

Soft X-ray holography is a lensless imaging technique that utilizes the interference of the object scattered wave with an unperturbed reference beam to record the phase information with a conventional intensity detector [12]. No further optical, electronic or mechanical elements are needed to obtain an image of the magnetic domain pattern. Hence, this technique is advantageous in view of employing in-situ techniques, for instance, the application of large magnetic fields. A scanning mask approach [13] together with a wave-field back-propagation algorithm for reconstructing the magnetic images [14] effectively combines the holography technique with the capabilities of a scanning microscope.
In Fig. 1 we see a micromagnetic simulation result of the magnetic spin configuration of a dot in the monobubble state (a magnetic bubble confined in the center of the disc). This is an out-of-plane configuration with the bubble pointing downwards and the surrounding domain pointing upwards, mediated by a symmetric domain wall. The arrow is pointing to a part of the wall, in order to indicate the axially

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symmetric nature of the bubble domain wall. This axially symmetric domain is the basic bubble configuration in such dots, and it is characterised by a Skyrmion number of unity. Its dynamical response, when displaced by a magnetic field gradient that would not influence the symmetry of the wall, would be to enter a damped gyrotropic motion to the center of the dot [9]. In order to study such a dynamical response, the first step would be to be able to create such states by external magnetic field manipulation during imaging.

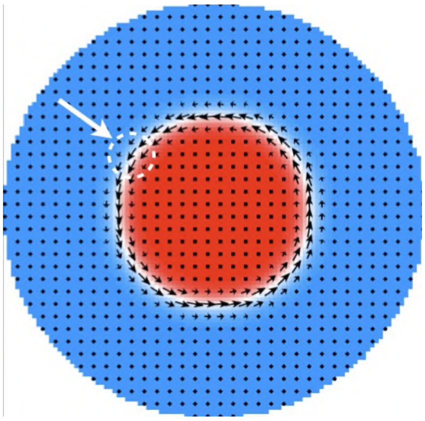

Figure 1: Numerical micromagnetic simulation of the magnetization configuration of a dot in the monobubble state. The blue-red contrast indicates a up-down out-of-plane magnetic configuration. The dashed-circle indicates the axially symmetric nature of the basic bubble configuration. This axially symmetric configuration corresponds to a bubble with a Skyrmion number unity.

For this investigation we fabricated Co/Pd multilayer films with the following composition Ta(30Å)/Pd(30Å) / $[Co(3Å)/Pd(9Å)]_x$ / Pd(11Å) on silicon nitride membranes where x= 30, 50 and 70 layers. The films were microfabricated into a patterned array of dots with a wide range of lateral dimensions (d=100 nm to 2000 nm) by e-beam lithography and lift-off. For the imaging we have used a movable mask design that allowed the scanning over the sample in order to select the desired dot to study, bringing the benefits of a scanning technique to holography [13]. For the larger dots the magnetic configuration consists of labyrinth domains, showing a film-like behaviour. As we scan magnetic dots of smaller lateral dimensions, the observed spin configurations become simpler and the effect of the dot boundaries becomes more predominant. In Fig. 2 we present the reconstructed images of the magnetic configuration of a Co/Pd disc with a diameter of 600 nm and thickness of x=50 layers during a sweep of an in-situ applied uniform perpendicular field for different field values. Here, we start with a random multi-domain remanent state in Fig. 2 a) with roughly equal proportion of "white" and "black" domains (corresponding to magnetization up and down). In Fig. 2 b) we increase the uniform magnetic field that favours the "black" domain directly manipulating the "black"/"white" ratio. By increasing the field to ~ - 2 kOe we drive the "white" domain out of the dot, reaching near saturation of the magnetisation in the direction of the field. We subsequently lower the field gradually in order to check when the domain reversal begins. At ~ - 0.5 kOe, we still have the monodomain state and we do not see reversed domains, at least to within the level of resolution of the microscope. This is a typical sign of the characteristic hysteresis of these systems showing that the history of the magnetic system is governing the spin structure. In e) we image the dot at remanence, with a magnetic state that looks roughly inverse to the one in a). In f) by using a magnetic field that favours the "black" domains we manage to create a bubble-like state in the center of the dot. This exemplifies the level of control we can have in order to prepare the system in the state that we want by a controlled sweeping of the external field and checking of the magnetization configuration by direct imaging in these applied fields. By suitably adjusting the magnetic field amplitude one is able to drive the magnetic dot to a bubble-like state.

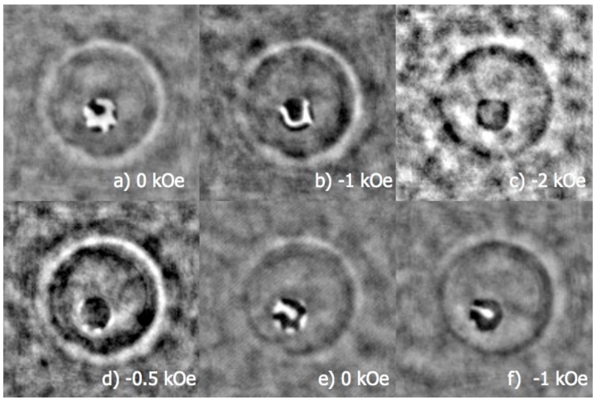

Figure 2: Imaging of a magnetic dot under in-situ magnetic fields. The field is uniform and out-of-plane and the field magnitude values are approximate. In a) we see the magnetic state at remanence. We apply a field that favours the black domain in b) and drive the dot to an almost saturated state in c). In d) we lower the field and in e) we return to remanence. By applying a magnetic field of the same direction in f) we manage to sustain a bubble-like magnetic configuration.

3 CONCLUSIONS

By using resonant soft X-ray holography, we have imaged the magnetic states in dots of Co/Pd multilayers of varying diameter and thickness and we also specifically identify a bubble-like domain in certain diameter for a range of uniform out-of-plane magnetic fields. This allows us to manipulate the magnetic states in-situ in order to utilise them for subsequent pump-and-probe experiments to study the system's dynamical response to magnetic field pulses by a neighbouring microstrip.

Acknowledgments

We acknowledge support from the German Science Foundation (DFG SFB 767, KL 1811, SPP 1459), the EU (Stg MASPIC ERC-2007-Stg 208162, MAGWIRE FP7-ICT-2009-5 257707) and the Swiss National Science Foundation.

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