MA 18: Magnetic Imaging and Sensors I

Time: Tuesday 9:30–13:00 Location: EB 301

MA 18.1 Tue 9:30 EB 301

Curvature-induced magnetic field generation in 3D nanostructures — •Sandra Ruiz-Gomez[1], Pamela Morales-Fernandez[1], Aurelio Hierro[2], Amalio Fernandez-Pacheco[3], and Claire Donnelly[1] — [1]Max Planck Institute for Chemical Physics of Solids, 01187, Dresden, Germany — [2]Depto. Física, Universidad de Oviedo, 33007 Oviedo, Spain — [3]Institute of Applied Physics, TU Wien, 1040 Vienna, Austria

Exploring three-dimensional nanomagnetic systems with unconventional spin textures opens the door to explore new magnetic phenomena. The impact of curvature on magnetic domain wall dynamics holds promise for new physics and functionalities. However, harnessing these effects requires an understanding of the fundamental properties and behaviour.

In the past few years, insight into the magnetisation configuration of three dimensional magnetic nanostructures has been achieved through developments in nanoscale magnetic tomography. However, many of these approaches primarily focus on large-scale facility of transmission electron microscopy-based methods, which are not always easily accessible. In our study, we demonstrate the feasibility of utilizing a magnetic force microscope (MFM) a standard lab-based technique, to gain insight into the magnetic behaviour of complex curved 3D nanostructures. In this way, not only are we able to identify and track the presence of magnetic textures such as domain walls but, by harnessing our sensitivity to the magnetic field, we map the generation of magnetic stray field due to local curvature-gradients in our nanostructures.

MA 18.2 Tue 9:45 EB 301

Failure Analysis and Characterization of Microwave Fields using a Scanning NV Microscope — •Bjorn Josteinsson, Andrea Morales, Gabriel Puebla Hellmann, Jan Rhensius, and Simon Josephy — QZabre, Zurich, Switzerland

Imaging of nano-meter scale current flows and microwave fields is crucial for failure analysis and verification in microchip and waveguide design. Scanning NV (Nitrogen-Vacancy) is an ideal candidate for measurements of such devices, as it has both high sensitivity and high spatial resolution at ambient conditions. To measure nano-scale currents, ac quantum sensing techniques are employed, achieving a resolution of a few tens of nanometers and resolving current densities as low as 40 nA/um. For the characterization of microwave fields, such as those from waveguides and ion-traps, we measure the Rabi rate of the NV. This involves selecting a qubit from the NV's triplet state and tuning its transition frequency to match the frequency of the device under test, achieved by applying an external magnetic bias field. The microwave emission from the device drives Rabi oscillation of the NV, and the oscillation rate directly indicates the microwave field's strength. We show how such measurements yield a three-dimensional microwave field map over a coupled waveguide using a commercial scanning NV system.

MA 18.3 Tue 10:00 EB 301

High-resolution nanoscale NMR for arbitrary magnetic fields — •Rouven Maier[1], Cheng-I Ho[2], Jonas Meinel[1], Vadim Vorobyov[1], and Jörg Wrachtrup[1] — [1]3rd Institute of Physics, University of Stuttgart, Germany — [2]Instititue of Organic Chemistry, University of Stuttgart, Germany

Nuclear magnetic resonance (NMR) spectroscopy poses one the most widely used spectroscopic techniques of modern times, with applications ranging from the serialized analysis of chemical structures at the molecular level to tissue imaging in clinical applications. However, the inherent insensitivity of conventional NMR spectroscopy prevents its use in studies of nanoscopic systems. By increasing the sensitivity by several orders of magnitude, nanoscale NMR spectroscopy based on the nitrogen vacancy (NV) center in diamond as quantum sensor has emerged as a promising research subject. Although recent developments of innovative NV-NMR detection schemes, such as the quantum-heterodyne (Qdyne) detection protocol enable high spectral resolutions, these schemes are inherently not applicable at high magnetic fields, to further improve the resolution and measurement times. Here we present a high-field compatible extension of the Qdyne measurement scheme by combining it with electron-nuclear-double-resonance (ENDOR) sequences. This approach paves the way for the application of NV-NMR spectroscopy in nano-scale studies of biomolecules and materials attached to the diamond surface.

MA 18.4 Tue 10:15 EB 301

Revealing the three-dimensional nature of the field-driven movement of magnetic topological defects — •Marisel Di Pietro Martínez[1], Luke Turnbull[1], Jeffrey Neethi Neethirajan[1], Max Birch[2], Simone Finizio[3], Jörg Raabe[3], Anastasios Markou[1], Edouard Lesne[1], María Vélez[4,5], Aurelio Hierro-Rodríguez[4,5], and Claire Donnelly[1] — [1]Max Planck Institute for Chemical Physics of Solids, Dresden, Germany — [2]RIKEN Center for Emergent Matter Science (CEMS) Wako, Japan — [3]Swiss Light Source, Paul Scherrer Institut, Villigen, Switzerland — [4]Departamento de Física, Universidad de Oviedo, Oviedo, Spain — [5]CINN (CSIC-Universidad de Oviedo), El Entrego, Spain

In recent years, there has been a surge of interest in expanding from two (2D) to three dimensional (3D) magnetic systems. This extra dimension brings new magnetic textures, which promise applications in information storage and processing. The experimental detection and 3D visualization of nanometric magnetic textures has been made possible by the development of 3D X-ray magnetic tomography. Here we have combined 3D soft X-ray magnetic imaging with the application of in situ magnetic fields, allowing us to draw a connection between the motion of 2D topological defects in magnetic thin films, and their underlying 3D magnetic structure. These advances establish the necessary capabilities for the study of the behavior of topological textures in 3D, opening the door to insights into the field-driven behavior of buried three-dimensional magnetic textures.

MA 18.5 Tue 10:30 EB 301

Mapping magnetic auto-oscillations using a single quantum sensor — •Toni Hache[1], Anshu Anshu[1], Frank Thiele[2], Gunther Richter[2], Rainer Stöhr[3], Klaus Kern[1,4], Jörg Wrachtrup[1,3], and Aparajita Singha[1,5] — [1]Max Planck Institute for Solid State Research, Stuttgart — [2]Max Planck Institute for Intelligent Systems, Stuttgart — [3]3rd Institute of Physics and Research Center SCoPE, University of Stuttgart — [4]Institute de Physique, École Polytechnique Fédérale de Lausanne — [5]IQST, University of Stuttgart

Magnetic auto-oscillations in nanoscale devices ($\sim$100 nm) have garnered significant interest in recent years as candidates for microwave or spin-wave sources and neurons in neuromorphic computing. They are generated during the interaction of spin currents with the magnetization in ferromagnetic materials via the spin-transfer torque. However, auto-oscillation modes can't be resolved with widely used laser-scanning methods. Furthermore, without additional effort they can't be measured with any stroboscopic technique. The mode formation has to be better understood to improve output power and coherence of such devices. Here we demonstrate high resolution spatial mapping of magnetic auto-oscillations with scanning nitrogen-vacancy (NV) center magnetometry. Our measurement relies on the synchronization of the microwave field generated by the auto-oscillation to the NV-spin resonance. The lateral extension of the auto-oscillation modes is obtained by measuring the intensity of the photoluminescence of the NV center which is low wherever the auto-oscillation mode is present.

MA 18.6 Tue 10:45 EB 301

Determination of Magnetic Symmetries by Electron Diffraction — •Oleksandr Zaiets[1,2], Carsten Timm[3], Jan Rusz[4], Subakti Subakti[1], and Axel Lubk[1,5] — [1]Leibniz Institute for Solid State and Materials Research Dresden, Dresden, Germany — [2]Faculty of Physics, TU Dresden, Dresden, Germany — [3]Institute of Theoretical Physics, TU Dresden, Dresden, Germany — [4]Department of Physics and Astronomy, Uppsala University, Uppsala, Sweden — [5]Institute of Solid State and Materials Physics, TU Dresden, Dresden, Germany

It is well known that convergent beam electron-beam diffraction methods can be used to determine spatial symmetries of crystalline samples, due to the relationship between the diffraction groups (symmetry group of electron diffraction pattern) and the point group of the sample.[1] In this work we show an extension toward magnetic point groups. We give a complete mapping of magnetic point groups to corresponding diffraction groups for different crystal orientations. We conduct electron scattering simulations in order to verify the group theoretical considerations and show first experimental results.

[1] B. F. Buxton, J. A. Eades, John Wickham Steeds, G. M. Rackham, and Frederick Charles Frank. The symmetry of electron diffraction zone axis patterns. Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences, 281(1301):171-194, 1976.

MA 18.7 Tue 11:00 EB 301

Novel micro-coil designs for investigations of individual magnetic nanowires — •Aniruddha Sathyadharma Prasad[1,2], Rachappa Ravishankar[1,2], Volker Neu[1], Bernd Büchner[1,2], and Thomas Mühl[1] — [1]IFW Dresden — [2]TU Dresden

Iron filled carbon nanotubes (FeCNTs) have been shown to be excellent magnetic sensors for use in magnetic force microscopy (MFM)[1]. The high aspect ratio and monopole like behaviour of FeCNTs allow for performing quantitative stray field measurements of various magnetic samples. Their magnetic switching fields are as high as 400 mT, which aids in the magnetic stability while performing MFM measurements.

In this work, we present novel micro-coil designs which can generate magnetic flux densities > 600 mT localised at the nanoscale. These coils can be utilized to investigate the switching behaviour of individual nanowires and can also be used to switch the direction of the magnetic moment in FeCNT-based MFM probes. Peak fields achieved by previous micro-coil designs were in the order of tens of mT, which is insufficient for switching the FeCNTs. We overcome the limitations of the conventional micro-coil design by integrating several heat-sink structures to carry heat away from the centre of the coil. This allows for higher currents to be pushed into the coil, while keeping the local temperature below the melting point of the materials involved.

The inhomogeneous field distributions generated by the micro-coils additionally presents an opportunity to study the behaviour of magnetic nanowires in non-uniform magnetic fields.

[1] Freitag, N.H. et al. Commun Phys 6, 11 (2023).

15 min. break

MA 18.8 Tue 11:30 EB 301

Coherent x-ray magnetic imaging with 5 nm resolution — •Riccardo Battistelli[1,2], Daniel Metternich[1,2], Michael Schneider[3], Lisa-Marie Kern[3], Kai Litzius[2], Josefin Fuchs[3], Christopher Klose[3], Kathinka Gerlinger[3], Kai Bagschik[4], Christian Günther[5], Dieter Engel[3], Claus Ropers[6,7], Stefan Eisebitt[3,8], Bastian Pfau[3], Felix Büttner[1,2], and Sergey Zayko[6,7] — [1]Helmholtz-Zentrum Berlin — [2]Experimental Physics V, Center for Electronic Correlations and Magnetism, University of Augsburg — [3]Max Born Institute for Nonlinear Optics and Short Pulse Spectroscopy — [4]Deutsches Elektronen-Synchrotron (DESY) — [5]Technische Universität Berlin, Zentraleinrichtung Elektronenmikroskopie (ZELMI) — [6]Max Planck Institute for Multidisciplinary Sciences — [7]4th Physical Institute, University of Göttingen — [8]Technische Universität Berlin, Institut für Optik und Atomare Physik

Soft x-ray microscopy plays an important role in modern spintronics, but the resolution of most x-ray magnetic imaging experiments is above 10 nm, limiting access to fundamental length scales. Here, we demonstrate x-ray magnetic microscopy with 5 nm resolution by combining holography-assisted coherent diffractive imaging with heterodyne amplification of the weak magnetic signal. The gain in resolution and contrast allows direct access to key magnetic properties, including domain wall profiles and the position of pinning sites.

MA 18.9 Tue 11:45 EB 301

Three-dimensional integrated circuit activity imaging using quantum defects in diamond — •Marwa Garsi[1], Rainer Stöhr[1], Andrej Denisenko[2], and Jörg Wrachtrup[1] — [1]3. Physikalisches Institut, Universität Stuttgart, 70569 Stuttgart, Germany — [2]SQUTEC-TTI GmbH, 70569 Stuttgart, Germany

The continuous scaling of semiconductor-based technologies to micron and sub-micron regimes has resulted in higher device density and lower power dissipation. Many physical phenomena, such as self-heating or current leakage, become significant at such scales. An efficient way to visualise such charge transport is to image the associated magnetic fields that pass unaffected through the materials used in semiconductor devices. However, advanced non-invasive imaging technologies are limited to the two-dimensional spatial realm only, while modern integrated circuits adopt a three-dimensional architecture. Here, we use near-surface nitrogen-vacancy centres in diamond with the unique ability to detect vectorial fields on the nanoscale. We optimise the Oersted field imaging procedure and present current distribution imaging within a multi-layered microchip designed with the recent back-end-of-line (BEOL) technology [1]. Our results provide, therefore, a decisive step toward three-dimensional current mapping in technologically relevant nanoscale electronics chips [2].

[1] J. Böck et al., Proceedings of the IEEE Bipolar/BiCMOS Circuits and Technology Meeting 121 (2015).

[2] M. Garsi et al., arXiv:2112.12242 (2021).

MA 18.10 Tue 12:00 EB 301

Utilizing NV Magnetometry in Materials Research — •Hayden Binger, Young-Gwan Choi, Luke Turnbull, Claire Donnelly, and Uri Vool — Max Planck Institute for Chemical Physics of Solids, Dresden, Germany

Measuring the local magnetic field has proven invaluable to the characterization of quantum materials. While there are several established techniques capable of this, challenges still remain such as low sensitivity, invasiveness, or required cryogenic temperatures. Single spin scanning magnetometry based on the Nitrogen Vacancy (NV) is a fast growing technology that provides a route to overcome these limitations, providing noninvasive nanoscale resolution of magnetic fields up to room temperature. As it combines qubit measurements with a scanning platform, it requires expertise in various fields, including optics, RF engineering, atomic force microscopy, and quantum control. With growing interest in the field, the NV platform is moving from being highly specialized to becoming accessible to the general condensed matter physicist. In this talk I will discuss the benefits and limitations of NV magnetometry and how it can be used to characterize phenomena ranging from nanoscopic magnetic domains to local current transport. Given the advantages and usability of this technique, we believe it will soon be considered a standard addition to the material researchers repertoire.

MA 18.11 Tue 12:15 EB 301

Opto-electrical approach to resolve magnetic nanostructures in ferromagnetic and antiferromagnetic thin films — •Atul Pandey[1,2], Jitul Deka[1], James m Taylor[2], Stuart s p Parkin[1], and Georg Woltersdorf[1,2] — [1]Max Planck Institute of Microstructure Physics, Weinberg 2, 06120 Halle, Germany — [2]Institute of Physics, Martin Luther University Halle-Wittenberg, Von-Danckelmann-Platz 3, 06120 Halle, Germany

We present an opto-electrical approach based on the anomalous Nernst effect (ANE) to image magnetic domain structures. For this, a focused laser beam creates a temperature gradient and the voltage due to ANE is detected. As this voltage is proportional to magnetization, a spatially-resolved measurement allows to image the domain structures and characterize magnetic properties. The spatial resolution in such an experiment is given by diffraction limited spot size of the focused laser beam, which is on the order of 300 nm for a green laser. A near-field optical microscope is utilized to make the improvement. This allows us to obtanin the resolution of 10s of nm. Traditional techniques for imaging magnetic domains rely on coupling of magnetic stray fields. Therefore, it is challenging to image domain structures in antiferromagnet due to their relatively small stray fields. Since ANE in antiferromagnets is a Berry curvature driven effect, our technique can also be used to image magnetic domains in antiferromagnets.

MA 18.12 Tue 12:30 EB 301

Ultrafast soft X-ray magnetic holography at SwissFEL — Boris Sorokin, Andre Al Haddad, Kirsten Schnorr, Joerg Raabe, and •Simone Finizio — Paul Scherrer Institut, Villigen PSI, Switzerland

X-ray imaging at synchrotrons have enabled a significant advancement in the understanding of the physics driving magnetic systems. Nevertheless, for X-ray imaging at ultrafast timescales, free-electron lasers become a necessity. In this presentation, an overview of the first results of the magnetic imaging setup recently commissioned at the Maloja endstation of the soft X-ray Athos beamline at SwissFEL (PSI, Switzerland), which is based on X-ray holography, will be given. This is a lensless imaging technique that allows the retrieval of both amplitude and phase information of the sample transmission function. Since X-ray holography is an intrinsically drift free technique and a full-field microscopy technique, it is well suited for free-electron lasers, where shot-to-shot variations render scanning microscopy techniques unbefitting. Athos beamline of SwissFEL, with its 16 Apple-X undulators, provides soft X-ray radiation with a fully controllable polarisation. This makes it particularly suitable for ultrafast X-ray magnetic imaging, where XMCD and XLD are employed as contrast mechanisms for both ferromagnetic and antiferromagnetic samples, respectively. During the commissioning phase, we demonstrated the possibility of measuring the static images of the labyrinth magnetic domain structures in thin films with perpendicular magnetic anisotropy. This is the first step towards ultrafast time-resolved soft X-ray magnetic imaging.

MA 18.13 Tue 12:45 EB 301

Non-invasive magnetic imaging and characterization of domain walls in synthetic antiferromagnets — •Ricardo Javier Peña Román[1], Dinesh Pinto[1,2], Sandip Maity[1], Fabian Samad[3,4], Olav Hellwig[3,4], Klaus Kern[1,2], and Aparajita Singha[1] — [1]Max Planck Institute for Solid State Research — [2]Institute de Physique, École Polytechnique Fédérale de Lausanne — [3]Institute of Ion Beam Physics and Material Research, Helmholtz-Zentrum Dresden-Rossendorf — [4]Insititute of Physics, Chemnitz University of Technology

Understanding the local properties of the domain wall (DW) spin textures is crucial for developing, engineering, and controlling them for potential applications in magnetic storage devices and spintronics.

For investigating DWs in synthetic antiferromagnets, here we utilize a home-built nitrogen-vacancy (NV) scanning probe microscope that combines the spatial resolution of atomic force microscopy with the exceptional magnetic sensitivity of a single NV defect in diamond as a sensor. This technique, being independent of any external perturbation, is the least-invasive scanning probe approach available at room temperature. It also allows quantitative measurements of the stray magnetic fields generated by the sample. By performing measurements with two different orientations of the AFM NV-probe, we reveal distinct fingerprints emerging from spin noise and constant magnetic stray fields from the sample. Our work opens up novel opportunities for understanding magnetic thin films quantitatively and non-invasively, along with exceptionally high magnetic sensitivity at the nanoscale.