Program

Advanced Imaging of Ferroic Materials

857. WE-Heraeus-Seminar

31 May – 04 June 2026

at the Physikzentrum Bad Honnef, Germany

WILHELM UND ELSE
HERAEUS-STIFTUNG

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de

Aims and scope of the 857. WE-Heraeus-Seminar:

The ferroic state, i.e., the property of matter to spontaneously organize itself magnetically, electrically or elastically, is one of the most fascinating phenomena in nature and is also extremely relevant for technological applications, ranging from energy conversion to unconventional computing. A paradigm shift is currently taking place in the field of ferroics research. New types of ferroic order are discovered and a new understanding of how a ferroic state is defined is emerging. New concomitant phenomena and applications, which often result from the topological properties of such ferroic states, are being researched. Novel imaging techniques for ferroic states, in particular in three dimensions, are being developed.

The aim of the seminar is to bring structure to the current progress in the field of ferroic ordering and imaging techniques, and thereby promote a coherent and synergetic development of the research field. The sessions will deal with the definition of the ferroic phase, the modelling of ferroic and antiferroic materials, spatial imaging techniques for ferroic structures, and ultrafast nonequilibrium processes. The preparation of a Roadmap will be one of the mid-term goals of the event.

Scientific Organizers:

Prof. Dr. Manfred Feibig	ETH Zurich, Switzerland e-mail: manfred.fiebig@mat.ethz.ch
Prof. Dr. Dennis Meier	University of Duisburg-Essen, Germany e-mail: dennis.meier@uni-due.de

Administrative Organization:

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Introduction

Venue:	Physikzentrum Hauptstraße 5 53604 Bad Honnef, Germany

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Registration:	Mojca Peklaj (WE Heraeus Foundation) at the Physikzentrum, Reception Office Sunday (16:00 h - 21:00 h) and Monday morning

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Sunday, 31 May 2026

16:00 – 21:00	Registration	
18:00	*BUFFET SUPPER and informal get together*	
19:30 – 19:40	Organizers	**Welcome and Introduction**
19:40 – 21:10	**Evening Session – Framing the Topic of the Seminar**	
	Introductory presentations:	
	Manfred Fiebig	**Modern Understanding of Ferroics**
	Dennis Meier	**Advanced Imaging – What's Possible and What's Not**

Monday, 01 June 2026

07:30	*BREAKFAST*	

Session 1 – Fundamentals of Ferroics I
(Chair: Gustau Catalan)

08:30 – 09:15	Andrés Cano	**Concept and Definition of Ferroic Order**
09:15 – 10:00	Jiri Hlinka	**Ferro-axial Order and Point-group Symmetry Breaking**
10:00 – 10:30	*COFFEE BREAK*	

Session 2 – Imaging of Ferroic Order I
(Chair: Andrés Cano)

10:30 – 11:15	Hiroko Yokota	**Polar Structure Imaging by Second Harmonic Generation Microscopy**

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Monday, 01 June 2026

11:15 – 12:00	Salia Cherifi-Hertel	**Imaging Polar Topological Textures Using Second-harmonic Generation Microscopy**
12:00 – 12:15	**Conference Photo (in front of the main entrance)**	
12:15 – 13:45	*LUNCH*	

Session 3 – Imaging of Ferroic Order II

(Chair: Salia Cherifi-Hertel)

13:45 – 14:30	Claire Donnelly	**Mapping Topological Textures in Compensated Magnets with X -rays**
14:30 – 15:15	Marco Beleggia	**Electron Optical Phase Contrast Imaging of Ferroic Materials**
15:15 – 15:30	*COFFEE BREAK*	
15:30 – 18:00	**Poster Session**	
18:30	*DINNER*	

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Tuesday, 02 June 2026

07:30	*BREAKFAST*	

Session 4 – Imaging of Ferroic Order III

(Chair: Christian Degen)

08:30 – 09:15	Marty Gregg	**Scanning Probe Tomography and Ferroelectric Domain Walls**
09:15 – 10:00	Colin Ophus	**4D-STEM Imaging of Functional Materials: From Nanobeam Diffraction to Neural-prior Ptychography**
10:00 – 10:30	*COFFEE BREAK*	

Session 5 – Modelling of Ferroics and Antiferroics I

(Chair: Jorge Íñiguez-González)

10:30 – 11:15	Anna Grünebohm	**Ferroelectric Switching in the Presence of Defects – Microscopic Insights from Ab Initio Based Simulations**
11:15 – 12:00	Thomas Lottermoser	**Multi-order Ferroics: A Playground for Domain Topologies**
12:15 – 13:45	*LUNCH*	

Session 6 – Modelling of Ferroics and Antiferroics II

(Chair: Marty Gregg)

13:45 – 14:30	Jorge Íñiguez-González	**Methods for Predictive Atomistic Simulations of Ferroic Materials**
14:30 – 15:15	Long-Qing Chen	**Thermodynamics and Phase-field Method of Ferroelectric Domain Structures**
15:15 – 15:45	*COFFEE BREAK*	

Session 7 – Dissemination and Funding
(Chair: Claire Donnelly)

15:45 – 16:30	Daniel McNally	**Inside Nature Materials: An Editor' Perspective**
16:30 – 17:15	Nicola A. Spaldin	**How the ERC Works (and How to Get a Grant)**
17:15 – 17:30	Stefan Jorda	**The Wilhelm and Else Heraeus Foundation**
17:30	**Appreciation of the WEH Poster Awards**	
18:30	*DINNER*	

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Wednesday, 03 June 2026

07:30	*BREAKFAST*

Session 8 – Imaging of Noncollinear and Anti-ferroic Order I
(Chair: Michele Conroy)

08:30 – 09:15	Christian Degen	**Imaging of Multiferroic Order Using Scanning Nitrogen-vacancy Microscopy**
09:15 – 10:00	Gustau Catalan	**Functional Oxide Membranes**
10:00 – 10:30	*COFFEE BREAK*	

Session 9 – Imaging of Noncollinear and Anti-ferroic Order II
(Chair: Felix Büttner)

10:30 – 11:15	Michele Conroy	**Probing Emergent Polar and Topological States in Ferroic Materials via Advanced In Situ Electron Microscopy**
11:15 – 12:30	Bernd Kaestner	**Nanoscale Imaging of Antiferromagnetic Domains via Nearfield-induced Photocurrents**
12:30 – 13:45	LUNCH	

Session 10 – Non-equilibrium and Control I
(Chair: Theo Rasing)

13:45 – 14:30	Kathrin Dörr	**Single-crystal-like Magnetic Switching of Antiferromagnetic LaFeO3 Films**
14:30 – 15:15	Felix Büttner	**Ultrafast Formation of Nanoscale Textured Ferroic Phases**
15:15 – 16:00	Martina Basini	**Dynamical Multiferroic States in Perovskites**

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16:15	**Excursion**
19:00	*HERAEUS DINNER* *(social event with cold & warm buffet with complimentary drinks)*

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Thursday, 04 June 2026

07:30	*BREAKFAST*	

Session 11 – Non-equilibrium and Control II
(Chair: Martina Basini)

08:30 – 09:15	Theo Rasing	**Ultrafast Magnetism**
09:15 – 10:00	Uwe Bovensiepen	**Non-equilibrium Dynamics of the Electron, Spin, and Structural Degrees of Freedom in Condensed Matter**
10:00 – 10:30	*COFFEE BREAK*	

Session 12 – Whither Ferroics
(Chairs: Manfred Fiebig & Dennis Meier)

10:30 – 11:15	Nicola A. Spaldin	**Ferroic Order in Antiferroics**
11:15 – 12:00	Paolo Radaelli	**Altermagnetism and Spin Groups**
12:00 – 12:15	**Closing remarks**	
12:30	*LUNCH*	

End of the seminar and departure

Posters

Poster Session, 01 June, 3:30 pm (CEST)

Andy Disheng An	**High-resolution optical imaging of multiferroic domain topology in ErMnO3**
Keito Arakawa	**Observation of Domains with Broken Space-Inversion, Time-reversal, and Rotational Symmetries in Antiferromagnetic Metals via Linear Optical Response**
Wakana Asahara	**Electric field-induced nonreciprocal directional dichroism of DyFeO3**
Rajdwip Bhar	**Towards table-top ultrafast soft X-ray absorption spectroscopy**
Sneha Mary Biju	**Second Harmonic Interferometric Imaging of Ferroelectric Domains in 3R-MoS2**
Tim Butcher	**Soft X-ray Microscopy of Ferroic Nanomaterials**
Andrin Caviezel	**THz-induced ultrafast dynamics in ferroics probed by nonlinear optics**
Gabriele De Luca	**Can we observe magnon transport processes using nonlinear optics?**
Xiaoxi Deng	**Optical Control of Ferroaxial Order in RbFe(MoO4)2**
Simone Finizio	**Bright days ahead - Soft X-ray scanning microscopy of ferroic materials at 4th generation lightsources**
Christoph Flathmann	**Advancing In Situ TEM Studies of Ferroic Materials with MEMS-Based Straining and Heating Devices**

Poster Session, 01 June, 3:30 pm (CEST)

Fabian Glatz	Nonlinear interference in a CrSBr BIC metasurface
Jiali He	Bias-controlled electronic broadening of an isolated ferroelectric domain wall
Xinxin Hu	Investigation of Polar Patterns in Twisted Oxide Membranes Using High-Resolution Imaging Methods
Lilia Huynh	Investigating metallicity in layered Carpy-Galy ferroelectrics through topotactic transformation.
Maxim Ivanov	Chiral Molecular Complexes with Room-Temperature Magnetic-Field Driven Reversal of Electrical Polarization
Meryem Lachhab	Quantitative 4D-STEM Analysis of Perovskite Oxides
Jingwen Li	Discovery of an intrinsic non-Hermitian phase transition in a bulk condensed-matter system
Klara Luenser	Time dependence of the ferroelastic transformation in Ni-Mn-Ga
Yingzhuo Lun	Ultralow Tip-Force Driven Sizable-Area Ferroelectric Domain Manipulation
Jan Lüning	50 kHz HHG-based Soft X-ray Source Spanning the Water Window
Annika Mechnich	Domain Contrast in Electric Field Imaging with a Diamond Tip

Poster Session, 01 June, 3:30 pm (CEST)

Fabian Meier	Nanoscale Imaging of Ferroelectric-Ferroelastic Domains in Triclinic K_2MgWO_2(PO_4)_2
Mariana Palos	Scan, Shift, Lock: Conrolling Ferroic Domains via STEM Probe Trajectories
Amirhosein Paryab	The correlation between grain size and dielectric performance of two medium-entropy compounds: (Ba0.34Sr0.33Ca0.33)TiO3 and (Ba0.25Sr0.25Ca0.25Pb0.25)TiO3
Manuel Gustavo Pinedo Cuba	Exploring polar metallicity in perovskites through strain gradients in non-planar structures
Debankit Priyadarshi	Temperature-independent linearity in optical conductivity of Weyl-Kondo semimetal CeCoGe3
Anitha Rajaram	Towards Perpendicular Magnetic Anisotropy in AlScN-Based Ferroelectric Heterostructures.
Mohammadali Razeghi	Heat as a Probe: Mapping Magnetic Domains in a Weyl Semimetal via the Anomalous Nernst Effect
Qi Ren	Strong Piezoelectric Response and Tunable Rectification in Mono- and Multilayer vdW Ferroelectrics
Vladimir Roddatis	STEM and EELS of (LaMnO3)m/(SrMnO3)n superlattices
Janina Roknic	Spontaneous Polarization in Pure and Ti-Doped (K0.5Na0.5)NbO3 Resolved by Atomic-Scale 4D-STEM and First Principles Calculations

Poster Session, 01 June, 3:30 pm (CEST)

Aiden Ross	**Phase-Field Modeling of Optical Second Harmonic Generation in Ferroelectrics**
Noah Schnitzer	**Liquid helium temperature atomic resolution STEM imaging and ptychography of ferroelectrics**
Jan Schultheiss	**Ferroelectricity and Magnetic Frustration in Hexagonal Oxides for Cryogenic Cooling**
Edith Simmen	**Understanding the interplay between ferroelectricity, polar discontinuity and screening in perovskite superlattices**
Janosch Tasto	**Analyzing the tetragonal-to-cubic phase-transition in ferroelectric BaTiO3 using EXAFS spectroscopy as a local probe**
Ivan Ushakov	**Hybrid antiferroelectric-ferroelectric domains and domain walls in noncollinear antipolar oxides**
Ewout van der Veer	**Polar WO3 and polarons by epitaxial shear strain**
Harsh Vardhan	**Thickness-Driven Phase and Magnetic Engineering in FeMn/CoFeB/Cr Multilayers for Next-Generation Spintronic Devices**
Samuel Vergara	**2D ferroelectrics for magnetic tunnel junctions**
Arnau Villalobos Martin	**Domain size control of the latent heat of the ferroelectric phase transition in Barium Titanate (BaTiO3) free-standing membranes**
Feifan Wang	**Domain-wall-induced engineering of thermoelectricity in a polar metal**

Poster Session, 01 June, 3:30 pm (CEST)

Freya Watson	**Nanoscale strain engineering of transition metal oxides using ferroelastic domain patterns**
Mads Weber	**Tuning Fe3+ Magnon Softening via Competing Magnetic Rare-Earth Anisotropies in DyxTb1-xFeO3: Revealing Hidden Spin Reorientation Instabilities**
Tomohiro Yamashita	**Second-harmonic generation study of polar e-twin walls in calcite**
Bixin Yan	**Local Control on Ferroic Orders in Multiferroic Thin Films**
Manuel Zahn	**Microscale coexistence of magnetic phases compatible with the Kagome spin-ice rule in HoAgGe**

Abstracts of Lectures

(in alphabetical order)

Dynamical multiferroic states in perovskites

M. Basini[1]

[1] *Physics Department, ETH Zürich, Zürich, Switzerland*

Angular momentum in matter is traditionally associated with electronic degrees of freedom such as spin and orbital motion. This connection underpins magnetism and forms the basis of modern information technologies, including spintronics and orbitronics. A key recent development is the realization that angular momentum is not exclusive to electrons: the **crystal lattice itself can carry angular momentum in the form of chiral phonons [1].** This insight opens a fundamentally new route to control matter. By driving lattice vibrations with tailored terahertz fields, it becomes possible to generate circular ionic motion and induce effective magnetic fields, enabling access to phenomena that do not exist in equilibrium.

In this talk, **I will discuss experimental approaches to prepare angular momentum states** for phonons, **and how these states generates macroscopic properties hidden at equilibrium (e.g. dynamical multiferroicity).**

In particular, I will focus on (i) the emergence of dynamical multiferroicity in $SrTiO_3$ [2] and $KTaO_3$ [3], where circularly driven phonons induce transient magnetization, and (ii) strain-assisted control of phonon angular momentum in $LaAlO_3$ [4,5].

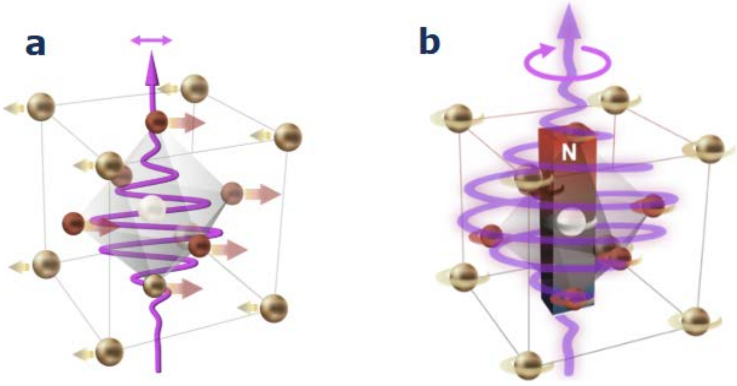

Fig. 1
(a) Linear vs (b) Circular excitation of coherent phonons in a perovskite structure.

These results establish phonon angular momentum as a functional degree of freedom in solids, providing a new pathway to engineer emergent properties beyond the equilibrium phase diagram and opening perspectives for ultrafast and low-dissipation control of quantum materials.

References:

[1] D.M. Juraschek *et al.* Nature Physics **21**, 1532–1540 (2025).
[2] M. Basini *et al.* Nature **628**, 534-539 (2024).
[3] C. Kadlec *et al. In preparation.*
[4] Basini *et al.* Phys. Rev. Lett. **136**, 156902 (2026)
[5] F. Graf *et al. In preparation.*

Electron optical phase contrast imaging of ferroic materials

M. Beleggia[1] and **R. E. Dunin-Borkowski[2]**

[1] *Department of Physics, Informatics and Mathematics, University of Modena and Reggio Emilia, Modena, Italy*

[2] *Ernst Ruska-Centre for Microscopy and Spectroscopy with Electrons, Forschungszentrum Jülich, Jülich, Germany*

Phase contrast techniques in the (scanning) transmission electron microscope can be used to record quantitative information about electric potentials and magnetic fields in materials with close-to-atomic spatial resolution. Ferroic materials are of particular interest, as their properties and functionalities are sensitive to their local charge and/ or spin distributions, which in turn depend on local variations in material composition, microstructure and morphology. Whereas magnetic fields in materials have been investigated routinely using phase contrast techniques, providing direct insight into both fundamental and applied aspects of magnetic moment distributions, similar measurements of ferroelectric polarisation have remained extremely challenging. Despite the close symmetry between electric and magnetic fields in Maxwell's equations, which suggests that imaging magnetization and polarization topographies should be analogous, the reality is different. While configurations of magnetic moments in ferromagnets, such as Landau states, magnetic vortices and Bloch-type skyrmions, can be studied almost trivially, identical topographies that are based on charge displacements and associated electric dipole moments are almost invisible to electron optical phase contrast techniques. This talk discusses the reasons underlying this difference and discusses the primary challenges in imaging ferroelectric polarization in materials using electron optical phase contrast techniques [1,2]. It provides an overview of recent attempts, successes and failures for mapping ferroelectric polarization, both at the near-atomic scale and at medium spatial resolution. A future perspective is also presented for providing access *via* the Aharonov-Bohm effect to one of the less studied manifestations of ferroic order in materials: ferrotoroidicity [3].

References

[1] M. Beleggia, L. C. Gontard and R. E. Dunin-Borkowski, J. Phys. D: Appl. Phys. **49**, 294003 (2016)

[2] F. Zheng, J. Caron, V. Migunov, M. Beleggia, G. Pozzi and R. E. Dunin-Borkowski, Journal of Electron Spectroscopy and Related Phenomena **241**, 146881 (2020)

[3] We are grateful to numerous colleagues for valuable contributions to this work, including G. Pozzi, S. Frabboni, V. Grillo, P. H.Kavkani, A. H. Tavabi, L. C. Gontard, M. Malac. Y. Zhu and R. F. Egerton.

Non-equilibrium Dynamics of the Electron, Spin, and Structural Degrees of Freedom in Condensed Matter

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Matter can be excited by means of external stimuli into non-equilibrium states. Analysis of the real time dynamics evolving under these conditions provides unique insights into elementary processes and fundamental interactions that govern the dynamics. Considering the electronic, spin, and structural degrees of freedom in condensed matter it is an essential question on which time scales these subsystems remain isolated / are interacting. These studies profit from a multi-modal experimental approach that addresses these subsystems specifically. We performed x-ray absorption spectroscopy at the synchrotron light source BESSY II [1], European X-ray Free Electron Laser (XFEL) [2,3,4], and table-top in the laboratory [5]. Ultrafast electron diffraction studies were performed at the MeV electron source at Stanford [6].

In this talk work that combines ultrafast x-ray absorption and electron diffraction experiments will be presented. In Fe/MgO heterostructures we identify electron-phonon coupling by a hybrid mode directly at the interface. This mode mediates energy transfer from electrons to phonons very efficiently on sub-picosecond timescales [7]. The ultrafast magnetization dynamics of these heterostructures exhibits a pronounced dependence on the Fe film thickness which is explained by the reduced spin coordination at the Fe-MgO interface [8]. Using the excellent spectral resolution of the SCS instrument at XFEL we analyzed the temporal evolution of the S=0 to S=2 transition in Fe-based spin crossover molecules that is mediated by an 11% bond length and the corresponding ligand field variations [9]. Most recently, we focus on the extended spectral range using EXAFS at the Ba L_3 and the Ti K absorption edges of $BaTiO_3$ to establish a structural probe with local sensitivity. Such methodology is desired to distinguish displacive and order-disorder types of structural transitions. The impact on the electric dipole dynamics will be discussed based on first results.

Funding by the Deutsche Forschungsgemeinschaft through SFB 1242 is gratefully acknowledged.

[1] K. Holldack et al., J. Synch. Rad. **21**, 1090 (2014).
[2] L. LeGuyader et al., J. Synchrotron Rad. **30**, 284 (2023).
[3] T. Lojewski et al., Mat. Research Lett. **11**, 655 (2023).
[4] T. Lojewski et al., Phys. Rev. B **110**, 245120 (2024).
[5] O. A. Naranjo-Montoya et al., Rev. Sci. Instrument. **95**, 103001 (2024).
[6] S. Weathersby et al., Rev. Sci. Instr. **86**, 073702 (2015)
[7] N. Rothenbach et al., Phys. Rev. B **100**, 174301 (2019).
[8] W. Windsor et al., under review.
[9] L. Kämmerer et al., ACS Nano **18**, 34596 (2024).

Ultrafast formation of nanoscale-textured ferroic phases

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Textures are a defining feature of ferroic materials. Their energetics are well established through decades of experimental and theoretical work, including advanced microscopy. However, the *kinetics* of their formation—for example, nucleation mechanisms, topological switching trajectories, localization dynamics, and shape evolution—remain an open question.

In this talk, I will present recent insights into the formation dynamics of magnetic textures in perpendicular magnetic films, combining quasi-static and time-resolved experiments with atomistic and micromagnetic modelling. We identify two distinct formation pathways.

The first proceeds via a high-temperature fluctuation regime characterized by rapid and uniform nucleation and decay of textures [1]. Upon cooling, textures equilibrate, evolving either toward mesoscopic sizes or annihilating depending on local interaction landscapes [2]. This localization-through-decay process, which can be described by an effective particle model [2,3], extends textbook phase transition theories and enables precise positioning of textures at sub-nanosecond timescales.

A second pathway emerges in systems with time-dependent interactions, such as during spin reorientation transitions. Here, modulational instabilities drive the system directly into a textured state without energy barriers. Remarkably, this mechanism can generate dense lattices of topological textures, in our system primarily due to chiral dipolar fields.

I conclude by discussing the potential transfer of magnetic switching concepts to ferroelectric systems [5], and by outlining prospects for direct time-resolved imaging of these processes using X-ray free-electron lasers.

References

1. Büttner, F. *et al*. Observation of fluctuation-mediated picosecond nucleation of a topological phase*. Nature Materials* **20**, 30 (2021).
2. Metternich, D. *et al*. Picosecond localization dynamics following ultrafast nanoscale magnetic switching*. arXiv.2512.17643*
3. Liefferink, R. *et al.* Effective Theory of Ultrafast Skyrmion Nucleation. *Phys. Rev. Lett.* **136**, 146705 (2026).
4. Battistelli, R. *et al*. A fluctuation-free pathway for a topological magnetic phase transition. *arXiv.2512.22947*
5. Horstmann, J. G. *et al.* Dynamic control of ferroic domain patterns by thermal quenching. *Nature Communications* **16**, 6802 (2025).

Concept and Definition of Ferroic Order

Andrés Cano

Institute NEEL, CNRS, Grenoble, France

In this talk, I will discuss the concept of ferroic order. I will deconstruct its terminology and draw analogies across different ferroic phenomena to clarify its fundamental meaning and highlight its universal aspects. I will also emphasize the fundamental connection between ferroic order and the notion of an order parameter. While the order parameter characterizes the nature of the ferroic state, its precise physical content is not unique and therefore a matter of convenience. This freedom has important practical consequences, particularly for the visualization and imaging of ferroic order, and thus for the understanding of ferroic materials.

References

[1] L. D. Landau and E. M. Lifshitz, Statistical Physics, Part 1, 3rd ed., Course of Theoretical Physics, Vol. 5 (Pergamon Press, Oxford, 1980).

[2] M. E. Holtz, K. Shapovalov, J. Mundy, C. S Chang, Z. Yan, E. Bourret, D. A. Muller, D. Meier, and A. Cano, *Topological Defects in Hexagonal Manganites: Inner Structure and Emergent Electrostatics*, Nano Lett. 2017, 17, 10, 5883–5890

Functional oxide membranes

Gustau Catalan

ICREA and ICN2, Barcelona, Catalonia

In the last decade, functional film research has undergone a revolution with the development of methods grow epitaxial, single-cristalline perovskite films and release them from the substrate by immersion in water. The resulting membranes have new mechanical degrees of freedom that allow them to bend, optical degrees of freedom that allows illuminating them from above or below, and stacking degrees of freedom that allows putting them together with a twist angle. The ability to make films without a substrate also allows studying intrinsic size effects in the absence of epitaxial strain, thus opening a window to the fundamental physics of thin films. Our group at ICN2 has been exploring several of the emerging possibilities of oxide membranes, and my talk will attempt to cover as many of our results as possible, trying to touch base on the microscopy challenges and opportunities that are emerging with membranes. These will include "polar" vortices in twisted metallic membranes, polar nanodomains in antiferroelectric membranes, and caloric consequences of domain configurations in ferroelectric membranes.

Thermodynamics and Phase-field Method of Ferroelectric Domain Structures

Long-Qing Chen
The Pennsylvania State University

This presentation will discuss the thermodynamics and the phase-field method of ferroelectric crystals and their applications to modeling and predicting the stability of domain structures and their responses to mechanical and electric fields. It will start with the basic principles of classical thermodynamics by introducing a modern version of the first law of thermodynamics and applying it to obtain the fundamental equation of thermodynamics for homogeneous ferroelectric crystals. It will then be followed by the discussion on the thermodynamics of ferroelectric crystals containing domain structures involving long-range elastic and electrostatic interactions and domain wall energy. The last part of the presentation will be focused on the applications of the phase-field method of ferroelectric domain structures. Examples will be presented to illustrate the application of the phase-field method to interpreting and understanding experimentally observed ferroelectric domain structures and to providing guidance to experimental growth of thin films and characterization to discover new mesoscale domain states of materials, achieve dramatically enhanced properties, and uncover hidden functionality.

Imaging Polar Topological Textures using Second-Harmonic Generation Microscopy

Salia Cherifi-Hertel

CNRS and Université de Strasbourg, IPCMS, France

The emergence of topological polarization textures in ferroelectric materials is reshaping our understanding of ferroic order, extending it beyond uniform states toward complex, spatially structured configurations. Non-Ising and chiral domain walls, bubble domains, (anti)vortices, and polar (anti)skyrmions illustrate how symmetry breaking, electrostatic boundary conditions, and reduced dimensionality give rise to rich polarization landscapes with functional potential.

A central challenge in this context is the development of imaging approaches capable of resolving such polarization textures in three dimensions, while preserving sensitivity to symmetry and chirality. Second-harmonic generation (SHG) microscopy provides a powerful platform in this regard, owing to its intrinsic sensitivity to broken inversion symmetry and polarization orientation [1]. In particular, SHG polarimetry enables the reconstruction of complex polar states [2,3] and the discrimination between different polar topological structures such as chiral Bloch walls, non-Ising Néel walls, and Bloch lines [4].

In this talk, I will present recent advances in SHG-based imaging of polar topological textures, combining polarimetric measurements with machine-learning-assisted analysis [5,6] to achieve rapid and quantitative 3D mapping of polarization fields. I will further show how circular dichroism in SHG (CD-SHG) can be harnessed to probe chiral ferroic states. The developed polarimetry and symmetry analysis framework establish SHG microscopy and CD-SHG, as reliable approaches for imaging and characterization of polar topological textures. It contributes to the broader effort of defining and probing complex ferroic states, and provides a general framework for nonlinear optical studies of ferroic order in anisotropic materials.

References

[1] Cherifi-Hertel *et al.*, *J. Appl. Phys.* **129**(8), 081101 (2021) https://doi.org/10.1063/5.0037286

[2] Acevedo-Salas et al., *Nano Letters* **23**, 3, 795–803 (2023) https://doi.org/10.1021/acs.nanolett.2c03579

[3] Croes et al., *Phys. Phys. Rev. Materials* **5**, 124415 (2021) https://link.aps.org/doi/10.1103/PhysRevMaterials.5.124415

[4] Cherifi-Hertel *et al.*, *Nature Communications* **8**, 15768 (2017). https://doi.org/10.1038/ncomms15768

[5] Croes et al; *Advanced Physics Research* **2**: 2200037 (2022). https://doi.org/10.1002/apxr.202200037

[6] Croes and Cherifi-Hertel, *Vision2P* https://hal.science/hal-05056312, https://github.com/Electromag-IPCMS/Vision2P

Probing Emergent Polar and Topological States in Ferroic Materials via Advanced In-Situ Electron Microscopy

S. Conroy1, N. Schnitzer1, M. Palos-Sanchez1, G. Topore1, F. Hardy1, I. Saddiq1

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During domain wall motion, local symmetry breaking and phase competition can stabilise transient or hidden states, giving rise to emergent ferroic phases across multiple length scales. Understanding these phenomena requires imaging and spectroscopy methods capable of resolving structural, electronic, and topological order simultaneously and under operando conditions. In this presentation, we demonstrate how advanced aberration corrected scanning transmission electron microscopy (STEM) enables direct probing of emergent polar phases in ferroic and multifunctional materials through a combination of atomic resolution imaging, STEM EELS, 4D STEM, and electron ptychography.[1][2]

We show how in situ stimuli including heating, electrical biasing, and cryogenic cooling to helium temperatures[3] can be combined with quantitative atomic scale imaging to capture the evolution of nanoscale polar order, symmetry breaking, and emergent phase formation in real time. By applying machine learning approaches during data acquisition,[4] we identify and map emergent phases on the fly, enabling truly in situ analysis of evolving ferroic behaviour. Particular emphasis is placed on correlating local structural distortions with electronic and spectroscopic signatures extracted from momentum resolved and energy resolved STEM techniques. Using electron ptychography and 4D STEM approaches, we further explore three dimensional mapping of higher order topological textures and buried ferroic structures with sub-Å precision.

Finally, we discuss extending these methodologies towards emergent magnetic and correlated electronic phenomena through the development of field free electron microscopy, diffraction, and spectroscopy approaches.[5] These capabilities open new opportunities for investigating coupled polar and magnetic textures, quantum phases, and non equilibrium ferroic behaviour with unprecedented spatial and functional sensitivity.

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Imaging of multiferroic order using scanning nitrogen-vacancy microscopy

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Diamond has emerged as a unique material for a variety of applications, both because it is very robust and because it has defects with interesting properties. One of these defects, the nitrogen-vacancy center (NV center), has a single spin associated with it that shows quantum behavior up to room temperature. Our group is harnessing the properties of single NV centers for high resolution magnetic and electric sensing applications.

In this talk, I will discuss application of scanning NV microscopy to image the magnetic and electric field from ferroic materials. After a brief introduction into the technique, I will present illustrative examples of applications to materials systems, including the imaging of antiferromagnetic and ferroelectric domains and domain walls. I will also show examples of simultaneous imaging of electric and magnetic fields in multiferroics. Finally, I will highlight the future prospects of the technique, including its unique capabilities and limitations.

Single-crystal-like magnetic switching of antiferromagnetic $LaFeO_3$ films

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Antiferromagnetic orthoferrites $RFeO_3$ (R = lanthanide or Y) have been a platform for exploring antiferromagnetic opto-spintronics.[1,2] They are insulators and high-temperature magnets, enabling ultrafast excitation and switching of Fe spins by femtosecond light pulses. Weak ferromagnetism arising from small canting of Fe spins (by about 0.5°) provides access to switching the magnetization (***M***) and the antiferromagnetic vector (***L***) using low magnetic fields. Surprisingly, no magnetism of fully oriented (i. e., twin-free orthorhombic) orthoferrite films has been in a focus of interest until recently.[3]

As shown by several groups, orthoferrites can be grown coherently on lattice-matching orthorhombic substrates like $NdGaO_3$, $DyScO_3$ or $GdScO_3$ in a way replicating the orthorhombic substrate orientation (e. g., [4]). Here we demonstrate the (longitudinal) magneto-optical Kerr effect (MOKE) as a sensitive and direct probe of magnetic switching and domain processes in such strained $LaFeO_3$ films. Fully oriented films have large Kerr signals, rectangular hysteresis loops, domain-free remanence and wall-motion-driven switching like bulk crystals. Longitudinal MOKE microscopy has been used to visualize domain processes during magnetic switching of films in various controlled strain states.

Our results establish MOKE as an efficient optical tool for probing magnetic switching of coupled weak magnetization and Néel vectors in orthoferrite films. This provides a foundation for strain-engineered orthoferrite thin films in antiferromagnetic spintronics and magnonics.

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Mapping topological textures in compensated magnets with X-rays

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Extending spin systems to three dimensions promise significant opportunities for applications, for example providing higher density devices and new functionalities associated with complex topology and greater degrees of freedom [1,2].

Until now, however, insight into three dimensional spin systems has mainly been limited to ferromagnetic and ferrimagnetic systems through X-ray magnetic tomography [3] – where a variety of topological textures [3,4], as well as 3D dynamics [5,6], have been observed.

In this talk I will describe our recent work mapping topological textures in compensated systems. I will first describe the development of X-ray linear orientation tomography [7,8], which we have harnessed to map three-dimensional orientation fields – both crystallographic, and antiferromagnetic – at the nanoscale. Second, I will present our recent mapping of topological textures in altermagnets [9,10], harnessing both X-ray circular and linear magnetic dichroism.

These insights into the formation of topological textures in compensated magnets not only paves the way not only for enhanced understanding of these systems, but also towards the next generation of technological devices.

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Contemporary understanding of ferroics

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Ferroic materials exhibit spontaneous long-range order that couples to an external field. The archetypal example is ferromagnetism, where atomic magnetic moments align collectively below a critical temperature, producing a macroscopic magnetization. Such ordering arises from cooperative interactions among many atoms and represents a classic instance of symmetry breaking in solids.

However, ferromagnetism is only one member of a broader class of ordering phenomena described by the term *ferroic*. In addition to magnetic order, there are *ferroelectrics*, characterized by a spontaneous electric polarization, and *ferroelastics*, which exhibit spontaneous strain.

Given that these phenomena have been known for millennia to decades, one might expect the concept of ferroic order to be clearly established and thoroughly documented in textbooks. Surprisingly, this is not the case. The first attempt to formulate an overarching definition of “ferroic” dates only to 1970 [1], and a more comprehensive, materials-oriented framework did not appear until the year 2000 [2], with relatively little development since [3]. As a result, important gaps remain. For example, there is still no universal agreement on the precise definition of an antiferromagnet.

In this talk I will review the status of the field. In particular, I will discuss potential extensions of ferroic order such as ferrotoroidicity and ferroaxiality, associated with magnetic or electric whirl-like structures, respectively. I will also briefly address the recently highlighted phenomenon of altermagnetism. Finally, I will consider the broader landscape of antiferroic order, hidden order, improper and secondary order, and other little familiar manifestations. One possible route toward unifying these phenomena is a description in terms of ordered multipoles which I will therefore highlight toward the end.

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Scanning Probe Tomography and Ferroelectric Domain Walls

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While, in its original form, the atomic force microscope (AFM) was a topographic imaging tool, it has since evolved to become a versatile platform capable of probing all manner of aspects of materials’ behaviours with nanoscale spatial resolution. It can, for example, readily map properties such as local electrical potential, temperature, thermal conductivity, piezo-activity, conductivity, magnetisation and mechanical hardness. In almost all such imaging, the scientific community has had a tendency to try to avoid surface wear, that might result from excessive force at the tip-sample contact point. Only relatively recently has it been recognised that sample wear and nanoscale probe microscopy might be deliberately combined to allow imaging as a function of depth beneath a sample surface and the associated generation of 3D tomographic information [1].

In this talk, the usefulness of Scanning Probe Tomography (SPT) will be demonstrated by considering a number of case studies involving ferroelectric domain walls: in the first, SPT was used to help reveal the conical nature of charged conducting domain walls in partially switched lithium niobate thin films. This conical form was invaluable in the interpretation of magnetotransport behaviour, allowing ultrahigh carrier mobilities to be determined [2]. In the second case study, SPT was used to uncover the reasons why seemingly charged ferroelectric domain walls in both lead germanate and triglycine sulphate did not conduct [3,4]. In this work, avoidance of polar divergence was found to be entirely enabled through the formation of domain wall saddle points, that could only really be seen through tomographic imaging. In the third case study, SPT was used to identify *p-n* junctions in conducting lithium niobate domain walls and hence allow a realisation that such junctions might not be as useful in domain wall nanoelectronics as had first been hoped [5].

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Ferroelectric switching in the presence of defects – microscopic insights from ab initio based simulations

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Functional properties of ferroelectrics are closely related to ferroelectric switching and field-induced domain wall motion. While ab initio-based simulations can contribute to the fundamental understanding and control of this motion, they are challenged by the scale-bridging and statistical nature of the underlying nucleation and pinning processes. This contribution discusses how the combination of atomistic [1, 2] and coarse-grained molecular dynamics simulations [3, 4] can overcome these challenges. We will discuss the microscopic mechanisms of switching, nucleation, and wall motion in the presence of point defects [5], dislocations [6], and optical excitations [7].

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Ferro-axial order and point-group symmetry breaking

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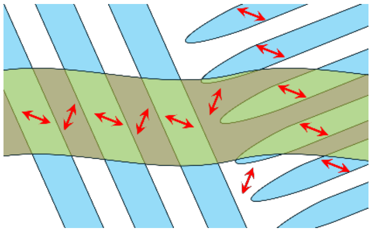
We are living in the era of powerfull experimental and computational tools allowing us to reach incredibly detailed insights into the microscopic mechanisms behind specific physical properties of virtually any crystalline material at the atomic and subatomic lengthscales. The representation theory of crystallographic space groups and their magnetic counterparts is not only a natural underlying framework allowing to simplify calculations, to classify the materials, to develop models or to interpret the properties, but also because many of the most fundamental condensed matter phenomena are directly related to the real or virtual symmetry breaking phase transitions.

Neverthless, many of the currently studied or exploited properties are related to the materials response to the perturbations varying at the lengthscales larger than that of the crystal structure unit cell itself. Such macroscopic properties have to comply with the macroscopic crystalline symmetry that is described by crystallographic point groups. Dealing with the point groups is obviously much easier then with the space groups and it is therefore instructive to explore what can be inferred from the macroscopic symmetry breaking alone. In this talk, we are aiming to explore the concept of classification of species of group-subgroup pairs within crystallographic point groups and their magnetic counter parts. Among others, the Aizu concept of species can be used to discuss scalar, vectorial and tensorial properties of multiferroic domains and domain walls, as well as the peculiar ordering in ferroaxial materials or in chiral ferroics.



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Methods for predictive atomistic simulations of ferroic materials

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I will give an overview of theoretical methods for predictive atomistic simulations in materials science. I will start with quantum-mechanical first-principles methods, such as those based on efficient schemes like density functional theory (DFT), establishing their strengths and limitations. The core of the talk will be devoted to effective interatomic potentials with parameters calculated from DFT. As an example of classic approaches, I will discuss the so-called second-principles methods, which enable nanoscale simulations and have played a key role in the field of topological ferroelectrics. I will then move to emerging machine-learning approaches that offer greater flexibility and accuracy, summarizing their status and the exciting prospects they bring. Time allowing, I will comment on our latest efforts to move beyond atomistic descriptions and develop predictive continuum simulation methods that we term "third principles." In all cases, I will give examples from my own research on ferroelectric and magnetoelectric multiferroic phenomena, focusing on nanostructures ranging from short-period superlattices to twisted membranes.

I will present results obtained in collaboration with numerous members of my group at LIST, including C. Escorihuela-Sayalero, M. Pulzone, N. Cernov, I Robredo-Magro, M. Gonçalves, X. Diaz de Cerio, C. Scott, U. Dey, H. Aramberri, and N.S. Fedorova. Work in Luxembourg was funded by the Luxembourg National Research Fund through multiple projects. For published articles and further information, please visit https://sites.google.com/site/jorgeiniguezresearch/

Nanoscale Imaging of Antiferromagnetic Domains via Nearfield-induced Photocurrents

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Antiferromagnetic materials are promising for ultrafast and highly integrated spintronic devices, yet direct imaging of their magnetic order remains challenging. In particular, 180°-reversed domains, which are technologically relevant, are typically inaccessible with established imaging techniques due to their vanishing net magnetization and magnetization-invariant contrast.

Here, we introduce a nanoscale imaging technique for antiferromagnetic domains based on a nearfield-induced photocurrent. We propose that the effect arises from a Néel-vector-dependent nonlinear anomalous Hall response, in which spin–orbit coupling and magnetic order break the symmetry between opposite crystal momenta, generating a directional DC photocurrent under optical excitation. This enables not only the identification of domain walls but also of the domains itself. Moreover, since the sign of this photocurrent depends on the orientation of the Néel vector this method allows to distinguish 180° rotated domains.

We implement this mechanism using infrared near-field photocurrent nanoscopy, where a metallic AFM tip focuses a predominantly perpendicular-to-plane polarized nearfield onto a nanoscale area. In this way a local photocurrent is induced which can be read out at remote contacts. We apply this appraoch to CuMnAs devices and directly image the antiferromagnetic domain structure with sub-100 nm resolution. We observe current-induced domain formation, resolve complex multidomain configurations, and track domain wall motion under electrical pulsing.

The results show that near-field photocurrent nanoscopy is a powerful tool for imaging antiferromagnetic order at the nanoscale, providing access to domain configurations that are invisible to conventional techniques and opening a novel route for studying ferroic order in spintronic materials.

Multi-order ferroics: A playground for domain topologies

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Multiferroics with three or more order parameters provide a platform for domain studies beyond the limits of standard systems. Here, we examine hexagonal manganites and the orthoferrite $Dy_{0.7}Tb_{0.3}FeO_3$ using second-harmonic generation microscopy and Faraday rotation. In $Dy_{0.7}Tb_{0.3}FeO_3$, a trilinear coupling connects antiferromagnetism and a weak ferromagnetic moment to an improper ferroelectric polarization. Such interactions enable the creation and control of diverse topological configurations. We demonstrate this by imprinting magnetic domain patterns directly into the ferroelectric order, mirroring the spin geometry in charge space. Beyond bulk domains, the system supports multiferroic walls that remain stable even in non-multiferroic surroundings. These nanoscale regions then act as seeds that grow again into full multiferroic domains. Thermal quenching further provides a means to understand and control the domain formation, even across phase transitions.

Hexagonal manganites illustrate how structural trimerization and improper ferroelectricity couple with antiferromagnetism to establish a complex domain topology. Lattice distortions anchor the magnetic spins through strong microscopic coupling, producing three classes of magnetic domain walls defined by spin rotation. While 60° and 120° walls remain clamped to the structural and ferroelectric boundaries, 180° walls exist independently. This results in sixfold magnetic vortices and new topological junctions such as threefold or fourfold magnetic vortices. Large-scale phase-field simulations demonstrate that this configuration extends into a complex three-dimensional network. The third dimension turns out to be essential for the stability of fourfold vortices at wall crossings and threefold vortices where magnetic walls merge with structural boundaries. These findings demonstrate that systems with three or more order parameters provide the flexibility needed to support domain topologies and functionalities unattainable for simpler multiferroics.

Advanced Imaging – What's Possible and What's Not

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The functional properties and rich physics of ferroic systems are intimately linked to their domains, domain walls, and the various defects that arise during synthesis or at phase transitions where electric, magnetic, or structural long-range order develops. Advancing the field thus relies on adequate imaging tools capable of resolving singularities in the long-range order and the property-defining defects that ultimately determine the behavior of the materials.

As modern ferroic materials become increasingly complex, our expectations for imaging and analytical techniques rise accordingly. Importantly, progress in methodology and progress in materials science often occur hand in hand. Whereas optical methods were essential for domain imaging during the first half of the last century, we can nowadays image individual atoms with precision limited only by thermal vibrations, map chemical composition at the atomic scale, and non-invasively record electric and magnetic order in three dimensions with unprecedented fidelity.

To set the stage for the upcoming workshop, I will present a non-comprehensive overview of selected imaging techniques that, in my view, have significantly shaped the field and opened new research directions. The goal is to ignite discussion and collaboratively begin pinpointing unmet needs, opening space to imagine future opportunities in the **Advanced Imaging of Ferroic Materials.**

Inside Nature Materials: An Editor’ Perspective

D.E. McNally[1]

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Nature Materials offers authors high visibility for their work. A team of full-time, professional editors select and commission articles that represent a substantial and arresting fundamental, mechanistic, methodological or practical advance. In this talk I will convey the editor’s perspective on the life of a manuscript after submission to Nature Materials, and provide an overview of the types of content that we publish. I will also discuss the emerging role of AI in publishing and materials science.

4D-STEM: from Nanobeam Diffraction to Neural-Prior Ptychography

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Functional materials require imaging methods that can measure structural, chemical, and electronic variations across length scales. Scanning transmission electron microscopy (STEM) provides atomic-scale imaging, while four-dimensional STEM (4D-STEM) records a full convergent-beam diffraction pattern at every probe position [1]. These datasets encode diffraction, phase contrast, strain, symmetry, electric field, and structure-property information, but require robust analysis methods and reproducible software workflows [2].

Nanobeam 4D-STEM can map crystal phase, orientation, strain, composition, and polarization over large fields of view. Scanning convergent-beam diffraction can recover local composition without spectroscopy by matching averaged diffraction patterns to simulated libraries [3]. Multiple-scattering inversion methods can also disentangle specimen tilt from internal structural distortions, enabling quantitative mapping of complex polar textures in thick or strongly scattering multilayers [4].

At higher spatial resolution, 4D-STEM enables electron ptychography, which reconstructs the phase of the electron wave from overlapping diffraction measurements. Ptychography provides a dose-efficient route to atomic-resolution imaging of light and heavy elements, buried interfaces, and electrostatic potentials, but practical reconstructions remain limited by noise sensitivity, slow convergence, incomplete sampling, and manual regularization. We address these challenges using deep generative priors, where convolutional neural networks parameterize the complex-valued sample and probe within an automatic-differentiation mixed-state multislice forward model [5]. This self-supervised approach improves low-dose robustness, accelerates convergence, suppresses high-frequency noise, and reduces manual tuning. Related deep-learning-enhanced 4D-STEM ptychography results further show the potential of neural reconstruction methods for experimental datasets [6]. We are developing these approaches in open software, including quantEM, to support nanobeam diffraction, ptychography, spectroscopy, and machine-learning-enabled reconstruction [8].

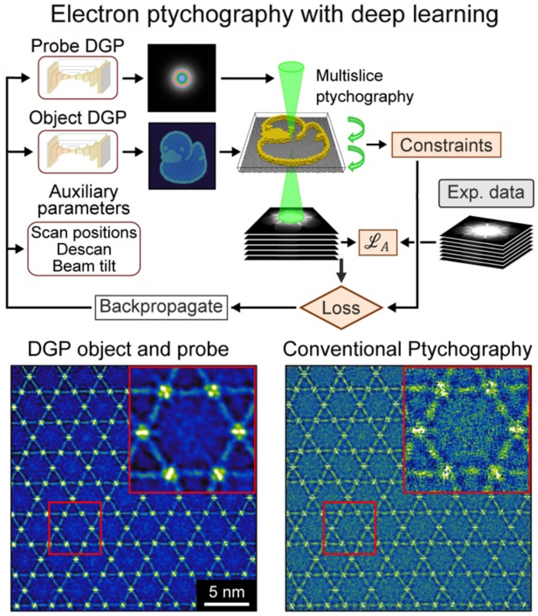

Figure 1. Deep learning electron ptychography [5, 6].

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Is there a universal classification of magnets? Lessons from magnetic imaging

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In the past two decades, there has been a resurgence of interest in compounds with electronic bands exhibiting lifted spin degeneracy, partly motivated by the need for new materials for spintronics. This has led to the introduction of the new category of 'altermagnets' – which in essence are (quasi-)collinear Γ-point antiferromagnets lacking PT symmetry. Although some altermagnets such as MnTe and SbCr have been relatively unexplored, most altermagnets are well-known antiferromagnets, and many of them are semiconductors or insulators, hence lacking low-energy spin-polarised electronic excitations. Nevertheless, many of these materials have fascinating properties that are not only extremely relevant for spintronics applications, but also serve to sharpen our understanding of what altermagnetism is (and what is not) and, more broadly, of how magnets should be classified. I will illustrate these concepts using magnetic imaging on α-Fe_2O_3 as a starting point. α- Fe_2O_3 (hematite) is a well-known insulating antiferromagnet that has been studied for more than 75 years. Spin ordering in α- Fe_2O_3 is altermagnetic with a single spin group, in spite of the fact that it supports multiple phases, each with a distinct magnetic point group. I will show that one can image the rich topological textures of α- Fe_2O_3 using X-ray linear [1] and circular dichroism [2] as well as N-V centre microscopy [3], and that all these imaging techniques are enabled by responses that are entirely due to SOC and are not directly related to altermagnetic band splitting. This is in fact a very common situation in most compensated magnets, where physical observables are typically associated with secondary order parameters that are linked to anisotropy. I will also demonstrate that this is best understood in the context of exchange multiplet representations, of which spin groups are a particular instance only in the collinear case. Finally, I will argue that the re-introducing the language of representations to the field of altermagnetism bridges the gap between the spintronics and magnetic structure solution communities.

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ULTRAFAST MAGNETISM: IMAGING AND CONTROLLING SPINS BY LIGHT

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The interaction of light with magnetic matter is of both fundamental as well as practical interest: already since Faraday and Zeeman we know that magnetic order can affect light, which has led to magneto-optical spectroscopy using the Faraday, Kerr and Magnetic Circular Dichroism and related effects but also applications such as Faraday isolators, MRI, HDD and measurements of magnetic fields of distant stars. Using modern femtosecond lasers, we can probe magnetic dynamics down to its fundamental time scale and, using XFELS, down to its fundamental length scale.

After the demonstration of ps demagnetization and magnetization reversal by a single femtosecond laser pulse, the manipulation of spins by ultra-short laser pulses has become a fundamentally challenging topic with a potentially high impact for future spintronics and data storage, as it provides an alternative and energy efficient approach to manipulate and record magnetic information. However, achieving nanoscale observation and control remains highly challenging. We recently employed a magnetic force microscope (MFM) to investigate the formation of homogeneous magnetization induced by circularly polarized picosecond laser pulses and observed the stochastic nucleation of complex nanotextured domains. The possibility to study this time-resolved will also be discussed.

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Ferroic order in antiferroics

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Many phenomena in antiferromagnets or antiferroelectrics are well described in terms of their constituent anti-aligned magnetic or electric dipole moments. However, in addition to the fact that *anti*-ferroism is aesthetically unpleasing, particularly in a conference about ferroics, there are ever more reports of intriguing behaviors that can't be explained in terms of anti-aligned dipole moments. These behaviors are often attributed to "hidden order" since their origin is difficult to decipher with conventional experimental probes. In this talk I will discuss some unusual magnetic effects in antiferromagnets, such as electric-field induced magnetism, magnetism on apparently non-magnetic surfaces, and unconventional spin splitting of energy bands, and show that they can be understood in terms of a hidden *ferroic* order of higher-order magnetic multipoles, beyond the magnetic dipole. While there are clear experimental signatures of such hidden multipolar order, and it is captured nicely in our computer simulations, attempts at direct measurement have so far proved elusive, and I will close with a plea for better ideas.

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Polar structure imaging by second harmonic generation microscopy

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Second harmonic generation (SHG) microscopy has been widely employed to visualize ferroelectric domain structures because of its high sensitivity to the breaking of centrosymmety. In this study, we apply this technique to investigate polar characteristics emerging at domain boundaries (DBs) in nonpolar materials. DBs in ferroic materials have recently attracted considerable attention, as they exhibit many physical properties distinct from those of bulk. Particularly, the appearance of polar nature at DBs in nonpolar materials provides a promising platform for nanoelectronic devices.

Through polarization-resolved SHG measurements, we confirm clear signatures of local polarity at DBs in various materials[1-3]. Furthermore, the application of the external stimuli suggests the possibility for controlling or manipulating their polar natures, highlighting their potentials for device applications.

Our investigation extends beyond ferroelastic DBs to include antiphase boundaries (APBs) in antiferroelectrics as well as twin walls. APBs are translational boundaries which give a phase shift between the adjacent domains. Although APBs exist various materials, their experimental characterization has remained challenging because they are typically invisible under conventional optical microscopy. By contrast, SHG microscopy enables to visualize APBs as SH-active regions. The observed SH response can be interpreted as the existence of a local polarization at APBs. Complementary diffuse scattering experiment and molecular dynamic simulations shows a good agreement with the SHG observations. These results suggest that the local polarization at APB originates from a ferri-like atomic configuration. This ferri-like structure is metastable and vanishes at temperatures much lower than the bulk phase transition temperature [4,5].

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Abstracts of Posters

(in alphabetical order)

High-resolution optical imaging of multiferroic domain topology in $ErMnO_3$

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We present a study of the multiferroic domain structure in $ErMnO_3$ using scanning second-harmonic generation (SHG) microscopy. As SHG can couple simultaneously to both magnetic and ferroelectric orders, this confocal technique enables artefact-free, high-resolution imaging of multiferroic order.

In the improper ferroelectric phase of the type-I multiferroic $ErMnO_3$, topological defects arise as vortices at the meeting points of six domain states, giving rise to the characteristic six-fold cloverleaf domain pattern. Here, we show that the SHG intensity is strongly suppressed at vortex cores and that light can couple directly to the local symmetry breaking at ferroelectric domain walls.

Below the Néel temperature, the ferroelectric domain pattern is transferred to the magnetic one, accompanied by the additional formation of free 180° domain walls. Phase-field simulations predict attractive interactions between the different types of magnetic domain walls in $ErMnO_3$ [1]. Using low-temperature confocal SHG imaging, we experimentally demonstrate that 180° domain walls preferentially combine with ferroelectric 60° domain walls or pass through vortex cores in order to minimize the magnetic free energy.

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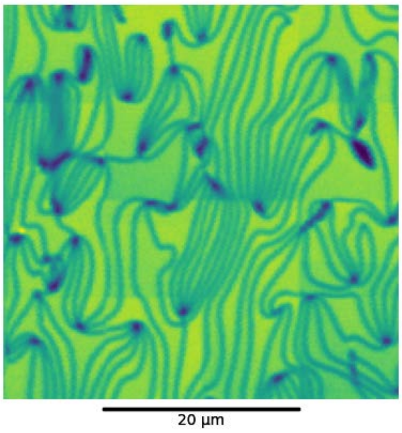

1 Scanning SHG image of ferroelectric domain structure in ErMnO3

Observation of Domains with Broken Space-Inversion, Time-reversal, and Rotational Symmetries in Antiferromagnetic Metals via Linear Optical Response

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Geometric frustration in crystal lattices induces non-trivial magnetic structures, known as frustrated magnets. Some of those materials break both space-inversion and time-reversal symmetries and exhibit cross-correlation phenomena such as the magnetoelectric effect. These phenomena are highly anticipated for future device applications. To detect such spin cluster ordering, or "cluster multipole order", domain imaging using linear optical responses can be one of the simplest and most effective methods. Here, we report the visualization of antiferromagnetic (AFM) domains in a metal using the optical magnetoelectric (OME) effect and birefringence.

We focused on the antiferromagnetic metals $Re\mathrm{B}_4$ (Re = Tb and Gd), which exhibit non-collinear magnetic structures at low temperatures due to the Shastry-Sutherland lattice [1, 2]. These materials break both space-inversion and time-reversal symmetries, under which the nonreciprocal rotation of reflected light, one of the OME effects, becomes finite [3]. To exploit this, we developed a custom-built polarizing microscope to perform domain imaging by detecting minute optical rotations [4]. Furthermore, since TbB_4 breaks rotational symmetry at even lower temperatures, ferroelastic domains can also be visualized via birefringence. By combining the OME effect and birefringence, we successfully visualized all antiferromagnetic domains in TbB_4 [5].

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Electric field-induced nonreciprocal directional dichroism of $DyFeO_3$

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Antiferromagnets which break time-reversal symmetry, have recently attracted attention for exhibiting phenomena such as the anomalous Hall effect and the magneto-optical Kerr effect—phenomena previously thought to be caused by ferromagnetism. Among these properties, "electric field-induced nonreciprocal directional dichroism (ENDD)," has recently been reported [1]. ENDD is a phenomenon in which the light absorption coefficient changes upon the application of an electric field, and it is discussed in terms of the induction of a magnetic toroidal moment by an electric field (the electrotoroidic effect) and second-order magnetoelectric effects [1,2]. The orthorhombic perovskite $DyFeO_3$ (space group *Pbnm*) studied in this work exhibits weak ferromagnetism (Γ_4 phase: magnetic point group *m'm'm*) at room temperature, and undergoes a spin-reorientation transition at T_{SR} = 50 K, transforming into an antiferromagnetic phase (Γ_1 phase: magnetic point group *mmm*). A previous study observed ENDD in the visible light region within the Γ_1 phase and reported antiferromagnetic domain imaging using this effect [3]. In this study, we performed measurements of ENDD in single crystals of $DyFeO_3$ in the visible and near-infrared regions. By investigating spectral and imaging characteristics in both the visible light region where Fe^{3+} *d-d* transitions dominate, and the near-infrared region where Dy^{3+} *f-f* transitions dominate, this work aimed to elucidate the origin of ENDD in this material and to detect time-reversal-breaking antiferromagnetic order parameters using this phenomenon.

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Towards table-top ultrafast soft X-ray absorption spectroscopy

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We present a table-top soft X-ray source based on high harmonic generation (HHG) in noble gases, enabling pump-probe X-ray absorption spectroscopy at the boron (B) K-edge. We have developed a four-stage optical parametric chirped pulse amplifier (OPCPA) to generate mid-infrared pulses at 1.5 µm and 3 µm with broad spectral bandwidth, supporting ultrashort pulse durations after compression. Using the 1.5 µm driving laser beam with a pulse energy of 1 mJ and a duration of $\sim$50 fs, and helium as the noble gas target, photon energies up to 350 eV have been generated. Recorded near-edge X-ray absorption spectra of hexagonal boron nitride (h-BN) and B foils are in agreement with spectra obtained at synchrotron facilities [1].

Ongoing efforts focus on implementing a pump-probe scheme to optically excite materials using 1.2 eV and 2.4 eV pump pulses, and probe the resulting dynamics with X-rays. This will facilitate the study of electron-phonon dynamics and energy relaxation pathways on ultrafast timescales in borophane and its polymorphs [2] by analyzing X-ray absorption at the B K-edge. Additionally, the setup is being upgraded to drive HHG using the 3 µm laser beam, which will extend the accessible photon energy range up to 1 keV. This will provide access to transition metal L-edges and the oxygen K-edge, covering a wide range of elements relevant to ferroic materials. By changing the polarization of the driving laser, the polarization of the generated X-rays can be controlled, enabling X-ray magnetic linear dichroism (XMLD) experiments. This will provide insights into magnetic anisotropy, antiferromagnetic order, and ultrafast magnetization dynamics in comparison to charge and lattice excitations in ferroic materials.

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Second Harmonic Interferometric Imaging of Ferroelectric Domains in 3R-MoS_2

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Sliding ferroelectricity has emerged as a topic of significant interest due to its possible applications in next-generation, nonvolatile memory devices [1]. In two dimensional van der Waals materials, domains of opposite electrical polarization, separated by narrow walls called domain boundaries arise from the intrinsic stacking orientation of the constituent layers and remain stable under normal environmental conditions. An external electric field applied perpendicular to the layers can change the stacking order between two energetically favourable configurations by sliding the layers relative to another and thus reversibly switch the polarization direction of the domains in a dynamic manner [2].

In order to make this phenomenon accessible to applications, it is important to precisely identify the ferroelectric domains and their domain boundaries. Using optical techniques to probe them offers a direct, faster, and more compact approach compared to standard techniques like Kelvin Probe Force Microscopy (KPFM), which is based on Atomic Force Microscopy (AFM) and measures local surface potential. Hence, a spatially resolved, all optical approach is a powerful tool for high-resolution and non-invasive imaging of domains with an added advantage of probing their coupling to other optical properties of the material [3].

In this study, we explore a nonlinear optical technique based on interference of signals from second harmonic generation to identify and characterize ferroelectric domains at room temperature. A suitable model system in this context is 3R-MoS2, which when compared to commonly studied 2H phase transition metal dichalcogenides, possesses broken inversion symmetry independent of the number of layers. This allows second harmonic generation also in samples with even number of layers.

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Soft X-ray Microscopy of Ferroic Nanomaterials

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Imaging antiferromagnetic order is challenging considering its lack of sensitivity to common magnetic microscopy methods. Multiferroicity with the presence of two distinct ferroic orders further complicates the analysis. Soft X-ray microscopy is a powerful tool for the characterisation of materials due to the ability to probe chemical, magnetic and ferroelectric properties. The microscopy technique of soft X-ray ptychography is a recent development at synchrotrons that can achieve sub-10 nm spatial resolutions [1]. Imaging ferroic order with ptychography relies on the collection of diffraction patterns from various positions of the sample under resonant conditions, which correspond to energies at the L-edge for transition metals and M-edge in the case of rare earths. The success of the approach will be presented for several ferroic materials in thin film and nanoparticle form. In the case of the room-temperature multiferroic bismuth ferrite ($BiFeO_3$), soft X-ray ptychography is able to provide unprecedented insight into the multiferroic domain structure by resolving both the antiferromagnetic spin cycloid and ferroelectric domains in a single image [2]. Ptychographic imaging provides clear evidence of magnetoelectric coupling by separation of the antiferromagnetic and ferroelectric components even in the collinear case by employing X-rays at the Fe L-edge or O K-edge, respectively [3].

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THz-induced ultrafast dynamics in ferroics probed by nonlinear optics

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Controlling ferroic order parameters on ultrafast timescales is of significant interest for the development of future high-speed devices. Optical pump-probe techniques have been a primary tool for stimulating and probing ferroics; however, using optical wavelengths to drive ferroic dynamics is often hindered by the large energy mismatch between optical photons and the physical excitations of the system, such as phonons and magnons.

In this work, we induce dynamics in ferroic materials using THz radiation, which offers the prospect of resonant coupling to the material's low-energy modes. We demonstrate preliminary results from THz-pump / SHG-probe experiments on ferroic systems. Furthermore, our experimental setup is designed to incorporate SHG imaging in the future, offering the possibility to investigate either ferroic domains or microscopic samples such as exfoliated flakes of van der Waals ferroics.

Can we observe magnon transport processes using nonlinear optics?

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Magnon transport phenomena (Spin Seebeck Effect, Spin Nernst Effect, and Magnon Hall Effect) encode fundamental information about spin dynamics, topology, and non-equilibrium physics in magnetic insulators [1]. Yet our ability to observe these processes, with spatial resolution and direct sensitivity to the magnetic order parameter, remains rather limited. Conventional detection in platinum/ferromagnetic insulator (Pt/FMI) heterostructures relies on electrical proxies that spatially average over the features we would like to resolve spatially.

Nonlinear optics can change this. Magnetization-induced Second Harmonic Generation (MSHG) is inherently sensitive to broken time-reversal symmetry at magnetic interfaces, offers sub-micron spatial resolution, and couples directly to the local magnetization thus making it a possible candidate to image the non-equilibrium magnon populations that are generated by the magnon transport processes. If successful, this would open new possibilities onto spin caloritronics and topological magnon physics, potentially accessible without leads, gates, or electrical contacts.

This vision is to be explored within a recently awarded ERC Starting Grant (TOPOLOGIQ) centered on ferromagnetic pyrochlore oxides, a largely unexplored family of magnetic insulators with rich potential for magnon spintronics thus offering a designable platform to test the idea of making spatial maps of magnon transport. This poster is an open invitation: to challenge the premise, stress-test the ideas, and collectively ask whether nonlinear optics can shed new light on magnon transport.

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Optical Control of Ferroaxial Order in $RbFe(MoO_4)_2$

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The ferroaxial (FA) order, characterized by the rotational alignment of electric dipoles, is an emergent ferroic order arising from a spontaneous mirror symmetry breaking. Due to its exotic nature, the order parameter does not couple linearly to conventional external perturbations, such as electric or magnetic fields. Only recently, we have demonstrated instead that a carefully engineered axial field, arising from the coherent excitation of circular phonons with intense terahertz (THz) light pulses, is capable of manipulating the FA order[1] (Fig.1). Circular dichroism in optical second-harmonic generation (SHG) has revealed that FA domains in the archetypal material $RbFe(MoO_4)_2$ (RFMO) are deterministically switched, with the helicity of the exciting electric field unidirectionally driving the crystal lattice towards one of its FA phases. The same optical excitation can induce a transient FA state in RFMO in its para-axial state above the ordering temperature.

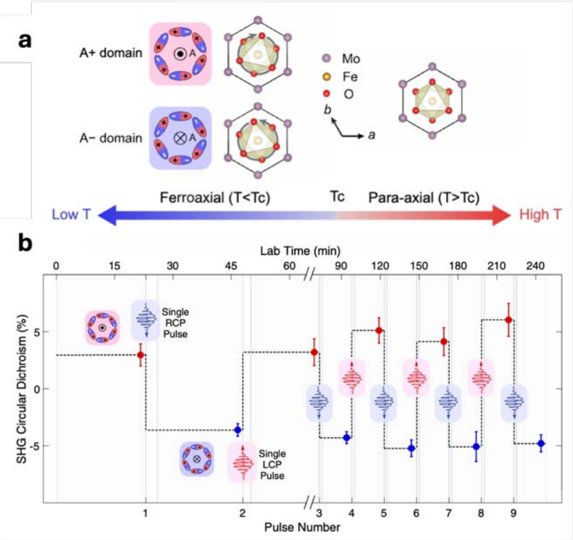

Fig. 1 Ferroaxial transition in $RbFe(MoO_4)_2$ and circularly-polarised terahertz pulse-induced ferroaxial switching[1]. a. Crystal structure of $RbFe(MoO_4)_2$ viewed along the c axis below and above Tc. b. Below-Tc single-shot switching of the ferroaxial state.

First experimental evidence from time-resolved SHG has recently been corroborated by time-resolved hard X-ray diffraction at the Swiss x-ray free-electron laser (SwissFEL). Transient dichroism in the diffraction intensity between a pair of peaks, which are related by the same mirror symmetry that drives the equilibrium FA phase transition, was found for circularly polarised THz pulses, with the sign of the dichroism depending on the pulse helicity. Comparing the quantitative changes in the Bragg scattering intensity will allow for an estimation of the angular momentum transferred to the FA soft mode.

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Bright days ahead - Soft X-ray scanning microscopy of ferroic materials at 4th generation lightsources

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Diffraction limited synchrotron (DLSR), or 4th generation, light sources are a novel design promising an increase in the coherent photon flux of several orders of magnitude compared to the current 3rd generation storage ring design. These improvements are revolutionizing synchrotron-based experiments, and several light sources around the world are currently undergoing or planning an upgrade to a DLSR. For scanning transmission X-ray microscopy (STXM), the increase in coherent photon flux will allow us to routinely perform high-resolution imaging, as it will tackle all the issues occurring for high-resolution X-ray optics. In addition, the combined increase in coherent photon flux, in the available (GPU) computational power, and in the performances of 2D soft X-ray detectors will also enable for the routine performing of high-resolution soft X-ray ptychographic imaging. In this presentation, I will show the current status of the commissioning of a new combined STXM and soft X-ray ptychography endstation at the SoftiMAX beamline of the MaxIV and SLS 2.0 DLSRs, and the first results in the ptychographic imaging of the magneto-electric coupling between ferroelectric domains and spin cycloid in freestanding $BiFeO_3$ thin films, which fully exploit the sub-5nm spatial resolutions achievable with the technique.

Advancing In Situ TEM Studies of Ferroic Materials with MEMS-Based Straining and Heating Devices

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Mechanical strain is a key factor governing a wide range of ferroic properties, including phase transitions, domain structures and domain switching [1]. Gaining precise control and understanding of strain-driven phenomena is essential for advancing the design of next-generation ferroic devices. While recent progress in in situ transmission electron microscopy (TEM) has enabled dynamic studies of ferroic materials under many relevant conditions, the simultaneous application of mechanical strain and other thermodynamic stimuli has remained challenging due to limitations in available in situ instrumentation.

To overcome this, we have developed a micro-electromechanical systems (MEMS)-based device capable of applying uniaxial mechanical stress and heating simultaneously [2,3]. This device is fully compatible with standard in situ TEM holders, supports double-tilt operation, and integrates seamlessly with established sample preparation workflows. By enabling simultaneous mechanical and thermal control, our approach opens new possibilities for comprehensive in situ TEM studies of strain- and temperature-dependent phenomena in ferroic materials.

In this contribution, we demonstrate how our MEMS device can be used to induce and observe phase transitions, as well as to perform advanced dynamic and in situ TEM experiments. We further discuss its application for imaging of ferroic materials at high resolution, enabling direct dynamical observation of domain walls under controlled conditions. Finally, we provide an outlook on ongoing and future developments aimed at further optimizing these devices for ferroic materials research.

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Nonlinear interference in a CrSBr BIC metasurface

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The active electrical [1] and all-optical [2] modulation of the nonlinear optical (NLO) response of layered materials has attracted great interest for nanophotonic applications. Ferroic layered materials, such as CrSBr, offer an alternative and powerful approach for NLO tuning thanks to temperature-dependent phase transitions [3]. Here, we present a new method where NLO modulation arises from interference effects between bound states in the continuum (BIC) resonances and the bulk NLO susceptibility of a CrSBr nanophotonic device. To achieve this, we patterned exfoliated CrSBr flakes into metasurfaces that exhibit BICs and investigated their NLO response. By varying the dimensions of the metasurface, we obtain direct control over the energy, linewidth and Q-factor of the BIC resonances [4]. When the energy of the BIC resonance is close to that of the CrSBr exciton, we further observe a strong modulation in third harmonic generation (THG), characterized by both constructive and destructive interference depending on the energy of the emitted TH signal. These results allow us to retrieve the real and imaginary parts of the BIC resonance, and they further demonstrate a new powerful approach for NLO engineering at the nanoscale.

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Bias-controlled electronic broadening of an isolated ferroelectric domain wall

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Ferroelectric domain walls are promising building blocks for future nanoelectronics, combining ultra-small feature size with a wide variety of emergent device-relevant behaviors. Most studies so far focused on bulk crystals and thin films, where the measured response reflects convoluted contributions from, e.g., the hidden sub-surface wall structures and the networks they form. The intrinsic behavior of isolated individual domain walls thus often remains unclear.

Here, we extract a single insulating ferroelectric domain wall, situated in a 1-μm-thick $ErMnO_3$ lamella, mounted on a conductive back electrode. This configuration enables a well-defined top-bottom current path using an AFM tip as a movable top electrode. Consistent with previous measurements on $ErMnO_3$ single crystals, we observe that the initially thin insulating wall (~200 nm electronic width) transforms under applied bias into a narrow conductive core surrounded by a broad depletion region, leading to a fivefold increase in apparent wall width. Systematic bias variation demonstrates a highly tunable electronic wall width, manifesting as voltage-controlled expansion and contraction of the depletion region. The results corroborate that functional domain wall properties known from crystals are transferable to nano-structured device-relevant systems and reveal new possibilities for electronic signal control.

Investigation of Polar Patterns in Twisted Oxide Membranes Using High-Resolution Imaging Methods

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Recent observations of polar patterns in twisted oxide membranes have revealed twist-angle–dependent in-plane vortex domains. We employed atomic resolution imaging techniques—including high-angle annular dark-field scanning transmission electron microscopy (HAADF-STEM) and phase imaging from 4D-STEM datasets—to resolve the polar structures in twisted oxides. The results suggest that these polar configurations arise from strain gradients induced by twist-stacking, likely mediated by flexoelectric effects. Notably, polar vortex structures were observed in metallic oxide membranes highlighting the universal ability of strain gradients to polarize materials.

In recent years, ferroelectric polarization–induced topological structures—such as polar skyrmions, vortices, flux-closure domains, and related configurations—have attracted considerable attention due to their emergent physical phenomena and potential applications in next-generation electronic devices. To date, however, these complex topological states have been predominantly realized in substrate-supported superlattice systems. In such platforms, limited structural tunability and fabrication complexity constrain their scalability and practical integration. In contrast, twisted free-standing thin films have recently emerged as a promising alternative platform, offering enhanced structural flexibility and tunable polar properties. In these systems, polar textures are strongly governed by strain gradients and lattice rotations induced by controlled twist angles. Despite their significant potential, direct investigation of these polar structures remains highly challenging, as uncovering their underlying formation mechanisms requires true atomic-scale characterization [1–4]. In this work, we fabricated a series of twisted free-standing oxide membranes and systematically investigated their structural and polar configurations.[5] By combining HAADF-STEM focal series and phase imaging reconstructed from 4D-STEM datasets, we visualized the evolution of the emergent chiral polar structures and verified the flexoelectric mechanisms driving their formation.

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Investigating metallicity in layered Carpy-Galy ferroelectrics through topotactic transformation.

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Combining seemingly incompatible properties within a single material can yield unconventional functionalities. For instance, polar metals[1] host inversion-symmetry breaking displacements despite finite metallicity. However, they remain scarce, as conventional ferroelectricity usually relies on orbital rehybridization and gets suppressed by free charge carriers[2]. Here, we report the epitaxial stabilization of layered Carpy–Galy ferroelectric $Sr_2Nb_2O_7$ ($A_nB_nO_{3n+2}$, $n = 4$), which exhibits a geometric in-plane polarization driven by collective octahedral rotations. Such thin films were first grown epitaxially by pulsed-laser deposition (PLD)[3], and interestingly they can be successfully transformed into the metallic perovskite $SrNbO_3$ through a topotactic interfacial reduction mediated by an Al overlayer, which drives oxygen-vacancy migration and electron doping. This redox-engineering route enables fine, continuous and even reversible tuning of oxygen stoichiometry, allowing us to stabilize intermediate $Sr_2Nb_2O_{7-x}$ phases, as confirmed by XRD, XPS, STEM, and transport measurements. In contrast to bottom-up synthesis of polar metals, this top-down strategy provides fine control of metallicity in a geometric ferroelectric host and opens avenues for exploring charge- and spin-transport phenomena in polar metallic oxides.

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Chiral Molecular Complexes with Room-Temperature Magnetic-Field Driven Reversal of Electrical Polarization

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The quest for materials capable of seamlessly bridging magnetic and electric functionalities remains a central pursuit in modern materials science. The synergistic combination of ferroelectricity and magnetism gives rise to magnetoelectrics (ME), which may enable the reciprocal control of magnetic and electric properties through their respective fields. Such coupling underpins disruptive technologies ranging from non-volatile memories to energy-efficient electronics and advanced sensing.[1-7] Despite intense efforts, robust room-temperature performance remains challenging in conventional single-phase inorganic magnetoelectrics, such as metal oxides and fluorides.[3, 6, 8, 9] While multiphase heterostructures have been explored to circumvent these limitations, [1, 6, 10] they often suffer from issues of phase connectivity and interface quality.[11] Molecular magnetoelectrics have emerged as a compelling alternative, offering high structural diversity and the ability to tune property-determining interactions at the molecular level. Yet, strong magnetoelectric effects in molecular systems remain limited, with progress still lagging behind inorganic counterparts.

In our works, we report a chiral molecular crystals Ni^{2+}/Yb^{3+} and Zn^{2+}/Yb^{3+} that integrates the strong local Yb^{3+} magnetic anisotropy with an optimized crystal geometry. This design enables robust room-temperature ferroelectricity and exceptionally strong magnetoelectric coupling. Notably, application of a magnetic field along the polar axis induces a nearly complete (180°) nanoscale polarization reversal at room temperature and a magnetoelectric coefficient, α_{31}, of approximately 222 $mV \cdot Oe^{-1} \cdot cm^{-1}$. This marks an advance over previous molecular systems, where only partial polarization modulation was possible. Such performance establishes a new benchmark for molecular magnetoelectrics and positions them as realistic competitors to state-of-the-art inorganic materials.

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Quantitative 4D-STEM Analysis of Perovskite Oxides

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Understanding local structural distortions and electrostatic fields in functional materials is essential for establishing structure-property relationships at the nano-to-microscale. Here, ferroelectric perovskites are investigated by four-dimensional scanning transmission electron microscopy (4D-STEM) using a pixelated detector, which records a diffraction pattern at every probe position during a STEM scan, enabling quantitative mapping of lattice distortions and electrostatic fields with atomic-scale resolution [1]. $SrTiO_3$ (STO) was first analysed as a structural benchmark with its centrosymmetric lattice to provide a reference for comparison with $BiFeO_3$ (BFO), a lead-free multiferroic rhombohedral perovskite with coupled ferroelectric and magnetic order [2]. Convergent-beam electron diffraction (CBED) patterns were recorded and analysed via centre-of-mass (CoM) shift measurements using py4DSTEM package to extract projected electric fields and local charge density distributions [3].

The influence of experimental parameters on centre-of-mass (CoM) measurements was systematically investigated by varying the convergence semi-angle (15, 21, and 30 mrad), which affects probe size and depth of focus, and the camera length (145, 285, and 460 mm), which determines the projected size of the CBED patterns. Experimental datasets were compared with multislice simulations performed using the abTEM module to interpret the observed trends. The results show that both parameters strongly influence the diffraction disk intensity distribution and the sensitivity of CoM measurements. while the overall behaviour for nonpolar STO and polar BFO remains consistent. With appropriate experimental setup and data treatment, the method can also reveal bond-related structural features, such as lone-pair electron distributions, highlighting the importance of carefully selecting experimental conditions for reliable 4D-STEM analysis.

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Discovery of an intrinsic non-Hermitian phase transition in a bulk condensed-matter system

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In phase transitions, a small parameter change near a critical point leads to a qualitative change in system properties. Across regular phase transitions, systems remain in thermal equilibrium. However, when a system is driven far from equilibrium, so-called non-Hermitian phase transitions may arise where the dynamical behavior rather than steady properties undergo a qualitative change at a critical, so-called exceptional point. We experimentally realize a non-Hermitian phase transition in a bulk condensed-matter system. Optical excitation creates charge carriers in ferromagnetic EuO. In a temperature-dependent interplay with the Hermitian transition to ferromagnetic order, a non-Hermitian change of the relaxation dynamics occurs, manifesting in our time-resolved reflection data as the transition from biexponential real to single-exponential complex decay. Our theory models this behavior and predicts through its universal ingredients that non-Hermitian phase transitions can generically emerge in bulk condensed matter, enabling sensitive control of dynamic properties [1].

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50 kHz HHG-based Soft X-ray Source Spanning the Water Window

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High-harmonic generation provides temporally and spatially coherent, femtosecond to attosecond short pulses in the soft x-ray spectral range. Repetition-rate upscaling of intense, femtosecond-duration pulses in the short-wave infrared is necessary to further develop and apply such tabletop, ultrafast soft-X-ray sources. Here, we present a 20 fs-pulse-duration, 2.1 μm-central-wavelength, optical parametric chirped-pulse amplification laser, which outputs 52 W of amplified signal power at a repetition rate of 52.6 kHz. Despite the potential for deleterious thermal processes, the laser output exhibits excellent spatial and temporal profiles in a 45 W beam at a soft-X-ray-generation target after ~5 m of propagation [1]. In helium gas, this enables high-harmonic generation up to ~600 eV photon energies, demonstrating the system’s potential for ultrashort soft-X-ray-pulse production.

We are currently setting up a pulse-duration conserving soft X-ray beamline, which will enable the application of soft x-ray spectroscopy techniques for the study of ultrafast electronic dynamics in liquids and condensed matter. At a second branchline, dedicated to applications exploiting the high degree of coherence of the HHG pulses, lensless imaging techniques like Coherent Diffraction X-ray Imaging, X-ray Fourier Transform Holography, and X-ray Ptychography will provide combined nanometer spatial and femtosecond temporal resolution for studying dynamics of charge, orbital, and spin ordering phenomena.

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Time dependence of the ferroelastic transformation in Ni-Mn-Ga

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Ferroelastic transformations are crucial for various emerging applications, including high stroke actuation, mechanocaloric refrigeration, and thermoelastic energy harvesting. However, the dynamics of ferroic ordering, particularly in the context of martensitic transformations in shape memory materials, are not yet fully understood. Here, we present a comprehensive investigation of ultrafast martensitic transformations in a Ni-Mn-Ga-based epitaxial thin film [1]. We used a millisecond flash lamp pulse of varying energy density to induce a martensitic transformation and analyze the hierarchical martensitic microstructure afterwards. Our results show substantial differences compared to slow cooling, which we attribute to the limited time available for the microstructure to form and to the thermal stress between film and substrate during rapid temperature changes. We also performed a synchrotron-based time-resolved X-ray diffraction study of a 270 fs laser-induced martensitic transformation in the same material system [2]. The results show that the transformation from martensite to austenite occurs within about 100 ps, and indicate that temperature and thermal film stress are competing influences on the transformation. This study provides new insights into the ultrafast dynamics of martensitic transformations and highlights the importance of considering temperature, thermal stress, and microstructure formation in the design of high power density applications.

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Ultralow Tip-Force Driven Sizable-Area Ferroelectric Domain Manipulation

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Ferroelectric polarization can be manipulated mechanically with a nano-tip through flexoelectricity [1-2]. However, it usually occurs in a very localized area in ultrathin films, with possible permanent surface damage caused by a large tip-force. Here, we demonstrated that the deliberate engineering of transverse flexoelectricity offers an effective tool for improving the mechanical domain switching [3]. Sizable-area domain switching under an ultralow tip-force can be realized in suspended van der Waals ferroelectrics with the surface intact, due to the enhanced transverse flexoelectric field (Fig. 1). The film thickness range for domain switching in suspended ferroelectrics is significantly improved by an order of magnitude to hundreds of nanometers, being far beyond the limited range of the substrate-supported ones. Furthermore, bidirectional and reversible ferroelectric polarization switching is achieved by controlling the dynamic pressure within the suspended membrane [4]. The experimental results and phase-field simulations further reveal the crucial role of the transverse flexoelectricity in the domain manipulation. This large-scale mechanical manipulation of ferroelectric domain provides opportunities for the flexoelectricity-based domain controls in emerging low-dimensional ferroelectrics and related devices.

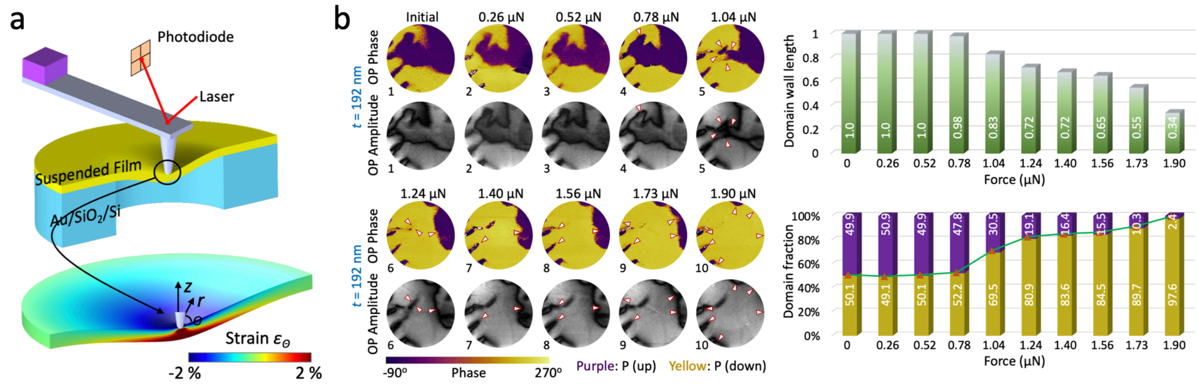

Figure 1. (a) Schematic illustration of the mechanical domain-switching setup in a suspended ferroelectric flake. (b) Evolution of domains during the mechanical switching process, as characterized by PFM phase and amplitude signals.

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Domain Contrast in Electric Field Imaging with a Diamond Tip

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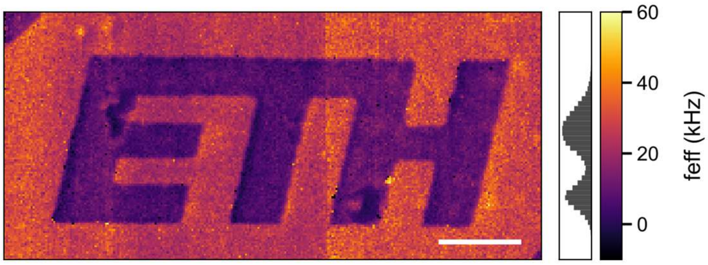

Figure 1: Poled domains on PZT imaged via modulating the distance between sample and NV. The scale bar is 2 µm.

Nitrogen-vacancy (NV) centers in diamond are versatile quantum sensors for magnetic and electric fields, strain and temperature [1]. While scanning NV microscopy has been applied to study a wide range of magnetic systems [2-4], its use for studying ferroelectrics via electric field detection remains less explored.

Previous studies demonstrated that electric field gradients can be detected using protocols based on lateral tip oscillations [5, 6]. In addition to the expected gradient signal at domain walls, an additional signal is sometimes observed above the domains. In this study we characterize and investigate the origin of this additional contrast. We attribute it to vertical oscillations of the tip perpendicular to the sample surface. By mounting the ferroelectric sample $Pb(Zr,Ti)O_3$ (PZT) on a piezo buzzer to drive and isolate the vertical motion, we decouple this effect from lateral movements. We propose a model in which the electric field of the ferroelectric polarizes the diamond tip, which in turn induces a local charge in the sample, generating a localized, distance-dependent electric field.

This mechanism results in a clear image of written ferroelectric domains in PZT, see Figure 1. Our results improve the interpretation of NV-based electric field measurements and support the development of NV microscopy as a tool for studying the ferroelectric phase of ferroelectrics and potentially multiferroics.

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Nanoscale Imaging of Ferroelectric-Ferroelastic Domains in Triclinic $K_2MgWO_2(PO_4)_2$

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The interplay between crystallographic symmetry and ferroic order gives rise to complex domain structures in low-symmetry materials. Here, we investigate the formation and response of domains in $K_2MgWO_2(PO_4)_2$, a triclinic compound that exhibits coupled ferroelectric and ferroelastic behavior at room temperature [1,2]. Piezoresponse force microscopy reveals a wide variety of coexisting domain morphologies, including superdomains, chevron-like patterns, as well as nanoscale zigzag structures. The domain variants reflect the triclinic symmetry of the system and the coexisting ferroic order parameters, which can be used to control the domain patterns. We show that domain walls can readily be moved by the application of local pressure and electric fields, making $K_2MgWO_2(PO_4)_2$ an interesting model system for domain engineering and the study of emergent (multi-)ferroic phenomena at the level of domains and domain walls.

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Scan, Shift, Lock: Controlling Ferroic Domains via STEM Probe Trajectories

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High-energy focused electron probes in scanning transmission electron microscopy (STEM) enable atomic-resolution imaging, but can also actively modify ferroic domain configurations. Here, we show that controlled probe trajectories provide a route to controllably manipulate and stabilize domain wall states in ferroic materials.

We investigate domain wall dynamics in copper–chlorine boracite ($Cu_3B_7O_{13}Cl$) and cryogenic $BaTiO_3$ using designed STEM scan strategies. Systematic variation of probe trajectories produces reproducible and trajectory-dependent domain evolution. Raster scans induce cumulative domain wall translation governed by scan direction and polarisation orientation, whereas inward spiral scans drive an initial displacement followed by stabilization into a locked configuration. When domain walls remain within the field of view, switching between scan patterns restores prior states, revealing reversible and cyclical control of domain configurations.

Using 4D-STEM diffraction, we track domain switching and symmetry changes. In boracite, ghost diffraction disks indicate polarisation rotation away from the [001] axis. In contrast, $BaTiO_3$ exhibits significantly higher sensitivity to experimental instability, where even sub-nanometre drift or minimal tilt suppresses Friedel-pair symmetry breaking signals.

These results demonstrate that electron probe trajectory design provides a powerful in-situ approach for controlling ferroic domain states, bridging imaging and functionality. Beyond mitigating beam-induced effects, this approach enables engineered domain architectures and functional control in ferroelectric and multiferroic materials.

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The correlation between grain size and dielectric performance of two medium-entropy compounds: $(Ba_{0.34}Sr_{0.33}Ca_{0.33})TiO_3$ and $(Ba_{0.25}Sr_{0.25}Ca_{0.25}Pb_{0.25})TiO_3$

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In the present work, the effect of grain size on the dielectric properties in two medium entropy titanate-based perovskite oxides of $(Ba_{0.34}Sr_{0.33}Ca_{0.33})TiO_3$ (CSBT) and $(Ba_{0.25}Sr_{0.25}Ca_{0.25}Pb_{0.25})TiO_3$ (CSBPT) was investigated. It is expected that dielectric properties are influenced by the internal stress caused by the grain size reduction and configurational entropy as an additional factor. First the two materials were fabricated through two distinct methods of solid state (SS) and sol-gel (SG) to yield different grain sizes and then they were characterized to find a correlation between their performance and their features. The sol-gel derived samples showed higher microstrain and lower grain size also, the incorporation of lead inside the lead-free CSBT enhances tetragonality and ferroelectricity. Raman analysis confirms the existence of internal lattice stress by a slight peak shift. Dielectric spectroscopy results show a shift of the transition point towards higher temperatures in small-grained CSBT and CSBPT materials. PFM analysis confirms the existence of 90^{o} domain walls which were smaller in CSBPT-SG compared with CSBPT-SS that explains the higher microstrain in the small-grained sol-gel derived sample.

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Exploring polar metallicity in perovskites through strain gradients in non-planar structures

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An inhomogeneous mechanical deformation, or strain gradient is well known to break the inversion symmetry of centrosymmetric insulating materials, thereby inducing and electric polarization [1]. This effect, known as flexoelectricity, may be understood as the material's intrinsic polarization response to a spatially varying strain, analogous to the way an electric field produces polarization through the conventional dielectric mechanism.

Metals, which are typically centrosymmetric, may also undergo a symmetry breaking in the presence of strain gradient, however it is not yet clear how the free carriers in a metal interact with the flexoelectric fields. In epitaxial films, significant strain gradients can be produced via mechanical deformation with a probe tip, stoichiometry gradients or strain relaxation. The latter has been exploited to demonstrate the presence of polar displacements in $SrRuO_3$ (SRO), a metallic and magnetic perovskite [2]. Here, we benefit from the flexibility of substrate-released (or freestanding) epitaxial oxide membranes which, in bilayer form can bend to produce micrometric rolling structures with large strain gradients [3].

We interface two metallic perovskite layers: LaNiO3 (LNO) and SRO, then we study the rolling process upon etching of a sacrificial Sr3Al2O6 layer, resulting in LNO/SRO microtubes and microhelices. Second Harmonic Generation Microscopy demonstrates the presence of inversion symmetry breaking in the rolled structures, which remain metallic down to cryogenic temperatures, hence we obtain a "polar metal" by bending. We then explore the depth dependent microstructure of the rolls using High Resolution Scanning Transmission Electron Microscopy (HR-STEM), evidencing a predominant role of lattice defects in the polarization. I will discuss the possible ways of engineering curvature and morphology with this approach and its potential for non-linear/non-reciprocal transport and photovoltaic effects.

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Temperature-independent linearity in optical conductivity of Weyl-Kondo semimetal $CeCoGe_3$

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We present a direct observation of linear optical conductivity from the Weyl-Kondo semimetal $CeCoGe_3$ due to carrier excitations from the Fermi level to the Weyl node closest in energy. In striking contrast to other Weyl semimetals, the linear frequency dependence, which the conductivity shows below 0.8 THz, is not washed out by thermal fluctuations and thus stable up to room temperature. This is consistent with DFT calculations [1] showing that in this material, strong correlations push the Weyl node close to the Fermi energy [2]. At these low energies, there are no other states that could contribute to the conductivity to wash out the linear characteristics.

Furthermore, we see a change in the temperature dependence of the slope of the linear dispersion behavior as we decrease the temperature, which seems to center around the Néel temperature T_N of the antiferromagnetic transitions [3]. The decrease in slope could be due to the crossover to flat bands, as predicted by the Kondo physics in this material [4]. The fact that this crossover occurs near T_N rather than the Kondo temperature T_K of ~ 50 K indicates that topological character and strong correlations are deeply entangled in $CeCoGe_3$, a rare observation in quantum materials.

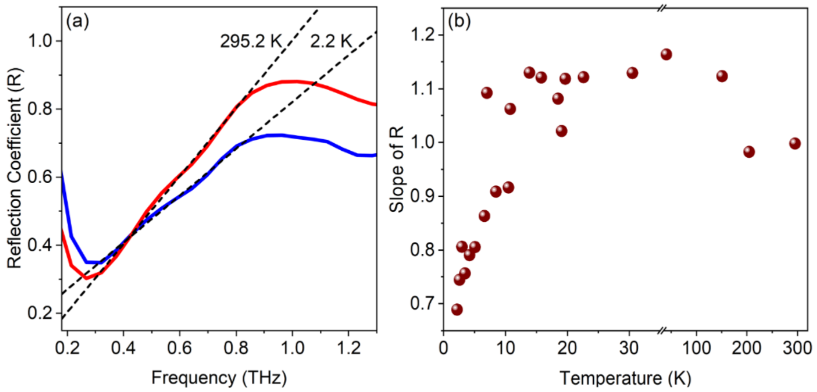

Figure 1: (a) Reflection coefficient (R) of $CeCoGe_3$ in the terahertz spectrum as a function of temperature. The black dashed lines are the linear fits at 295.2 K and 2.2 K, showing a decrease in the steepness of the linear dispersion with decreasing temperature. (b) The evolution of the slope of the linear fits in R with temperature.

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Towards Perpendicular Magnetic Anisotropy in AlScN-Based Ferroelectric Heterostructures.

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Aluminum scandium nitride (AlScN), a wurtzite III-nitride was recently identified as a ferroelectric material [1] with large remanent polarization (~100 µC/cm²) and strong potential for CMOS back-end-of-line (BEOL) integration. In this work, we explore the role of top electrode materials in sputtered AlScN thin films, as part of a broader effort to establish a BEOL-compatible platform for magnetoelectric memory devices. Within this framework, leakage, a standing issue in AlScN, is addressed through electrode and process optimization. We compare Pt and Ti top electrodes (Fig. 1a), observing that Ti reduces leakage currents, most strongly evident in reverse bias, and yields more stable ferroelectric hysteresis, attributed to its oxygen-scavenging nature. Further improvements are pursued via post-deposition and post-metallization annealing.

Building on this platform, AlScN is integrated with ferromagnetic (FM) multilayers to investigate magnetoelectric coupling as a pathway toward electric-field-driven magnetization switching. We investigate perpendicular magnetic anisotropy (PMA) in AlScN/Co/Pt heterostructures. It is observed that PMA can be tuned through thermal annealing; as shown in Fig. 1b, as-deposited stacks exhibit partial in-plane magnetic behaviour, while annealed samples show enhanced out-of-plane magnetization. Further optimization of FM materials (Co, CoFeB), capping layers (Pt, Au, Ta, Tb), and thickness scaling is aimed at maximizing electric-field coupling effects. These results establish sputtered AlScN, combined with electrode engineering, as a viable platform for CMOS-compatible magnetoelectric devices, targeting electric-field-driven 180° reversal of out-of-plane magnetization toward magnetoelectric RAM.

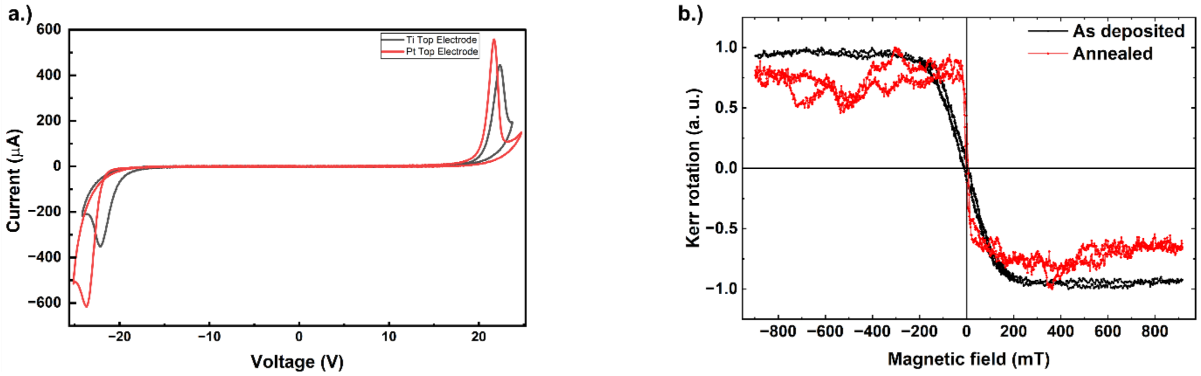

Fig. 1.(a) Current vs voltage hysteresis loops of AlScN capacitors with Pt and Ti top electrode; (b) magnetic hysteresis loops of AlScN/Co/Pt stack.

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Heat as a Probe: Mapping Magnetic Domains in a Weyl Semimetal via the Anomalous Nernst Effect

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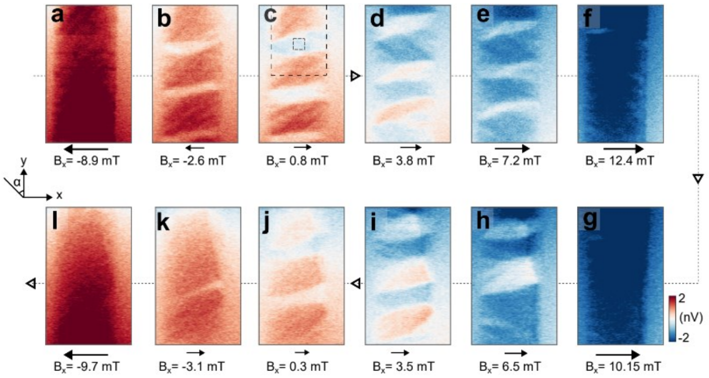
Magnetic Weyl semimetals exhibit a nontrivial electronic band topology that, in the absence of time-reversal symmetry, generates a finite Berry curvature from which anomalous transport phenomena emerge. Exceptionally large thermoelectric effects, including the anomalous Ettingshausen [1] and Nernst [2] effects, have been observed in the Weyl semimetal Co_2MnGa. The magnitude and spatial distribution of these responses are governed by the underlying nanoscale magnetic structure, making a detailed understanding of the domain configuration essential for both the design and interpretation of functional devices.

Here, we employ scanning thermal microscopy (SThM) under an in situ applied magnetic field to acquire high-resolution anomalous Nernst effect maps of a ferromagnetic thin film. SThM is an atomic force microscopy-based technique in which a resistive heater integrated at the probe tip scans the sample surface, enabling nanoscale thermoelectric imaging. This approach resolves individual magnetic domains and tracks their nucleation and propagation (image below), providing spatially resolved insight into magnetization reversal dynamics.



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Strong Piezoelectric Response and Tunable Rectification in Mono- and Multilayer vdW Ferroelectrics

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Van der Waals (vdW) layered ferroelectrics have attracted significant interest due to their atomically thin layers, dangling-bond-free surfaces, and tunable polarization states, which are essential for emerging memory, neuromorphic, and flexible electronic applications. Recent study has demonstrated the efficient reversible and cyclic ferroelectric domain switching under a unipolar erelectric field in van der Waals ferroelectric $CuInP_2S_6$ (CIPS), enabled by Cu-ion migration across van der Waals gaps. It further unveils the remarkable “shape memory” effect of manipulated domains, and the programmable domain patterning under a unipolar electric field [1]. In this work, we focus on the piezoelectric response of mono- and few-layer CIPS. Monolayer CIPS is successfully exfoliated and its strong piezoelectricity in the out-of-plane direction with an effective coefficient d_{33} of around 5.12 pm V^{-1}, which is one or two orders of magnitude higher than that of most existing monolayer materials with intrinsic d_{33}, is confirmed. Mono-and multilayered CIPS also detective dependence of piezoelectricity on the layer thickness. Bilayer and trilayer CIPS has a d_{33} of 8.49 and 14.76 pm V^{-1}, respectively. Furthermore, vertical nanoscale devices exhibit tunable current rectification via flexoelectricity induced by local mechanical forces. These findings manifest that CIPS possesses promising application in vertical nanoscale piezoelectric devices and provides a novel strategy for achieving a good current rectification in ultrathin piezoelectrics [2].

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STEM and EELS of $(LaMnO_3)_m/(SrMnO_3)_n$ superlattices

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Scanning Transmission electron microscopy (STEM) and Electron Energy Loss Spectroscopy (EELS) are the state-of-the-art methods to investigate atomic and electronic structure of different thin film ferroic materials. Epitaxial $(LaMnO_3)_m/(SrMnO_3)_n$ (LMO_m/SMO_n) superlattices (SL's), being thoroughly studied during the last years [1-3], demonstrate a metal-insulator transition and complex magnetic behavior with FM/AFM phase transitions all controlled by the thickness of constituting layers and their ratio "m/n".

In this work, we explore unusual morphology of TEM specimens, namely a needle-like tips, prepared by using a focused-ion-beam (FIB), to study atomic structure and EELS spectra of several LMO_m/SMO_n SLs along three different crystallographic orientations. This specimen geometry also ensures more uniform removing of material, thus, minimizing bending of specimens, and therefore the influence of possible mechanical stress on their structure.

Our results demonstrate that LMO layers in the SL with m=12, n=6 consist of domains having [211] and [010] orientation; the domains are not visible if the thickness of specimen is less than 20nm. Moreover, we could demonstrate that EELS spectra allow to reveal a difference in Mn L3,2 edge depending on the position of electron beam inside an LMO unit cell. These results can be useful for more reliable interpretation and applicability of TEM to correlate physical properties with atomic structure of ferroic materials.

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Spontaneous Polarization in Pure and Ti-Doped $(K_{0.5}Na_{0.5})NbO_3$ Resolved by Atomic-Scale 4D-STEM and First Principles Calculations

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Spontaneous polarization in perovskite ferroelectrics arises from B-site cation displacements. In $(K_{0.5}Na_{0.5})NbO_3$ (KNN), Nb shifts along the polarization direction, opposite to the surrounding oxygens. Its orthorhombic symmetry permits 12 displacement directions, reduced to 8 when projected along the $[100]_{pc}$ zone axis. Such picometer-scale displacements are difficult to quantify by conventional STEM.
4D-STEM addresses this limitation by recording a full diffraction pattern at each probe position, enabling local structural and electrostatic mapping[1]. Using atomic-resolution 4D-STEM on a Cs-corrected ARM200CF (Jeol) with a Merlin detector (Quantum Detectors), combined with QSTEM[2]-simulated diffraction patterns based on the orthorhombic structure (ICSD #186310), we map polarization direction and magnitude in KNN. Combined 4D-STEM charge density mapping and density functional theory (Quantum ESPRESSO) show that intrinsic point defects, particularly oxygen vacancies, locally shift Nb ions and modify polarization, indicating defect contribution to polar order. We extend this approach to acceptor-doped KNN, where defects are intentionally introduced. Ti substitution on the Nb site creates charge-compensating defects, like oxygen vacancies, and hardens the ferroelectric response upon aging[3], though its structural role remains unclear. X-ray diffraction confirms a single perovskite phase (0.1-1 mol% Ti), while STEM-EDXS reveals Ti segregation at grain boundaries. HAADF-STEM simulations predict Nb displacements below the ~5 pm detection limit, yet experimentally measured shifts are nearly an order of magnitude larger, again hinting at the important effect of point defects on polar ordering in KNN.

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Phase-Field Modeling of Optical Second Harmonic Generation in Ferroelectrics

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Optical second-harmonic generation (SHG) is a sensitive probe of broken inversion symmetry and is widely used to characterize the microstructures of polar materials such as ferroelectrics. Although computational methods can predict the formation, evolution, and dynamics of ferroelectric microstructures, it remains difficult to directly connect the computed microstructure to its corresponding SHG response. In this work, we develop a theoretical approach, based on the phase-field method, that connects ferroelectric microstructures to their local nonlinear optical properties, enabling the prediction of their spatially resolved SHG responses. We validate our approach by comparing computational and experimental microstructures under different electrical and thermal conditions. This approach connects computational modeling with SHG-based imaging, providing new opportunities to interpret experimental measurements and design tailored ferroelectric materials for photonic applications.

Liquid helium temperature atomic resolution STEM imaging and ptychography of ferroelectrics

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High-resolution real-space characterization at cryogenic temperatures is increasingly important for the study of ferroics and functional oxides, where competing low-temperature electronic and magnetic phases and associated subtle structural distortions require atomically resolved probes to understand, and ultimately control, exotic low-temperature behaviour of both technological and fundamental physical interest [1]. Scanning transmission electron microscopy (STEM) offers unique insight into material structure down to atomic resolution, however in situ under cryogenic conditions reduced mechanical stability presents significant challenges for high-resolution STEM imaging and analysis. Atomic-resolution scanning transmission electron microscopy (STEM) imaging and spectroscopy have previously been extended to ~100 K using liquid-nitrogen cooling, however, phenomena of prime interest emerge only at lower temperatures in many relevant oxide systems, necessitating liquid helium cooling [2,3].

Combining advances in cryogenic hardware with optimized acquisition and data processing approaches, here we demonstrate atomic-resolution STEM imaging and multislice electron ptychography (MEP) at controlled temperatures under liquid helium cooling on two protype ferroic systems [4]. Imaging an epitaxial SrTiO3 thin film grown on (110) $GdScO_3$, we achieve sub-angstrom resolution necessary to resolve octahedral distortions imaging across the film-substrate interface, while in the multiferroic boracite $Fe_3B_7O_{13}I$ MEP reconstructions show improved resolution and strong sensitivity to low-Z boron-oxygen clusters key to locally characterizing inhomogeneity in the system.

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Ferroelectricity and Magnetic Frustration in Hexagonal Oxides for Cryogenic Cooling

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Hexagonal rare-earth oxides are a versatile platform combining improper ferroelectricity with rich and tunable magnetic behavior.[1] Their functionality arises from the interplay of lattice, charge, and spin degrees of freedom, enabling both topological ferroelectric domains and diverse magnetic states, including frustrated and spin-liquid-like phases.[2-4]

Here, we show that spin-liquid candidate systems such as $TbInO_3$ exhibit ferroelectricity with a Curie temperature around 1350°C and characteristic six-fold-like domain structures, while we demonstrate that sister compounds display strong and tunable magnetocaloric effects at cryogenic temperatures. In particular, magnetic frustration in materials such as $DyInO_3$ enables cooling to temperatures as low as ~240 mK via adiabatic demagnetization. The coexistence of ferroelectricity and magnetic frustration in this material class motivates the emerging concept of *"Frustronics"*, where magnetic frustration may be tuned via new degrees of freedom, including microstructure in polycrystals or the ferroelectric order.

Our results highlight hexagonal oxides as a chemically flexible platform for engineering coupled ferroelectric and magnetic responses, opening new pathways toward energy-efficient solid-state cooling for quantum and energy technologies.

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Understanding the interplay between ferroelectricity, polar discontinuity and screening in perovskite superlattices

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We present a density functional theory study on the interplay between ferroelectricity and formal layer charge mismatch in perovskite superlattices. In our systems, the ferroelectric II-IV perovskite $BaTiO_3$ is interfaced with a III–III or IV-II perovskite nickelate, introducing a formal layer charge mismatch at its interface. While such polar discontinuities have been extensively studied in insulating systems, their role in metallic perovskites has received far less attention. In a previous work, we demonstrated that layer charge plays a role in the metallic III-III perovskite $SmNiO_3$ [1], despite the metallic screening charges. We found that the interface to $BaTiO_3$ stabilizes a preferred polarization direction, and allows ferroelectricity even in ultra-thin films, without the usual critical thickness observed in $BaTiO_3$ thin films. The opposite polarization orientation is highly disfavoured and only emerges in thicker slabs.

In this work, we extend our study to explore the interplay between the formal-charge polar discontinuity and the screening state (metallic or insulating) of the nickelate slab in more detail. We compare the contributions to the screening of the formal-charge polar discontinuities in superlattices with $BaTiO_3$ and insulating III-III $SmNiO_3$ or IV-II $BiNiO_3$, which has a formal-charge polar discontinuity twice as high as in systems with insulating $SmNiO_3$. We find that, while for superlattices with $SmNiO_3$, the $BaTiO_3$ polarization is sufficient to screen the polar discontinuity, additional charge transfer is needed inside the $BaTiO_3$ at interfaces with $BiNiO_3$. For systems with $SmNiO_3$, switching the polarization to the disfavored direction induces a change in the charge-disproportionation pattern in the nickelate adjacent to the interface. Our results offer new insights into the screening of polar discontinuities and routes to improved device applications.

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Analyzing the tetragonal-to-cubic phase-transition in ferroelectric BaTiO3 using EXAFS spectroscopy as a local probe

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This work aims to establish time-resolved Extended X-ray Absorption Fine Structure (tr-EXAFS) spectroscopy as a methodology for solids where the structural information of the EXAFS is combined with a pump-probe setup to study local dynamic lattice processes in the time domain. As proof of concept, we analyze the structural transition from tetragonal to cubic phase in the perovskite BaTiO3, that is associated with the ferro- to paraelectric transition. The displacement of the Ti ion from the center of the O octahedron thereby determines the magnitude and orientation of the ferroelectric polarization. However, the exact mechanism governing this transitions, whether displacive, order-disorder, or a hybrid of both, remains unresolved. By using optical above-bandgap excitation, we drive the system into the cubic state and subsequently probe it by X-ray pulses (at the Stanford Synchrotron Radiation Lightsource). The difference-EXAFS between the pumped and unpumped state at the Ti K and Ba L3-edge provide a direct way to investigate changes in lattice structure and thermal-induced disorder. Our findings indicate a slight repositioning of the Ti ion within the O octahedron during the phase-transition, as well as a residual displacement from its central position, even in the cubic phase, pointing towards an order-disorder mechanism. In addition, the O octahedron is expected to shift in the direction opposite to that of the Ti ion. To further support these first results, we performed a static temperature dependent EXAFS study at the National Synchrotron Light Source to identify the structural and thermal contributions to the Debye-Waller factors (analysis in progress). Our spectroscopic findings are correlated with ab initio multiple-scattering calculations using the FEFF10 code to quantify structural dynamics. We thank the DFG (CRC1242) for financial support.

Hybrid antiferroelectric-ferroelectric domains and domain walls in noncollinear antipolar oxides

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Antiferroelectrics are emerging as advanced functional materials with unique electric properties enabled by the antipolar arrangement of their electric dipoles. Additional functionalities and novel physical nanoscale phenomena are expected in systems with noncollinear antipolar dipole structures. Here we demonstrate how the onset of antiferroelectricity in $K_3[Nb_3O_6|(BO_3)_2]$ drives noncollinear ordering of electric dipole moments, which leads to unusual hybridization of antiferroelectric and ferroelectric responses. Besides the double-hysteresis loop common to antiferroelectrics, a pronounced piezoresponse and electrically switchable hybrid domains are observed using scanning probe microscopy. The domains are separated by atomically sharp and micrometre-long charged domain walls with inseparably entangled discontinuities in the antiferroelectric and ferroelectric orders as demonstrated by scanning transmission electron microscopy. Such hybrid antiferroelectric–ferroelectric responses are expected in a wide range of noncollinear systems.

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Polar WO_3 and polarons by epitaxial shear strain

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Tungsten oxides have been a topic of research interest for their gas sensing, catalytic and electrochromic capabilities. Recently, it was found that epitaxial thin films of tungsten trioxide (WO_3) grown on a substrate of (110)-oriented yttrium aluminate ($YAlO_3$) even exhibit piezoelectricity and enhanced conductivity localized to the monoclinic twin walls as a result of strain gradients at those walls.

We have grown epitaxial films of WO_3 on a different orientation of the same substrate, (001)$YAlO_3$, by pulsed laser deposition and reveal the emergence of a previously unreported polar phase in these films.

We accomplish this by imposing epitaxial shear strain, which stabilizes a low-symmetry triclinic structure that persists up to large film thicknesses and elevated temperatures. The films exhibit a periodic in-plane polarized stripe domain configuration with needle-like bifurcations with strongly enhanced electrical conductivity at the domain walls. Scanning transmission electron microscopy shows that these domain walls are associated with a pronounced reduction of a distortive structural mode, providing the first experimental evidence for the formation of anti-distortive polarons recently predicted in WO_3.

Our epitaxial WO_3 films are structurally and functionally different from known bulk phases of the same material as well as from previously reported epitaxial films and have a strongly distorted structure and behavior due to subtle epitaxial interactions. Their characteristics make them attractive candidates for application in oxide electronics, neuromorphic computing and catalysis.

Thickness-Driven Phase and Magnetic Engineering in FeMn/CoFeB/Cr Multilayers for Next-Generation Spintronic Devices

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CoFeB-based multilayers constitute a cornerstone of modern spintronics owing to their high spin polarization, amorphous-to-crystalline tunability, and strong sensitivity to interfacial effects, which are critical for realizing energy-efficient magnetic memory and logic devices [1]. In particular, FeMn/CoFeB/Cr heterostructures offer a unique platform to investigate the interplay between antiferromagnetic exchange coupling, interfacial strain, and thickness-driven magnetic engineering. In this work, multilayers with systematically varied CoFeB thickness were fabricated and investigated using X-ray reflectivity (XRR), grazing-incidence X-ray diffraction (GIXRD), magneto-optical Kerr effect (MOKE), and vibrating sample magnetometry (VSM). XRR confirms high structural quality with well-defined thickness and low interface roughness, while GIXRD reveals a thermally driven amorphous-to-nanocrystalline transition mediated by boron redistribution and strongly influenced by layer thickness. Magnetic measurements demonstrate a distinct evolution from stress-induced anisotropy in the amorphous regime to microstructure-governed magnetic behavior upon crystallisation, accompanied by a pronounced thickness-dependent modulation of coercivity and anisotropy arising from interfacial exchange interactions and strain relaxation. These results establish thickness as a decisive control parameter for tailoring phase stability and magnetic functionality, providing critical insights for the design of scalable, high-performance spintronic devices where interfacial phenomena dominate at the nanoscale [2].

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2D ferroelectrics for magnetic tunnel junctions

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In the field of spintronics, 2D materials have unleashed a multitude of previously unexploited possibilities, opening paths towards low energy magnetic tunnel junctions (MTJ) switching and gating [1][2]. In this work we focus on the potential of integrating 2D ferroelectrics into MTJs. Indeed, ferroelectric materials present a remanent polarization that can modify the interface interaction with other 2D materials. Additionally, thanks to their atomic scale thickness, it is possible to embed them in 2D heterostructures with strong interfacial proximity interactions. Theoretical calculations have shown [3] that van der Waals heterostructure formed by combining 2D ferromagnetic and a 2D ferroelectric materials could offer novel opportunities or enhance existing ones, such as raising Curie temperature or tuning the electronic and spintronic properties by gating. Therefore, developing a van der Waals heterostructure that combines 2D ferroelectric and ferromagnetic materials in an MTJ have become highly desirable, as it holds significant technological promise.

In this work, we will discuss the investigation of two different 2D ferroelectric materials, In2Se3 and CuInP2S6 which both present a strong out of plane polarization at room temperature targeting their integration in MTJs. Those materials have been exfoliated using different methods, mechanical exfoliation and electrochemical exfoliation. Their properties have been studied using piezoelectric force microscopy coupled with Raman spectroscopy. A correlation between the Raman response and the polarization of the ferroelectric flake has been observed leading to a fast polarization reading. Finally, we will also discuss the extension of this work to large scale with preliminary results on pulsed laser deposition (PLD) of those 2D ferroelectrics.

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Domain size control of the latent heat of the ferroelectric phase transition in Barium Titanate (BaTiO3) free-standing membranes

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Using free-standing membrane-based thermodynamic measurements, we have studied the behavior of the latent heat in the ferroelectric phase transition of Barium Titanate (BaTiO3) membranes with different domain sizes [1]. Using the sacrificial layer approach, BaTiO3 membranes have been obtained after releasing the epitaxially grown films from the single crystalline substrate. The released membranes are then stamp-transferred on a substrate for their characterization. Piezoresponse Force Microscopy (PFM) is used to identify the domain structure of the BaTiO3 membranes, showing that domain size scales with the thickness of the membranes. Calorimetry measurements are carried out on a free-standing membrane platform to ensure thermal isolation of the oxide from the substrate [2]. This technique provides insight into the heat capacity of the BaTiO3 membrane, which reveals the nature of the ferroelectric phase transition. We have observed how domain size influences the latent heat of transformation: membranes with larger domain sizes exhibit some latent heat at the transition, which vanishes in membranes with smaller domains, suggesting the domain structure causes a change in the order of the ferroelectric phase transition in BaTiO3 free-standing membranes.

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Domain-wall-induced engineering of thermoelectricity in a polar metal

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Thermoelectric materials enable the direct interconversion of heat and electricity. Achieving high thermoelectric performance requires the simultaneous optimization of electronic transport and lattice thermal properties. In polar metals, this has been accomplished through atomic-scale tuning of high configurational entropy, Rashba spin–orbit coupling, and lattice anharmonicity.[1] However, the potential role of macroscopic inhomogeneity—such as domain and domain-wall formation—in further enhancing thermoelectric performance has so far been overlooked. Here, using GeTe as a model system, we demonstrate through nonlinear optical microscopy,[2] photothermoreflection, and conductive force microscopy that the formation of micrometer-scale ferroelectric domains with antiparallel polarization during crystal growth suppresses thermal conductivity by a factor of five, while leaving electrical conduction largely unaffected. These findings are consistent with density-functional theory calculations, which reveal band-gap reduction and electron–lattice decoupling within the domain walls. The direct link established here between domains and transport identifies domain and domain-wall engineering as a promising strategy for advancing polar-metal-based thermoelectrics.

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Nanoscale strain engineering of transition metal oxides using ferroelastic domain patterns

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Strain engineering is a powerful tool for accessing new and versatile properties of materials. The use of ferroelectric domain patterns instead of conventional substrates further allows for the modification of the properties of these materials using electric fields [1]. $PbTiO_3$ is a ferroelectric and ferroelastic perovskite which forms a periodic in-plane and out-of-plane domain structure when deposited on (110)-$DyScO_3$ substrates, caused by lattice mismatch [2]. This is shown schematically below. In this work, we explore strain engineering of metallic perovskite thin films grown on this $PbTiO_3$ domain structure. Using this approach, we are able to effectively couple strain between heterostructure interfaces and produce large anisotropy in electronic transport and material properties, which are found to be tunable by altering $PbTiO_3$ layer thickness, and thus domain period. The effects of this strain engineering are demonstrated by scanning probe techniques, microscopy imaging and 4-probe resistivity measurements.

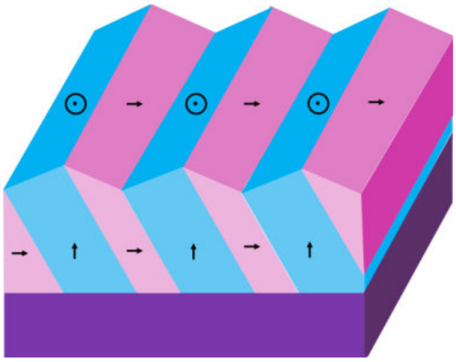

Figure 1- Schematic representation of a/c domain structure which forms when $PbTiO_3$ is grown on $DyScO_3$ $(110)_o$ substrates.

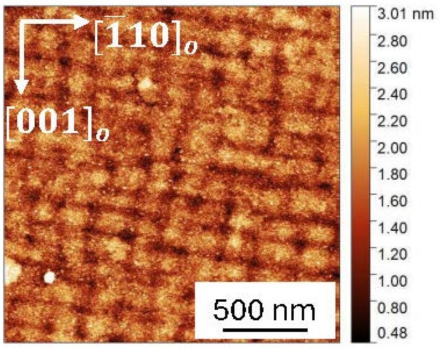

Figure 2- AFM morphology of SrRuO3 capping layer, with modulations caused to coupling to PbTiO3 ferroelastic domains.

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Tuning Fe^{3+} Magnon Softening via Competing Magnetic Rare-Earth Anisotropies in $Dy_xTb_{1-x}FeO_3$: Revealing Hidden Spin Reorientation Instabilities

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In rare-earth orthoferrites ($REFeO_3$), the spontaneous ordering temperatures of iron and rare-earth magnetism are separated by about 650 K with the spontaneous magnetic RE order occurring typically below 4 K. The RE's magnetic anisotropy however, induces spin reorientations in the magnetic Fe^{3+} order shaping the magnetic phase diagram of these materials. Macroscopically, the magnetization changes in the direct vicinity of this phase transition. On the microscopic scale, the spin reorientations are accompanied by a magnon softening that indicates the instability at substantially higher temperatures than the macroscopic properties.

Here, we show that using $RE/RE'FeO_3$ solid solutions we can induces substantial competition between the rare earths' magnetic anisotropies. We base our study on $Dy_xTb_{1-x}FeO_3$ (x = 0, 0.25, 0.75, 1) with the two end members $DyFeO_3$ and $TbFeO_3$ with different types of spin reorientations at 50 and 7K, respectively. Once Tb is present in the material, it dominates the macroscopic magnetic phase diagram. Our temperature-dependent magnon measurements, however, show a different picture. The magnons of all materials but x=0 follow a $DyFeO_3$-like trend. This trend remains hidden to the macroscopic properties as the Tb contribution eventually prevents the $DyFeO_3$-type phase transition.

Our findings show, that it is possible to substantially tune the Fe^{3+} magnon frequencies through the introduction of a competition between magnetic RE anisotropies, an important aspect for the application in spintronics. Furthermore, the magnons reveal hidden instabilities that may allow to induce a spin reorientation transition through external stimulus, e.g. magnetic fields or optical light pulses.

Second-harmonic generation study of polar *e*-twin walls in calcite

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It is well known that material boundaries can exhibit various physical properties distinct from those of the bulk. In this study, we focus on twin walls in calcite, one of the most abundant minerals on Earth. Calcite undergoes mechanical twinning deformation, primarily exhibiting *r*{10–14} and *e*{01–18}-twin systems. Recently, molecular dynamic (MD) calculations predicted that *r*-twin boundary would possess polarity [1]. To confirm it experimentally, we investigate the polar nature of these twin walls by using optical second-harmonic generation (SHG) microscopy.

Our measurements reveal that, contrary to the predictions of previous MD simulations, *r*-twin walls show no detectable SHG response, whereas *e*-twin walls exhibit clear SH-activity. Polarization-resolved SHG measurements further indicate that the symmetry of the *e*-twin walls is reduced to the polar point group *m*, demonstrating that these walls possess polarity.

The MD simulations comparing *r* and *e*-twin walls provide insight into the macroscopic origin of such polarity. At *r*-twin walls, Ca ions in adjacent layers are displaced in alternating directions, resulting in cancellation of the net polarization. In contrast, at the *e*-twin walls, displacements of charge-center occur in the same direction within two atomic layers, producing a local polarization. The calculations also suggest a strong coupling between polarization and shear strain.

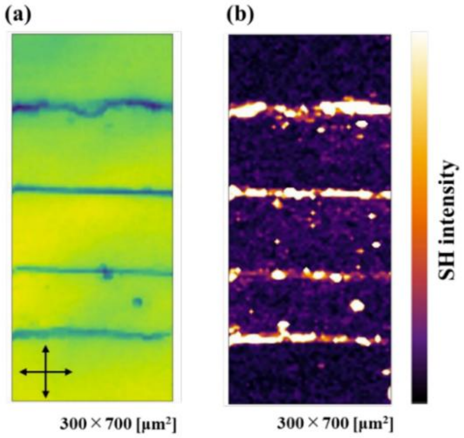

Figure.
(a) Polarizing microscope image of the *e*-twin walls, (b) 2D map of SH-wave intensity from the same region as in (a).

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Local Control on Ferroic Orders in Multiferroic Thin Films

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The breaking of inversion symmetry correlates with the emergence of polar states in materials and is a ubiquitous concept in condensed matter science. It is a prerequisite for technologically relevant effects such as ferroelectricity, nonlinear optical properties, and spin-transport phenomena. Hence, the ability to reversibly control the onset of such symmetry breaking may be instrumental in the establishment of energy-efficient devices and emergent computing schemes. For instance, in multiferroic $BiFeO_3$, which hosts coexisting and coupled ferroelectric and magnetic ordering, this control may enable the manipulation of the symmetry-sensitive Dzyaloshinskii–Moriya interaction and, consequently, facilitate the development of magnetoelectric-based technologies.

In this work, we present a novel approach to manipulate the ferroic orders in multiferroic $BiFeO_3$-based thin films via the direct control of the symmetry. By utilizing epitaxial strain engineering and crystal chemistry, we flatten the energy landscape of the polar ordering in our films to increase responsiveness to external stimuli. Taking advantage of this delicate energetic balance, we explore the impact of localized external stimuli—including light illumination, mechanical pressure, and electric fields—on the material's symmetry and its corresponding ferroic states. Using a combination of optical second harmonic generation imaging, piezoresponse force microscopy, and scanning nitrogen-vacancy magnetometry, we directly track the induced modifications of both the ferroelectric and magnetic orderings.

Microscale coexistence of magnetic phases compatible with the Kagome spin-ice rule in HoAgGe

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HoAgGe realizes kagome spin-ice with a series of fractionalized magnetization plateau states for applied in-plane magnetic fields [1]. Corresponding magnetoresistance and Hall effect reveal a hysteresis at the plateau states, indicating field-history dependent occupation of magnetic domains with opposite chirality and Berry curvature [2].

In the presented study, we investigate the microscale magnetic patterns, using low-temperature atomic force microscopy to visualize possible phase coexistence. By studying different crystal cuts and varying magnetic fields using a vector magnet, we reconstruct the full 3D magnetic texture of phase coexistence. Our results provide insights into the interplay of geometrical, topological and frustrated properties of spin ice materials and demonstrate pathways for external manipulation of magnetic textures in highly-frustrated systems.

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