# SP 14 Domain walls, vortices and skyrmions

## SP14 - Parallel Session 1

### SP14 - Parallel Session 1

### SP14.1.02

### Electric field modulation of magnetic domain wall velocity in Pt/Co/Pd structure

T. Koyama, D. Chiba

**Text** Electric field (EF) effect on magnetic properties in a capacitor structure has been actively studied. We have reported the influence of the Pd layer insertion between a Co and an insulator layer (Pt/Co/Pd structure) on the EF effect. In this study, we investigated the EF effect on the magnetic domain wall (DW) velocity in Pt/Co/Pd structures.
The Pt(2.4 nm)/Co(tCo)/Pd(0.4) structures with Ta buffer layer were deposited on thermally oxidized Si substrates and the films were patterned into a 20-um-width wire structure. Then, HfO2 gate insulator layer and Au gate electrode were deposited on the wire. The HfO2 layer was formed using an atomic layer deposition at 150 ℃. The referenc
under the gate voltage (VG) was determined using a magneto-optical Kerr microscope.
In the case of the creep regime, in which the thermally activated DW motion occurs, we observed that v largely depends on VG and the v difference between the results for VG = ±15 V was approximately 100 times for tCo = 0.96 nm sample. Such a large magnitude of v modulation was not observed in the reference samples. We also found that the effective DW pinning strength was significantly modulated by VG in the Pt/Co/Pd sample. In particular, non-linear VG dependence of the DW pinning strength is shown in the tCo = 0.96 nm sample, resulting in the large change in v in this sample.

# SP 14 Domain walls, vortices and skyrmions

**SP14 - Parallel Session 1**

**SP14.1.03**

## Magnetoelectric effect and orbital magnetization in skyrmion crystals: New ways for detection and characterization of skyrmions

B. Göbel, A. Mook, J. Henk, I. Mertig

**Text** Skyrmions are small magnetic quasiparticles, which are uniquely characterized by their topological charge and their helicity [1]. We present theoretically how both properties can be determined without relying on realspace imaging [2].
The topological Hall effect of electrons allows to distinguish skyrmions from antiskyrmions by sign of the topological Hall conductivity [3,4] and the orbital magnetization [2,5]. Here, we predict a magnetoelectric effect in skyrmion crystals [2], which is the generation of a magnetization (polarization) by application of an electric (magnetic) field. Its dependence on the skyrmion helicity fits that of the classical toroidal moment of the spin texture and allows to differentiate skyrmion helicities: it is largest for Bloch skyrmions and zero for Neel skyrmions. We predict distinct features in the magnetoelectric polarizability that can be used to detect and characterize skyrmions in experiments.

[1] N. Nagaosa et al., Nature Nano. 8, 899 (2013)
[2] B. Göbel et al., arXiv 1802.06411 (2018)
[3] B. Göbel et al., Phys. Rev. B 95, 094413 (2017)
[4] B. Göbel et al., New J. Phys. 19, 063042 (2017)
[5] M. dos Santos Dias et al., Nat. Commun. 7, 13613 (2016)

# SP 14 Domain walls, vortices and skyrmions

**SP14 - Parallel Session 1**

**SP14.1.04**

## Ultrafast toggle switching of magnetic skyrmions

M. Stifano, M. Barbeau, T. Rasing, J. H. Mentink

**Text** Magnetic skyrmions appear as stable or meta-stable states in magnetic materials due to the interplay between the symmetric and antisymmetric exchange interactions, applied magnetic field and/or uniaxial anisotropy. Their small size and internal stability make them prospective objects for data storage. For applications, controllable writing and erasure of skyrmions at high speeds is essential. So far, controllable writing and erasure of single magnetic skyrmions has been demonstrated using scanning tunneling microscopy [1] and spin-orbit torques [2]. However, electrical control of skyrmions inherently limits device operation speeds to the GHz regime. Here, on the basis of atomistic spin dynamics simulations, we present an alternative scenario, based on excitation with ultrashort perturbations of the intrinsic symmetric and antisymmetric exchange interactions by laser-generated acoustic pulses. We find that for optimized pulse parameters the same excitation pulse can both generate and erase a single skyrmion. For realistic model parameters, this leads to toggle switching at 10-100 GHz rates, considerably higher than feasible with electrical currents. We show that the nucleation mechanism is based on bringing the system in the vicinity of an instability of the ferromagnetic phase and support our scenario with calculations of the perturbations of exchange interactions by acoustic pulses.

[1] N. Romming et al., Science 341, 636 (2013)
[2] S. Woo et al., arXiv:1706.06726 (2017)

# SP 14 Domain walls, vortices and skyrmions

**SP14 - Parallel Session 1**

**SP14.1.05**

## Study of nanoscale laser- and magnetic field-induced domain-wall dynamics

M. Logunov, S. Nikitov, M. Gerasimov, S. Ilin, S. Safonov, A. Spirin

**Text** Domain-wall (DW) based structures are considered as one of the key elements of future nanomagnetic devices [1]. Magnetic-field pulses are used for the study of DW dynamics, as well as current pulses in conducting materials. The discovery of ultrafast laser-induced magnetization dynamics [2] has opened the possibility of laser-pulse magnetization control. Recently, it has been shown that DWs can be moved by the action of single laser pulse [3], and the direction of DW motion is determined by the laser pump-pulse helicity.

Here, we will report both on the technique for nanoscale DW dynamics and on the results of the DW dynamics study in magnetic dielectrics, iron garnet films. We used diffraction and induction techniques for studying the time evolution of DW motion with the sensitivity to DW displacements up to 5 nm [4], with spatial filtering of the output optical flux of Fraunhofer-diffraction pattern from a domain structure and impulse transient response jointly and in real-time. The results of the laser- and magnetic-field induced DW dynamics study at the same film will be presented and compared.

[1] A. Fernandez-Pacheco, R. Streubel, O. Fruchart et al., Nature Comm. 8, 15756 (2017).
[2] E. Beaurepaire, J.-C. Merle, A. Daunois, and J.-Y. Bigot, Phys. Rev. Lett. 76, 4250 (1996)
[3] M. V. Gerasimov, M. V. Logunov, A. V. Spirin et al., Phys. Rev. B 94, 014434 (2016).
[4] M. V. Gerasimov, S. V. Ilin, M. V. Logunov et al., Instrum. Exp. Tech. 60, 716 (2017).

# SP 14 Domain walls, vortices and skyrmions

**SP14 - Parallel Session 1**

**SP14.1.06**

## Isolated skyrmions with vanishing anisotropy in Co/Ru(0001)

M. Böttcher, M. Hervé, J. Sinova, W. Wulfhekel, B. Dupé

**Text** Magnetic skyrmions are localized and topologically stabilized non-collinear spin structures. They offer attractive perspectives for future spintronics applications, because they can be manipulated at lower current densities than domain walls [1]. The stabilization of skyrmions is usually attributed to a large Dzyaloshinskii-Moriya interaction (DMI). Here, we show that a strong DMI is not a necessary condition to obtain skyrmions in ultrathin films. Co/Ru(0001) possesses a spin spiral ground state, although the DMI is weak. We attribute the stability of this spin texture to the simultaneous vanishing of anisotropy [2]. We determine the B-T phase diagram for this system using Monte Carlo simulations and show the magnetic field dependence of isolated skyrmions at magnetic fields with a ferromagnetic ground state. [1] A. Fert, et al. Nature Nano. **8**, 152 (2013). [2] M. Hervé *et al*., Nat. Comm. **9**, 1015 (2018)

# SP 14 Domain walls, vortices and skyrmions

**SP14 - Parallel Session 1**

**SP14.1.07**

### Chiral spin spiral and isolated skyrmions with vanishing anisotropy in Co/Ru(0001)

M. Hervé, B. Dupé, R. Lopez, M. Böttcher, M. D. Martins, T. Balashov, L. Gerhard, C. Gorenflo, J. Sinova, W. Wulfhekel

**Text** The stabilization of non-collinear chiral magnetic structure is usually attributed to a large Dzyaloshinskii-Moriya interaction (DMI). DMI is enhanced at surfaces and interfaces via the hybridization of the magnetic atoms with 5d elements. In our work, we show that a strong DMI is not a necessary condition to obtain a chiral magnetic order in ultra-thin films.

Our spin-polarized scanning tunneling microscopy study shows that one monolayer of Co/Ru(0001) possesses a spin spiral ground state, although the DMI is weak. Under moderated magnetic field (≈150 mT) isolated skyrmions can be stabilized. We attribute the stability of this spin texture to a vanishing magnetic anisotropy energy.



## SP14 - Parallel Session 2

### SP14 - Parallel Session 2

### SP14.2.01

## Theory of isolated magnetic skyrmions: From fundamentals to room temperature applications

F. Buettner, I. Lemesh, G. Beach

**Text** Skyrmions are the smallest non-trivial entities in magnetism with great potential for data storage applications. They were recently observed at room temperature in magnetic multilayer systems [1-4], most of them in materials with sizable Dyzaloshinskii-Moriya interaction (DMI). Despite this experimental breakthrough, our understanding of skyrmions is still limited because existing theories cannot analytically predict how the skyrmion energy changes as a function of its size. In particular, for many decades, the 6-fold integral of the stray field energies was considered unsolvable.

This problem has now been solved. In this talk, I will present a unified theory that analytically approximates the energy, including stray fields, of isolated skyrmions of all sizes with 1% precision [5]. I will show that there are two types of skyrmions, 'stray field skyrmions' and 'DMI skyrmions', with rigorous and practical distinction criteria. I will furthermore show that our model can predict materials with sub-10 nm skyrmions at zero field and room temperature, where those skyrmions can be moved with velocities exceeding 1000 m/s at reasonable current densities of $10^{12}$ A/m$^2$.

[1] Büttner et al., Nat Phys. 11, 225 (2015).
[2] Woo et al., Nat Mater. 15, 501 (2016).
[3] Moreau-Luchaire et al., Nat Nano. 11, 444 (2016).
[4] Boulle et al., Nat Nano. 11, 449 (2016).
[5] Büttner et al., Sci. Rep. 8, 4464 (2018).

# SP 14 Domain walls, vortices and skyrmions

**SP14 - Parallel Session 2**

**SP14.2.02**

### Hybrid chiral domain skyrmions in magnetic multilayers

W. Legrand, J.-Y. Chauleau, D. Maccariello, N. Reyren, S. Collin, K. Bouzehouane, N. Jaouen, V. Cros, A. Fert

**Text** Magnetic skyrmions are non trivial topological magnetic textures, holding a lot of promise for applications as well as of fundamental interest [1]. In magnetic multilayers, a key to stabilize skyrmions is the Dzyaloshinskii-Moriya interaction (DMI), existing at the interfaces between magnetic and heavy metal layers [1]. However, the exact role of the interfacial DMI, and jointly the one of the dipolar effects, in stabilizing these skyrmions, are not yet fully understood.
Here, we prove that a vertical dependent reorientation of the chirality is present, resulting in the stabilization of a chiral composite Néel-Bloch DW or skyrmion. Such hybrid chiral magnetic textures are indeed a direct consequence of the balance between the interfacial DMI, the exchange and the dipolar interaction between the different magnetic layers, as confirmed by our micromagnetic simulations. After having demonstrated a direct evidence of such hybrid chirality by probing the surface spin ordering of multilayers with circular dichroism in X-ray resonant magnetic scattering [2], we will also discuss the impact of such hybrid chiral skyrmions to achieve efficient current-induced motion [3].
Ackn: FLAG-ERA SoGraph, the European Union grant MAGicSky FET-Open-665095 and the ANR project TOPSKY are acknowledged.
References:
[1] A. Fert, N. Reyren, V. Cros, Nature Rev. Mat. 2, 17031 (2017);
[2] J.-Y. Chauleau et al, Phys. Rev. Lett. 120, 037202 (2018);
[3] W. Legrand et al, arXiv:1712.05978v2 (2017);

# SP 14 Domain walls, vortices and skyrmions

**SP14 - Parallel Session 2**

**SP14.2.03**

## Chiral thin-film magnetic structures display the Mallinson-Halbach effect

M. A. Marioni, M. Penedo, M. Baćani, H. J. Hug

**Text** The net interfacial Dzyaloshinkii-Moriya interaction that is conferred to magnetic material films using dissimilar material layers on either side of it has been shown to give rise to chiral magnetic structures. In particular, the formation of Néel type magnetic domain walls in such systems would result in an arrangement of magnetic moments that has the same topology of Halbach arrays. We study this possibility in thin film multilayers of Si/Pt/[Ir(1nm)/Co(0.6nm) /Pt(1nm)]$_{\times 5}$/Pt and other material systems using magnetic force microscopy. Exploiting the ability of that technique of providing quantitative measures of a sample's stray magnetic field we can show that the field strength is indeed weaker on one side of the film stack and stronger on the other. This characteristic can also be used to determine the sign of the Dzyaloshinkii-Moriya interaction, given its magnitude is known from e.g. the analysis of the domain structure's geometry. In our case and is found to be about 1.97 mJ/m$^2$. An interesting particular case of Halbach effect here concerns skyrmions, for which we likewise determine the attenuation/enhancement of stray field depending on the stack orientation. This could affect the design of devices based on stacked chiral magnetic structures.

# SP 14 Domain walls, vortices and skyrmions

**SP14 - Parallel Session 2**

**SP14.2.04**

### Skyrmion formation in $SrRuO_3$-$SrIrO_3$ epitaxial bilayer

H. J. Hug, A. O. Mandru, M. Bacani, X. Zhao, M. Penedo, M. Marioni, A. S. Ahmed, K.-Y. Meng, F. Y. Yang

**Text** $SrRuO_3$-$SrIrO_3$ bilayers have recently attracted attention due to their topological Hall effect (THE) as an evidence of interfacial Dzyaloshinskii–Moriya interaction (DMI), which may lead to the formation of a skyrmion phase. Strong THE was observed at 5 K, it decreases with increasing T, vanishes at 60 K, reappears at 90 K and persists until $T_C$(SRO). On the same bilayer we have performed high-sensitivity, high-resolution magnetic force microscopy (MFM) at 10, 30, 60 and 100 K and in fields up to a few Teslas. At 10 K we observe maze pattern of up/down domains of ~70 nm in size. At various locations domains with the same magnetization touch each other, and a narrow 360° wall forms. If an external field is applied, domains with a magnetization opposite to applied field shrink. At ~2250 mT both smaller bubble domains with sometimes irregular shape and circular domains with a di-ameter of 10-20 nm that may be stabilized by DMI and not solely by magnetostatics, i.e., skyrmions appear. MFM measurements performed at higher T show that the coercive field decreases with increasing T. MFM data acquired at 60K, where no THE is observed, indicate that fewer skyrmions exist. At 100 K, a higher number of skyrmions is observed again. Our measurements prove that a strong THE can occur even though no skyrmion phase but solely small bubble domains and a few skyrmions exist.

# SP 14 Domain walls, vortices and skyrmions

**SP14 - Parallel Session 2**

**SP14.2.05**

## First-principles study of skyrmion formation at 3d/4d transition-metal interfaces

S. Haldar, S. von Malottki, S. Meyer, P. Bessarab, S. Heinze

**Text** Typically, it is assumed that for the formation of skyrmions with a diameter of a few nanometers a 3d/5d transition metal (TM) interface is required due to the large spin-orbit coupling of heavy TMs which leads to large DMI. Here, we use DFT as implemented in FLEUR code (www.flapw.de)to demonstrate that ultrasmall skyrmions can also emerge at 3d/4d TM interfaces. We have calculated the magnetic interactions in atomic bilayers of Pd/Fe on the Rh(111) surface – a system which is similar to Pd/Fe/Ir(111)~[1-3] since Rh and Ir are isoelectronic 4d and 5d TMs. From our DFT calculations we parametrize an atomistic spin model including exchange interactions, DMI and the MAE. We find that both DMI and MAE are reduced with respect to Pd/Fe/Ir(111) which still allows a spin spiral phase at zero magnetic field due to DMI. Using spin dynamics simulations we find that a skyrmion phase occurs for both fcc and hcp stacking of the Pd layer at small magnetic fields of ~ 1 T. Depending on the stacking the skyrmion diameters amount to 4 to 6 nm. Skyrmion lifetimes and barrier heights for skyrmion collapse have been calculated using the geodesic nudged elastic band method and harmonic transition state theory [3,4].

[1] Romming N., et al., Science 341, 6146 (2013).
[2] Dupé B., et al., Nature Comm. 5, 4030 (2014).
[3] von Malottki, S., et al., 7, 12299 (2017).
[4] Bessarab, P. F., et al., Scientific Reports, 8, 3433 (2018).

# SP 14 Domain walls, vortices and skyrmions

**SP14 - Parallel Session 2**

**SP14.2.06**

## Damped localized excitations in *k*π-skyrmions

L. Rózsa, J. Hagemeister, E. Y. Vedmedenko, R. Wiesendanger

**Text** Magnetic skyrmions are particle-like magnetic structures with intriguing proposed applications in memory and logic devices. Localized spin wave excitations of skyrmions have also been investigated in the field of magnonics [1]. The *k*π-skyrmions are cylindrically symmetric spin configurations where the out-of-plane magnetization component rotates by *k*π between the center of the structure and the ferromagnetic background, with *k*=1 describing the conventional skyrmion [2].
Here we investigate the localized magnon modes of *k*π-skyrmions by relying on the Landau-Lifshitz-Gilbert equation, both analytically by expansion in small deviations around the equilibrium structure and numerically via spin dynamics simulations. For increasing values of *k* we find a higher number of localized modes, characterized by larger angular momentum quantum numbers or multiple nodes. By investigating the relaxation process, we demonstrate that the different modes exhibit different effective Gilbert damping parameters due to the noncollinearity of the spin structures, with some of the magnons becoming overdamped. It is discussed how the localized modes are connected to the creation process of *k*π-skyrmions [3].

[1] M. Garst et al., J. Phys. D: Appl. Phys. **50**, 293002 (2017).
[2] A. Bogdanov et al., J. Magn. Magn. Mater. **195**, 182 (1999).
[3] J. Hagemeister et al., arXiv:1802.09257 (2018).

# SP 14 Domain walls, vortices and skyrmions

**SP14 - Parallel Session 2**

**SP14.2.07**

## Multiscale model for the noncentrosymmetric B20-type crystals

S. Grytsiuk, N. Kiselev, F. Rybakov, M. Hoffmann, J.-P. Hanke, Y. Mokrousov, P. Mavropoulos, G. Bihlmayer, S. Blügel

**Text** The magnetic noncentrosymmetric crystals of B20-type, such as the transition-metal germanides and silicides, are the materials for which the direct observation of chiral magnetic skyrmions had been reported first. Over the past decade the study of these materials developed into a fascinating topic due to their potential application in skyrmion-based solid-state memory. Nevertheless, a complete model of these type of magnetic crystals, which would allow their study on a different scale is still missing. Most of the theoretical studies on B20 compounds use a model of classical Heisenberg ferromagnetism with Dzyaloshinskii-Moriya interaction assuming a homogeneous helix. However, with such a model only a qualitative description of the magnetic phenomena in B20 compounds is obtained so far.
We use first-principles calculations based on different DFT approaches in order to understand the non-collinear magnetism, focusing on B20 FeGe. Going beyond the approximation of homogeneous flat spin-spiral we have revealed (i) the complex relation between micromagnetic and atomistic parameters and (ii) the appearance of the local anisotropy associated to the atomic sub-lattices with different orientation of their three-fold rotation axes. Our findings extend the widely used microscopic model and form a basis for the development of a new advanced micromagnetic model of B20-type magnetic crystals providing quantitative agreement with experimental observations.

# SP 14 Domain walls, vortices and skyrmions

**SP14 - Parallel Session 2**

**SP14.2.08**

### Skyrmions with arbitrary topological charge in chiral magnets

F. N. Rybakov, N. S. Kiselev

**Text** It is widely thought that chiral interactions in magnets provide the stability of skyrmions [1] but at the same time dramatically restrict their diversity. In contrast to idealized isotropic ferromagnets (Belavin-Polyakov solutions) and baby Skyrme models, the coexistence of stable static solutions with different topological charges was questionable for chiral magnets. Recently it has been established that, for example, antiskyrmion (topological charge Q=1) is unstable [2] in conventional chiral magnets hosting skyrmions with Q=-1. The coexistence of these two states is possible in special magnets [3] where atomic structural asymmetries leads to anisotropic Dzyaloshinskii-Moriya interaction (DMI). Despite that, we show that the skyrmions with Q=-1, Q=1, and with an arbitrary integer Q can co-exist as stable spin textures even in conventional chiral magnets (the model includes: isotropic exchange interaction, isotropic DMI, external magnetic field and/or uniaxial anisotropy). The solutions were found by numerical energy minimization for initial states with sophisticated morphology.
[1] A. N. Bogdanov, D. A. Yablonskii, Sov. Phys. JETP 68, 101 (1989).
[2] W. Koshibae, N. Nagaosa, Nat. Commun. 7, 10542 (2016).
[3] M. Hoffmann et al., Nat. Commun. 8, 308 (2017).

# SP 14 Domain walls, vortices and skyrmions

## SP14 - Parallel Session 3

### SP14 - Parallel Session 3

### SP14.3.01

### Trochoidal motion and pair generation in skyrmion and antiskyrmion dynamics driven by spin-orbit torques

U. Ritzmann, S. von Malottki, J.-V. Kim, S. Heinze, J. Sinova, B. Dupé

**Text** Skyrmions and antiskyrmions can be stabilized in ultrathin magnetic films due to competing interactions as Dzyaloshinskii-Moriya interaction (DMI) and exchange interaction beyond the nearest neighbor approach. These spin states are characterized by opposite topological charges, which govern the sense of gyration in their dynamics. Until now, the robustness of the symmetry between opposite topological charges has not been examined in detail. In particular, the roles of core deformation, the internal degrees of freedom, and the underlying symmetry of the magnetic interactions remain an open question.
We used atomistic spin dynamics simulations with parameters derived from DFT, reduced variable modeling, and machine learning algorithms to study skyrmion and antiskyrmion dynamics under spin-orbit torques. While the expected rectilinear motion is found for skyrmions, we discover new dynamical regimes involving antiskyrmions: trochoidal motion and skyrmion-antiskyrmion pair generation. When a DMI symmetry is chosen that favors antiskyrmions over skyrmions, the opposite behavior is found — antiskyrmions follow rectilinear paths, while skyrmions undergo trochoidal motion and can generate skyrmion-antiskyrmion pairs. This illustrates the importance of the symmetry of the DMI, rather than the topological charge, in governing the dynamics. Our results suggest new avenues for exploiting skyrmion and antiskyrmion dynamics in nanodevices through DMI engineering.

# SP 14 Domain walls, vortices and skyrmions

**SP14 - Parallel Session 3**

**SP14.3.02**

## Understanding and controlling singularities in magnetic multilayers with X ray microscopy.

C. Quiros, M. Velez, A. Hierro-Rodriguez, A. Sorrentino, I. Estebanez, J. I. Martin, R. Valcarcel, L. M. Alvarez Prado, J. M. Alameda, E. Pereiro, S. Ferrer

**Text** Soft X ray transmission microscopy with circularly polarized photons tuned at specific resonant energies allows to image magnetic textures by exploiting the atom specific dichroic absorption contrast which depends on the angle of the magnetization and X ray beam. Changing their relative orientations allows determining the orientation of the magnetization of the sample. The reversal of the magnetization of40Py/60nm NdCo/40 nm GdCo trilayers grown by DC sputtering has been investigated with X ray microscopy and micromagnetic calculations. The intermediate layer is relatively magnetically hard compared to the other two and displays characteristic stripe domains with canted magnetization having in-plane and out of plane components. The stripes often have bifurcations that were found to be crucial for the inversion of the magnetization which proceeds from a Bloch point originated at a meron located at their branching. The topology of the bifurcations determines their localization either at the top or bottom side of the central NdCo layer the reason being the specific symmetry of the stray field . Our measurements and magnetic simulations indicate that the inversion of a stripe proceeds with the formation of a vortex-antivortex pair that moves for several µm upon applying the reversal field . As the motion is controllable, it might be of practical interest. Then, a second mechanism consisting on the appearance of cycloidal domains takes over continuing the inversion.

# SP 14 Domain walls, vortices and skyrmions

**SP14 - Parallel Session 3**

**SP14.3.03**

## Skyrmion lifetimes in exchange frustrated ultrathin films

S. von Malottki, P. Bessarab, A. Delin, S. Heinze

**Text** The thermal stability of magnetic skyrmions is a key issue for potential applications in spintronic devices. An Arrhenius law can be used to describe the skyrmion lifetime as a function of temperature, which requires knowledge of the energy barrier and the pre-exponential factor. While the energy barrier has already been addressed by several studies [1], the pre-exponential factor for the skyrmion collapse remains unexplored [2, 3].
Here, we address the dependence of the pre-exponential factor on the external magnetic field and demonstrate that its trend changes qualitatively when exchange frustration is taken into account. The origin of this effect can be traced back to a few skyrmion and saddle point modes, which will be discussed in detail. We focus on the model system Pd/Fe/Ir(111) [4], described by an atomistic spin model based on parameters from density functional theory [1]. The minimum energy paths are calculated using the geodesic nudged elastic band method, while the pre-exponential factors are determined by harmonic transition state theory [3].

[1] von Malottki, S., et al. (2017) Enhanced skyrmion stability due to exchange frustration. Sci. Rep. 7, 12299.
[2] Wild, J., et al. (2017) Entropy-limited topological protection of skyrmions. Sci. Adv. 3, e1701704.
[3] Bessarab, P. F., et al. (2017) Lifetime of racetrack skyrmions. Sci. Rep. 8, 3433.
[4] Romming, N., et al. (2015) Field-Dependent Size and Shape of Single Magnetic Skyrmions. Phys. Rev. Lett. 114, 177203.

# SP 14 Domain walls, vortices and skyrmions

**SP14 - Parallel Session 3**

**SP14.3.04**

## Simultaneous stabilization of skyrmions and antiskyrmions in rank-1 DMI materials allowing the concept of a skyrmion-antiskyrmion racetrack memory

M. Hoffmann, B. Zimmermann, G. P. Müller, N. S. Kiselev, C. Melcher, S. Blügel

**Text** Recently, we extended the scope of skyrmions and antiskyrmions and introduced a classification scheme of chiral magnets [1]. Typically investigated Bloch-type skyrmions in B20 alloys and Néel-type skyrmions at (111) oriented interfaces belong to isotropic rank-three Dzyaloshinskii-Moriya (DM) bulk and rank-two DM film magnets with a DM interaction described by a single spiralization constant. Within this class, antiskyrmions are stable only for bulk crystals with certain point group symmetries. New are the anisotropic rank-two DMI film magnets where skyrmions and antiskyrmions can coexist while the determinant of the spiralization tensor determines which of them have lower energy. Finally, zero determinant indicates a rank-one DMI material in which skyrmions and antiskyrmions have the same energy.
Here, we discuss the behavior of skyrmions and antiskyrmions in the same magnetic system of rank-one solids. Our focus lies on the analysis of their (common) motion and the orientation dependent interaction between the two skyrmionic objects of opposite topological charge.
Based on this, we propose a design of a racetrack memory based on the coexistence of skyrmions and antiskyrmions [2].

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[1] M. Hoffmann *et al.*, Nature Comm. **8**, 308 (2017)
[2] M. Hoffmann *et al.*, to be submitted

# SP 14 Domain walls, vortices and skyrmions

**SP14 - Parallel Session 3**

**SP14.3.05**

## Thermal stability of metastable magnetic skyrmions: Entropic narrowing and significance of internal eigenmodes

L. Desplat, D. Suess, J.-V. Kim, R. L. Stamps

**Text** We compute annihilation rates of metastable magnetic skyrmions using a form of Langer's theory in the intermediate-to-high damping regime. We look at three possible paths to annihilation that we relax via a geodesics nudged elastic bands scheme: isotropic collapse, isotropic collapse induced by another skyrmion and escape through a boundary. We find that the skyrmion's internal modes play a dominant role in the thermally activated transitions compared to the spin-wave excitations and that the relative contribution of internal modes depends on the nature of the transition process. Our calculations for a small skyrmion stabilized at zero-field show that the annihilation is largely dominated by the mechanism at the boundary, even though the activation energy is higher than that of isotropic collapse. In the present case, a potential source of stability of metastable skyrmions is therefore found not to lie in high activation energies, nor in the dynamics at the transition state, but comes from entropic narrowing in the saddle point region which leads to lower attempt frequencies. This narrowing effect is found to be primarily associated with the skyrmion's internal modes. Isotropic collapse induced by another skyrmion exhibits the same internal energy barrier as a single skyrmion, but a different entropic barrier.

# SP 14 Domain walls, vortices and skyrmions

**SP14 - Parallel Session 3**

**SP14.3.06**

### Skyrmion diffusion in thin film multilayers

M. Weißenhofer, J. Zázvorka, F. Jakobs, D. Heinze, N. Keil, S. Kromin, S. Jaiswal, K. Litzius, G. Jakob, P. Virnau, A. Donges, M. Kläui, U. Nowak

**Text** While being of fundamental interest as the type of diffusion yields information on transport and dissipation processes, thermally activated diffusion processes can also serve as a sensitive tool to analyze system properties. We use the stochastic Landau-Lifshitz-Gilbert equation to simulate diffusive motion of Skyrmions in a (Pt0.95Ir0.05)/Fe-bilayer on a Pd(111) surface. Here, the frustration of the isotropic exchange interactions in connection with the Dzyaloshinskii-Moriya interaction is responsible for the creation of skyrmionic structures [1].
We demonstrate the validity of the existing analytical theory for diffusion in flat energy landscapes [2] by calculating the diffusion coefficient for Skyrmions with different topological charges finding a linear temperature dependence as analytically expected.
Simulations including a heterogeneous energy landscape with pinning sites, however, lead to an exponential dependence of the diffusion coefficient on temperature in accordance with experimental findings. This observation can be explained by thermally activated depinning processes. For higher temperatures we find the expected transition into the linear regime, as the activation energy of the pinning site is overcome by thermal fluctuations. Finally, we investigate the effects of a thermal gradient on the diffusive motion and analyze the transition to a systematic propagation.
[1] Rózsa et al., Phys. Rev. B 95, 094423 (2017).
[2] Schütte et al., Phys. Rev. B 90, 174434 (2014).

# SP 14 Domain walls, vortices and skyrmions

**SP14 - Parallel Session 3**

**SP14.3.07**

## Fluctuating skyrmion ensembles on finite Pd/Fe/Ir(111) nanoislands

A. F. Schäffer, J. Berakdar, E. Y. Vedmedenko

**Text** Controlling magnetic textures is one of the main challenges on the path of developing the next generation of digital storage devices. Magnetic skyrmions as an example for such textures are an extremely promising candidate for new technologies, as they not only offer a small feature size of only a few nanometers, but also a theoretically predicted strong stability against external perturbations. This stabilization is mainly obtained due to their topologically non-trivial structure.

Before controlling skyrmion dynamics, e.g. by electric currents, pulsed laser or electron beams, it is necessary to understand the intrinsic properties itself.

In this study, we will present results on the thermal stability of magnetic skyrmions in systems of finite size, obtained from micromagnetic simulations. The special focus will be on the skyrmions' dynamics including defect-induced pinning and skyrmion-skyrmion interaction. In order to bridge the characteristic time-scale of the fluctuations to experimentally accessible time spans the influence of time-averaging of the magnetization dynamics will be discussed and compared to previous experimental studies.

# SP 14 Domain walls, vortices and skyrmions

**SP14 - Parallel Session 3**

**SP14.3.08**

## *In situ* Lorentz TEM of Magnetic Domains in FeRh Thin Film

M. S. Gorji, D. Wang, R. Witte, X. Mu, R. Kruk, C. Kübel, H. Hahn

**Text** Iron-rhodium (FeRh) with nearly equiatomic composition is an interesting material that exhibits two magnetic phase transitions. A first-order magnetic transition at slightly above room temperature (~77 ºC) from anti-ferromagnetic (AF) to ferromagnetic (FM) phase, and a second-order magnetic transition at ~402 ºC (Curie temperature) to paramagnetic phase. The AF-FM magnetic phase transition in FeRh is reversible and accompanied by an isotropic lattice expansion and an increase in resistivity. The near-room-temperature AF-FM transition makes FeRh an interesting choice to fabricate room-temperature AF spintronic memory devices. However, to understand the underlying fundamental dynamics of the FeRh AF-FM transition under the effect of magnetic field or as a function of temperature more comprehensive studies are required. An aberration-corrected transmission electron microscope (TEM) was used here to investigate the dynamics of the AF-FM transition using a Gatan heating holder. *In situ* TEM Lorentz measurements were carried out as a function of temperature and by performing *in situ* magnetization inside the microscope using the magnetic field induced by the objective lens of the TEM. In addition, the crystal structure was analyzed in high resolution (HR) TEM mode and then correlated to the observed magnetic properties of FeRh thin films. Our results help in understanding the correlation between crystal structure and the formation and evolution of magnetic domains and domain walls.

# SP 14 Domain walls, vortices and skyrmions

## SP14 - Parallel Session 4

### SP14 - Parallel Session 4

**SP14.4.01**

### Exchange coupling torque in antiferromagnetically coupled Co/Gd bi-layer system

R. Bläsing, T. Ma, S.-H. Yang, C. Garg, S. Parkin

**Text** In antiferromagnetic and ferrimagnetic thin films the efficiency of current-induced domain wall motion (CIDWM) by spin Hall currents from a heavy metal underlayer like Pt can be dramatically raised compared to ferromagnetic systems. As soon as the total angular momentums of the magnetic sublattices are equal, the torque due to the Dzyaloshinskii Moriya interaction (DMI) tends to zero and the more efficient exchange coupling torque becomes the dominant driving force. We carried out CIDWM experiments in antiferromagnetically coupled Co/Gd systems at base temperatures between 125 K and 250 K. The change of the magnetization of Gd due to the change of temperature within this range allows to compensate the total magnetic angular momentum of the Gd and Co sublayers at a compensation temperature T_A ≈ 219 K which is slightly higher than the magnetic moment compensation temperature at T_M = 210 K. Our data suggests the existence of DMI in Co arising at the Co/Gd interface which effective field is opposite to that of the DMI at the Pt/Co interface. Based on findings of our 1D model, we develop a novel method to measure heating effects in a two-material based magnetic bi-layer system and prove an efficiency boost due the exchange coupling torque at T_A.

# SP 14 Domain walls, vortices and skyrmions

**SP14 - Parallel Session 4**

**SP14.4.02**

## Two creep regimes induced by strong current actions on ferrimagnetic domain walls

E. Haltz, A. Mougin, J. Sampaio, R. Weil

**Text** Ferrimagnetic materials have coveted tunable magnetic properties, as required for proposed devices in the storage and processing information non-volatile low energy consumption. Very recent experimental and theoretical studies show the extent and diversity of domain wall (DW) motion (DWM) dynamics in ferrimagnetic materials .

To explore this landscape of magnetic dynamics, using direct Magneto-Optic Kerr imaging, we studied effects of current on DW in ferrimagnetic tracks made in TbFe ferrimagnetic amorphous alloys thin film with perpendicular magnetic anisotropy. We first clearly identified and quantified a creep regime of DWM under field. We next observed DWM under combined effect of field and low current. We determined how Joule heating modifies the mobility of the DW in the creep regime. We also determined the efficiency of spin transfer torque on DWM by considering an equivalent field approach in a 1D model extended for creep. We measured a strong efficiency, 2.10^-2mT/GA/m^2 more than 100 times larger than in classical ferromagnetic materials. Finally, we observed a discontinuous current dependence of this effective field, which is the signature of two different DW propagation modes. These two regimes are separate by a critical value of current, necessary to induced modifications of internal magnetic structure of the DW. Due to the strong spin transfer torque action on ferrimagnetic DW, this critical current density becomes accessible in ferrimagnets.

# SP 14 Domain walls, vortices and skyrmions

**SP14 - Parallel Session 4**

**SP14.4.03**

## Ultrafast and ultrasmall: domain walls and skyrmions in compensated ferrimagnetic thin films

L. Caretta, M. Mann, F. Buettner, K. Ueda, B. Pfau, C. Guenther, P. Hessing, A. Churikova, C. Klose, M. Schneider, D. Engel, C. Marcus, D. Bono, K. Bagschik, S. Eisebitt, G. Beach

**Text** Spintronics is a research field geared towards understanding and controlling spins on the nanoscale, enabling next generation data storage and manipulation. The technological and scientific challenge is to stabilize ultrasmall spin textures (bits) and to move them efficiently with ultrahigh velocities. Inspired by hard disk materials, research so far has focused on ferromagnetic materials, but these materials show fundamental limits for speed and size, calling for radically new materials systems and different ideas. Here, we demonstrate by direct imaging that compensated ferrimagnets are not affected by these limits. Using ferrimagnetic Pt/GdCo/Ta films with sizable Dzyaloshinskii-Moriya interaction (DMI), we realize a record-high current-driven domain wall velocity of 1.3 km/s and room-temperature stable 10 nm diameter skyrmions near the angular momentum ($T_A$) and magnetic compensation ($T_M$) temperatures, respectively. FiM are a promising spintronics candidate as their properties can be controlled by a range of easily accessible knobs, such as interfaces, annealing, sample temperature, and composition. We present a simple theory explaining that our observations are universal and that high speed, high density spintronics devices can only be realized using materials where $T_A$ and $T_M$ are close together.

# SP 14 Domain walls, vortices and skyrmions

**SP14 - Parallel Session 4**

**SP14.4.04**

## Material Systems for Skyrmions in Co-based Multilayers

H. Jia, B. Zimmermann, G. Bihlmayer, S. Blügel

**Text** Magnetic skyrmions, in particular skyrmions in synthetic antiferromagnets, are considered to be ideal candidates for high storage-density information carriers. Magnetic multilayers (MMLs) with composite structures provide a great platform for the design of magnetic skyrmions, spin spirals, or domain walls with optimal properties. In this context, the Dzyaloshinskii-Moriya interaction (DMI), which arises at the interfaces of MMLs, plays a particularly important role.

In this contribution, we explore the properties of MMLs of the type {*Z*|Co|Pt}, where we consider for *Z* prominent 4*d* transition metals, noble metals, as well as Zn and Cd. Our investigations are based on density-functional theory (FLAPW method as implemented in the FLEUR code, www.flapw.de). The large DMI of the Co/Pt interface can be drastically tuned by hybridization with the third layer, *Z*, and can even be enhanced. We predict *Z*=Cd or Zn as interesting combinations of materials to realize skyrmions in a synthetic antiferromagnet. We demonstrate that a fine-tuning of interlayer exchange coupling can be achieved by varying the Pt thickness. We even find materials regimes where, due to frustrated exchange, a non-collinear order arises along the stack. We further relate the strength of DMI to a descriptor that can be calculated quickly and be used for screening of chiral MMLs by high throughput methods.

We acknowledge funding by EU-H2020 project MAGicSky (No 665095) and DARPA TEE program (#HR0011831554) from DOI.

# SP 14 Domain walls, vortices and skyrmions

**SP14 - Parallel Session 4**

**SP14.4.05**

## Interlayer Dzyaloshinskii-Moriya interactions

E. Y. Vedmedenko, J. A. Arregi, P. Riego, A. Berger

**Text** Interfacial Dzyaloshinkii-Moriya interaction defines a rotational sense for the magnetization of two-dimensional films making it responsible for the formation of chiral magnetic structures like spin-spirals and skyrmions in those films [1]. Here we show by means of atomistic calculations that in heterostructures magnetic layers can be additionally coupled by an interlayer Dzyaloshinskii-Moriya interaction across a spacer. We quantify this interaction in the framework of the Levy-Fert model for trilayers consisting of two ferromagnets separated by a non-magnetic spacer yielding non-trivial three-dimensional spiral states across the trilayer. This analysis enables three-dimensional tailoring of the magnetization chirality in magnetic multilayers [2].

[1] J. Hagemeister, N. Romming, K. von Bergmann, E. Y. Vedmedenko, R. Wiesendanger, Nature Communications 6, 8455 (2015).
[2] E. Y. Vedmedenko, J. A. Arregi, P. Riego, A. Berger, ArXive: 1803.10570.

# SP 14 Domain walls, vortices and skyrmions

**SP14 - Parallel Session 4**

**SP14.4.06**

## Effective description of magnetic domain walls and skyrmions in ferromagnets and antiferromagnets

D. Rodrigues, A. Abanov, J. Sinova, K. Everschor-Sitte

**Text** We derive a microscopic-detail-independent Hamiltonian formalism for spin textures in ferro- and antiferromagnetic nanowires and thin films. Within the effective one-dimensional model, we treat domain walls as objects whose dynamics are described by two soft modes, their position and azimuthal angle. By extending our model to a bipartite lattice we derive a theory for the dynamics of antiferromagnetic domain walls revealing an orientation switching mechanism.[1] In thin films, however, domain walls exhibit a richer structure including vortices and curvatures. We provide a theory in terms of soft modes that allows to analytically study the physics of extended domain walls and their stability. By considering irregular shaped skyrmions as closed domain walls, we analyze their plasticity and compare their dynamics with those of circular skyrmions. Going beyond the often-used circular approximation for skyrmions we find for example that deformations in the skyrmion shape travel along its border. Our theory directly provides an analytical description of the excitation modes of magnetic skyrmions, previously only accessible by sophisticated micromagnetic numerical calculations and spectral analysis.[2][1] Rodrigues, et al., PRB 95, 174408 (2017); [2] Rodrigues, et al., arxiv:1712.09918

# SP 14 Domain walls, vortices and skyrmions

**SP14 - Parallel Session 4**

**SP14.4.07**

## Skyrmions like it Hot – Temperature Dependence of the Skyrmion Hall Effect

K. Litzius, P. Bassirian, J. Leliaert, S. Kromin, J. Zázvorka, I. Lemesh, K.-J. Lee, N. Kerber, A. Churikova, D. Heinze, N. Keil, A. Pfeiffer, M. Weigand, G. Schütz, G. S. D. Beach, M. Kläui

**Text** Magnetic skyrmions are nanoscale magnetic defects with spherical topology. They are promising candidates for future spintronic devices and in interfacial systems usually stabilized by the Dzyaloshinskii-Moriya interaction that favors a chiral spin canting. Additionally, these films can provide efficient spin dynamics, making them extremely promising for applications. It was found very recently that during their dynamics a sizeable skyrmion Hall angle (SkHA) occurs that surprisingly depends on the skyrmion velocity [1-3]. Different theoretical models have been put forward for the creep [1,2] and viscous flow [3] regime to explain this behaviour.

By X-ray microscopy, we investigate skyrmion dynamics at varying temperatures and at the complete velocity regime from creep to viscous flow to determine their dependence on thermal activation. We find that the skyrmion Hall angle is independent of the temperature when plotted as a function of the skyrmion velocity. We identify two different mechanisms that lead to distinctly different spin Hall angles in the creep and the flow regimes. Furthermore, we find highly temperature dependent skyrmion velocities and critical current densities and identify thermal activation and temperature dependent spin orbit torques as possible explanations for this behaviour.

Ref.: [1] W. Jiang et al., Nat. Phys. 13, 162-169 (2017). [2] C. Reichhardt & C. J. O. Reichhardt, New J. Phys. 18, 095005 (2016). [3] K. Litzius et al., Nat. Phys. 13, 170-175 (2017).

# SP 14 Domain walls, vortices and skyrmions

**SP14 - Parallel Session 4**

**SP14.4.08**

## Probing the ultimate size limit of artificial magnetic domains in exchange-biased thin films

A. Gaul, D. Emmrich, T. Ueltzhöffer, H. Huckfeldt, H. Doğanay, J. Hackl, M. I. Khan, D. M. Gottlob, G. Hartmann, A. Beyer, S. Nemšák, D. Holzinger, C. M. Schneider, A. Gölzhäuser, G. Reiss, A. Ehresmann

**Text** Magnetic domains with individually designed geometry and local magnetic anisotropies play a key role in the advance of data processing, sensor applications or engineering of magnetic stray field tracks, suitable for remote motion control of magnetic nanoobjects. The intrinsic domain size limit for in-plane magnetized thin films is strongly correlated to energy contributions, i.e. anisotropy, exchange interaction and demagnetization energy, and typically in the range of a few 100 nm. Therefore, experimental access to the microscopic formation of the magnetization distribution is a demanding task for commonly available techniques.

Here we present a novel method for direct domain writing in exchange biased multilayer systems by using an ultra-highly focused ion beam of a helium ion microscope. We investigate the ultimate size limits of an $Ir_{17}Mn_{83}/Co_{70}Fe_{30}$ prototype system in dependence on the domain geometry and the domain wall orientation with respect to the unidirectional anisotropy of the system through the fabrication of differently sized and shaped domain patterns. These patterns were investigated by Kerr-microscopy, magnetic force microscopy and resonant X-ray photo emission electron microscopy. Micro magnetic simulations were performed to interpret the experimental findings. It is shown that the ultimate domain size depends on the domain wall widths and therefore on material properties and the orientation of the domain walls with respect to adjacent domain anisotropies.

# SP 14 Domain walls, vortices and skyrmions

## SP14 - Parallel Session 5

**SP14 - Parallel Session 5**

**SP14.5.01**

### Polymorphism of the low-temperature metastable magnetic states in a strained FeGe lamella

V. Ukleev, Y. Yamasaki, O. Utesov, K. Shibata, N. Kanazawa, Y. Tokura, T.-h. Arima

**Text** Strain effect plays an important role for the magnetic properties of cubic helimagnets with Dzyaloshinskii-Moriya interaction (DMI). Recently, Shibata et al. has shown that the deformation of the skyrmion crystal (SkX) takes place due to the strain-induced anisotropy of DMI in FeGe lamella [1]. Furthermore, transformation of the ground state of $Cu_2OSeO_3$ from proper-screw structure to chiral soliton lattice (CSL) due to the tensile strain, also accompanied by the elliptical deformation of the SkX has been observed by Okamura et al. [2].

In a thin plate of FeGe a robust zero-field SkX state can be obtained at low temperature by field cooling procedure, which provides a versatile opportunities to investigate SkX stability under oblique, perpendicular and negative magnetic fields. In present work we report resonant small-angle X-ray scattering (RSXS) study on the polymorphism of the magnetic states in a thin plate of FeGe containing the tensile strain. We demonstrate that the SkX and CSL can be achieved as the metastable states in the strained FeGe lamella as a distinct states or even simultaneously. The RSXS data is discussed with the analytical model which is sufficient to describe the experimental results for CSL. Behavior of the metastable SkX in the perpendicular magnetic field as seen by RSXS experiment is compared with the results of micromagnetic simulation.

[1] K. Shibata, et al., Nature nanotechnology 10, 589 (2015).
[2] Y. Okamura, et al., Phys. Rev. B 96, 174417 (2017).

# SP 14 Domain walls, vortices and skyrmions

**SP14 - Parallel Session 5**

**SP14.5.02**

## Effect of extended defects over the skyrmionic dynamics. Analytical and numerical treatment

C. Navau, N. Del-Valle, J. Castell-Queralt, L. González-Gómez, A. Sanchez

**Text** The movement of current-driven skyrmions along nanotracks can be used to pass information from one point to another through a defined path. This guiding of the information coded in the skyrmionic structure depends on the interaction of the skyrmions with the borders of the track and is highly affected by the defects in the materials. We present a theory to account for the effect that extended (one-dimensional) defects produce over interfacial skyrmion dynamics. The defect is modelled as a local modification of exchange, Dzyaloshinskii-Moriya and/or anisotropy interaction. From the Hamiltonian at the atomic level, the micromagnetic energy density and the effective field produced by the defect are obtained. We also present analytical expressions for the forces exerted by the defect over a skyrmion within the Thiele's rígid approximation. Interesting results on the dynamics produced by the one-dimensional defects such as a guiding and an acceleration of skyrmions along the defects are obtained, regardless of the presence of the borders in the nanotrack. We find that under the adequate conditions, the skyrmions can be used as an efficient way for transmiting information. Micromagnetic simulations are also done to validate the results and also to bound the range of applicability of the analytic treatment.

## SP 14 Domain walls, vortices and skyrmions

**SP14 - Parallel Session 5**

**SP14.5.03**

### Complex Magnetic Bubbles in Patterned NdCo5 Films with Weak Perpendicular Magnetic Anisotropy

A. Hierro Rodriguez, G. W. Paterson, G. Macauley, L. M. Alvarez-Prado, M. Velez, J. M. Alameda, J. I. Martin, S. McVitie

**Text** The study of topological magnetic textures attracts great research interest in the field of magnetism. The importance of skyrmions in the development of novel spintronic devices for greener and more sustainable technologies supports this focus, as does the beauty and complexity of topological magnetic texture physics. In this framework, we report here on the observation of a very complex magnetic configuration consisting in two Bloch points coupled to Néel skyrmion and anti-skyrmion-like textures in a NdCo5 film patterned into a series of grooves. The core of the structure is similar to a type II bubble[1], but because of the weak perpendicular magnetic anisotropy of the magnetic alloy[2] the two skyrmion-like textures are formed at different surfaces of the film. Differential phase contrast imaging in a scanning transmission electron microscope[3] has been used to characterize the magnetic system, revealing the presence of the magnetic texture. Micromagnetic simulations have been performed to unravel the 3-D magnetic configuration of the texture, and its formation and evolution into a standard bubble. Importantly, the thickness steps are found to stabilize the texture at the edges of the grooves and can be used to nucleate and arrange them in a controlled manner.

[1] X. Yu et al, Proc.Natl.Acad.Sci. U.S.A. 109, 8856 (2012).
[2] A. Hierro-Rodriguez et al, Phys.Rev.Lett. 109, 117202 (2012).
[3] S. McVitie et al, Ultramicroscopy 152, 57 (2015).

# SP 14 Domain walls, vortices and skyrmions

**SP14 - Parallel Session 5**

**SP14.5.04**

## Universality of defect-skyrmion interaction profiles

I. L. Fernandes, J. Bouaziz, S. Blügel, S. Lounis

**Text** Owing to their topological properties, magnetic skyrmions are prime candidates for future spintronic devices. However, incorporating them as possible bits of information hinges on their interaction with inhomogeneities present in any device since their nucleation, motion and velocity are heavily affected. Thus, a detailed knowledge of defects-skyrmion interaction is desirable but unknown, which limits the realization of such topological magnetic entities as possible bits of information. We map from full ab initio, the energy-landscape of single magnetic skyrmions interacting with single-atom impurities, establishing a generic shape as function of the defect's electron filling. Depending on their chemical nature, foreign 3d and 4d transition metal adatoms or surface-implanted defects can either repel or pin skyrmions generated in a PdFe bilayer deposited on Ir(111) surface. With a careful analysis of the hybridization of the electronic states, the mechanism behind the expulsion and pinning can be related to the degree of filling of bonding and anti-bonding electronic states inherent to the proximity of the non-collinear magnetic structure. The universality of the interaction profile may give guidance for the ultimate design of devices generating, controlling and guiding skyrmions.
- Funding provided by the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (ERC-consolidator grant 681405 — DYNASORE).

# SP 14 Domain walls, vortices and skyrmions

**SP14 - Parallel Session 5**

**SP14.5.05**

### Experimental observation of chiral magnetic bobbers in nanostructured FeGe

N. S. Kiselev, F. Zheng, F. N. Rybakov, A. B. Borisov, D. Song, S. Wang, Z.-A. Li, H. Du, J. Caron, A. Kovács, M. Tian, Y. Zhang, S. Blügel, R. E. Dunin-Borkowski

**Text** Chiral magnets represent a special class of magnetically ordered crystals that are characterized by broken inversion symmetry and strong spin-orbit coupling, giving rise to the Dzyaloshinskii-Moriya interaction (DMI). The presence of the DMI usually prevents the stability and coexistence of topological excitations of different types. Nevertheless, recently a new type of localized particle-like object -- the chiral bobber (ChB) - was predicted theoretically in such materials[1]. Such a hybrid 3D magnetic soliton can be thought of as a skyrmion tube, which is coupled to the surface and whose end takes the form of a Bloch point. Here, we report the direct observation of ChBs in nanostructured samples of B20-type FeGe[2]. We use quantitative off-axis electron holography to identify ChBs in a thin plate of B20-type FeGe and to find the range of their stability in a temperature-field phase diagram. We reveal two distinct mechanisms of ChB nucleation and confirm the coexistence of ChBs with ordinary magnetic skyrmions over a wide range of field, temperature and film thickness. The coexistence of ChBs and skyrmion tubes provides a perspective for practical applications in novel racetrack memory devices, in which a stream of binary data bits is encoded by a sequence of skyrmions and bobbers[2].

[1] F. N. Rybakov et al. Phys. Rev. Let. **115**, 117201 (2015).
[2] F. Zheng et al., Nat. Nanotech. (2018) in press

# SP 14 Domain walls, vortices and skyrmions

**SP14 - Parallel Session 5**

**SP14.5.06**

### Straight motion of magnetic defects in Fe-N thin films

S. Fin, R. Silvani, S. Tacchi, M. Marangolo, L.-C. Garnier, M. Eddrief, C. Hepburn, F. Fortuna, A. Rettori, M. G. Pini, D. Bisero

**Text** The field-dependent motion of magnetic edge dislocations, embedded in a stripe domain pattern have been investigated in Fe-N thin films presenting a moderate perpendicular magnetic anisotropy (PMA). $N_2^+$ ions were implanted in gold-capped iron layers epitaxially grown on ZnSe-buffered GaAs(001) substrates. The Fe-N thin films (about 80 nm-thick) present a PMA of about $10^5$ J/m$^3$ and exhibit magnetic stripe domains with a period of about 100 nm. These domains are particularly straight and display spontaneously bifurcations identified as edge dislocations, at room temperature, as remanence is approached. The study is focused on the driving effect exerted on the magnetic defects by an external DC magnetic field applied along the axis of the stripes. Combining magnetic force microscopy measurements and micromagnetic simulations, we find that, for moderate field intensity, the edge dislocations are displaced along a straight trajectory parallel to the stripes. Based on the Thiele equation, this straight trajectory is found to be due only to the external and dissipative forces, whose directions are parallel to the stripes. As for the gyrotropic force on an edge dislocation, it is shown to vanish owing to the periodic stripe domain pattern. In comparison with skyrmions which have a gyrotropic motion when they are subjected to a magnetic field, the straight motion of magnetic edge dislocations could be advantageous for use as information carriers in defect-based spintronics.

# SP 14 Domain walls, vortices and skyrmions

**SP14 - Parallel Session 5**

**SP14.5.07**

## Quantitative magnetic imaging of skyrmions and related spin structures using off-axis electron holography

A. Kovács, N. Kiselev, Z.-A. Li, H. Du, F. Zheng, D. Song, F. Rybakov, J. Caron, J. Zang, S. Blügel, R. Dunin-Borkowski

**Text** Magnetic skyrmions promise to provide significant advantages over domain walls in racetrack memory devices, as their sizes can be reduced to a few tens of nm and the electric current densities that are required for their motion are orders of magnitude lower. The family of skyrmion-hosting materials and heterostructures is expanding rapidly, resulting in significant challenges in the quantitative measurement and visualization of magnetic states with high spatial resolution. Here, we use off-axis electron holography in the transmission electron microscope to study the stabilities of Bloch-type skyrmions in samples of FeGe that take the forms of nanostripes [1] or nanodisks [2]. We find that the skyrmions are able to adopt a wide range of sizes and shapes. We use iterative model-based reconstruction to determine the local magnetization distribution in a lattice of Bloch-type skyrmions and reveal the magnetic-field-driven formation of chiral edge states [3]. We also obtain direct experimental evidence for the formation of chiral bobbers, which are particle-like objects that are able to coexist with skyrmions over a wide range of temperatures and applied magnetic fields and provide additional possibilities for practical applications.

1. C. Jin et al., Nat. Comm. 8, 15569 (2017)
2. F. Zheng et al., Phys. Rev. Lett. 119, 197205 (2017)
3. D. Song et al., Phys. Rev. Lett. (2018) in press
4. F. Zheng et al., Nat. Nanotech. (2018) in press

# SP 14 Domain walls, vortices and skyrmions

**SP14 - Parallel Session 5**

**SP14.5.08**

## Towards retrieving the 3D Spin Texture of Skyrmions in Thin Helimagnets

S. Schneider, D. Wolf, M. J. Stolt, S. Jin, D. Pohl, B. Rellinghaus, M. Schmidt, B. Büchner, S. T. Goennenwein, K. Nielsch, A. Lubk

**Text** Skyrmions [1] are topologically non-trivial vortex-like spin textures, anticipated for application in spintronic technologies, referred to as skyrmionics [2,3]. Knowledge about the full three-dimensional spin texture is of particular importance. We combine inline and off-axis electron holography (EH) to quantitatively reconstruct the projected magnetic field pertaining to both the helical and the skyrmion lattice phase of chiral magnet Fe0.95Co0.05Ge. In combination with electron tomography and magnetostatic simulations, we extract quantitative information on the 3D spin texture of skyrmions. Our experiments yield an in-plane magnetic flux of up to 0.3 T in the skyrmions, which is substantially smaller than the field values expected for z-invariant Bloch skyrmions. The analysis of a cryogenic tilt series of the helical phase results in the observation of a sinusoidal modulation of the Lorentz contrast [4]. Both findings provide evidence for a characteristic 3D modulation of the skyrmionic spin texture. They highlight the relevance of surfaces for the formation of skyrmions in thin film geometries and may pave the way towards a surface-induced tailoring of the skyrmion structure.

[1] A. N. Bogdanov and A. Hubert, J. Magn. Magn. Mater. 138, 255 (1994).
[2] N. Nagaosa and Y. Tokura, Nature Nanotechnology 8, 899 (2013).
[3] N. Kanazawa et al., “Noncentrosymmetric Magnets Hosting Magnetic Skyrmions” (2017).

# SP 14 Domain walls, vortices and skyrmions

## SP14 - Parallel Session 6

### SP14 - Parallel Session 6

### SP14.6.02

### Unidirectional magnon-induced domain wall motion in the presence of interfacial Dzyaloshinskii-Moriya interaction

S.-W. Lee, K.-W. Kim, J.-H. Moon, G. Go, A. Manchon, H.-W. Lee, K. Everschor-Sitte, K.-J. Lee

**Text** We present a magnon-induced domain wall motion whose direction is independent of the direction of the incident magnonic flow. In previous studies, the magnon-induced domain wall motion is known to change its direction upon changing the direction of the magnon injection. In this work, we show that the interfacial Dzyaloshinskii-Moriya interaction (DMI) can change the phenomenology completely. Based on the asymmetric nature of the DMI, we show by means of a general symmetry argument that the first order DMI contribution to the domain wall velocity is independent of the sign of incident magnon momentum, thus it is unidirectional. We performed micromagnetic simulations with an in-plane transverse domain wall to explicitly show that the unidirectional contribution is the dominant over a wide range of parameters in a realistic regime. We also show that thermal magnons result in a unidirectional motion, thus for example, heating both sides of a domain wall symmetrically will still result in a motion along a particular direction. Our analytical calculation reveals that the unidirectional ity originates from an asymmetric momentum transfer from magnons to the domain wall, which gives rise to a much larger contribution to the domain wall velocity than the conventional angular momentum transfer mechanism considered in non-DMI systems.

# SP 14 Domain walls, vortices and skyrmions

**SP14 - Parallel Session 6**

**SP14.6.03**

## Asymmetric Non-collinear Magnetic Domain Wall Motion Induced By Electric Current

M. A. Nsibi, J. Nath, I. Joumard, S. Auffret, I. M. Miron, G. Gaudin

**Text** Novel devices based on current domain wall (DW) motion have regained attention after evidencing spin-orbit torques (SOT) and Dzyaloshinskii-Moriya interaction (DMI) in stacks with a structural inversion asymmetry (SIA). SOT and DMI were proposed to explain the fast motion of DW. Other mechanisms, like chiral damping, have been demonstrated to play a role in DW dynamics in Pt/Co/Pt with a perpendicular magnetic anisotropy. We pursue the study of electric current DW motion, with Kerr effect microscopy, in this structure to investigate DMI and SOT contributions in the presence of chiral damping. The motion was studied in a non-collinear configuration with respect to the current consisting on a DW moving along a direction at a non-zero angle with respect to the direction of the current. The displacements are asymmetric with respect to the collinear configuration. At a certain angle, the DW is at its largest displacement. Whereas, it is shorter at its corresponding conjugate angle. The motion was also examined in the presence of an external in-plane magnetic field. By acting on the internal configuration of the DW, the field alters the action of SOT. The results are only partially accounted for by the combined action of DMI and SOT. Our findings uncover new aspects of DW dynamics in SIA stacks. There is so a need for an extended model to understand DW dynamics. Moreover, this asymmetric DW motion offer new ways to manipulate ferromagnetic pillars in spintronic devices.

# SP 14 Domain walls, vortices and skyrmions

**SP14 - Parallel Session 6**

**SP14.6.04**

## Depinning of magnetic domain walls in thin Ferromagnets

V. Jeudy, R. Diaz Pardo, W. Savero Torres, S. Bustingorry, A. Kolton

**Text** We will present quantitative investigations on magnetic domain wall pinning in thin magnetic films with perpendicular anisotropy. A self-consistent description of the depinning and thermally activated subthreshold creep universal regimes [1-2] is used to determine the pinning parameters parameters (depinning threshold, velocity at depinning and effective height of pinning barriers) controlling magnetic field induced domain wall motion. From this analysis, we propose a quantitative comparison between the pinning properties of different magnetic materials (Pt/Co/Pt; CoFeB/MgO, Co/Ni, (Ga,Mn)(As,P) …) and discuss the variation of the pinning parameters with the micromagnetic properties. Based on scaling arguments, the microscopic parameters controlling the pinning are estimated: correlation length of pinning, collectively pinned domain wall length (Larkin length), the strength of pinning disorder [3].

[1] V. Jeudy et al., Phys. Rev. Lett. 117, 057201 (2016) [2] R. Diaz Pardo et al.,Phys. Rev. B 95, 184434 (2017) [3] V. Jeudy et al., arXiv:1709.08009

# SP 14 Domain walls, vortices and skyrmions

**SP14 - Parallel Session 6**

**SP14.6.05**

## Anisotropic domain wall velocity in quasi-perpendicularly magnetized Ta/Pt/CoFeB/Pt multilayers

S. Guddeti, A. Kollakuzhiyil Gopi, P. S. A. Kumar

**Text** We report anisotropic domain wall velocity profiles in quasi-perpendicularly magnetized Ta/Pt/CoFeB/Pt multilayer thin films. Ta(3 nm)/Pt(3 nm)/CoFeB(x nm)/Pt(1 nm) multilayer thin films are deposited on $SiO_2$ substrate using oblique-angle sputter deposition technique with a thickness gradient in CoFeB layer and uniform thickness for the rest of the layers resulting in a slight tilt (0.70°) in the anisotropy away from the perpendicular direction. The thickness gradient direction and the in-plane tilt direction, defined as the direction of in-plane projection of tilt, are orthogonal to each other. Magnetic bubble domain expansion measurements using wide field differential Kerr microscopy on Ta(3 nm)Pt(3 nm)CoFeB(0.38 nm)Pt(1 nm) reveals anisotropic domain wall expansion across the film plane. The domain wall velocity along the in-plane tilt direction is maximum(9.0 $cms^{-1}$ at 80 Oe) and that along perpendicular to in-plane tilt direction is minimum (6.7 $cms^{-1}$ at 80 Oe) leading to an elliptical profile for the magnetic bubble domain. Domain wall velocities are measured by pulsing magnetic fields and the anisotropic expansion of the domain wall is calculated from the differential images before and after the pulse using image processing. The pulse width is varied from 5 ms to 2000 ms and the applied perpendicular field varies from 10 Oe to 50 Oe. Further measurements to quantify Dzyaloshinskii-Moriya interaction are done by applying an additional in-plane magnetic field.

# SP 14 Domain walls, vortices and skyrmions

**SP14 - Parallel Session 6**

**SP14.6.06**

## SEMPA investigation of the Dzyaloshinskii-Moriya interaction in the single, ideally grown Co/Pt(111) interface

R. Frömter, E. C. Corredor, S. Kuhrau, F. Kloodt-Twesten, H. P. Oepen

**Text** The experimental investigation of the Dzyaloshinskii-Moriya interaction (DMI) of a single, ideally grown interface is compelling, as it allows the direct comparison with ab-initio calculations. We present a study [1] of domains and domain walls in epitaxial, single-layer cobalt films on Pt(111) with a pseudomorphic, atomically flat interface by means of scanning electron microscopy with polarization analysis (SEMPA), which is a surface-sensitive, vectorial imaging technique with a magnetic probing depth of less than 5 atomic layers.

Uncapped, thermally evaporated cobalt on a clean platinum single-crystal surface is imaged in situ in ultrahigh vacuum. For a cobalt thickness of 1.4 nm we observe Néel-like domain walls that show a fixed, counterclockwise sense of rotation, indicating a strong DMI that originates from the single Co/Pt interface. From the observation of a pure Néel-like rotation we derive a lower bound for the DMI strength of $0.5\times10^{-3}$ $J/m^2$, which is equivalent to a DMI energy per interface bond larger than 0.8 meV. An upper bound for the DMI energy of 4.3 meV per interface bond is derived from the observation of stable domains at the onset of ferromagnetism at 0.3-nm Co thickness, corresponding to an average Co coverage of 1.5 monolayers.

[1] E.C. Corredor et al., PRB **96**, 060410(R), 2017.

# SP 14 Domain walls, vortices and skyrmions

**SP14 - Parallel Session 6**

**SP14.6.07**

## Current driven domain wall motion in individual cylindrical magnetic nanowires

M. Schöbitz, S. Martin, S. Bochmann, L. Cagnon, L. Ranno, C. Thirion, J. Bachmann, O. Fruchart

**Text** Fabricating a 3D matrix of magnetic nanowires (NWs), for a nonvolatile 3D memory device as proposed by Parkin *et al*. in 2008, is now more achievable due to progress made in the electrodeposition of metallic material into nanoporous membranes [1]. It was predicted that cylindrical rotation symmetry in NWs allows high velocity domain wall (DW) motion due to the absence of Walker breakdown [2]. A present challenge is to implement a reliable procedure to move DWs with a current pulse. Here we report results on DW motion in cylindrical nickel NWs electrodeposited in alumina templates.

To access individual NWs, a membrane is dissolved and wires are dispersed on a wafer surface. We developed a nanofabrication process to contact single wires. It is optimized to minimize the electrode resistance and to obtain an Ohmic contact, allowing us to inject current pulses of magnitudes up to $2.5\times10^{12}$ $A/m^2$ and lengths up to 100 ns half width.

With this setup we performed current driven DW motion which was measured using MFM. DWs were moved with a threshold current around $1.0\times10^{12}$ $A/m^2$ and a 30 ns current pulse width. The lowest estimate for the DW speed is 350 m/s, which suggests a high mobility of DWs under spin-polarized current. Upcoming research focusses on imaging current driven DWs using synchrotron PEEM XMCD with higher quality materials for a better insight of internal DW structures.

[1] D. J. Sellmyer *et al*., J. Phys.: Cond. Mat. 13 (2001)
[2] M. Yan *et al*., PRL 104 (2010)

# SP 14 Domain walls, vortices and skyrmions

## SP14 - Parallel Session 7

### SP14 - Parallel Session 7

### SP14.7.01

### Phase-locking and modulation in spin torque oscillators

J. Létang, M.-W. Yoo, T. Devolder, J.-P. Adam, S. Petit-Watelot, K. Bouzehouane, V. Cros, J.-V. Kim

**Text** Spin-torque nano-oscillators (STNO) have strong potential for applications such as rf communications and neuro-inspired computing. An important aspect involves phase-locking [1] and modulation [2] due to external signals. However, the role of vortex core reversal [3] in this context has remained largely ignored. Indeed, in nanocontact-based systems, core reversal can give rise to more complex states such as chaos [4].
We have conducted experiments to probe how nanocontact vortex oscillators can be modulated in different dynamical states by an external signal. In the absence of core reversal, we observe little interaction between the external signal and the oscillator, in stark contrast to other kinds of spin-torque nano-oscillators. When core reversal occurs, on the other hand, the external signal is observed to strongly modulate the core reversal rate, which can be clearly seen in the modulation sidebands. These modulation patterns can be explained by first- or second-order modulation between core reversal, gyration and external frequencies. The salient features are reproduced in micromagnetics simulations.

This work was supported by the Agence Nationale de la Recherche (France) under grant agreement No. ANR-17-CE24-0008 (CHIPMuNCS).

[1] M. R. Pufall et al. Applied Physics Letters 86, 082506 (2005)
[2] W. H. Rippard et al. Physics Review Letters 95, 067203 (2005)
[3] B. Van Waeyenberge et al. Nature 444, 461-464 (2006)
[4] S. Petit-Watelot et al. Nature Physics 8, 682-687 (2012)

# SP 14 Domain walls, vortices and skyrmions

**SP14 - Parallel Session 7**

**SP14.7.02**

### Tuneable vortex dynamics with ion implantation

L. Ramasubramanian, A. Kákay, C. Fowley, O. Yildirim, P. Matthes, J. Lindner, A. Deac

**Text** The fundamental oscillation mode of magnetic vortices in thin-film elements has been proposed as working principle for spin-torque-driven nano-oscillators [Nat. Phys., 3:498, 2007]. Commercial applications require tuning of the output frequency by external parameters, such as spin-polarized currents. The tunability of vortex-based devices is limited, since the gyrotropic frequency is specific to the individual sample design. The fundamental frequency is determined by the saturation magnetisation, $M_s$, as well as the geometrical confinement of the magnetisation i.e. the diameter and height of a magnetic disk. Our micromagnetic simulations have shown that if regions with different $M_s$ can be induced in a magnetic disk, multiple precession frequencies can be generated. Here, we show that ion implantation [Phys. Rev. B 73, 184410, 2006] is a novel route to fabricate such devices.
Permalloy (Py) disks of various diameters and thicknesses were patterned and contacted to study the interaction of an applied AC current with the magnetic vortex. Using a conventional lock-in technique, the resonance frequencies are measured based on the anisotropic magnetoresistance (AMR) effect. Regions of different $M_s$ are induced in single disks by ion implantation, yielding different resonance frequencies corresponding to the specific area where the core is precessing. The work represents a novel way to obtain multiple oscillation frequencies from a single disk.

# SP 14 Domain walls, vortices and skyrmions

**SP14 - Parallel Session 7**

## Spin-vortex order in iron-based superconductors – insights from first principles

V. Borisov, R. Valenti

**Text** The unconventional superconductivity in iron pnictides is closely related to the nature of magnetism in their parent compounds. Most common types of magnetic order in these materials are the spin-density and charge-spin density waves. Just recently, theoretical studies predicted the existence of a new type of magnetism – the spin-vortex crystal – which has been observed, for the first time, shortly afterwards in the electron-doped $CaKFe_4As_4$ [1], first extensively studied 1144 material.

In the present work, we analyze the key properties of this compound that stabilize the spin-vortex crystal [1]. Using density functional theory we reveal the effects of doping and the crystal symmetry on the magnetic ground state. The important factor is the periodic arrangement of Ca and K layers which reduces the crystal symmetry of $CaKFe_4As_4$, compared to 122 materials, and favors a non-collinear magnetic order. Further systematic study of the spin-vortex crystal in the 1144 iron pnictides can lead to the discovery of novel superconductors and useful magnetic materials.

1. W. R. Meier et al., Nat. Quant. Mat. 3, 5 (2018).

This work was done in collaboration with Paul Canfield, William Meier, Yuji Furukawa, Peter Orth (Ames Lab), Rafael Fernandes (University Minnesota) and Cristian Batista (University Tennessee). The financial support by the German Research Foundation (DFG) and the computer time by the Center for Supercomputing (CSC) in Frankfurt are acknowledged.

# SP 14 Domain walls, vortices and skyrmions

**SP14 - Parallel Session 7**

**SP14.7.04**

### Electric control of magnetic vortex core gyration dynamics

M. Filianina, L. Baldrati, T. Hajiri, K. Litzius, L. Aballe, M. Foerster, M. Kläui

**Text** Electric field control of magnetism is attractive for applications being more energy efficient compared to conventional approaches using magnetic fields or spin-torques generated by power-dissipating currents. It was shown that piezoelectric strain alters the magnetic anisotropy of magneto-elastic materials via magneto-elastic coupling, i.e. the effect of lattice strain on magnetic properties [1-4]. While the quasi-static influence of strain has been thoroughly analyzed and the response can be well described by a simple magneto-static model [1], there are only a few experimental studies of the effect of stain on the dynamical behavior of the magnetization [3,4].

Here we report on the electric field control of magnetic vortex core gyration dynamics in magnetostrictive microstructures fabricated on top of a piezoelectric substrate. Modulated by piezoelectric strain, the ME anisotropy modifies the magnetic configuration of the microstructures and influences the vortex trajectory, which we determine by time-resolved photoemission electron microscopy combined with x-ray magnetic circular dichroism and compare with micromangetic simulations. We find that the dynamic trajectory can be tailored from circular to highly elliptical depending on the anisotropy.

1. S. Finizio et al., *Phys. Rev. Appl.* **1**, 021001 (2014).
2. L. Baldrati et al., *Adv. Electron. Mater.* **2**, 1600085 (2016).
3. M. Foerster et al., *Nat. Commun.* **8**, 407 (2017).
4. S. Finizio et al., *Phys. Rev. B* **96**, 054438 (2017).

# SP 14 Domain walls, vortices and skyrmions

**SP14 - Parallel Session 7**

**SP14.7.05**

### Probabilistic computing devices based on room temperature skyrmion diffusion

J. Zázvorka, D. Heinze, N. Keil, S. Kromin, K. Litzius, S. Jaiswal, F. Jakobs, A. Donges, P. Virnau, G. Jakob, K. Everschor-Sitte, D. Pinna, U. Nowak, M. Kläui

**Text** A key problem for probabilistic computing is that cascading gates propagate undesired correlations and thus vitiate the functionality of the logic device. Therefore, in order to implement probabilistic computing, one needs to reshuffle the signals to keep them uncorrelated for further calculations. While for many non-conventional computing approaches non-magnetic implementations have been identified as promising, for building a reshuffler device skyrmions might be ideally suited due to the low footprint and low power compared to e.g. CMOS implementations [1].
We present a Ta-seeded multistack material, where we can stabilize skyrmions and controllably nucleate and displace them by current injection due to spin-orbit torques. We find topologically non-trivial N=1 skyrmions that move synchronously due to the application of current pulses. We find strong motion also at zero applied current, which we ascribe to thermally activated skyrmion dynamics. After tracking the trajectories of skyrmions and based on the dependence of their mean-square-displacement on time, we can identify motion by diffusion and obtain the diffusion coefficient.
As a reshuffler, we develop a device with leads for skyrmion transport and a chamber where the reshuffling occurs. We evaluate its performance for the decorrelation of the input signal and find an uncorrelated output signal while keeping the stream’s mean value with high fidelity.
[1] D. Pinna et al., arXiv:1701.07750, 2017.

# SP 14 Domain walls, vortices and skyrmions

**SP14 - Parallel Session 7**

**SP14.7.06**

### Reservoir computing based on magnetic textures

D. Pinna, K. Everschor-Sitte, G. Bourianoff

**Text** Thanks to their many nanoscale properties, skyrmions claim promise in many applications ranging from non-volatile memory and spintronic logic devices, to enabling the implementation of unconventional computational standards such as Stochastic computing and Reservoir Computing. Particularly, Reservoir Computing is a type of recursive neural network commonly used for recognizing and predicting spatio-temporal events. Its basic functioning does not require any knowledge of the reservoir topology or node weights for training purposes and can therefore utilize naturally existing networks formed by a wide variety of physical processes. This talk will discuss how random skyrmion magnetic textures can be effectively employed to implement a functional reservoir. This is achieved by leveraging the nonlinear resistive response of the individual skyrmions arising from their current dependent AMR. Complex time-varying current signals injected via contacts into the magnetic substrate are shown to be modulated nonlinearly by the fabric's AMR due to the current distribution following paths of least resistance as it traverses the geometry. By tracking resistances across multiple input and output contacts, we show how the instantaneous current distribution, reminiscent of Atomic Switch Networks, effectively carries temporally correlated information about the injected signal. This in turn allows us to numerically demonstrate simple pattern recognition.

# SP 14 Domain walls, vortices and skyrmions

**SP14 - Parallel Session 7**

**SP14.7.07**

## Skyrmions Driven by Intrinsic Magnons

C. Psaroudaki, S. Hoffman, J. Klinovaja, D. Loss

**Text** We provide a full quantum description of the propagation of skyrmions in insulating magnetic films at zero and finite temperatures. The coupling of the skyrmion center with the magnon-like modes around it gives rise to microscopic damping terms in the equation of motion that are non-local in time. As a striking consequence we find that the skyrmion can acquire an inertial mass due to non-uniform magnetic terms such as defects, magnetic traps, or variations of the exchange constants [1]. In particular, we have discovered that the skyrmion dynamics becomes fully massive in a quantum confined geometry such as a quasi-one dimensional wire, similar to linear tracks used for magnetic memory devices.

In addition we demonstrate that time-dependent oscillating magnetic field gradients act as a net driving force on the skyrmion via its own intrinsic magnetic excitations. The unavoidable coupling of the ac external field to the magnons gives rise to time-dependent dissipation for the skyrmion. We demonstrate that the magnetic ac field induces a super-Ohmic to Ohmic crossover behavior for the skyrmion dissipation kernels with time-dependent Ohmic terms. The ac driving of the magnon bath at resonance results in a unidirectional helical propagation of the skyrmion in addition to the otherwise periodic bounded motion [2].

[1] C. Psaroudaki, S. Hoffman, J. Klinovaja, and D. Loss, Phys. Rev. X 7, 041045 (2017).
[2] Christina Psaroudaki and Daniel Loss, arXiv:1803.04001 (2018)

# SP 14 Domain walls, vortices and skyrmions

**SP14 - Parallel Session 7**

**SP14.7.08**

## Speed Limits for Skyrmions

J. Müller, B. McKeever, D. Rodrigues, K. Everschor-Sitte

**Text** Magnetic skyrmions are particle-like textures in the magnetization, characterized by a topological winding number. Nanometer-scale skyrmions have been observed at room temperature in magnetic multilayer structures. The combination of small size, topological quantization, and their efficient electric manipulation makes them interesting candidates for information carriers in high-performance memory devices which rely on mobile bits.

Skyrmion racetrack memory devices have been suggested where skyrmions move in a one-dimensional nanostrip. The information in the racetracks is encoded either in the distance between skyrmions or in additional attributes of these, e.g. shifts from the center of the track or different winding numbers. In order to drive skyrmions along the racetrack, it is often suggested to apply spin-polarized currents. Besides moving the skyrmions, the applied currents, however, also deform them, which is usually assumed a negligible effect.

We study the deformation of a skyrmion due to spin-transfer torque and show that it triggers the bimeron instability, which sets an ultimate speed limit for skyrmions in racetracks. We furthermore observe in our simulations that at significantly higher current densities, skyrmions are stabilized again as strongly deformed shooting star skyrmions in sufficiently clean systems.