TOPO 2016

Dresden, 16 - 19 August 2016

International Workshop on Topological Structures in Ferroic Materials

International Workshop on Topological Structures in Ferroic Materials

Abstract Book

Dresden, 16 – 19 August 2016

TECHNISCHE UNIVERSITÄT DRESDEN

Acknowledgements

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The kind cooperation with the **Technische Universität Dresden** as the host university of the TOPO2016 workshop is gratefully acknowledged.

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Contents

Welcome

Following the great success of the TOPO2015 workshop in Sydney, the 2nd International Workshop on Topological Structures in Ferroic Materials, TOPO2016, takes place on the campus of the Technische Universität Dresden.

Since current research interests regarding interfaces, domains, domain walls, vortices, spin currents and spin torque, spin textures and skyrmions in (multi)ferroics constitute an emerging field in solid state physics and materials science, the workshop is intended to connect these research fields with topological concepts in physics and thus to contribute to the fundamental understanding of these hot topics. With a clear focus on (multi)ferroic materials, the following aspects are under discussion:

- Domains and domain walls.
- Skyrmions and chiral spin textures.
- Vortex, anti-vortex and vertex structures.
- Interfaces and topologies.
- Spin torque and spin waves.
- Nanoscale characterization.
- Photoelectricity and photovoltaics.

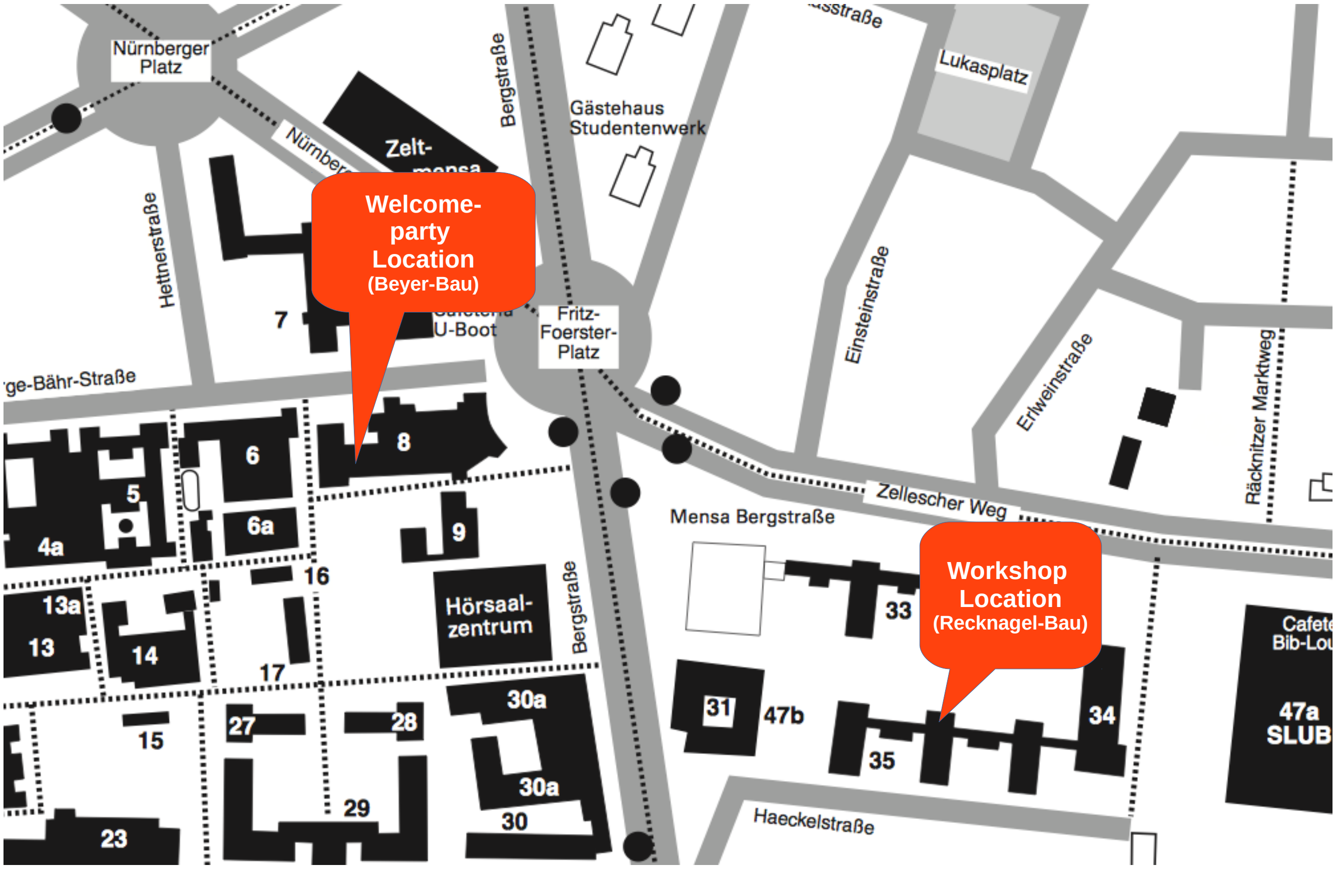
Visit our website for **late-breaking information** before and during the workshop:

https://topo2016.wordpress.com

Local organization: **Prof. Lukas M. Eng**
Institute of Applied Physics
Technische Universität Dresden

Venue

The **campus of the Technische Universität Dresden** can be reached easily by either bus lines 61 or 66 (leave at *Technische Universität*) or tram lines 3 or 8 (leave at *Nürnberger Platz*).



- On August, 16th, **registration and welcome reception** will start at 04:00 p.m. and 06:00 p.m., respectively, in **Beyer-Bau, room BEY 103** (see map).

  → Google maps link to Beyer-Bau, George-Bähr-Straße 1, 01069 Dresden:

  https://goo.gl/maps/PLRoyP8Geuj

  → Campus navigator link to room BEY 103:

  http://bit.ly/29q3glQ

- The **conference sessions** from August 17th–19th are held in the **Recknagel-Bau** (note: the former name *Physikgebäude / Physics Building* alias PHY might still be present at some plans), **lecture hall REC C213**.

  → Google maps link to Recknagel-Bau, Haeckelstraße 3, 01069 Dresden:

  https://goo.gl/maps/7Z6pNcmkkaG2

  → Campus navigator link to lecture hall REC C213:

  http://bit.ly/29HUi1C

Schedule - Overview

Tuesday, August, 16th			
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04:00 – 08:00	p.m.	Registration	BEY 103 (TUD)
06:00 – 08:00	p.m.	Welcome Reception	BEY 103 (TUD)
Wednesday, August, 17th			
08:00 – 08:30	a.m.	Registration	REC C213 (TUD)
08:30 – 09:00	a.m.	**Welcome** (30 min)	REC C213 (TUD)
09:00 – 09:40	a.m.	**Session 1** (40 min)	REC C213 (TUD)
09:40 – 10:10	a.m.	Coffee Break (30 min)	
10:10 – 12:10	a.m.	**Session 2** (120 min)	REC C213 (TUD)
12:10 – 01:00	p.m.	Lunch Break (50 min)	
01:00 – 02:00	p.m.	**Poster Session** (60 min)	REC C213 (TUD)
02:00 – 04:00	p.m.	**Session 3** (120 min)	REC C213 (TUD)
04:00 – 04:30	p.m.	Coffee Break (30 min)	
04:30 – 05:50	p.m.	**Session 4** (80 min)	REC C213 (TUD)
Thursday, August, 18th			
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10:10 – 10:40	a.m.	Coffee Break (30 min)	
10:40 – 12:00	a.m.	**Session 2** (80 min)	REC C213 (TUD)
12:00 – 02:00	p.m.	Lunch Break + SLUB[1] (120 min)	SLUB
02:00 – 03:50	p.m.	**Session 3** (110 min)	REC C213 (TUD)
03:50 – 04:20	p.m.	Coffee Break (30 min)	
04:20 – 06:00	p.m.	**Session 4** (100 min)	REC C213 (TUD)
07:30 – 11:00	p.m.	Conference Dinner	Brühl's Terrace (or Bierhaus Dampfschiff)[2]
Friday, August, 19th			
08:30 – 10:00	a.m.	**Session 1** (90 min)	REC C213 (TUD)
10:00 – 10:30	a.m.	Coffee Break (30 min)	
10:30 – 11:50	a.m.	**Session 2** (80 min)	REC C213 (TUD)
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01:00 – 02:30	p.m.	**Session 3** (90 min)	REC C213 (TUD)
02:30 – 02:40	p.m.	**Closing** (10 min)	REC C213 (TUD)
04:30 – 07:30	p.m.	Excursion[3]	

[1] Here, a guided tour inside the treasure chamber of the University Library (SLUB) can be joined.

[2] Open-air buffet at the historical "Brühl's Terrace" – for the case of rainy weather, the dinner takes place in the restaurant "Bierhaus Dampfschiff".

[3] Historical old town of Dresden – guided tour.

Scientific Program

Wednesday, August, 17th

08:00–08:30		Registration	

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08:30–09:00	Welcome by	*Prof. Michael Ruck*, Vice-Rector for Structure and Development, and *Prof. Lukas M. Eng*, Chair of the TOPO2016 Workshop	

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09:00–09:40	R. Wiesendanger	Nanoscale skyrmions – A new twist for spintronics	1

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Session 3 · 02:00 p.m. – 04:00 p.m. (120 min) · Chair: Prof. C. Felser

Session 4 · 04:30 p.m. – 05:50 p.m. (80 min) · Chair: Dr. J. Hlinka

Thursday, August, 18th

Session 1 · 08:30 a.m. – 10:10 p.m. (100 min) · Chair: Prof. A. N. Bogdanov

Session 2 · 10:40 a.m. – 12:00 p.m. (80 min) · Chair: Prof. S. Goennenwein

Session 3 · 02:00 p.m. – 03:50 p.m. (110 min) · Chair: Associate Prof. L. Martin

Session 4 · 04:20 p.m. – 06:00 p.m. (100 min) · Chair: Prof. R. Ramesh

Friday, August, 19th

Session 1 · 08:30 a.m. – 10:00 a.m. (90 min) · Chair: Prof. V. Shur

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Wednesday, 17^{th} August 2016

Nanoscale Skyrmions – A New Twist For Spintronics

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Nanoscale magnetic knots, called skyrmions, are novel types of localized non-collinear spin textures which offer great potential for future magnetic memory and logic devices [1]. The twisting in the skyrmions' magnetization profile leads to a gain in energy with respect to a homogeneously magnetized, ferromagnetic state. As a result of this magnetization twisting, skyrmions have non-trivial topological properties, described by a topological charge, and are topologically protected against a transition into topologically trivial states. The energetics of skyrmionic states is explained by the Dzyaloshinskii-Moriya interaction [2] being relevant in material systems exhibiting large spin-orbit coupling and a lack of inversion symmetry.

Skyrmion lattices were initially observed in bulk non-centrosymmetric materials based on neutron diffraction experiments and Lorentz microscopy observations. However, recent experimental and theoretical work has focused on atomic- and nanolayers of magnetic materials with intrinsic or interface-induced chiral interactions, thereby achieving full compatibility with state-of-the-art technology which has been developed over the past decades in the field of GMR- and TMR-based devices. It has been shown both experimentally and theoretically that magnetic skyrmions in ultrathin film systems can be as small as one nanometer in diameter [3] and that their properties can largely be tuned by the choice of the substrate and overlayer materials [4].

Atomic-resolution spin-polarized scanning tunneling microscopy (SP-STM) [5] has proven to be an invaluable tool for revealing the atomic-scale properties of ultimately small skyrmions [6, 7, 8, 9]. By locally injecting spin-polarized electrons from an atomically sharp SP-STM tip, we are able to write and delete individual skyrmions one-by-one, making use of spin-transfer torque exerted by the injected high-energy spin-polarized electrons [4]. Switching rate and direction can be controlled by the parameters used for current injection. Alternatively, individual skyrmions can be created and deleted by local electric fields [10], which can be of great advantage in view of energy-saving skyrmionic device concepts. The subsequent detection of the written skyrmions can also be achieved by electrical means rather than by using a magnetic sensing element [11]. The demonstration of various methods for the creation, detection, and annihilation of individual nanoscale skyrmions highlight their great potential for future spintronic devices making use of individual topological charges as information carriers.

[1] A. Fert et al., Nature Nanotechnology **8**, 152 (2013).
[2] A. A. Khajetoorians et al., Nature Commun. **7**, 10620 (2016).
[3] S. Heinze et al., Nature Physics **7**, 713 (2011).
[4] N. Romming et al., Science **341**, 6146 (2013).
[5] R. Wiesendanger, Rev. Mod. Phys. **81**, 1495 (2009).
[6] N. Romming et al., Phys. Rev. Lett. **114**, 177203 (2015).
[7] K. von Bergmann et al., Nano Lett. **15**, 3280 (2015).
[8] A. Sonntag et al., Phys. Rev. Lett. **113**, 077202 (2014).
[9] J. Brede et al., Nature Nanotechnology **9**, 1018 (2014).
[10] P.-J. Hsu et al., arxiv.org/abs/1601.02935.
[11] C. Hanneken et al., Nature Nanotechnology **10**, 1039 (2015).

Skyrmion density, vorticity and divergence of polarization in ferroelectric materials

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Topological defects play an important role in many areas of physics, ranging from particle physics to cosmology and liquid crystals science. Ferroelectric and ferromagnetic domain boundaries belong to the standard examples of such defects [1]. Over the last few years, however, more and more attention is payed to lower-dimensional topological defects, such as skyrmion lines, vortex cores, domain-wall junctions or intersections, point like hedgehog defects, etc. [2]. Various differential quantities, such as skyrmion density or vorticity have been used to characterize the topological defects of interest [4]. In our group, we have been studying a range of polarization defects within the framework of Ginzburg-Landau-Devonshire theory and phase-field simulations. In this contribution, we would like to review the results of our research activities in a broader context. Finally, we will briefly discuss the properties expected at the so-called ferroaxial domain walls [5].

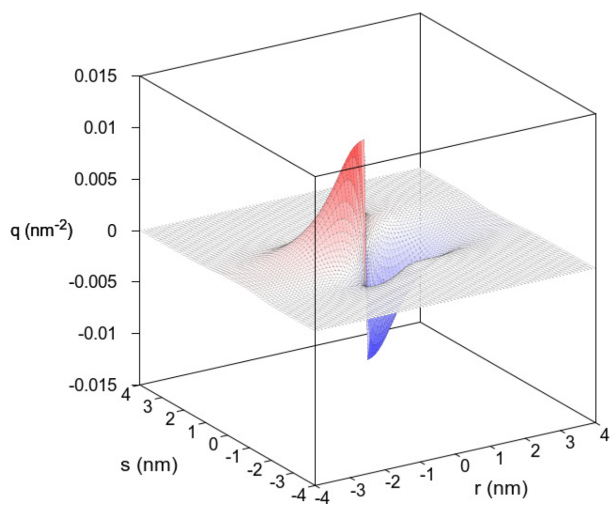

Figure 1: Skyrmion density in the vicinity of the Ising line

[1] N.D. Mermin, *The topological theory of defects in ordered media*, Rev Mod Phys., **51** (1979), 51–591.

[2] J. Seidel, editor, *Topological structures in ferroic materials*, Switzerland: Springer International Publishing; 2016.

[3] V. Stepkova, P. Marton, J. Hlinka, *Ising lines: Natural topological defects within ferroelectric Bloch walls*, Phys Rev B., **92** (2015), 094106.

[4] Y. Nahas et al, *Discovery of stable skyrmionic state in ferroelectric nanocomposites*, Nat Commun., **6** (2015), 8542.

[5] J. Hlinka, J. Privratska, P. Ondrejkovic, V. Janovec, *Symmetry guide to ferroaxial transitions*, Phys Rev Lett., **116** (2016), 177602.

Heusler compounds: Tunable materials with non trivial topologies

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Heusler compounds are a remarkable class of materials with more than 1,000 members and a wide range of extraordinary multifunctionalities [1] including tunable topological insulators (TI) [2]. There are two classes of Heusler compounds: half Heusler XYZ and Heusler X2YZ compounds, where Z is a main group metal and X and Y are transition metals. Many of the XYZ compounds are semiconductors or topological semimetals [2]. The ternary zero-gap semiconductors (LnAuPb, LnPdBi, LnPtSb and LnPtBi) contain the rare-earth element Ln, which can realize additional properties ranging from superconductivity (for example LaPtBi) to magnetism (for example GdPtBi) and heavy fermion behavior (for example YbPtBi). These properties can open new research directions in realizing the quantized anomalous Hall Effect and topological superconductors. C1b Heusler compounds have been grown as single crystals and as thin films. The control of the defects, the charge carriers and mobilities can be optimized [3]. The band inversion was observed by angle resolved photoemission spectroscopy [4]. Dirac cones and Weyl points can occur at the critical points in the phase diagrams of TI or can be induced via a magnetic field in all magnetic Heusler compounds with an inverted band structure [5].

Co2YZ and Mn2YZ Heusler compounds play an important role for future spintronic devices because of their half-metallic band structure [1]. Recently a high spinpolarisation for spintronic applications was proven by spin resolved photoemission [6]. The Curie temperature are far above room temperature, up to 1200 K. Recently Co2TiSn and other Co2-Heusler compounds were found to be Weyl semimetals [7]. Manganese-rich Heusler compounds are attracting interest in the context of spin transfer torque based data storage [8, 9], spin Hall effect, non collinear magnetism [10] and rare-earth free hard magnets. The Mn^{3+} ions in Mn2YZ cause a Jahn Teller distortion [8, 11]. New properties can be observed such as, large exchange bias, non-collinear magnetism topological Hall effect, spin gapless semiconductivity and Skyrmions [10, 12-14]. Weyl points and the corresponding Berry phase induce in Mn3Ge a giant anomalous Hall effect [15, 16].

[1] Graf, et al., Progress in Solid State Chemistry **39** (2011), 1.
[2] Chadov, et al., Nature Mater. **9** (2010), 541; Lin, et al., Nature Mater. **9** (2010), 546.
[3] Shekhar, et al., Phys. Rev. B **86** (2012), 155314.
[4] Liu, et al., Nature Communications, accepted, arXiv:1602.05633 (2016).
[5] Hirschberger, et al., arXiv:1602.07219 (2016).; C. Shekhar, et al., arXiv:1604.01641 (2016).
[6] Jourdan, et al, Nature Commun. **5** (2014), 3974.
[7] Wang, et al., arXiv:1603.00479 (2016).; J. Kübler and C. Felser, Europhys. Lett. **114** (2016) 47005.
[8] Winterlik, et. al., Adv. Mat. **24** (2012), 6283.
[9] Jeong, et al., Nature Commun. **7** (2016), 10276.
[10] Meshcheriakova, et al., Phys. Rev. Lett. **113** (2014), 087203.
[11] Wollmann, et al. Phys. Rev. B **92** (2015), 064417.
[12] Nayak, et al. Phys. Rev. Lett. **110** (2013), 127204.
[13] Ouardi, et al., Phys. Rev. Lett. **110** (2013), 100401.
[14] Nayak, et al., Nature Mater. **14** (2015), 679.
[15] Kübler and C. Felser, Europhys. Lett. **108** (2014) 67001.
[16] Nayak, et al., Science Advances **2** (2016) e1501870; Nakatsuji, et al., Nature **527** (2015) 212.

Scanning Force Microscopy Investigation of Skyrmions

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Recently, a lot of interest was spurred by discoveries that established the existence of vortex-like magnetic states, so-called skyrmions, in some helimagnetic compounds characterized by the anisotropic Dzyaloshinskii-Moriya (DM) interaction. Originally introduced in the context of pion fields, the expression skyrmion today is used in a more general sense as a term for a mathematical construct, that describes a topologically stabilized, particle-like object. Magnetic skyrmions are discussed as promising novel candidate for elementary magnetic storage units even at room temperature, due to their size and their topological nature, which makes them stable against the superparamagnetic effect.

We report on scanning force microscopy investigations of skyrmions covering three different materials, namely $Fe_xCo_{(1-x)}Si$ ($x = 0.5$), GaV_4S_8 and Cu_2OSeO_3 [1, 2, 3].

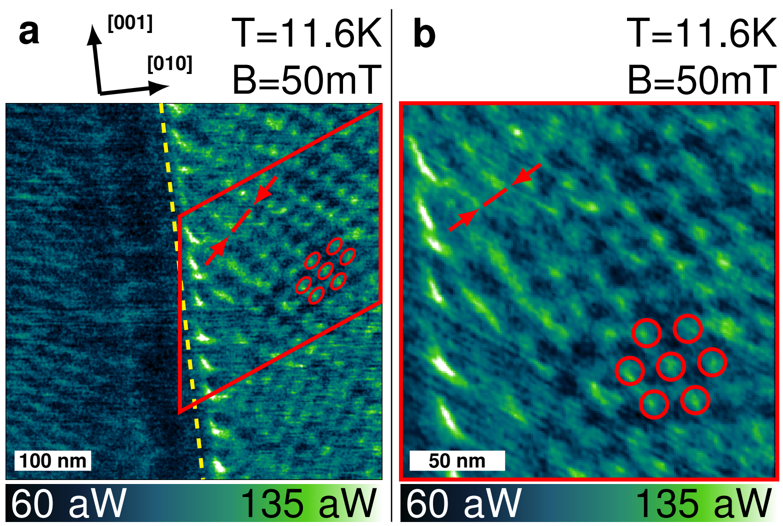

Figure 1: Imaging of a skyrmion lattice in GaV_4S_8. (a) Due to the magnetic anisotropy the skyrmion cores are not oriented along the external magnetic field (in the direction of sight) but rather along the magnetic easy axis. In consequence, the skyrmion lattice appears stretched in the image. (b) The hexagonal arrangement of skyrmions is recovered, when the image is scaled by $\sqrt{3}$ along the direction of the magnetic easy axis projected onto the sample surface.

[1] Milde, P.; Koehler, D.; Seidel, J.; et al., *Unwinding of a Skyrmion Lattice by Magnetic Monopoles*, Science, **340** (2013), 1076-1080.

[2] Kezsmarki, I.; Bordacs, S.; Milde, P.; et al., *Neel-type skyrmion lattice with confined orientation in the polar magnetic semiconductor GaV_4S_8*, Nat. Mat., **14** (2015), 1116-1123.

[3] Zhang, S. L.; Bauer, A.; Burn, D. M.; et al., *Multidomain Skyrmion Lattice State in Cu_2OSeO_3*, Nano Letters, **16** (2016), 3285-3291.

Towards functional ferroic domain walls for all-domain-wall devices

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Ferroelectric domain walls hold great promise as functional 2D-materials because of their unusual electronic properties [1]. Particularly interesting are the so-called charged walls where a polarity mismatch causes local, diverging electrostatic potentials requiring charge compensation and hence a change in the electronic structure. These walls can exhibit significantly reduced or enhanced conductivity and may serve, for instance, as insulating barriers or circuit path for future nanoelectronics. Thus, it has become a major goal in the field of domain-wall engineering [2] to control the electronic domain-wall behavior and eventually tune the properties towards a technologically feasible working range. Going beyond just insulating and conducting walls, however, the development of all-domain-wall devices also requires walls with tunable output to emulate electronic components such as diodes and transistors. In my talk I will present different pathways for optimizing and controlling the functionality at domain walls in improper ferroelectrics. I will focus on geometrically driven charged domain walls in hexagonal manganites [3], including the manipulation of their transport properties by chemical doping [4], as well as the voltage-controlled switching between resistive and conducting domain-wall states. The emergent domain-wall properties are explained based on the formation of electronic accumulation and inversion layers, respectively, and foreshadow the possibility to design elementary binary domain-wall devices such as switches and gates.

[1] D. Meier, J. Phys.: Condens. Mater. **27**, 463003 (2015).

[2] E. K. H. Salje, H. Zhang, Phase Transitions **82**, 452–469 (2009).

[3] D. Meier et al., Nature Mater. **11**, 284–287 (2012).

[4] J. Schaab et al., Adv. Electron. Mater. **2**, 1500195 (2016).

Interplay between the Domain Structure, Local Switching and Bulk Properties of the Lead-Free Ferroelectric Ceramics

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The piezoelectric device market is dominated by lead containing $Pb(Zr_{1-x},Ti_x)O_3$ (PZT) based materials because of its versatility and robust functional properties. The toxicity of lead however, has raised health concerns and in the last two decades legislative changes have stimulated intensive research into suitable lead-free PZT alternative materials [1]. Among the numerous lead-free oxides and solid solution systems investigated for their piezoelectric potential $K_{1-x}Na_xNbO_3$ (KNN) and $BiFeO_3$ (BFO) based systems have received enormous attention following publications by Saito et al. in 2004 and Wang et al. in 2003 respectively, which reported piezoelectric constants for KNN comparable to PZT and high remnant polarizations of BFO approximately double those of PZT [2].

Despite the significant focus on KNN and BFO, and the subsequent high volume of scientific publications, commercial realization of their piezoelectric properties has not been forth coming, as both materials experience difficulties with synthesis in the bulk ceramic form. Present studies of these materials tend to focus on either the macroscopic properties of bulk ceramics or the local properties of thin films.

In this work we have combined both approaches by discussing the ferroelectric and piezoelectric properties of ceramics using both macroscopic and local experimental techniques. Scanning electron microscopy in couple with electron back-scattered diffraction (Carl Zeiss Auriga Crossbeam Workstation) was used for the measuring of the grain sizes and orientations. Nano-size grain boundaries and nanodomain structure was analyzed by transmitting electron microscopy (JEOL JEM 2010).

Piezoresponse force microscopy (Asylum Research MFP-3D, NT-MDT NTEGRA Aura) provided information about domain shape, distribution of domain sizes and local switching behavior. Advanced statistical analysis of the piezoresponse force microscopy images based on autocorrelation function, histogram of oriented gradients and cluster analysis has been proposed to extract the geometrical characteristics of the domain structure. Switching spectroscopy and visualization of domain shape during step-by-step polarization reversal have been used for studying of the local polarization reversal in single grain.

This is then discussed together with the macroscopically measured strain and polarization hysteresis and dielectric behavior of the bulk ceramics, providing an encompassing perspective of the functional behavior of both KNN and BFO based ceramics.

The equipment of the Ural Center for Shared Use "Modern nanotechnology" UrFU was used. The research was made possible in part by the Ministry of Education and Science of RF (Contract 14.587.21.0022) and with the financial support of RFBR (Grant 16-32-60083-mol_a_dk).

[1] J. Rödel, W. Jo, K. T. P. Selfert, E.-M. Anton, T. Granzow, D. Damjanovic, *Perspective on the development of lead-free piezoceramics*, J. Am. Ceram. Soc. **92** (2009), 1153-1177.

[2] Y. Saito, H. Takao, T. Tani, T. Nonoyama, K. Takatori, T. Homma, T. Nagaya, M. Nakamura, *Lead-free piezoceramics*, Nature **432** (2004), 84-87.

Domain structures created by ion beam irradiation in MgO doped lithium niobate single crystals

D. S. Chezganov[1,2], E. O. Vlasov[1], L. V. Gimadeeva[1], M. M. Neradovskiy[1], A. R. Akhmatkhanov[1,2], M. A. Chuvakova[1], D. O. Alikin[1], and V. Ya. Shur[1,2]

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The formation of ferroelectric domains by ion beam irradiation of Z^+-polar surface has been studied in single crystals of 5 weight % MgO doped lithium niobate (MgOLN). The obtained results were analyzed in terms of kinetic approach [1].

The irradiation of Z^+-polar surface of 1-mm-thick plates covered by dielectric layer (resist or SiO_2) and without artificial layer was performed by workstation Auriga Crossbeam (Carl Zeiss) equipped by ion-beam lithography system Elphy Multibeam (Raith) using dot and stripe exposures. Z^--polar surface was covered by solid Cu electrode and grounded. The domain patterns revealed by selective chemical etching were visualized by optical, atomic force, piezoresponse force and confocal Raman microscopies.

The shape and sizes of isolated domains created by dot exposure have been studied. The dependence of domain size on the charge dose was measured. The obtained difference of experimental dependences for various dielectric layers and surface without artificial layer was attributed to different localization of the space charge induced by irradiation [2]. The revealed change of the domain shape with dose increase from regular polygons to circle was attributed to reduction of dielectric layer thickness by ion beam etching and transition of prevailed bulk screening mechanism from anisotropic electronic to isotropic ionic. The formation of hexagonal domains on Z^--polar surface at any dose was attributed to anisotropic bulk screening by electrons. The obtained ensembles of nanodomains around the growing isolated domain were attributed to correlated nucleation effect due to existence of the dielectric layer between the injected charge and the crystal surface [3].

The obtained knowledge allowed us to create the 2D domain patterns with minimal period about 800 nm, width down to 250 nm and domain depth up to 250 µm. The 1D periodic stripe domain structure with period of 2 µm and through domains was created also. The produced periodical domain structures can be used for second harmonic generation.

The equipment of the Ural Center for Shared Use "Modern nanotechnology" UrFU was used. The research was made possible in part by RFBR (15-32-21102-mol_a_ved), by Government of the Russian Federation (Act 211, Agreement 02.A03.21.0006) and by President of Russian Federation grant for young scientists (Contract 14.Y30.16.8441-MK).

[1] V.Ya. Shur, *Kinetics of ferroelectric domains: Application of general approach to $LiNbO_3$ and $LiTaO_3$*, J. Mater. Sci. **41** (2006), 199-210.

[2] V.Ya. Shur, D.S. Chezganov A.R. Akhmatkhanov, D.K. Kuznetsov, *Domain patterning by electron beam of MgO doped lithium niobate covered by resist*, Appl. Phys. Lett. **106** (2015), 232902.

[3] V.Ya. Shur D.K. Kuznetsov, E.A. Mingaliev, E.M. Yakunina, A.I. Lobov, A.V. Ievlev, *In situ investigation of formation of self-assembled nanodomain structure in lithium niobate after pulse laser irradiation*, Appl. Phys. Lett. **99** (2011), 082901.

Low-temperature scattering scanning near-field optical microscopy on barium titanate

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At low temperatures, matter reveals intriguing physics such as quantum effects, superconductivity, skyrmionic phases, and structural phase transitions. We developed a low-temperature scattering scanning near-field optical microscope (LT-s-SNOM) in order to study optical material properties at temperatures as low as 10 K. Independently of the illuminatin wavelength, near-field microscopy allows for the investigation of optical sample properties at a scale of few tens of nanometers. This is especially advantegeous in the mid-to-far infrared regime, where the resolution limit of conventional microscopy can be surpassed by several orders of magnitude. Therefore we combined our LT-s-SNOM with the free-electron laser FELBE at the Helmholtz-Zentrum Dresden-Rossendorf, which provides high power IR radiation in the regime of 4 - 250μm.

Here, we investigate low-temperature phase transitions in barium titanate (BTO) single crystals [1, 2]. As a prototype of the perovskite material group, BTO is ferroelectric at room temperature with a tetragonal crystal structure. Different regions of the crystal, so-called domains, feature different directions of both the optical axis and the spontaneous polarization. We image the domain pattern by piezoresponse force microscopy (PFM) and s-SNOM. The near-field measurements are performed at wavelengths around 16.5 μm, at which the near-field signal is strongly enhanced due to a phonon resonance at slightly longer wavelengths. The spectral position of this near-field resonance slightly shifts between different domains, resulting in a strong domain contrast at specific wavelengths. Upon cooling, the crystal structure of BTO changes to orthorhombic at 263 K and to rhombohedral at 173 K. While the material remains ferroelectric upon both phase transitions, the directions of the optical axes and the ferroelectric polarization change, which causes an alteration of the domain pattern. We image the domain configuration in each of the three phases via s-SNOM and PFM. Moreover, we observe a blue-shift of the spectral position of the near-field resonance with decreasing temperature.

[1] J. Döring, H.-G. von Ribbeck, M. Fehrenbacher, S. C. Kehr, and L. M. Eng, *Near-field resonance shifts of ferroelectric barium titanate domains upon low-temperature phase transition*, Appl. Phys. Lett. **105** (2014), 053109.

[2] J. Döring, L. M. Eng, and S. C. Kehr, *Low-temperature piezoresponse force microscopy on barium titanate*, J. Appl. Phys, submitted.

Enhancing the domain wall conductivitiy in lithium niobate single crystals

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Highly conductive ferroelectric domain walls (DWs) were found for thin films [1] as well as single crystals [2]. In lithium niobate (LNO) this effect was forecast by theoretical considerations [3]. However, such a high conductivity has so far only been reported under support of super band-gap illumination [4]. We show here that high voltage treatment of domain walls (Fig. 1a) in bulk lithium niobate single crystals, when applying voltage ramps of up to 1 kV to macroscopic electrodes, results in the desired high conductivity as well (Fig. 1b, c). An increase in domain wall conduction of several orders of magnitude can then be measured. High voltage treatment also affects the 3-dimensional domain wall shape, which was complementarily delineated by Cherenkov second harmonic generation (C-SHG) [5]. As a result, we are able to correlate the local domain wall conductive paths (measured by cAFM) to the DW inclination angle as deduced by C-SHG.

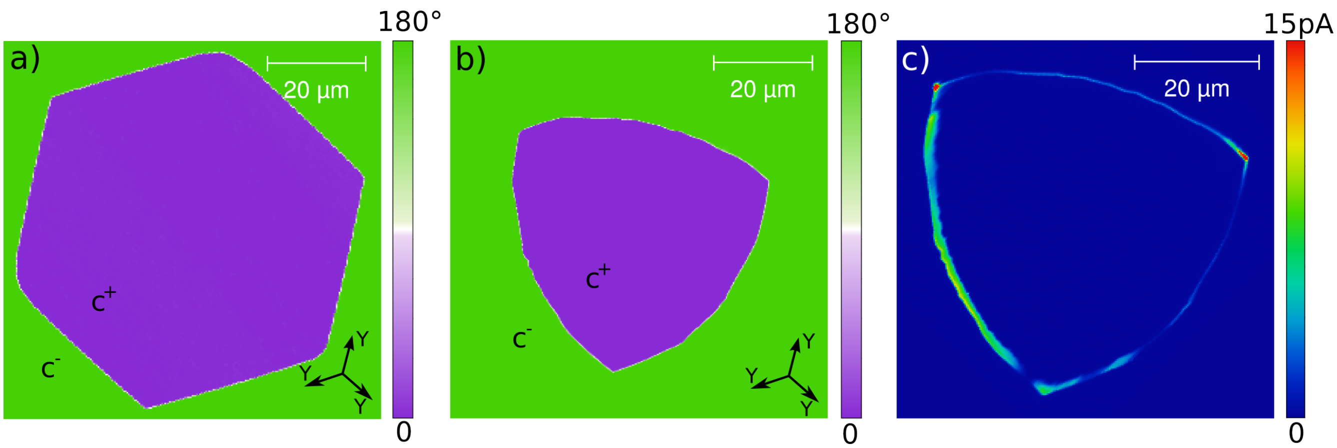

Figure 1: Pre-treatment domain state: a) PFM (no measureable currents in cAFM); Post-treatment domain state: b) PFM and c) cAFM

[1] J. Seidel, L. W. Martin, Q. He, Q. Zhan, Y.-H. Chu, A. Rother, M. E. Hawkridge, P. Maksymovych, P. Yu, M. Gajek, N. Balke, S. V. Kalinin, S. Gemming, F. Wang, G. Catalan, J. F. Scott, N. A. Spaldin, J. Orenstein, R. Ramesh, *Conduction at domain walls in oxide multiferroics*, Nature Materials, **8** (2009), 229.

[2] T. Sluka, A. K. Tagantsev, P. Bendyakov, N. Setter, *Free-electron gas at charged domain walls in insulating $BaTiO_3$*, Nature Communications, **4** (2013), 1808.

[3] E. A. Eliseev, A. N. Morozovska, G. S. Svechnikov, V. Gopalan, V. Y. Shur, *Static conductivity of charged domain walls in uniaxial ferroelectric semiconductors*, Physical Review B, **83** (2011), 235313.

[4] M. Schröder, A Haußmann, A. Thiessen, E. Soergel, T. Woike, L. M. Eng, *Photoinduced Conductivity: Conducting Domain Walls in Lithium and Niobate Single and Crystals*, Advanced Functional Materials, **22** (2012), 3926.

[5] T. Kämpfe, P. Reichenbach, M. Schröder, A Haußmann, L. M. Eng, T. Woike, E. Soergel, *Optical three-dimensional profiling of charged domain walls in ferroelectrics by Cherenkov second-harmonic generation*, Physical Review B, **89** (2014), 035314.

Heteroepitaxial $CoFe_2O_4$/Muscovite Bimorph with Large Magnetostriction for Flexible Electronics

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Nowadays, the flexible devices have caught a significant spotlight due to their potential to change our daily life. Flexibility, closely linked to the strain in materials, is the most vital property for flexible materials. However, to explore more possibilities in flexible devices, additional degrees of freedom are highly on demand. In this study, we demonstrate an elegant approach to combine the magnetostrictive phenomenon with the flexibility for expanding the applications of flexible electronics. Epitaxial ferrimagnetic cobalt ferrite ($CoFe_2O_4$, CFO) exhibiting high negative magnetostrictive coefficient was grown on flexible muscovite substrate. The combination of x-ray diffraction and transmission electron microscopy was conducted to reveal the heteroepitaxy of CFO/muscovite system. The large magnetostrictive behavior of CFO film was then determined by digital holographic microscopy, while the robust magnetic behaviors against bending was characterized by various magnetic measurements. Such a heteroepitaxial CFO/muscovite system that combines both flexibility and magnetostriction provides a new platform to develop next-generation flexible devices.

Giant resistive switching by conductive domain walls in exfoliated thin-film lithium niobate - Nanoscopic transport mechanism and GHz AC conductivity inspection

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We investigate the formation of conductive domain walls (CDWs) in exfoliated thin-film lithium niobate ($d = 600$ nm) on a global Pt back-electrode under both Cr/Au plane electrodes ($A \approx 200\ \mu m^2$) as well as sharp Pt-AFM probes ($A \approx 300\ nm^2$). We observe a very distinct and abrupt increase in the conductivity over at least 5 orders of magnitude at $V_{set} = 21.05$ V. The set voltage V_{set} is as precisely defined as $\Delta V_{set}/V_{set} < 10^{-3}$. The set-voltage was sufficiently correlated with the coercive voltage in the material by switching-spectroscopy (ss) PFM. Plane electrode and AFM-based resistive switching were sufficiently found to be correlated to the formation of CDWs both by local cAFM and PFM measurements. ssPFM shows the coercive voltage to be very homogeneously distributed in the single crystalline film ($\Delta V_c < 1V$) with a small internal field. Scanning microwave impedance microscopy (sMIM) and comparative FEM simulation reveal a clear increase in conductivity at the domain wall from 10^{-8} S/m to 10^{3} S/m, which gives a significantly larger ratio of 10^{11} as the background is distinctly measurable.

The application of CDWs for resistive switching devices was investigated. We were able to measure a stable on- and off-current for $> 10^4$ s in the metal-ferroelectric-metal stack at read-voltages < 10 V. It was possible to cycle the device for as much as 10^5 cycles with a resistance window of 10^4. The read-current in such a device was tunable both by writing voltage and time with a variation of 10^2. The transport mechanism was found to be space-charge limited current both by direct $I-V$ curve analysis as well as by $d\log(I)/dV$.

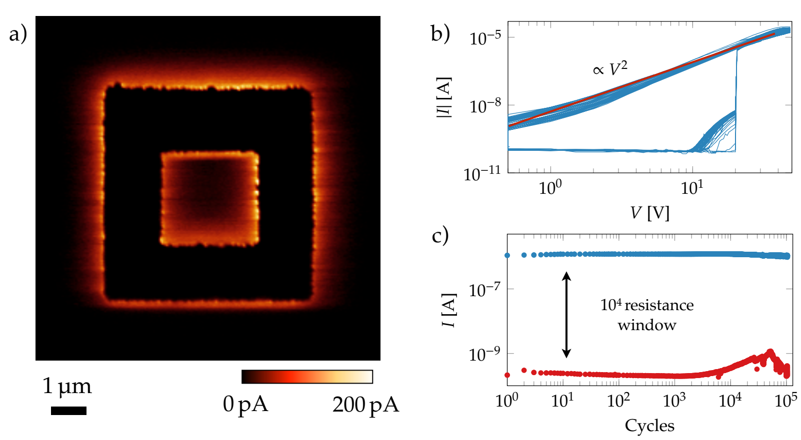

Figure 1: Resistive switching by ferroelectric domain walls in lithium niobate a) conductive AFM measurement at V= 3 V, b) 100 cycles of current-voltage ($I-V$) curves on metal-ferroelectric-metal stack c) cyclic resistive switching with a read-out voltage $V_{\mathrm{read}} = 10$ V.

Infrared sub-wavelength imaging with ferroelectric superlenses

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The wave nature of light limits the resolution in conventional microscopy to the order of the wavelength. Superlenses overcome this limit via coupled polariton modes on the two interfaces of a thin layer transferring sub-wavelength information to a near-field image plane [1].

We study superlenses that consist of perovskites such as ferroelectric $BaTiO_3$, $BiFeO_3$, and PZT, which show phonon polariton modes in the mid-infrared regime. The superlensed image is measured with our near-field microscope in combination with the free-electron laser FELBE at Helmholtz-Zentrum Dresden-Rossendorf with a wavelength range from 4 to 250 μm [2]. We found that perovskite superlenses generate images beyond the diffraction limit [3] and that different combinations of materials show superlensing at different wavelengths [4]. Moreover, free-standing sub-wavelength sized lamella are placed in a contact superlens fashion directly on the objects of interest, allowing for the direct integration into a lab-on-chip geometry [5].

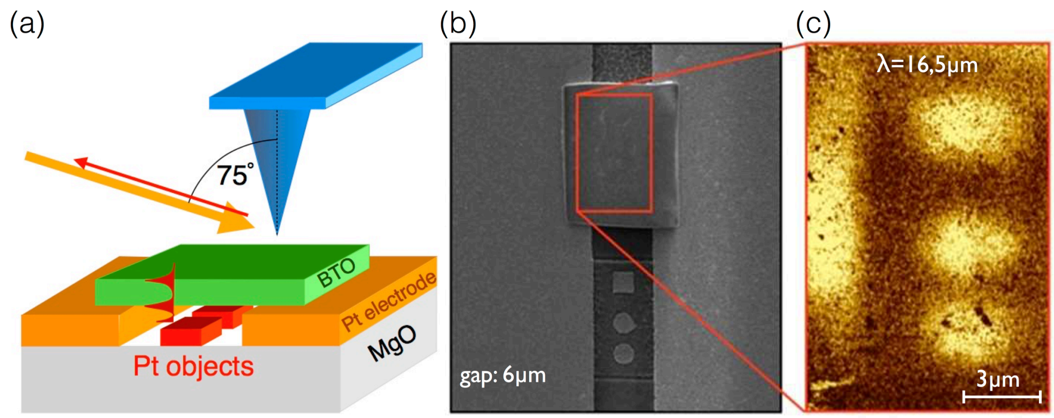

Figure 1: Near-field microscopy on ferroelectric superlenses. (a) Sketch of the setup including near-field probe, $BaTiO_3$-lamella superlens, and Pt objects. (b) Scanning electron microscopy image of the sample with a sub-wavelength sized lamella above a 6 μm-sized gap. (c) Near-field examination of the superlensed image at $\lambda = 16.5\ \mu m$ clearly resolves the 2 μm-sized objects.

[1] J. B. Pendry *Negative refraction makes a perfect lens*, Phys. Rev. Lett., **85** (2000), 3966.

[2] F. Kuschewski, et al. *Narrow-band near-field nanoscopy in the spectral range from 1.3 to 8.5 THz*, Appl. Phys. Lett., **108** (2016), 113102.

[3] S. C. Kehr, Y. M. Liu, et al. *Near-field examination of perovskite-based superlenses and superlens-enhanced probe-object coupling*, Nat. Commun., **2** (2011), 249.

[4] S. C. Kehr et al. *Microspectroscopy on perovskite-based superlenses*, Opt. Mater. Express, **1** (2011), 1051–1060.

[5] S. C. Kehr et al. *A Local Superlens*, ACS Photonics, **3** (2015), 20–26.

Topological defects and domain walls of helimagnetic order

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The Dzyaloshinskii-Moriya interaction in chiral magnets like MnSi, FeGe or Cu_2OSeO_3 stabilizes a magnetic helix with a magnetization that is periodic along the pitch vector. We consider defects of this helimagnetic ordering and their properties. Similar to cholesteric liquid crystals, there exist disclination defects around which the pitch vector rotates by π. A dislocation is formed by combining a π and $-\pi$ disclination whose distance is directly related to the Burgers vector. We find that dislocations fall into two classes with vanishing or a finite topological skyrmion number depending on whether the length of their Burgers vector is a half-integer or integer multiple of the helix wavelength, respectively. As a result, only the latter will couple to spin currents via Berry phases. Dislocations have been recently identified to be important for the relaxation of helimagnetic ordering in FeGe [1]. Moreover, we show how disclinations and dislocations can be combined to form topological domain walls, and we compare our theoretical predictions to experimental results on FeGe.

[1] A. Dussaux, P. Schoenherr, K. Koumpouras, J. Chico, K. Chang, L. Lorenzelli, N. Kanazawa, Y. Tokura, M. Garst, A. Bergman, C. L. Degen, and D. Meier, *Local dynamics of topological magnetic defects in the itinerant helimagnet FeGe*, submitted, arXiv:1503.06622

Topological magnetic defects in intinerant helimagnet FeGe

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Chiral magnetic interactions induce complex spin textures including helical and conical spin waves, as well as particle-like objects such as magnetic skyrmions and merons. These spin textures are the basis for innovative device paradigms and give rise to exotic topological phenomena, thus being of interest for both applied and fundamental sciences. Present key questions address the dynamics of the spin system and emergent topological defects.

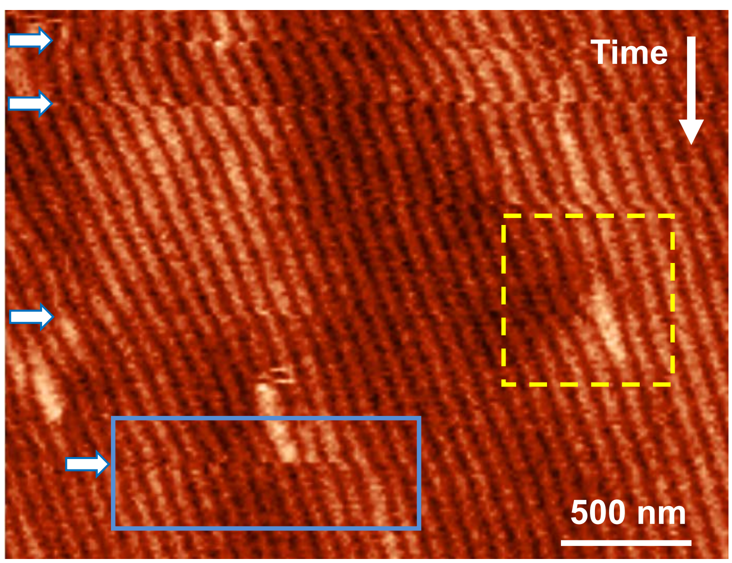

Figure 1: Motion of edge dislocation induces collective jumps in the helimagnetic pattern.

Here we present topological defects and their dynamics in the helimagnetic phase of FeGe. By combining magnetic force microscopy, single-spin magnetometry, and simulations we analyze the local behavior of magnetic defects. The nanoscale dynamics, for instance, are governed by the depinning and subsequent motion of magnetic edge dislocations. The motion of these topologically stable objects triggers perturbations that can propagate over mesoscopic length scales. Moreover, topological defects are found to play an important role for the formation of helimagnetic domain walls. Our experimental observations provide new insight to the spatio-temporal dynamics of itinerant helimagnets and topological defects, and disclose novel challenges regarding their technological usage.

Fabrication of ferromagnetic nanorod arrays using porous aluminum oxide templates

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We prepared ferromagnetic nanorods using porous aluminum oxide templates. This method is based on the formation of nanometer-sized pores within sputter-deposited layers of aluminum by means of anodization. These pores are subsequently used as a template for guiding the electro-depostion of metals, thus forming extended arrays of metal nanorods (several cm^2). Depending on the deposited materials, this type of nanostructure may serve, e.g., as plasmonically active substrate for optical applications [1].

Alternatively, by using magnetic materials, this method may result in an array of ferromagnetic nanopillars. The fabrication of pillars can be even extended to produce alternating thin layers of a ferromagnetic and a non magnetic material, e.g., Ni and Cu, thus providing the foundation for building up a GMR sensor from these structures. This combination of a cost-effective fabrication of large-area ferromagnetic nanostructures, with the easy implementation of the GMR effect may bear high potential for magnetic storage applications.

In this work, we show the preparation of Ni nanorods, as well as layered Cu/Ni nanorods produced by pulsed deposition. Samples of Ni/Cu nanorod arrays were investigated by magnetic force microscopy, SQUID magnetometry and magnetoresistance measurements.

[1] V. Fiehler, F. Patrovsky, L. Ortmann, S. Derenko, A. Hille and L. M. Eng, *Plasmonic Nanorod Antenna Array: Analysis in Reflection and Transmission*, J. Phys. Chem. C, **120** (2016), 12178–12186.

In situ observation of ferroelectric domain wall dynamics close to the Curie temperature in triglycine sulfate (TGS)

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The exact structure of ferroelectric domains and domain walls is of crucial importance for understanding a ferroelectric material's behaviour. Applications of ferroelectric materials generally depend directly on the ability to precisely engineer this domain structure, which has lead to a great variety of corresponding measuring techniques. Most of these techniques yield information about a material's surface only. However, this surface-related information is not always sufficient for a thorough understanding of a sample's properties. A prominent example is domain wall conductivity, which strongly depends on a domain wall's three-dimensional (3D) structure, especially its inclination. A technique that allows obtaining information about the domain wall structure inside a material is second harmonic generation microscopy (SHGM). Indeed, SHGM has already proven to be a useful tool for determining domain wall inclination angles [1].

We used SHGM to obtain new insight into the domain wall dynamics of the ferroelectric-paraelectric phase transition in triglycine sulfate (TGS). Being purely of second-order and, hence, interesting from a fundamental point of view, this phase transition has been thoroughly investigated. However, only surface sensitive techniques have been applied so far. Here, we present time-resolved measurements of the domain wall dynamics inside a TGS crystal, close to its Curie temperature of $49\,^{\circ}\mathrm{C} = 322\,\mathrm{K}$. Furthermore, we show a 3D-representation of spike domains in TGS. Spike domains are a good example of how the domain structure at a material's surface may differ from its structure inside the material.

[1] T. Kämpfe, P. Reichenbach, M. Schröder, A. Haußmann, L. M. Eng, T. Woike, and E. Soergel *Optical three-dimensional profiling of charged domain walls in ferroelectrics by Cherenkov second-harmonic generation*, Physical Review B, **89**(3) (2014), 035314.

Modeling Conductive Domain Walls by means of Random Resistor Networks

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Random Resistor Networks have been used for modeling the electronic transport in composite media [1], under an insulator-metal-transition as it occurs in manganites [2] or even along a DNA helix [3]. Following this macroscopic approach the resistors of an equivalent circuit of the considered system are chosen randomly to be either metallic, insulating or belonging to a certain resistance distribution.

Here the random resistor network approach has been employed to model the conductivity of domain walls in uniaxial ferroelectrics, such as lithium niobate. Recently the domain wall inclination angle in lithium niobate has been measured locally by Godau et al. (unpublished, P 04), using a Cherenkov second-harmonic generation method for 3-dimensional domain wall mapping. This data has been used as experimental input for a random resistor network model - addressing both the DC and the AC case.

[1] O. Levy and D. J. Bergman, *Clausius-Mossotti approximation for a family of nonlinear composites*, Physical Review B, **46** (1992), 7189.

[2] M. Mayr, A. Moreo, J. Vergés, J. Arispe, A. Feiguin and E. Dagotto, *Resistivity of Mixed-Phase Manganites*, Physical Review Letters, **86** (2001), 135–138.

[3] R. Marshall, *Modeling DNA/RNA Strings Using Resistor--Capacitor (RC) Ladder Networks*, The Computer Journal, **53** (2010), 644-660.

Anisotropic Domain Wall Conductivity in $LiNbO_3$ single crystals

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Nowadays, investigating the origin and nature of domain wall conductivity (DWC) in different ferroelectric materials such as BFO [1, 2] and PZT thin films [3], but equally in $LiNbO_3$ (LNO) single crystals [4] are of broad scientific interest. The work presented here reports on anisotropic DWC, as shown in Fig. 1, found between head-to-head (h2h) and tail-to-tail (t2t) 180° DWs in z-cut PPLN single crystal, as measured with Tunneling AFM (ICON) and Optimized Resistance Conductance Amplifier (Cypher). The three dimensional polarization distribution is analyzed at the same position via Piezoresponse Force Microscopy (PFM) and Cherenkov Second Harmonic Generation (CSHG). The origin of the different DWC between h2h and t2t is studied by both phenomenological theories and dipole modeled tunneling simulations.

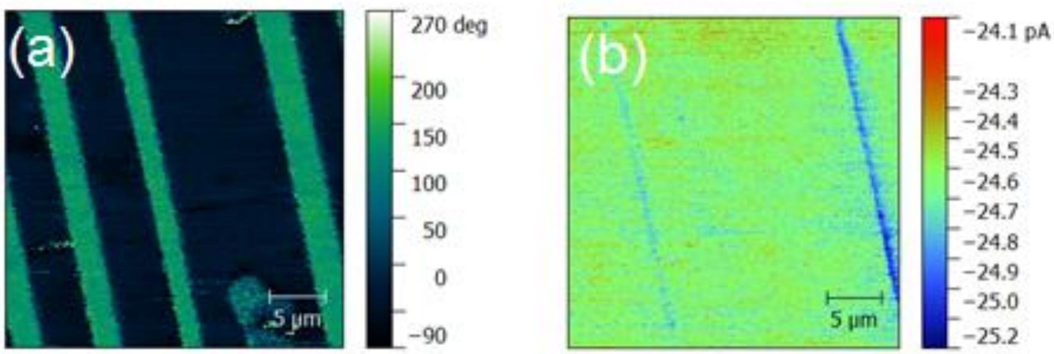

Figure 1: In-situ PFM and C-AFM images. (a) PFM, (b) conductivity image of an area in 30 microns.

As a conclusion, the different conductivities might arise due to the differently charged DWs, as results from the DW inclination with respect to the z-axes and this conductivity might be influenced by DW roughness as well.

[1] J. Seidel, L. W. Martin, Q. He, Q. Zhan, Y.-H. Chu, A. Rother, M. E. Hawkridge, P. Maksymovych, P. Yu, M. Gajek, N. Balke, S. V. Kalinin, S. Gemming, F. Wang, G. Catalan, J. F. Scott, N. A. Spaldin, J. Orenstein, R. Ramesh, *Conduction at domain walls in oxide multiferroics*, Nat. Mater., **8** (2009), 229.

[2] S. Farokhipoor, B. Noheda, *Conduction through 71° Domain Walls in $BiFeO_3$ Thin Films*, Phys. Rev. Lett., **107** (2011), 127601.

[3] J. Guyonnet, I. Gaponenko, S. Gariglio, P. Paruch, *Conduction at Domain Walls in Insulating $Pb(Zr_{0.2}Ti_{0.8})O_3$ Thin Films*, Adv. Mater., **23** (2011), 5377.

[4] M. Schröder, X. Chen, A. Haußmann, A. Thiessen, J. Poppe, D. A Bonnell, L. M. Eng, *Nanoscale and macroscopic electrical ac transport along conductive domain walls in lithium niobate single crystals*, Mater. Res. Express, **1** (2014), 035012.

Skyrmions with ferroelectric polarization in multiferroic GaV_4S_8

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The lacunar spinel GaV_4S_8 undergoes orbital ordering at 44 K and reveals a complex magnetic phase diagram below 13 K, including a ferromagnetic, cycloidal and skyrmion lattice phase [1]. Skyrmions are topologically protected nano-scale spin vortices with fascinating physical properties and high potential for future data storage. GaV_4S_8 is a magnetic semiconductor with strong easy-axis anisotropy and is the first bulk system revealing Néel-type skyrmions characterized by spins rotating in the radial plane from the core to the periphery. The existence of Néel-type skyrmions has been deduced from magnetic susceptibility, atomic force microscopy and small angle neutron scattering [1]. In addition, we provide a thorough study of the polar properties of GaV_4S_8, revealing that its orbitally ordered phase is ferroelectric with sizable polarization of $\sim 1\ \mu C/cm^2$. Moreover, spin-driven excess polarizations emerge in all magnetic phases. Hence, GaV_4S_8 hosts three different multiferroic phases including the skyrmion lattice formed by spin vortices dressed with ferroelectric polarization [2]. Based on measurements of dielectric constants, heat capacity and pyrocurrent, all as function of temperature and magnetic field, we construct a detailed phase diagram documenting a zoo of multiferroic phases. By taking into account the crystal symmetry and the spin patterns of the magnetically ordered phases, exchange striction is identified as the main microscopic mechanism behind the spin-driven ferroelectric polarization of all multiferroic phases [2]. The polar crystal structure of GaV_4S_8 is unique among the known skyrmion-lattice host materials and the ferroelectric SkL phase certainly can be exploited for nondissipative electric-field control of skyrmions.

In the second part of this talk, we present detailed results on excitations utilizing THz and broadband microwave spectroscopy. We find an intriguing relaxation dynamics in the THz range indicating the divergence of relaxation times coupled to the orbital dynamics and establishing an orbitally driven ferroelectric phase [3]. In addition, using coplanar waveguide absorption spectroscopy we study the generic magnetic excitations of the skyrmion lattice, as well as magnetic resonances of helical and induced ferromagnetic phases [4].

This work supported by Deutsche Forschungsgemeinschaft (DFG) via the Transregional Research Collaboration TRR 80 "From Electronic Correlations to Functionality".

[1] I. Kézsmárki et al., *Néel-type skyrmion lattice with confined orientation in the polar magnetic semiconductor* GaV_4S_8, Nature Materials **14** (2015), 1116.

[2] E. Ruff et al., *Multiferroicity and skyrmions carrying electric polarization in* GaV_4S_8, Science Advances **1** (2015), e1500916.

[3] Zhe Wang et al., *Polar dynamics at the Jahn-Teller transition in ferroelectric* GaV_4S_8, Phys. Rev. Lett. **115** (2015), 207601.

[4] D. Ehlers et al., *Skyrmion dynamics under uniaxial anisotropy*, (2016), Phys. Rev. B, accepted, arXiv:1512.02391

Interface-driven topological Hall effect in oxide heterostructures

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In the past several decades, electron transport intertwined with magnetism has been a focus of intensive research. One of the interesting transport phenomena is topological Hall effect (THE) derived from the Berry phase in real space and therefore is proportional to neither magnetic field (H) nor magnetization (M). THE has been widely observed in metallic magnets that host magnetic skyrmions, which are topologically protected nanometer-sized spin swirling textures [1]. The promising mechanism of the skyrmion formation is Dzyaloshinskii-Moriya (DM) interaction, arising from spin-orbit coupling combined with broken inversion symmetry.

In order to artificially introduce DM interaction at interface, here we investigate bilayers consisting of m unit cells of $SrRuO_3$ (m = 4–7) and 2 unit cells of $SrIrO_3$ by measurements of THE. While $SrRuO_3$ is a well-known itinerant ferromagnet, $SrIrO_3$ is a paramagnetic semimetal that has been lately clarified to host 5d electrons with strong-spin orbit coupling [2]. We have observed THE in bilayers over a wide region of both temperature and magnetic field [Fig. 1(a)]. The topological term rapidly decreases with the thickness of $SrRuO_3$, ending up with the complete disappearance at m = 7 [Fig. 1(b)]. These results suggest that the THE is indeed driven by interface DM interaction. The size of possible skyrmion is estimated to be ∼10 nm.

This work has been done with collaboration with N. Ogawa, K. Yasuda, F. Kagawa, W. Koshibae, N. Nagaosa, Y. Tokura, and M. Kawasaki.

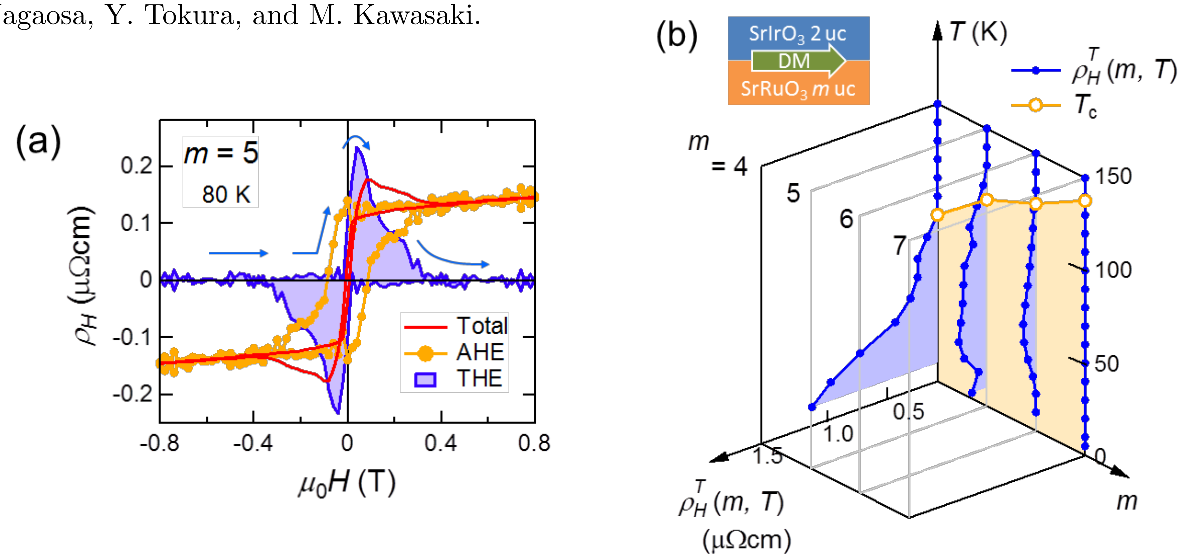

Figure 1: (a) Hall resistivity of m = 5 at 80 K. Topological term (THE) can be obtained by subtracting anomalous term (AHE) which is proportional to magnetization. (b) Topological Hall resistivity as functions of m and temperature (T).

[1] N. Nagaosa, Y. Tokura, *Topological properties and dynamics of magnetic skyrmions*, Nat. Nanotechnol. **8** (2013), 899.

[2] J. Matsuno et al., *Engineering a spin-orbital magnetic insulator by tailoring superlattices*, Phys. Rev. Lett. **114** (2015), 247209.

Roughness, dynamics and conduction at domain walls in $Pb(Zr_{0.2}Ti_{0.8})O_3$ thin films: understanding the role of defects, surface adsorbates and substrate

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Defects and electrostatic boundary conditions determined by electrodes or surface adsorbates have been shown to greatly impact the intrinsic configuration, geometry and growth dynamics of polarization domains in ferroelectric thin films [1, 2]. In $Pb(Zr_{0.2}Ti_{0.8})O_3$ we have previously shown that screening by surface water, weak collective random bond pinning, and individual strong defects determine the roughness and creep dynamics of 180° domain walls [2, 3, 4]. The interplay between surface adsorbates and defects can also be used to reversibly control the electrical conduction at such domain walls [5], while the radius of curvature of nanoscale domains can modulate the measured currents over orders of magnitude [6]. However, there has not been a detailed study considering the interplay of all these aspects, and specifically the interrelation of domain wall roughness and local conductance variations.

Here, we present our results on $Pb(Zr_{0.2}Ti_{0.8})O_3$ thin films grown simultaneously by pulsed laser deposition on STO, DSO, GSO and LSAT substrates to address this general question. The choice of substrate provides control over the intrinsic defect landscape, while thermal annealing in ultra-high vacuum (UHV) allows for the (partial) removal of surface adsorbates, thus providing an opportunity to study the role of defects and adsorbates on the functional and fundamental physical properties of domain walls in the overlying ferroelectric film.

Using piezoresponse force microscopy (PFM) and switching spectroscopy PFM (SSPFM) at ambient conditions as well as in ultra high vacuum, we study the effect of the substrate and surface adsorbates on the roughness and growth dynamics of domains as well as on the conduction behaviour of the domain walls, thus providing insight into the effect of the substrate on the intrinsic defect configuration of the overlying films.

[1] Lichtensteiger et al., *Ferroelectric size effects*, Topics APL **105**, 305-338 (2007).

[2] Paruch et al., *Nanoscale studies of ferroelectric domain walls as pinned elastic interfaces*, CRAS **14**, 667 (2013).

[3] Blaser, Paruch, *Subcritical switching dynamics and humidity effects in nanoscale studies of domain growth in ferroelectric thin films*, NJP **17**, 013002 (2015).

[4] Guyonnet et al.; *Multiscaling Analysis of Ferroelectric Domain Wall Roughness*, PRL **109**, 147601 (2012).

[5] Gaponenko et al., *Towards reversible control of domain wall conduction in $Pb(Zr_{0.2}Ti_{0.8})O_3$ thin films*, APL **106**, 162902 (2015).

[6] Maksymovych et al., *Tunable metallic conductance in ferroelectric nanodomains*, NL **12**, 209-213 (2012).

Quantitative Materials Metrology on Picometers Length Scale

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Materials-by-design paradigm ideally begins with atomic level structure in the density functional theory (DFT) approach and ends up with a macroscopic functional material. To close the design loop between experiments and theory, one has to directly compare them on the picometers length scale at which the relevant electronic and atomic structure details exist. Such unprecedented materials metrology on picometer scale is being enabled by new coherent diffraction techniques as well as improvements in direct imaging techniques with electrons and photons. In this talk, I will provide two examples of such metrology and its direct comparison with DFT using aberration-corrected transmission electron microscopy, and coherent Bragg Rod Analysis (COBRA) on various oxide thin film structures. An example of $Sr_7Ti_6O_{19}$ layered oxide films is shown in Figure 1. A large high-frequency dielectric tunability and low dielectric loss was reported [1], arising from competing polar phases predicted by DFT [2]. We will present direct imaging of these competing phases and a direct comparison with the DFT.

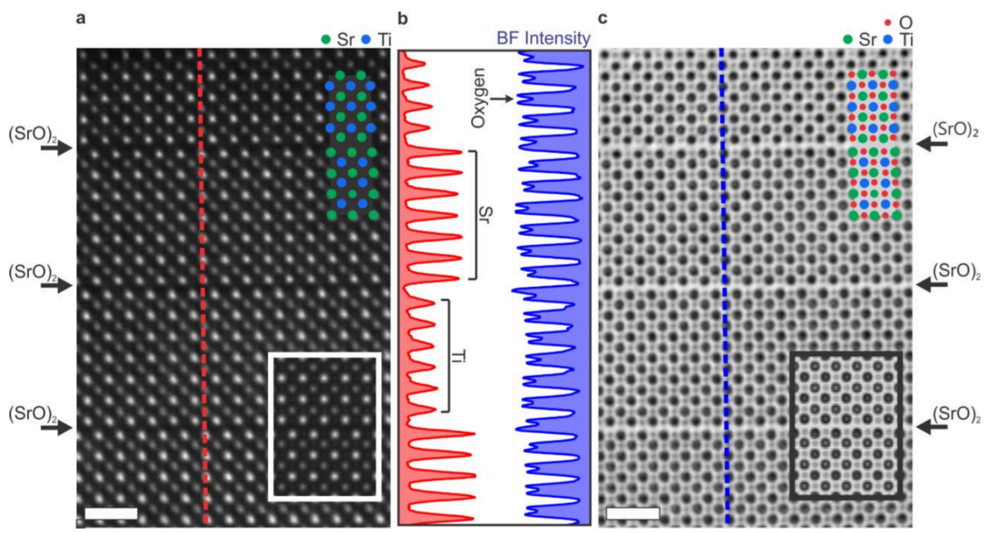

Figure 1: Atomic images of $Sr_7Ti_6O_{19}$ thin film grown on $GdScO_3$ (110)Pnma. (a) Drift corrected high-resolution high angle annular dark-field (HAADF) STEM image of the $(SrO)_2$ rock salt and perovskite blocks of the Ruddlesden-Popper structure with the corresponding simulated HAADF image, in the white box. (b) Intensity line profiles from the HAADF (red) and bright-field (BF) (blue) STEM images. (c) Simultaneous BF image showing oxygen atoms along with a simulated BF image within the black box in the lower right. The oxygen atoms are highlighted by the superimposed filled red dots. Scale bar 1 nm.

[1] C.-H. Lee et al., *Exploiting dimensionality and defect mitigation to create tunable microwave dielectrics*, Nature **502**, 532–536 (2013).

[2] T. Birol, N. A. Benedek, and C. J. Fennie, *Interface control of emergent ferroic order in Ruddlesden-Popper $Sr_{n+1}Ti_nO_{3n+1}$*, Phys. Rev. Lett. **107**, 257602 (2011).

Introduction into Physics of Chiral Magnetic Skyrmions

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Two dimensional chiral magnetic vortices or *skyrmions* represent areas of reverse magnetization localized into tubes with the diameters of nanoscale sizes. In most of nonlinear physical systems such multidimensional *static* solitonic states are unstable and collapse spontaneously under the influence of external or internal perturbations. In condensed matter systems lacking inversion symmetry two- and three-dimensional localized states (*chiral skyrmions*) are stabilized by a specific mechanism imposed by handedness of the underlying structure [1, 2]. This single out condensed matter systems with intrinsic and induced chirality (noncentrosymetric magnetic crystals, multiferroics, ferroelectrics, and liquid crystals) into a particular class of materials where skyrmions can be induced and manipulated.

Until recently chiral magnetic skyrmions have been observed only in a form of skyrmionic condensates (hexagonal lattices and other mesophases) ([3] and following papers). The first *isolated* chiral magnetic skyrmions have been discovered in the saturated states of PdFe/Ir(111) films [4], and subsequently their internal structure has been resolved [5, 6]. Contrary to a common belief, isolated chiral skyrmions (not their lattices) are the key elements in potential spintronic devices. They are also of fundamental importance in physics of solitons.

The talk overviews basic properties of isolated and bound chiral magnetic skyrmions in bulk and confined noncentrosymmetric ferromagnets [3-6].

[1] A. N. Bogdanov, D. A. Yablonskii, *Thermodynamically stable "vortices" in magnetically ordered crystals.*, Sov. Phys. JETP **68** (1989), 101–103.

[2] A. Bogdanov, A. Hubert, *Thermodynamically stable magnetic vortex states in magnetic crystals*, J. Magn. Magn. Materials **138** (1994), 255–269.

[3] X. Z. Yu et al., *Real-space Observation of a Two-dimensional Skyrmion Crystal*, Nature, **465** , (2010) 901–904.

[4] N. Romming et al., *Writing and Deleting Single Magnetic Skyrmions*, Science **341** (2013), 636–639.

[5] N. Romming et al., *Field-Dependent Size and Shape of Single Magnetic Skyrmions*, Phys. Rev. Lett. **114** (2015), 177203.

[6] A. O. Leonov et al., *The properties of isolated chiral skyrmions in thin magnetic films*, New J. Physics **18** (2016), 065003.

In-situ 3D nano-imaging of embedded ferroelectric topologies, and their strain and misorientation fields

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The intrinsic strain and misorientation fields around domain walls, dislocations and substrate-film interfaces can profoundly affect both local and global functionality. Understanding how and over what range they occur necessitates spatially mapping strain at the sub-micron scale without spurious effects from the sample geometry – a critical and outstanding challenge for many characterization techniques. We present a new way of mapping ferroelectric topology as well as strain and orientation gradients within millimeter-sized samples using *dark field x-ray microscopy* [1]. Spatial and angular resolution is ∼100 nanometers and ∼0.001 $^\circ$, respectively, while measurements are sufficiently fast that domain reconfiguration can be captured *in situ* in real time. We demonstrate the technique on $KNbO_3$ crystals and $BiFeO_3$ thin films, revealing that the strain fields associated with embedded domain walls and misfit dislocations extend up to several micrometers into the domain topology – in contrast with theoretical predictions. The strain landscape is therefore highly homogeneous, with average symmetry broken in the majority of the material. This has the potential to explain many phenomena observed in macroscopic samples and devices that are not expected in thin cross-sections or unconstrained continuums. Furthermore, this new ability to directly characterize complex topological phenomena *in situ* is a key step towards formulating and validating multi-scale models that account for the entire heterogeneity of the material.

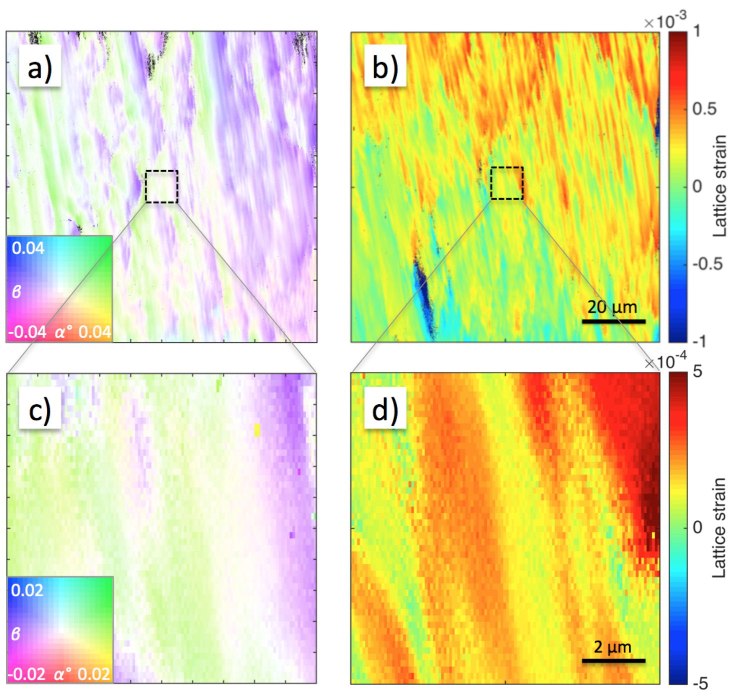

Figure 1: False-color maps of orientation (a) and strain (b) in a $KNbO_3$ crystal. Corresponding zoom images (c, d) show local gradients around domain walls. From [2].

[1] H. Simons, A. King, W. Ludwig, C. Detlefs, W. Pantleon, S. Schmidt, F. Stöhr, I. Snigireva, A. Snigirev, H. F. Poulsen, Nature Comm. **6**, 6098 (2015).

[2] H. Simons, A. C. Jakobsen, S. R. Ahl, C. Detlefs, H. F. Poulsen, MRS Bulletin **41**, 454 (2016).

Complex Phase Evolution and Coexistence in Polar Vortex Structures

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High-temperature superconductivity, colossal magnetoresistance, and (multi-)ferroism represent some of the most important topics in condensed matter physics in recent history. In all cases, emergent phenomena arise from the interplay between spin, charge, orbital, and/or lattice degrees of freedom and related couplings that can generate a rich spectrum of competing phases and novel physical responses. The presence of several competing phases close in energy results in spontaneous phase separation and nanoscale complexity (in the form of chemical, ionic, electronic, etc. variations) that can be readily controlled using external stimuli (*e.g.*, temperature, electric or magnetic field, stress, etc.) and can result in colossal changes in physical responses as the material transforms between the various states. More recently, researchers have also discovered that a diverse range of properties can be produced at interfaces between seemingly innate materials. The emergence of such exotic phenomena builds from the same interactions – spin, charge, orbital, and lattice – and thus should potentially exhibit the same types of nanoscale complexity and phase competition. In turn, there has been increasing interest in new types of emergent phenomena in the form of complex topological states with toroidal order in zero-dimensional magnets and ferroelectrics. Recent experimental work has highlighted the potential of creating such novel topological states of electrical polarization in superlattices of $(PbTiO_3)_n/(SrTiO_3)_n$ wherein the Landau chemical, electrical, elastic and polarization gradient energies are placed into competition to drive an exotic structural transformation [1].

Building from this work, we will report on the observation of a novel phase boundary between polar and toroidal states in $(PbTiO_3)_n/(SrTiO_3)_n$ superlattices. In particular, we observe a coexistence of classical *a1/a2/a1/a2* ferroelectrics domains and polar anti-ferrotorroidal structures (comprised of periodic arrays of alternating clockwise and anti-clockwise electrical polarization vortices). We willprovide a detailed analysis of the symmetry of the coexisting order parameter states, a map of their nanoscale spatial distribution, and the superlattice period, temperature-, and field-dependent evolution of the competition between the ferroelectric and toroidal phases. In this process we observe a reversible first-order temperature-dependent evolution along with a reversible and deterministic electric-field control of the ferroelectric-to-vortex phase transition. Such electric-field control is indicative of a strong coupling between polar and toroidal orders, which is exciting for new cross-coupled functions (piezotoroidic, electric toroidal susceptibility, pyrotoroidic, etc.) and opens up exciting avenues for their utilization in next-generation devices [2].

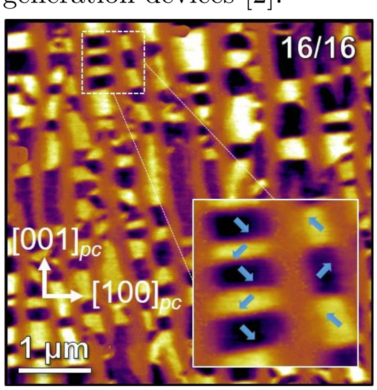

Figure 1: Piezoresponse force microscopy image of a 16×16 $PbTiO_3/SrTiO_3$ superlattice showing mesoscale evidence for phase coexistence of vortex/anti-vortex and *a1/a2* domain structures.

[1] A. K. Yadav, et al., *Observation of polar vortices in oxide superlattices*, Nature, **530** (2016), 198–201.

[2] A. R. Damodaran, et al., *Ferroelectric vortex phase coexistence and colossal electric-field tunability in oxide superlattices*, in preparation (2016).

Thursday, 18^{th} August 2016

Spin Hall Magnetoresistance in Collinear and Canted Magnetic Phases

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The spin Hall magnetoresistance (SMR) effect originates from spin current transport across the interface between an (insulating) magnet and a metal with finite spin Hall angle [1, 2]. The SMR manifests itself as a characteristic modulation of the metals resistance, as a function of the orientation of the magnetic moments in the adjacent magnet. To date, most SMR experiments have been performed in simple collinear ferrimagnets, e.g., Yttrium Iron Garnet (YIG). Since the corresponding data can be well described using a macrospin picture, the SMR is usually discussed considering the bulk magnetization of the ferrimagnet.

In magnets with non-collinear magnetic texture, however, the SMR response is more complex [3, 4]. In particular, it can no longer be described in terms of a net magnetization, raising the question which magnetic quantity indeed governs the effect. To address this issue, we compare the SMR experimentally observed in the collinear and the canted magnetic phases of Gadolinium Iron Garnet (GdIG) with atomistic spin model calculations of the magnetic configuration. We find that the magneto-transport for the different magnetic phases can be rationalized in terms of individual magnetic sublattice moment orientations. In other words, the microscopic magnetic texture determines the SMR – and not the net (average) magnetization. This makes spin-current based transport experiments very attractive for the investigation of non-collinear magnetic structures.

[1] H. Nakayama, M. Althammer, Y.-T. Chen, K. Uchida, Y. Kajiwara, D. Kikuchi, T. Ohtani, S. Geprägs, M. Opel, S. Takahashi, R. Gross, G. E. W. Bauer, S. T. B. Goennenwein, and E. Saitoh. *Spin Hall Magnetoresistance Induced by a Nonequilibrium Proximity Effect*, Phys. Rev. Lett. **110** (2013), 206601.

[2] Y.-T. Chen, S. Takahashi, H. Nakayama, M. Althammer, S. T. B. Goennenwein, E. Saitoh, and G. E. W. Bauer, *Theory of spin Hall magnetoresistance (SMR) and related phenomena*, J. Phys.: Condens. Matter **28** (2016), 103004.

[3] A. Aqeel, N. Vlietstra, J. A. Heuver, G. E. W. Bauer, B. Noheda, B. J. van Wees, and T. T. M. Palstra, *Spin-Hall magnetoresistance and spin Seebeck effect in spin-spiral and paramagnetic phases of multiferroic $CoCr_2O_4$ films*, Phys. Rev. B **92** (2015), 224410.

[4] K. Ganzhorn, J. Barker, R. Schlitz, M. Althammer, S. Geprägs, H. Huebl, B. A. Piot, R. Gross, G. E. W. Bauer, and S. T. B. Goennenwein, *Spin Hall Magnetoresistance in a Canted Ferrimagnet*, arXiv:1605.07441 (2016).

Multifunctionalities driven by Periodic Ferroic Domain Structures

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Considerable attention has been paid to ferroic systems in pursuit of advanced applications in past decades. Most recently, the emergence and development of multiferroics, which exhibit the coexistence of different ferroic natures, has offered a new route to create functionalities in the system. In this talk, I will step from domain engineering to explore a roadmap for discovering intriguing phenomena and multifunctionalities driven by periodic domain patterns. As-grown periodic domains, offering exotic order parameters, periodic local perturbations and the capability of tailoring local spin, charge, orbital and lattice degrees of freedom, are introduced as model templates for fundamental studies and novel applications. I will discuss related significant findings on ferroic domain, nanoscopic domain walls, and conjunct heterostructures based on the well-organized domain patterns, and end with future prospects and challenges in the field.

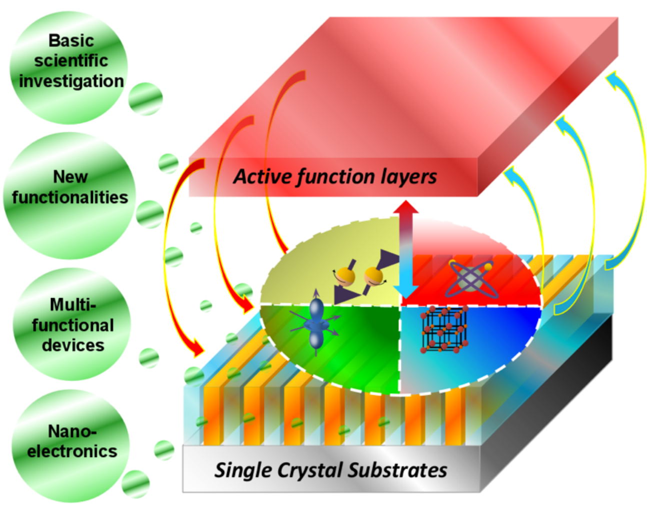

Figure 1: A general roadmap for developing multifunctionalities with periodic domain patterns as well as the conjunct heterostructures, which paves an innovation way to basic scientific investigation, new functionalities, multi-functional devices, and new nanoelectronics.

[1] J. C. Yang, Y. L. Huang, Q. He, Y. H. Chu, *Multifunctionalities driven by Periodic Ferroic Domain Structures*, Journal of Applied Physics **116**, 066801 (2014).

Chiral Interactions in Thin Film Magnets

A. Hrabec[1], N. A. Porter[1], K. Zeissler[1], P. M. Shepley[1], M. J. Benitez[2], J. Pulecio[3,4], C. S. Spencer[1], R. C. Temple[1], J. C. Gartside[1], C. J. Kinane[5], T. R. Charlton[5], A. Wells[1], A. P. Mihai[1], G. Burnell[1], D. McGrouther[2], T. A. Moore[1], S. Langridge[3], Y. Zhu[4], S. Finizio[6], J. Raabe[6], S. McVitie[2], and C. H. Marrows[1]

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The Dzyaloshinskii-Moriya interaction (DMI) arises in situations where structural inversion symmetry is broken in a magnetic material. It favours chiral magnetic states and is able to stabilise spin textures with non-trivial topology, most notably skyrmion states. In order to realise skyrmion-based spintronics, thin films showing strong DMI are needed.

Structural inversion symmetry is broken in bulk in the B20 lattice, which is possessed by the helimagnetic metal FeGe. We have grown epilayers of this material that show interesting transport properties [1], can have their chiral states controlled by ferromagnetic capping layers [2], and show an inversion of the sign of the DMI on doping with Co.

On the other hand, structural inversion asymmetry is also naturally present at an interface, and ultrathin (sub-nm) magnetic layers can also show DMI. This leads to homochiral domain walls that are topologically protected against mutual annihilation [3]. We have shown that the DMI of sputtered Pt/Co/Pt layers can be inverted by the insertion of an Ir overlayer [4], and that the DMI can be made to oscillate by varying the electron count of the top layer in $\mathrm{Pt/Co/Pt}_{1-x-y}\mathrm{Ir}_x\mathrm{Au}_y$ trilayers. Small skyrmion bubbles have been observed in perpendicularly magnetised $\{\mathrm{Pt/Co/Ir}\}\times N$ multilayers by both scanning X-ray transmission microscopy using XMCD contrast (in patterned dots) and Lorentz transmission electron microscopy (in sheet films).

[1] N. A. Porter, J. Carter Gartside, and C. H. Marrows, *Scattering mechanisms in textured FeGe thin films: Magnetoresistance and the anomalous Hall effect.* Phys. Rev. B **90** (2014), 024403.

[2] N. A. Porter, C. S. Spencer, R. C. Temple, C. J. Kinane, T. R. Charlton, S. Langridge, and C. H. Marrows, *Manipulation of the spin helix in FeGe thin films and FeGe/Fe multilayers.* Phys. Rev. B **92** (2015), 144402.

[3] M. J. Benitez, A. Hrabec, A. P. Mihai, T. A. Moore, G. Burnell, D. McGrouther, C. H. Marrows, and S. McVitie, *Magnetic microscopy and topological stability of homochiral Néel domain walls in a Pt/Co/AlO$_x$ trilayer.* Nature Commun. **6** (2015), 8957.

[4] A. Hrabec, N. A. Porter, A. Wells, M. J. Benitez, G. Burnell, S. McVitie, D. McGrouther, T. A. Moore, C. H. and Marrows, *Measuring and tailoring the Dzyaloshinskii-Moriya interaction in perpendicularly magnetized thin films.* Phys. Rev. B **90** (2014), 020402.

Resonance Terahertz Electrodynamics of Domain Walls in Thin Ferroelectric Films: Effect of Negative Capacitance

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Polarization domains that alternate the surface charge distribution, first proposed by Landau (1935) and Kittel (1946) in contents of ferromagnetism can be formed in finite-size ferroelectrics as an effective mechanism to confine the depolarization field to the near-surface layer and diminish the depolarization energy. However their existence have long been considered as barely possible until recent direct theoretical predictions [1, 2, 3] and experimental evidences [4, 5] in thin oxide films and superlattices. Polarization distribution in domains in few-nanometer-thick films has the gradual "soft" profile [3], resembling the vortex-like flux closure texture [5].

We consider the ultra-high-frequency dynamics of few-nanometer wavelength periodic domain structure observed in $PbTiO_3/SrTiO_3$ superlattices [6]. The calculated frequency dependence of dynamical permittivity, $\varepsilon(\omega)$ of thin layer of $PbTiO_3$ with domains exhibits striking feature: its real part is negative at low frequencies that is explained by the opposite orientation of the depolarizing field with respect to the field-induced averaged polarization, phenomenon known as "ferroelectric negative capacitance". However, in sub-THz region Re $\varepsilon(\omega)$ becomes positive, passing through 0 at $\omega_c \sim$ 0.3-3 THz.

The resulting collective oscillation mode is associated with domain-wall vibrations. It becomes active in the near-THz frequency region and can be excited and detected by methods of Reflection Absorption Spectrometry. The corresponding reflectivity $\Delta R/R \sim \mathrm{Im}\, \varepsilon^{-1}(\omega)$ reveals the clear resonance at $\omega \sim \omega_c$ for the THz beam, incident at the Brewster angle. This unique property makes ferroelectric films a promising candidate for compact and tunable devices working in the sub- and low THz range.

[1] A. M. Bratkovsky and A. P. Levanyuk, Phys. Rev. Lett. **84**, 3177 (2000).

[2] V. A. Stephanovich, I. A. Luk'yanchuk, M. G. Karkut, Phys. Rev. Lett. **94**, 047601 (2005).

[3] I. A. Luk'yanchuk, L. Lahoche, and A. Sené, Phys. Rev. Lett. **102**, 147601 (2009).

[4] S. K. Streiffer, J. A. Eastman, D. D. Fong et. al., Phys. Rev. Lett. **89**, 067601 (2002).

[5] P. Zubko, N. Jecklin, A. Torres-Pardo et al., Nano Lett. **12**, 2846 (2012).

[6] I. Luk'yanchuk, A. Pakhomov, A. Sené, V. Sidorkin, and V. Vinokour, arXiv:1410.3124 (2014).

Domain Formation of Epitaxial Tetragonal Pb(Zr, Ti)O_3 Thin Films Grown Under Tensile Strain

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The ferroelectric and piezoelectric properties are widely known to be strongly affected by the film orientation and domain structure, which are closely related to the in-plane strain in case of the ferroelectric films. The impact of the in-plane strain on the film orientation and domain structure has been extensively investigated [1]. The so-called "strain map", which illustrates the stable constituent phases and their domains as functions of temperature and in-plane strain, has summarized the theoretical approach. In the case of a tetragonal ferroelectric film, the polarization direction tends to be parallel with the out-of-plane direction (e.g., the (001) orientation: *c-domain*) of the substrate surface under an in-plane compressive strain, but contrary aligned along the in-plane direction (e.g., the (100) orientation: *a-domain*) under an in-plane tensile strain. In addition, the strain map indicates a mixed orientation of (100) and (001) for ferroelectric films with a small in-plane strain [2, 3]. However, few experimental investigations have been performed on a mixed orientation (mixture of *a-domain* and *c-domain*) region as a function of tensile in-plane strain. In the present study, we investigated the domain structure at room temperature as a function of tensile strain in addition to their temperature dependency.

Figs.1(a) and (b) show vertical and lateral *PFM* images, respectively for 30nm-thick (100)/(001)-oriented tetragonal Pb($Zr_{0.05}Ti_{0.95}$) films grown on (100)(Ba,Sr)RuO_3//(100)$KTaO_3$ substrates. Volume fraction of (001) orientation is ascertained to be 11% from the XRD analysis. Two types of domain structure consists of *a1/a2* domain combination with in-plane polarization and *a3/c* domain combination as shown in Figs.1 (c) and (d), respectively with in-plane two directions are detected. Noticeable thing is that *a3/c* domain combinations can be seen between two variants of *a1/a2* domain combinations with in-plane 90° tilted by each other. It is ascertained from XRD measurements that this film changed from perfectly (100) orientations to the mixture of (100) and (001) ones under the cooling process after the deposition. Based on this XRD data, *a3/c* domains combinations is considered to preferentially nucleate at the boundaries of *a1/a2* domain combinations with in-plane 90° tilted by each other.

This work was partially supported by the JSPS KAKENHI Grant Nos. 26220907, 15H0421, and 16J10098.

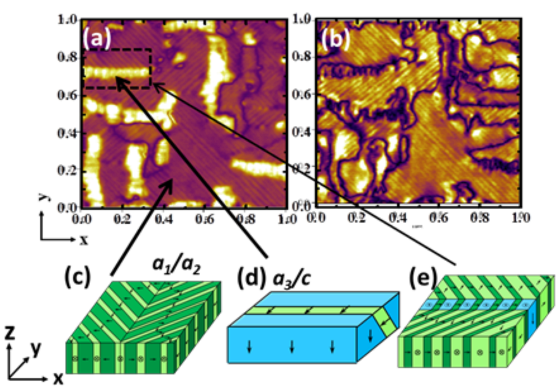

Figure 1: (a) Vertical and (b) lateral *PFM* images and the model structure of (c) *a1/a2* and (d) *a3/c* domains combinations and (e) the combinations of *a1/a2* and *a3/c* domains combinations.

[1] D. G. Schlom et al., Annu. Rev. Mater. Res. **37**, 589 (2007).

[2] V. Kukhar et al., Phys. Rev. B **73**, 214103 (2006).

[3] G. Sheng et al., J. Appl. Phys. **104**, 054105 (2008).

Robust in-plane ferroelectricity over room temperature in atomic-thick SnTe

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Stable ferroelectricity with high transition temperature in nanostructures is needed for miniaturizing ferroelectric devices. Here, applying molecular beam epitaxy (MBE) and variant temperature scanning tunneling microscopy (VT-STM), we have studied the stable in-plane spontaneous polarization in atomic-thick SnTe, down to a 1-unit cell (UC) limit. The ferroelectric transition temperature T_C of 1-UC SnTe film is greatly enhanced from the bulk value of 98 K [1] and reaches as high as 270 K. Moreover, 2- to 4-UC SnTe films show robust ferroelectricity at room temperature [2]. Recent high temperature STM experiments show that the ferroelectricity of 2- and 3-UC SnTe films persists even up to 380 K, comparable with the classical perovskite ferroelectric $BaTiO_3$. The interplay between semiconducting properties and ferroelectricity in this two-dimensional material may enable a wide range of applications in nonvolatile high-density memories, nanosensors, and electronics.

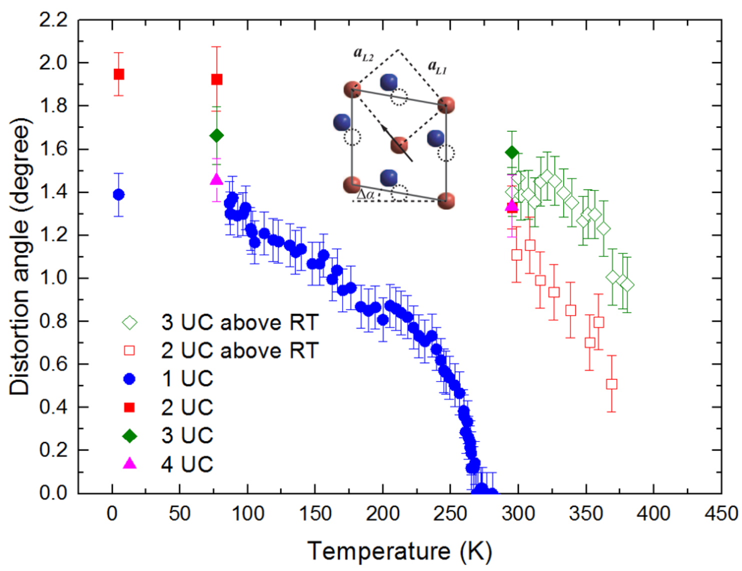

Figure 1: Temperature dependence of the distortion angle $\delta\alpha$ for the 1- to 4-UC SnTe films. The data points lower than or at room temperature are adopted from reference [2].

[1] M. Iizumi et al., *Phase transition in SnTe with low carrier concentration*, J. Phys. Soc. Jpn. **38** (1975), 443–449.

[2] K. Chang et al., *Discovery of robust in-plane ferroelectricity in atomic-thick SnTe*, Science **353** (2016), 274–278.

Observation of Polar Vortices in Oxide Superlattices

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The complex interplay of spin, charge, orbital, and lattice degrees of freedom has provided for a plethora of exotic phase and physical phenomena. Among these, in recent years, topological states of matter and spin textures have emerged as fascinating consequences of the electronic band structure and the interplay between spin and spin-orbit coupling in materials.

In this work, we leverage the competition between charge, orbital, and lattice degrees of freedom in superlattices of $PbTiO_3/SrTiO_3$ to produce complex, vortex-antivortex pairs (that exhibit smoothly varying ferroelectric polarization with a 10 nm periodicity) that are reminiscent of topological features such as skyrmions and merons. Using a combination of advanced layer-by-layer growth techniques, atomic-resolution mapping of structure and local polar distortions using scanning-transmission electron microscopy, and phase-field modeling approaches we present a comprehensive picture of the nature of the varying polarization profile in such vortex states. The continuous rotation of the polar state into the vortex structures is thought to occur from an interplay of polar discontinuities at the $PbTiO_3/SrTiO_3$ interface (where $\nabla \cdot P \neq 0$), the phase transformation strain and gradient energy in the $PbTiO_3$ layer, and the strain imposed by the substrate. Finally, the implications of these observations are discussed as they pertain to producing new states of matter and emergent phenomena (such as chirality) in such superlattices.

Growth temperature as a tuning parameter for intrinsic polarization orientation in ferroelectric thin films

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In ferroelectric ultrathin films, the depolarization field arising from bound charges on the surface of the film and at the interface with the substrate must be compensated in order to maintain the polarization. This can be achieved by screening either by external free charges from metallic electrodes or ions from the atmosphere, or by internal mobile charges from within the large-band-gap semiconducting ferroelectric itself. In the absence of sufficient free charges, a ferroelectric has several other ways of minimizing its energy while preserving its polar state, e.g., by forming domains of opposite polarization, or rotating the polarization into the plane of the thin ferroelectric slab [1, 2].

Another frequently observed feature in ferroelectric thin films is the presence of a built-in voltage. Such a built-in voltage can also originate both from external sources by asymmetrical screening, or internal ones, such as trapped charges or strain gradients leading to flexoelectricity. The properties of ferroelectric thin films are also to a large degree modified by the presence of such a built-in voltage. A residual field present in a ferroelectric thin film will result not only in a shifted P-E hysteresis loop, but will also modify the intrinsic polarization configuration and the stability of reversed domains [3].

A novel approach to off-axis RF sputtering allowed us to obtain high quality samples over a wide growth temperature range. By modulating the growth temperature of $PbTiO_3$ thin films, we engineered several series of ferroelectric samples with the same external electrical boundary conditions, but distinctively different built-in fields. We used piezoresponse force microscopy, both in spectroscopic and in imaging mode, to investigate the intrinsic domain configuration, written domain stability, and local ferroelectric switching loops of these samples. Our results open up a straightforward method to control the intrinsic polarization orientation in such ferroelectric oxide thin films, which is crucial to applications.

[1] C. Lichtensteiger et al., *Ferroelectricity in ultrathin-film capacitors*, Ch. 12 in *Oxide Ultrathin Films, Science and Technology*, Wiley (2011).
Preprint —> arxiv.org/abs/1208.5309

[2] C. Lichtensteiger et al., *Tuning of the depolarization field and nanodomain structure in ferroelectric thin films*, NanoLetters **14**(8), 4205 (2014).

[3] C. Lichtensteiger et al., *Built-in voltage in thin ferroelectric $PbTiO_3$ films: the effect of electrostatic boundary conditions*, New Journal of Physics **18**, 043030 (2016).

Domain nucleation and positive influence of depolarization fields in ultrathin epitaxial PZT films

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The role of a paraelectric spacer in the nucleation and growth domains is presented. In the first part domain nucleation in epitaxial (001)-oriented $Pb(Zr_{0.2}TiO_{0.8})O_3$ (PZT) ultrathin ferroelectric films (without spacer) under a sub-critical field regime is investigated by means of piezoresponse force microscopy (PFM). Analytical fits to the domain radius and velocity as a function of time indicate that 180° domain nucleation and growth under a biased PFM tip exhibits a thermally activated, creep behavior. It is also found that an electric field of less than half of the local coercive (or critical) field detected by PFM, can create stable domains under prolonged bias application. Under these sub-critical bias conditions, it is the temporal evolution of the local electric-field profile due to the slow drift of screening charges or defects (e.g. ionic vacancies) that dictates domain nucleation and growth [1].

Next, the effect of intentionally introducing a large depolarization field is presented. Inserting between 3 to 10 unit cells of paraelecric spacer (STO) between two 3 nm thick PZT films significantly influences the out-of-plane (c) lattice constant as well as the virgin domain state. Piezoresponse force microscopy images reveal a nanoscale (180°) polydomain structure in these films. The insertion of STO drives a 180° polydomain transition in the as-grown state, which reduces the imprint by 80 %. The insertion of the STO also profoundly improves dielectric leakage and hence the distribution of the applied electric field. Consequently, the critical pulse duration of the electric field required to initiate domain switching is reduced by two orders of magnitude relative to the reference sample. These results demonstrate the possibility of manipulating the depolarization field in such a way that it has positive effects on the ferroelectric behavior of ultrathin PZT films [2].

[1] J. Chen, et al., *Sub-critical field domain reversal in epitaxial ferroelectric films*, J. Appl. Phys. **116**, 124109 (2014).

[2] G. Liu, J. Chen, et al., *Topological Structures in Ferroic Materials: Positive Effect of an Internal Depolarization Field in Ultrathin Epitaxial Ferroelectric Films*, Adv. Electron. Mater. **2** (2016).

Spin Dynamics of Topological Spin Structures

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Topological spin structures that emerge due to the Dzyaloshinskii-Moriya interaction (DMI), such as chiral domain walls and skyrmions possess a high stability and are of key importance for magnetic memories and logic devices [1, 2]. We have investigated in detail the dynamics of topological spin structures, such as chiral domain walls that we can move synchronously with field pulses [3].

For current-induced dynamics we find in addition to spin transfer torques [1] that spin-orbit torques dominate the dynamics. We determine these independently of the DMI [4, 5] and we find that the sign of the DMI is opposite for stacks with CoFeB compared to stacks with a CoFe as the magnetic layer due to B diffusion at the interface [4].

For strong DMI novel topologically stabilized skyrmion spin structure emerge and we demonstrate for the first time that we can move a train of skyrmions in a "racetrack"-type device [1] due to spin-orbit torques reliably [6] and we find skyrmion lattices at room temperature in confined geometries [6].

Finally we study the field - induced dynamics of skyrmion [7] and find that the trajectory of the skyrmion's position is accurately described by our quasi particle equation of motion. From a fit we are able to deduce the inertial mass of the skyrmion and find it to be much larger than inertia found in any other magnetic system, which can be attributed to the non-trivial topology [7].

[1] S. S. P. Parkin et al., Science **320**, 209 (2008);
O. Boulle et al., Mater. Sci. Eng. **R 72**, 159 (2011).

[2] M. Jourdan et al., Nature Comm. **5**, 3974 (2014);
Z. Jin et al., Nature Phys. **11**, 761 (2015).

[3] J.-S. Kim et al., Nature Comm. **5**, 3429 (2014).

[4] R. Lo Conte et al.; Appl. Phys. Lett. **105**, 122404 (2014);
R. Lo Conte et al.; Phys. Rev B **91**, 014433 (2015).

[5] T. Schulz et al., Appl. Phys. Lett. **107**, 122405 (2015).

[6] S. Woo et al., Nature Mater. **15**, 501 (2016)).

[7] F. Büttner, M. Kläui et al., Nature Phys. **11**, 225 (2015).

Re-writable Nanoscale Circuitry on Graphene through Flexoelectric Switching of a Ferroelectric Superlattice

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We exploit nanoscale flexoelectric switching of an artificially layered ferroelectric material, used as an active substrate, for inducing the local manipulation of the electrical transport properties of graphene. In Graphene Ferroelectric Field Effect Transistors (GFeFETs), the graphene channel's charge state is controlled by an underlying ferroelectric layer. The tip of an atomic force microscope (AFM) can be used to mechanically "write" nanoscale regions of the graphene channel and "read" off the modulation in the transport behavior. The written features associated with the switching of ferroelectric domains remain polarized until an electrical reset operation is carried out. Our result paves the way to flexible and reversible nano-scale manipulation of the transport properties of a broad class of 2D materials.

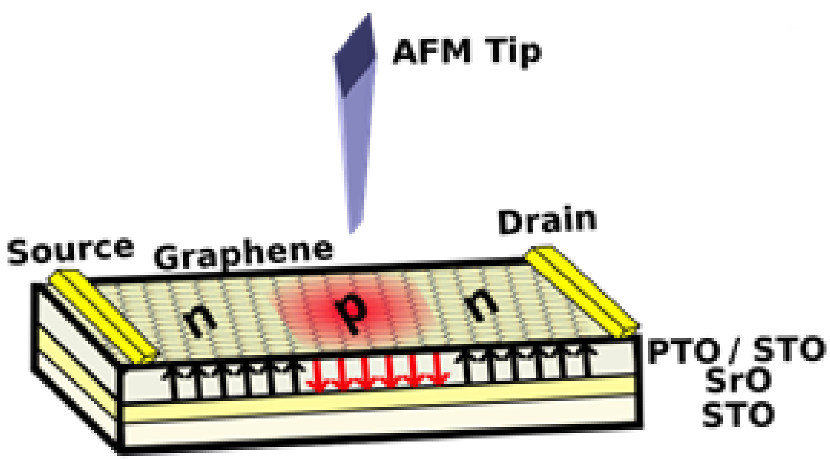

Figure 1: Schematic of the mechanical writing procedure. Regions that are poled down after the application of pressure by an AFM tip are p-doped, as compared to the upward-poled background which is n-doped.

Probing the interfacial phases of correlated oxides tuned by ferroelectric polarization and ionic gating

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Interface in oxide heterostructures has become a ubiquitous tool for discovering novel properties and phenomena not observed in bulk materials. In fact, many would claim that controlling and understanding the interface is essential for the advancement and fabrication of new devices. This is evidenced by discoveries of 2-dimensional electron gas at the $LaTiO_3/SrTiO_3$ interface, superconductivity existing between two non-superconducting cuprates, and electric-field control of spin polarization between ferroelectric and ferromagnetic layers, which are all phenomena observed on a length scale of less than a few nanometers. However, direct probing of such subtle interfacial phenomena is challenging especially for understanding the spatial contribution of interfacial magnetism. Here, we use polarized neutron reflectivity (PNR) to explore the detailed magnetic structure of ferromagnetic, $La_{0.8}Sr_{0.2}MnO_3$ (LSMO) and ferroelectric $PbZr_{0.2}Ti_{0.8}O_3$ (PZT) heterostructures. We find that the addition of PZT has the capability to both deplete and accumulate holes at the interface depending upon the polarization direction. Specifically, we have determined that the suppressed magnetization common to the manganite-air interface can be enhanced if the polarization in PZT is oriented in a way to accumulate holes. Through these carefully designed heterostructures, we show that field effect doping by means of ferroelectrics and ionic liquid gating is an efficient and powerful method to effectively tune the hole concentrations and phase diagrams of a wide range of materials.

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Underlying topological features in ferroelectrics

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Topological point defects such as vortices, antivortices, hedgehogs and antihedgehogs constitute a prime topic in different areas of physics, ranging from cosmology to liquid crystals and, to a lesser extent, ferroelectrics. We here examine these topological defects *(i)* correlate to geometric frustration within a ferroelectric nanocomposite, and further show that *(ii)* defects bear the imprint of relaxor behavior in disordered ferroelectrics.

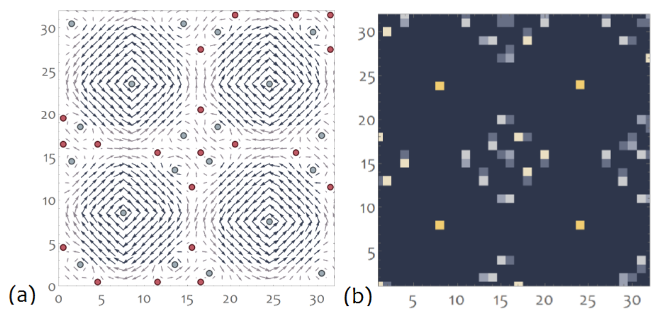

Figure 1: (a) Microstructure (in-plane component of local dipoles and defects distribution) and (b) spatial probability distribution of defects at 5 K for the same configuration in geometrically frustrated nanocomposite revealing the floating character of defects self-assembly.

(i) Using a first-principles-based effective Hamiltonian (H_{eff}) technique, we investigate a chiral ferroelectric nanocomposite consisting of a square array of $BaTiO_3$ nanowires embedded in a less polarizable matrix ($Ba_{0.15}Sr_{0.85}TiO_3$). We find that, as a result of the weak coupling between the chiralities of the wires, independent choices of spontaneous chiral symmetry breaking in each of the wires geometrically constrains the matrix to incompatible orientational boundary conditions. In response to frustration, the matrix features a self-assembled ordered structure of vortices and antivortices. Such structures are found to spatially fluctuate while preserving the energy, thereby pointing to a residual entropy at the origin of ground state degeneracy [1].

(ii) First-principles-based effective Hamiltonian simulations are used to reveal the hidden connection between topological defects (hedgehogs and antihedgehogs) and relaxor behavior. Such defects are discovered to lie at the border of polar nanoregions in both $Ba(Zr_{0.5}Ti_{0.5})O_3$ (BZT) and $Pb(Sc_{0.5}Nb_{0.5})O_3$ (PSN) systems, and the temperature dependency of their density allows to distinguish between non-canonical (PSN) and canonical (BZT) relaxor behaviors (via the crossing or not of a percolation threshold). Moreover, defects are found to be mobile excitations, and the dynamical nature of their annihilation is demonstrated (using simple hydrodynamical arguments) to follows laws, such as Vogel-Fulcher and Arrhenius, that are those characteristic of dipolar relaxation kinetics of relaxor ferroelectrics [2].

These works are supported by ARO grant W911NF-12-10085 and DARPA grant HR0011-15-2-0038 (under the MATRIX program).

[1] Y. Nahas, S. Prokhorenko, L. Bellaiche, *Frustration and Self-Ordering of Topological Defects in Ferroelectrics*, Phys. Rev. Lett. **116** (2016), 117603.

[2] Y. Nahas, S. Prokhorenko, I. Kornev, L. Bellaiche, *Topological Point Defects in Relaxor Ferroelectrics*, Phys. Rev. Lett. **116** (2016), 127601.

Resonant and Non-resonant AFM Oscillatory Modes Combined with Near-field IR Microscopy for Compositional Mapping of Surface Properties

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A family of atomic force microscopy (AFM) techniques has recently been enriched by an addition of the HybriD Mode, in which a cantilever deflection during oscillatory non-resonant tip-sample force interactions is tracked with high sensitivity. Such operation, which becomes possible with an implementation of fast data acquisition and real-time signal processing, leads to new advanced applications. The recording of the deflection response in the different parts of the interaction cycle offers new capabilities for the feedback control and mapping of local mechanical and electromagnetic properties. The experimental data collected with the HybriD Mode on a variety of samples demonstrate the unique features of this mode and provide its rational comparison with the results of Amplitude Modulation technique, which is more broadly applied so far.

The set of oscillatory resonance AFM modes is expanded with frequency modulation (FM) mode and frequency imaging (FI) in amplitude modulation mode (Fig. 1). The backgrounds of these modes are discussed and their capabilities are compared on the practical examples. The data show how these techniques complement the amplitude modulation with phase imaging. The frequency imaging enhances the compositional mapping of heterogeneous samples. Frequency modulation mode provides a superior capability in imaging at low tip-sample forces.

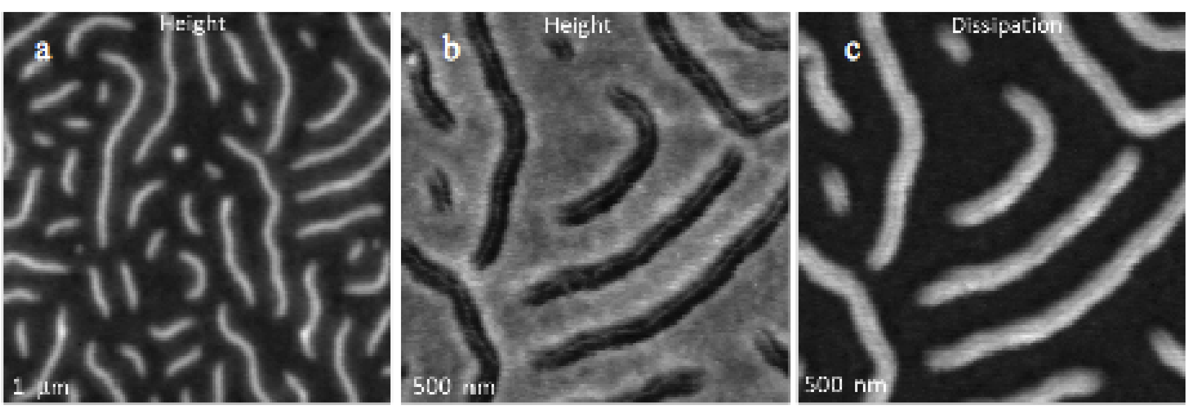

Figure 1: The height (a)–(b) and dissipation (c) images of brush-like macromolecules on mica in FM mode at $\Delta\omega_{sp} = -24$ Hz at the large (a) and small (b)–(c) tip-sample distances. The height contrast in (a)–(b) is in the 0–8 nm range. The contrast in (c) is in the relative units.

Expansion of AFM proceeds by combining this technique with vibrational spectroscopy instruments. Following the efforts that have led to AFM/Raman devices, which provide a chemically-specific mapping of materials, the capabilities of AFM/IR characterization are intensively exploring now. Here we are presenting several applications, which were performed with the set-up, in which AFM microscope (NTEGRA, NT-MDT) is merged with an optical device (Evanescent Solutions Inc), consisting of IR laser source, Michelson interferometer, and cooled MCD detection system.

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Control of skyrmions by electric field and mechanical strain

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Magnetic skyrmion, i.e. vortex-like swirling spin texture with particle nature, has recently attracted much attention as the potential information carrier for next generation of magnetic storage device [1, 2, 3]. In metallic system, skyrmions interact with conduction electrons through the spin transfer torque and emergent electromagnetic field, enabling the current-driven control of skyrmion dynamics. In insulating materials, in contrast, skyrmions can induce electric polarization through the magnetic symmetry breaking, which is expected to be manipulated by electric field [4, 5].

Toward the local writing and deleting of skyrmions, the modulation of skyrmion stability by external perturbation is an important issue. For this purpose, we have investigated the stability of skyrmions under electric field [6] as well as mechanical expansive strain. For each case, the dramatic change of magnetic phase diagram has been observed, demonstrating the potential of these perturbations as the method for efficient skyrmion control without the loss of Joule heating.

[1] N. Nagaosa, and Y. Tokura, Nature Nanotech. **8**, 899 (2013).

[2] A. Fert, V. Cros, and J. Sampaio, Nature Nanotech. **8**, 152 (2013).

[3] S. Seki, M. Mochizuki, *Skyrmions in Magnetic Materials* (Springer, 2015).

[4] S. Seki, X. Z. Yu, S. Ishiwata, Y. Tokura, Science **336**, 198 (2012).

[5] S. Seki, S. Ishiwata, Y. Tokura, Phys. Rev. B, **86**, 060403(R) (2012).

[6] Y. Okamura, F. Kagawa, S. Seki, and Y. Tokura (submitted).

Probing the interaction of surface adsorbates with ferroelectric domains

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Surface adsorbates are an ubiquitous presence on all materials exposed to ambient environmental conditions. Water, in particular, by virtue of its polar nature, has been shown to interact strongly with domains and domain walls in ferroelectric materials. We have previously focused on the influence of water on polarisation switching dynamics in $Pb(Zr_{0.2}Ti_{0.8})O_3$ thin films [1], and demonstrated its key role (together with redistribution of oxygen vacancies) in the reversible control of electrical transport at 180° domain walls in this material [2]. However, in these systems the reciprocal effect of polarization also needs to be considered, as it will induce changes in the behaviour of surface adsorbates.

Here, we present our studies of the interaction of adsorbed water with artificial ferroelectric domains in thin films of $Pb(Zr_{0.2}Ti_{0.8})O_3$ by functional scanning probe microscopy imaging. Comparing domains written with positive and negative tip voltage, and the as-grown state of the film, we map out the changes in the strength of the electrostatic interactions between the microscopy tip and surface as a function of changing humidity and time, as well as demonstrate that the surface arrangement of the water depends on the ferroelectric domain orientation.

[1] C. Blaser and P. Paruch, *Subcritical switching dynamics and humidity effects in nanoscale studies of domain growth in ferroelectric thin films*, New J. Phys. **17**, 013002 (2015).

[2] I. Gaponenko, P. Tückmantel, J. Karthik, L. W. Martin and P. Paruch, *Towards reversible control of domain wall conduction in $Pb(Zr_{0.2}Ti_{0.8})O_3$ thin films*, Appl. Phys. Lett. **106**, 162902 (2015).

Topological structures as nanoscale functional elements: Electrical and mechanical properties of phase boundaries in $BiFeO_3$

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Topological structures in functional materials have recently received increased attention due to the fact that their properties, which are linked to the inherent order parameters of the material, its structure and symmetry, can be completely different from that of the parent bulk material [1, 2]. I will present an overview of recent results regarding new intrinsic properties of multiferroic phase boundaries, domain walls, and other topological defects in $BiFeO_3$ [3, 4, 5, 6]. The origin and nature of the observed confined nanoscale properties are probed using a combination of nanoscale transport measurements based on scanning probe methods, high resolution transmission electron microscopy and first-principles density functional theory. I will also give an outlook on how these special properties can be found in other material systems and discuss possible future applications of domain walls as nanoscale functional elements [7].

[1] J. Seidel, et al., Nature Materials **8**, 229 (2009).

[2] J. Seidel (ed.), *Topological structures in ferroic materials: domain walls, skyrmions and vortices*, ISBN: 978-3-319-25299-5, Springer, Berlin (2016).

[3] J. Seidel, et al., Advanced Materials **26**, 4376 (2014).

[4] Y. Heo, et al., Advanced Materials **26**, 7568 (2014).

[5] G. Catalan, J. Seidel, et al., Reviews of Modern Physics **84**, 119 (2012).

[6] P. Sharma, et al., Advanced Materials Interfaces, DOI: 10.1002/admi.201600033 (2016).

[7] J. Seidel, Nature Nanotechnology **10**, 109 (2015).

Twisting ferroic order-parameters: ubiquity of Lifshitz invariants, frozen gauge background, and proper or improper Dzyaloshinskii textures

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Properties and phase transitions leading to orientable ordered media are well understood in the framework of Landau theory of phase transitions and the general phenomenology of homogeneous phases. Considering gradients of the order-parameters to describe inhomogeneous distortions of these states is formulated by appropriate Landau-Ginzburg-(LG)-functionals. However, if the underlying symmetry of the system allow free energy linear in gradients, that are known as Lifshitz invariants (LIs), then Landau theory may fail and the possible stable states can be twisted into a multitude of textures or localized states. Generically, such textures can be found for a single basic ordering mode in a crystalline medium with broken inversion symmetry. Such textures can be understood as proper Dzyaloshinskii textures. The LG-functionals with LIs are known as Dzyaloshinskii models and include fixed gauge-fields acting on the order-parameter field. Spin-spirals and chiral skyrmions in cubic chiral helimagnets and in cholesteric liquid crystals are the most prominent example of such textures. In the talk, I will discuss how novel types of these textures can exist in much wider classes of systems, where several order parameters are coupled. I will first introduce the basic notions and symmetry requirements for the occurrence of such *improper Dzyaloshinskii textures*. They are suggested to occur in certain multisublattice magnetic crystals, multiferroics with flexoelectric couplings, involving ferroelastic strains, and magnetoelectric systems near multicritical points. Then, specific properties of such textures including multidimensionally twisted condensed states, ball skyrmions, and condensed phases of skyrmions and defects will be discussed. Finally, some directions will be given. where to detect these textures in ferroic condensed-matter systems

2D and 3D investigations of novel domain wall functionalities in $LiNbO_3$ single crystals

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Both the discoveries of domain-wall (DW) localized photochemistry and DW conductivity have dramatically increased the interest in ferroelectric $LiNbO_3$ during the last decade. Surprisingly, it turned out that the DW geometries in this material differ consistently from the ideal equilibrium "textbook" arrangement of 180° domain walls: Low inclinations with respect to the polar (z) axis ($< 0.5^\circ$) as well as unexpectedly complex topologies have been regularly observed, depending on composition, doping and subsequent heat treatment of the material. Furthermore, we have developed methods to deliberately increase and decrease the inclination angles of existing DWs.

Within this talk, I will discuss multiple detection methods that allow for a comprehensive characterization of both the geometry and the resulting electronic properties of DWs in $LiNbO_3$. The portfolio of techniques contributing to this study range from high-resolution surface-sensitive techniques (such as PFM, cAFM [1], KPFM, PEEM) to complementary optical methods allowing for a full 3D inspection (Cherenkov SHG [2], interferometric quasi-phase-matched SHG [3], multiphoton photoluminescence [4], and optical coherence tomography).

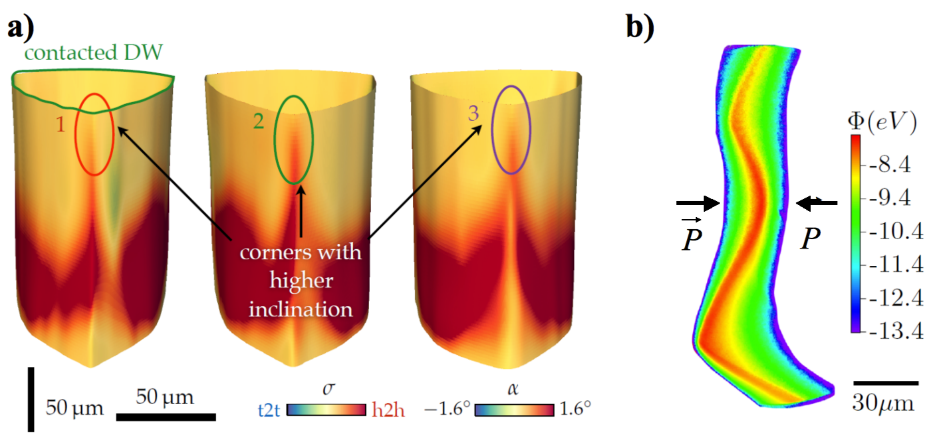

Figure 1: a) Three views on a DW with deliberately increased inclination in 5% Mg doped congruent $LiNbO_3$, imaged in 3D by Cherenkov SHG, b) surface potential map of a highly inclined DW in undoped congruent $LiNbO_3$, recorded by PEEM.

[1] M. Schröder, A. Haußmann, A. Thiessen, E. Soergel, T. Woike, L. M. Eng, *Conducting Domain Walls in Lithium Niobate Single Crystals*, Adv. Funct. Mater. **22** (2012), 3936–3944.

[2] T. Kämpfe, P. Reichenbach, M. Schröder, A. Haußmann, L. M. Eng, *Optical three-dimensional profiling of charged domain walls in ferroelectrics by Cherenkov second-harmonic generation*, Phys. Rev. B **89** (2014), 035314.

[3] T. Kämpfe, P. Reichenbach, A. Haußmann, T. Woike, E. Soergel, L. M. Eng, *Real-time three-dimensional profiling of ferroelectric domain walls*, Appl. Phys. Lett. **107** (2015), 152905.

[4] P. Reichenbach, T. Kämpfe, A. Thiessen, M. Schröder, A. Haußmann, T. Woike, L. M. Eng, *Multiphoton-induced luminescence contrast between antiparallel ferroelectric domains in Mg-doped $LiNbO_3$*, J. Appl. Phys **115** (2014), 213509.

Shape of isolated domains in uniaxial ferroelectrics. From polygons to dendrites

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The shapes of isolated domains from classical polygons to self-assembled dendrites and their dependence on the switching conditions have been studied on polar and non-polar surfaces of uniaxial ferroelectrics with high temporal and spatial resolution. The highly non-equilibrium switching conditions caused by ineffective screening of depolarized field were realized by several methods [1].

The domain evolution has been studied by optical and confocal Raman microscopy. The static domain patterns have been visualized by scanning electron microscopy and piezoelectric force microscopy [2]. The domain shapes were studied in uniaxial ferroelectrics with C3v symmetry ($LiNbO_3$, $LiTaO_3$, $SrBaNbO_3$, $Pb_5Ge_3O_{11}$) and C2v symmetry ($KTiOPO_4$). The variety of the domain shapes from polygons to dendrites has been revealed. The special attention has been paid to formation of the micro- and nanoscale dendrite domains in crystals with artificial surface dielectric layers at elevated temperatures [3] and after pulse laser heating [4]. The analogy between formation of dendrite domains and crystals has been shown for the first time. The computer simulation allowed us to obtain the snowflake-like domain shapes similar to experimental ones. The correlated nucleation attributed to the spatial distribution of the residual depolarized field near the domain wall has been demonstrated. Two variants of the shape evolution after merging have been distinguished: (1) fast recovery of the polygon shape, and (2) independent domain growth. The domain growth in polar direction has been studied for the first time with high spatial resolution by local polarization reversal of $LiNbO_3$ non-polar cuts by conductive tip of scanning probe microscope [5]. The wedge-like domain shape and large domain length differ drastically from the theoretical prediction. We attributed the domain growth in the area with negligible applied field to the self-maintained domain growth as a result of interaction of the charged elementary steps [5]. The obtained results have been discussed in the framework of the kinetic approach to the domain growth based on the analogy of domain evolution with the first order phase transformation, which allowed to explain the formation of the metastable domain patterns with energy essentially exceeding the equilibrium ones [1]. The ineffective screening of depolarizing field leads to change of the domain shape and formation of isolated nanodomains. The obtained knowledge was applied successively for domain patterning.

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[1] V. Ya. Shur, *Kinetics of ferroelectric domains: application of general approach to $LiNbO_3$ and $LiTaO_3$*, J. Mater. Sci. **41** (2006), 199–210.

[2] V. Ya. Shur, P. S. Zelenovskiy, *Micro- and nanodomain imaging in uniaxial ferroelectrics: joint application of optical, confocal Raman and piezoelectric force microscopy*, J. Appl. Phys. **116** (2014), 066802.

[3] V. Ya. Shur, D.S. Chezganov, M. S. Nebogatikov, I. S. Baturin, M. M. Neradovskiy, *Formation of dendrite domain structures in stoichiometric lithium niobate at elevated temperatures*, J. Appl. Phys. **112** (2012), 104113.

[4] V. Ya. Shur, M. S. Kosobokov, E. A. Mingaliev, D. K. Kuznetsov, P. S. Zelenovskiy, *Formation of snowflake domains during fast cooling of lithium tantalate crystals*, J. Appl. Phys. **119** (2016), 144101.

[5] D. O. Alikin, A. V. Ievlev, P. Turygin, I. Lobov, S. Kalinin, V. Ya. Shur, *Tip-induced domain growth on the non-polar cuts of lithium niobate single crystals*, Appl. Phys. Lett. **106** (2015), 182902.

Helimagnetic order: spinwaves and topological defects

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The Dzyaloshinskii-Moriya interaction in chiral magnets stabilizes helimagnetic order – a one-dimensional magnetic crystal – in a wide parameter regime. In the first part of the talk, we discuss the spinwaves [1] and, in particular, the magnetic resonances [2]. We show that the symmetry of the helix ensures that its two resonances, $+Q$ and $-Q$, become linearly polarized in zero magnetic field allowing to address them in a controlled fashion [3]. In the second part, we discuss the topological defects of helimagnetic order. The orientation of the helix is effectively described by a pitch director allowing for π-defects, so-called disclinations. Bound π and $-\pi$ disclinations form an edge-dislocation whose slow dynamics has been identified to govern the equilibration of helimagnetic ordering after a quench [4]. We discuss the topological skyrmion number of these dislocations and its relation to the Burger's vector. A finite skyrmion number should allow to manipulate dislocations by spin currents. Finally, we show how these topological defects can be combined to topological domain walls separating domains of helimagnetic order.

[1] M. Kugler, G. Brandl, J. Waizner, M. Janoschek, R. Georgii, A. Bauer, K. Seemann, A. Rosch, C. Pfleiderer, P. Böni, and M. Garst, *Band Structure of Helimagnons in MnSi Resolved by Inelastic Neutron Scattering*, Phys. Rev. Lett. **115**, 097203 (2015).

[2] T. Schwarze, J. Waizner, M. Garst, A. Bauer, I. Stasinopoulos, H. Berger, C. Pfleiderer, and D. Grundler, *Universal helimagnon and skyrmion excitations in metallic, semiconducting and insulating chiral magnets*, Nature Materials **14**, 478 (2015).

[3] I. Stasinopoulos, S. Weichselbaumer, A. Bauer, J. Waizner, H. Berger, M. Garst, C. Pfleiderer, and D. Grundler, *Linear dichroism of collective spin precession at low GHz frequencies induced by Dzyaloshinskii-Moriya interaction*, submitted (2016).

[4] A. Dussaux, P. Schoenherr, K. Koumpouras, J. Chico, K. Chang, L. Lorenzelli, N. Kanazawa, Y. Tokura, M. Garst, A. Bergman, C. L. Degen, and D. Meier, *Local dynamics of topological magnetic defects in the itinerant helimagnet FeGe*, Nature Commun., submitted (2016).

Cycloidal and Néel-type skyrmion glass in multiferroic GaV_4S_8

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The existence of magnetic skyrmions was predicted more than 25 years ago in non-centrosymmetric magnets [1]. For the first time, a lattice of Bloch-type skyrmions was observed in chiral magnets, which emerges as a superposition of spin helices [2]. Recently, we observed Néel-type skyrmions, which are formed by spin cycloids, in the type-I multiferroic GaV_4S_8 using small angle neutron scattering (SANS) and magnetic force microscopy (MFM) [3]. We found that the orientation of the skyrmion tubes is not controlled by the external magnetic field, but instead confined to the magnetic easy axis. As the orientation of the cycloidal wave vector is disordered within the rhomboheral plane and the magnetic correlations depend on the sample history cycloidal and skyrmion glass states are realized in the studied crystals. Due to the polar lattice of GaV_4S_8, these magnetic skyrmions have ferroelectric structure as well and they exhibit strong static and dynamic magnetoelectric effects [4].

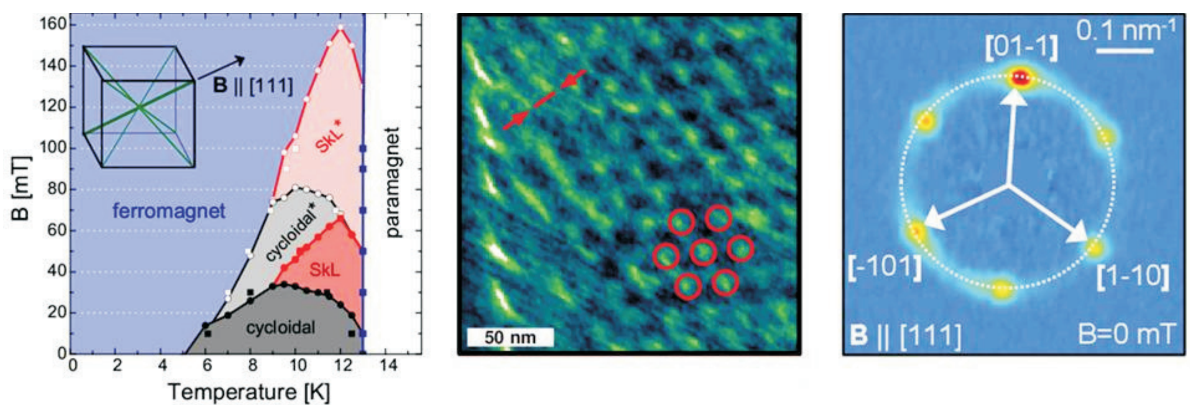

Figure 1: Left: Magnetic phase diagram of GaV_4S_8 including the cycloidal, skyrmion lattice (SkL) and ferromagnetic states. Middle: MFM image of the magnetic pattern in the skyrmion lattice state. Right: SANS image taken at zero magnetic field in the cycloidal phase.

[1] A. N. Bogdanov, and D. A. Yablonskii, *Thermodynamically stable "vortices" in magnetically ordered crystals. The mixed state of magnets*, Zh. Eksp. Teor. Fiz., **95** (1989), 178.

[2] S. Mühlbauer, et al., *Skyrmion Lattice in a Chiral Magnet*, Science, **323** (2009), 915.

[3] I. Kézsmárki, et al., *Néel-type skyrmion lattice with confined orientation in the polar magnetic semiconductor GaV_4S_8*, Nature Materials, **14** (2015), 1116.

[4] E. Ruff, et al., *Multiferroicity and skyrmions carrying electric polarization in GaV_4S_8*, Science Advances, **1** (2015), e1500916.

Skyrmionic states in ferroelectric nanocomposites

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Skyrmions, are now widely recognized as objects of both fundamental interest and technological relevance. So far, skyrmions were amply investigated in magnets, where due to the presence of chiral interactions, these topological objects were found to be intrinsically stabilized. Ferroelectrics on the other hand, lacking such chiral interactions, were somewhat left aside in this quest.

Here we demonstrate, via the use of a first-principles-based framework, that skyrmionic configuration of polarization can be extrinsically stabilized in ferroelectric nanocomposites. The interplay between the considered confined geometry and the dipolar interaction underlying the ferroelectric phase instability induces skyrmionic configurations. Such electrical skyrmions can be as small as a few nanometers, thus revealing prospective skyrmion-based applications of ferroelectric nanocomposites. We find that the topological structure of the obtained electrical skyrmion can be mapped onto the topology of domain-wall junctions. This property not only constitutes an important difference between electric and magnetic skyrmions but also highlights the importance of domain wall junctions in ferroelectric materials. Finally, we investigate the topological properties of such junctions in proper ferroelectrics as well as their connection to point defects and domain walls.

This work is financially supported by DARPA grant HR0011-15-2-0038 (under the MATRIX program) and by the Physics department of the University of Arkansas. Y.N., Z.G. and L.B. also acknowledge the ARO grant W911NF-12-1-0085. S.P. acknowledges the support of Marie Curie COFUND fellowship.

[1] Y. Nahas, S. Prokhorenko, L. Louis, Z. Gui, I. Kornev, L. Bellaiche, *Discovery of stable skyrmionic state in ferroelectric nanocomposites*, Nature Communications, **6** (2015), 8542.

[2] S. Prokhorenko, Y. Nahas, L. Bellaiche, *Fluctuations, topological defects and domain wall junctions in proper ferroelectrics*, under review.

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Wednesday 17th August 2016

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05:10 PM	05:40 PM	**Nahas**
05:40 PM	06:00 PM	**Polyakov**
07:30 PM		***DINNER***

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11:00 AM	11:20 AM	**Haußmann**
11:20 AM	11:50 AM	**Shur**
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Session 3		
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01:30 PM	02:00 PM	**Bordács**
02:00 PM	02:30 PM	**Prokhorenko**
Closing		
02:30 PM	02:40 PM	**Eng**
04:30 PM		***EXCURSION***