DF 8: Ferroics - Domains, Domain Walls and Skyrmions I

Subsequently to the symposium "Novel functionality and topology-driven phenomena in ferroics and correlated electron systems" four Focus Sessions "Ferroics - Domains, Domain Walls and Skyrmions I - IV" cover recent developments in analyzing (multi-)ferroic materials, investigations of domain and domain-wall phenomena, the introduction of novel key concepts as well as methods for advanced characterization.

Chairs: Markus Garst and Manuel Bibes

Time: Tuesday 9:30–13:30 Location: WIL B321

Topical Talk DF 8.1 Tue 9:30 WIL B321

Room temperature skyrmions and robust metastable skyrmion states in $Co_8Zn_8Mn_4$ — •Jonathan White[1], Kosuke Karube[2], Nicole Reynolds[1,3], Jorge Gavilano[1], Hiroshi Oike[2], Akiko Kikkawa[2], Fumitaka Kagawa[2], Yusuke Tokunaga[4], Henrik Ronnow[3], Yoshinori Tokura[2,5], and Yasujiro Taguchi[2] — [1]Paul Scherrer Institut, Switzerland — [2]RIKEN CEMS, Wako, Japan — [3]EPFL, Switzerland — [4]Department of Advanced Materials Science, University of Tokyo, Japan — [5]Department of Applied Physics, University of Tokyo, Japan

Magnetic skyrmions are being intensely studied in various noncentrosymmetric magnets. Among them, the chiral cubic magnets are well-known to host a hexagonal skyrmion lattice as a thermodynamic equilibrium state. However, this state exists only over a narrow temperature and magnetic field region just below the magnetic transition temperature. Using both ac susceptibility and neutron scattering, we study metastable Skyrmion states in the room-temperature skyrmion host material $Co_8Zn_8Mn_4$. These states, created by a conventional field-cooling through the equilibrium skyrmion state, survive over the major part of the phase diagram, including down to zero temperature and up to the critical magnetic-field of the ferromagnetic transition. Furthermore, the metastable skyrmion lattice is observed to transform between conventional hexagonal and a novel square-like coordinations upon varying the temperature and magnetic field. These findings exemplify the topological robustness of the once-created skyrmions, and establish metastable states as a promising technological platform.

DF 8.2 Tue 10:00 WIL B321

Universal relations between electromagnetic response functions: towards a first-principles description of magneto-electric materials — •Giulio Schober[1] and Ronald Starke[2] — [1]Institute for Theoretical Physics, Heidelberg University, Philosophenweg 19, 69120 Heidelberg, Germany — [2]Institut für Theoretische Physik, TU Bergakademie Freiberg, Leipziger Str. 23, 09596 Freiberg

Based on modern microscopic approaches to electrodynamics of materials, we systematically investigate the mutual functional dependencies of induced, external and total electromagnetic field quantities. This allows for a unified, relativistic description of the electromagnetic response without assuming the material to be composed of electric or magnetic dipoles. Using this approach, we derive universal (material-independent) relations between electromagnetic response functions such as the dielectric tensor, the magnetic susceptibility and the microscopic conductivity tensor. Our formulae can be reduced to well-known identities in special cases, but more generally include the effects of inhomogeneity, anisotropy, magneto-electric cross-coupling and relativistic retardation. If combined with the Kubo formalism, they would therefore lend themselves to the ab initio calculation of all linear electromagnetic response functions, thus paving the way for a first-principles description of magneto-electric materials for spintronics applications.

DF 8.3 Tue 10:15 WIL B321

Giant Rashba effect in ferroelectrics from first principles — •Louis Ponet[1,2], Urko Petralanda[1], Silvia Picozzi[3], and Sergey Artyukhin[1] — [1]Quantum Materials Theory, Istituto Italiano di Tecnologia, Via Morego, 30, Genova, Italy. — [2]Scuola Normale Superiore, Piazza dei Cavalieri, 7, Pisa — [3]CNR-SPIN, UOS L'Aquila, Via Vetoio, 10, Coppito, L'Aquila (IT)

Spintronics has been an exciting area in the last decades, due to a promise for devices that exploit the existence of spin-polarized states [1]. Important applications include storage media, where the use of spins to store data has been widespread since the earliest days of computing. However, these storage devices use magnetic fields to orient magnetic domains, an approach that is making further miniaturization increasingly difficult. A possible solution could be using spin torques provided by spin-polarized currents for more fine-grained and efficient control of magnetic domains. However, to access these states in electronics, there is also a pressing need for electric control of the states, which was recently demonstrated in materials that showcase an anomalously large Rashba-effect [2]. This effect allows for electric control of very highly spin-polarized states, but the origin of the behaviour is not thoroughly understood yet. We used model Hamiltonians and ab-initio calculations to examine the effect.

[1] S. D. Bader and S. S. P. Parkin, Spintronics, Ann. Rev. Cond. Matt. Phys. 1, 71 (2010).

[2] D. Di Sante, P. Barone, R. Bertacco, S. Picozzi, Advanced Materials, 25, 509 (2013).

15 min. break

DF 8.4 Tue 10:45 WIL B321

Constant-current calligraphic domain-inversion in lithium-niobate crystals — •Christoph S. Werner[1], Simon J. Herr[1], Karsten Buse[1,2], and Ingo Breunig[1] — [1]Department of Microsystems Engineering, University of Freiburg — [2]Fraunhofer Institute for Physical Measurement Techniques, Freiburg, Germany

Lithium-niobate is commonly applied as a nonlinear crystal in nonlinear, optical frequency converters. In order to phase-match the interacting waves, a periodic domain inversion of the crystal is often necessary. The standard method to create the necessary domain pattern uses a structured electrode which defines the position of the domains. While this method is good in batch-processing large quantities of crystals, it is unflexible for prototyping domain patterns since every pattern requires an individual photolithographic mask. We present a technique to rapidly create high-quality domain-structures in congruent-melting, MgO-doped lithium-niobate crystals by defining the position of the domain with a metallic needle. Therefore, the needle is moved along the desired position of the domain. A current-control-loop maintains a constant current and adjusts the necessary poling-voltage accordingly while the needle moves across the crystal. This ensures a high-quality domain-formation independent of the crystal orientation. This method is especially useful for creation of radially-poled domains which are suited for whispering-gallery resonators.

DF 8.5 Tue 11:00 WIL B321

Giant charged-domain-wall conductivity in lithium-nioabte — •Simon J. Herr[1], Christioph S. Werner[1], Cina Razzaghi[2], Elisabeth Soergel[2], Boris Sturman[3], Karsten Buse[4], and Ingo Breunig[1] — [1]Department of Microsystems Engineering, University of Freiburg — [2]University of Bonn, Bonn, Germany — [3]Institute for Automation and Electrometry of Russian Academy of Science, Novosibirsk, Russia — [4]Fraunhofer Institute for Physical Measurement Techniques, Freiburg, Germany

Charged-domain-walls in ferroelectric materials are known to show increased conductivity compared to the bulk-material. These domain-walls could play the key-role in a new type of electronic or electro-optic devices making use of the functional features of the host crystals. So far, the limiting factors are the high resistivity of the domain walls and the lack of a mechanism to create an ohmic interface to the domain-wall. Based on our method of calligraphic domain-inversion, we were able to create conducting domain-walls in lithium-niobate which show a highly increased conductivity, comparable to that of semiconductor materials. Further, we demonstrate that we can achieve diode-like behaviour as well as ohmic conduction.

DF 8.6 Tue 11:15 WIL B321

Functional electronic inversion layers at ferroelectric domain walls — •Jakob Schaab[1], Julia A. Mundy[2], Yu Kumagai[1], Andres Cano[3], Massimiliano Stengel[4], Darrel G. Schlom[2], David A. Muller[2], Ramamoorthy Ramesh[5], Manfred Fiebig[1], Nicola A. Spaldin[1], and Dennis Meier[6] — [1]ETH Zürich — [2]Cornell University — [3]CNRS, Université de Bordeaux — [4]ICMAB-CSIC Barcelona — [5]UC Berkeley — [6]NTNU Trondheim

Ferroelectric domain walls hold great promise as functional 2D-materials because of their unusual electronic properties. Particularly intriguing are the so-called charged walls where a polarity mismatch causes local, diverging electrostatic potentials requiring charge compensation and hence a change in the electronic structure. These walls can exhibit significantly enhanced conductivity and serve as a circuit path. The development of all-domain-wall devices, however, also requires walls with controllable output to emulate electronic nano-components such as diodes and transistors.

Here, we will present electric-field control of the electronic transport at ferroelectric domain walls. We reversibly switch from resistive to conductive behavior at charged walls in semiconducting $ErMnO_3$. We relate the transition to the formation - and eventual activation - of an inversion layer that acts as the channel for the charge transport. Our conductive atomic force microscopy (cAFM) and electron energy loss spectroscopy (EELS) data provide new insight to the domain-wall physics in ferroelectrics and foreshadow the possibility to design elementary digital components for all-domain-wall circuitry.

DF 8.7 Tue 11:30 WIL B321

In-situ 3D observation of the domain wall dynamics of triglycine sulfate upon ferroelectric phase transition — •Lukas Wehmeier, Thomas Kämpfe, Alexander Haussmann, and Lukas M. Eng — Institute of Applied Physics, Technische Universität Dresden, Dresden, Germany

Second harmonic generation microscopy (SHGM), also known as Cherenkov-SHG, allows for the 3-dimensional (3D) observation of ferroelectric domain walls (DWs) across millimeter-thick bulk materials [1,2]. We apply here SHGM in order to quantify the DW dynamics in triglycine sulfate (TGS) single crystals upon the ferroelectric-to-paraelectric phase transition around Tc = 49°C. Although having been in the focus of many works, this second-order phase transition is still of fundamental interest, especially in the view of our novel 3D techniques at hand or with respect to explore charged domain walls [3-5] in bulk single crystals. SHGM allows, for the first time, to watch the time-resolved dynamics in real time and in 3D, here when crossing the Curie temperature Tc. Furthermore, we also monitor the spike domain growth in TGS using SHGM. Spike domains are an excellent example of transient charged domain walls that topologically differ completely from the equilibrium bulk domain structure.

[1] T. Kämpfe et al., Phys. Rev. B 89, 035314 (2014)
[2] T. Kämpfe et al., Appl. Phys. Lett. 107, 152905 (2015)
[3] M. Schröder et al., Mater. Res. Express 1, 035012 (2014)
[4] M. Schröder et al., Adv. Funct. Mater. 22, 3963 (2012)
[5] T. Sluka et al., Nat. Commun. 3, 748 (2012)

DF 8.8 Tue 11:45 WIL B321

Anisotropic domain wall conductivity (DWC) of neighboring 180° DWs in $LiNbO_3$ single crystals — •Shuyu Xiao[1,2], Thomas Kaempfe[2], Yaming Jin[1], Alexander Haussman[2], Xiaomei Lu[1], and Lukas Eng[2] — [1]Physics School, Nanjing University, 210093 Nanjing, P. R. China — [2]Institute of Applied Physics, Technical University of Dresden, George-Baehr-Strasse 1, Dresden, Germany

Investigating the origin and nature of the domain wall conductivity (DWC) in different ferroelectric materials such as $BiFeO_3$ [1], $ErMnO_3$ [2] and $LiNbO_3$ (LNO) [3] is of a major scientific interest today. Here, we report on anisotropic DWC, as found between neighboring head-to-head (h2h) and tail-to-tail (t2t) 180° DWs in z-cut LNO single crystals. We applied conductive atomic force microscopy (cAFM) to quantify the local DW currents, probed the local polarization by piezo-response force microscopy (PFM), and mapped the 3D domain topology via Cherenkov Second Harmonic Generation (CSHG) microscopy [4]. The origin of the different DWC between h2h and t2t is studied by both phenomenological theories and dipole modelling assuming a quantum-mechanical tunneling process for electron transport. The domain wall inclination is found to account for the different conductivities in neighboring 180° DWs, while the material symmetry determines whether h2h or t2t DW becomes more conductive. In addition, domain wall roughness plays an important role in DWC as well.

[1] J. Seidel et al., Nat. Mater., 8 (2009), 229 [2] D. Meier et al., Nat, Mater., 11 (2012), 284 [3] M. Schroeder et al., Mater. Res. Express., 1 (2014), 035012 [4] T. Kaempfe et al., Phys. Rev. B, 89 (2014), 035314

15 min. break

DF 8.9 Tue 12:15 WIL B321

Electric conduction and dynamics of ferroelectric domain walls in $SrTiO_3$ — •Haijiao Harsan Ma, Daniel Kohlberger, Matthias Lange, Sebastian Scharinger, Reinhold Kleiner, and Dieter Koelle — Physikalisches Institut and Center for Quantum Science (CQ) in LISA$^+$, Universität Tübingen, Germany

Domain walls in $SrTiO_3$ could play a significant role in future oxide electronics, given their small size at the nanoscale as well as the fact that their occurrence can be controlled by an external electric field. Here, we report on the low-temperature electric conductance properties of domain walls in $SrTiO_3$ and their response to an external electric field. These properties are probed by using a combination of low-temperature scanning electron microscopy, polarized light microscopy and electric transport measurements. Our measurements show that above the threshold electric field $\sim 1\,\mathrm{kV/cm}$ for field-induced electric order [1], the domain walls show strongly increased conductance as compared to the bulk $SrTiO_3$. We will also address observations of complex dynamic behavior of the domain wall conductance properties.

[1] H. J. Harsan Ma *et al.*, Phys. Rev. Lett. **116**, 257601 (2016).

DF 8.10 Tue 12:30 WIL B321

Conductive domain walls in $SrMnO_3$ thin films under epitaxial tensile strain — •Lokamani Lokamani[1], Carina Faber[3], Peter Zahn[1], Nicola Spaldin[3], and Sibylle Gemming[1,2] — [1]Institute of Ion Beam Physics and Materials Research, HZDR, 01314 Dresden, Germany — [2]Institute of Physics, Technische Universität, 09107 Chemnitz, Germany — [3]Materials Theory, ETH, 8093 Zürich, Switzerland

Strontium manganate ($SrMnO_3$), a perovskite polymorph, exhibits cubic structure at low temperatures, which transforms into a hexagonal one at high temperatures. Density-functional calculations showed earlier, that under tensile strain the ground state of bulk $SrMnO_3$ corresponds to a G-type-antiferromagnetic (G-AFM) cubic structure. If deposited as epitaxially strained thin film a rearrangement of the MnO_6 coordination polyhedra was calculated, which is antiferrodistortive in the plane parallel to the substrate[1]. Recently, ferroelectric domains have been observed experimentally in 20nm thin films of $SrMnO_3$ under 1.7% tensile strain on (001)-oriented LSAT[2]. Strikingly, the domain walls were found to be electrically insulating, rendering the domains to form stable nano-capacitors.

Here, we present a first-principle investigation of the domain wall formation in epitaxially strained $SrMnO_3$ and a discussion of the electronic properties.

[1] J. H. Lee et al., PRL 104, 207204 (2010)
[2] C. Becher et al., Nature Nanotechnology 10, 661 (2015)
Funding by VI Memriox(VH-VI-422) & Nanonet(VH-KO-606)

DF 8.11 Tue 12:45 WIL B321

Local probe studies of switching and current dynamics in $Pb(Zr_{0.2}Ti_{0.8})O_3$ thin films — •Philippe Tückmantel[1], Iaroslav Gaponenko[1], Stefano Gariglio[1], Benedikt Ziegler[1], Joshua Agar[2], Lane W. Martin[2], and Patrycja Paruch[1] — [1]DQMP, University of Geneva, Geneva, Switzerland — [2]DMSE, University of California, Berkeley, USA

Defects and electrostatic boundary conditions have been shown to greatly impact the intrinsic configuration, geometry and growth dynamics of polarization domains in ferroelectric thin films. Indeed, defects can induce different switching dynamics, where the polarization reversal can be dominated by the nucleation of new domains or by the lateral growth of existing domains. Defects such as oxygen vacancies can also play an important role in controlling the electrical conduction at ferroelectric domain walls and, in conjunction with electrostatic boundary conditions can even allow fully reversible control of this phenomenon.

Here, we present our results on $Pb(Zr_{0.2}Ti_{0.8})O_3$ thin films showing both different switching dynamics and different domain wall current behaviours in samples grown by pulsed laser deposition and off-axis RF magnetron sputtering. Using piezoresponse force microscopy (PFM) and conductive atomic force microscopy (c-AFM) in ultra-high vacuum, we study the nanoscale nucleation and motion of domains as a function of applied tip voltage and their relation to the corresponding currents and defect densities.

DF 8.12 Tue 13:00 WIL B321

Enhancement of local photovoltaic current at ferroelectric domain walls in $BiFeO_3$ — •Ming-Min Yang and Marin Alexe — Department of Physics, University of Warwick, Coventry, UK

Domain walls, which are intrinsically two-dimensional nano-objects exhibiting nontrivial electronic and magnetic behaviors, have been proven to play a crucial role in photovoltaic properties of ferroelectrics. Despite this recognition, the electronic properties of domain walls under illumination until now have been accessible only to macroscopic studies and their effects upon the conduction of photovoltaic current still remain elusive. The lack of understanding hinders the developing of nanoscale devices based on ferroelectric domain walls. Here, we directly characterize the local photovoltaic and photoconductive properties of 71 degree domain walls on $BiFeO_3$ thin films with a nanoscale resolution. Local photovoltaic current, proven to be driven by the bulk photovoltaic effect, has been probed over the whole illuminated surface by using a specially designed photoelectric atomic force microscopy and found to be significantly enhanced at domain walls. Additionally, spatially resolved photoconductive current distribution reveals a higher density of excited carriers at domain walls in comparison with domains. Our measurements demonstrate that domain wall enhanced photovoltaic current originates from its high conduction rather than the internal electric field. This photoconduction facilitated local photovoltaic current is likely to be a universal property of topological defects in ferroelectric semiconductors.

DF 8.13 Tue 13:15 WIL B321

Reconfigurable domain wall conductance by inclination tuning — •Thomas Kämpfe[1], Bo Wang[2], Scott Johnston[3], Eric Y. Ma[3], Alexander Haussmann[1], Hui Hu[4], Zhi-Xun Shen[3], Long-Qing Chen[2], and Lukas M. Eng[1] — [1]Institute of Applied Physics and Center for Advancing Electronics (CFAED), TU Dresden, Germany — [2]Department of Materials Science and Engineering, Pennsylvania State University, University Park, USA — [3]Department of Applied Physics and Geballe Laboratory for Advanced Materials (GLAM), Stanford University, USA — [4]School of Physics, Shandong University, Jinan, China

We report on ferroelectric domain wall (DW) conductance in lithium niobate thin films that allows reproducibly writing/erasing DWs by proper voltage adjustment. The DWs are conductive and show persistent DWC at least for two months. Mandatory to DW conductance is a minimal DW inclination that promotes electron transport without illumination [1]. We proof this dependence indirectly: we compare cAFM measurements for domains written at various writing voltages and compare it with the simulated inclination angles obtained from phase-field modeling, which shows a decrease in inclination the larger the writing voltage. The conductance was further investigated by scanning-microwave impedance microscopy (sMIM) revealing a conductivity of about 100 to 1000 S/m at 1 GHz, hence an increase of about 10^{11} to the bulk conductivity of about 10^{-8} S/m.

[1] M.Schröder et.al., Adv. Funct. Mater. 22, (18), 3936 (2012)