O 16: Scanning Probe Techniques: Method Development

Time: Monday 15:00–18:00 Location: H25

O 16.1 Mon 15:00 H25

Fast and quantitative nanomechanical mapping using photothermal off-resonance tapping atomic force microscopy (AFM) — •Gunstheimer Hans[1,2], Fläschner Gotthold[1], Adams Jonathan[1], Hölscher Hendrik[2], and Hoogenboom Bart[1] — [1]Nanosurf AG, Gräubernstrasse 12-14, 4410 Liestal, Switzerland — [2]Institute of Microstructure Technology (IMT), Karlsruhe Institute of Technology, Karlsruhe, Germany

Multifunctional imaging, makes AFM a powerful tool for nanoscale surface analysis. However, most scanner-based methods for measuring mechanical properties are slow, limiting their use in fast mapping of mechanical characteristics. The main source of limitation is the piezo scanner, used to modulate tip-sample distance. This can be overcome by direct cantilever actuation, such as photothermal excitation. By moving the cantilever's comparably smaller mass, higher actuation bandwidths are accessible, enabling new approaches for AFM-based nanomechanical characterization. Here, we share insights on applying photothermal off-resonance tapping to fast nanomechanical property mapping. Based on simulations of cantilever bending due to laser-induced heating, we predict the cantilever response and propose a procedure to convert thermomechanical cantilever behavior into a calibrated nanomechanical measurement. We present the experimental method validation by measurements of polymer samples and reference structures. This novel photothermal off-resonance tapping mode enables quantitative nanomechanical mapping at frequencies of several tens of kHz, unlocking new insights into dynamic sample behavior.

O 16.2 Mon 15:15 H25

Multifrequency Excitation and High Dynamic Range Tunneling Spectroscopy — Philipp E.J. Maier, Ajla Karić, Carolina A. Marques, Berk Zengin, and •Fabian D. Natterer — Department of Physics, University of Zurich, Winterthurerstrasse 190, CH-8057, Switzerland

The massive number of spectra required for high-resolution quasiparticle interference of low-dimensional quantum materials motivates the development of faster point spectroscopies. While the advent of parallel spectroscopy and compressive sensing enhancements has provided welcome speed boosts, these come at a cost. The application of a sinusoidal voltage on the nonlinearities in the current-voltage characteristics of a tunneling junction generates a frequency comb of higher order current-harmonics. While their parallel measurement enables faster tunneling spectroscopy, it unfortunately averages longest where the currents are largest, leading to poor signal-to-noise ratios for smaller signals associated with features close to the Fermi level. Here, we introduce a multifrequency excitation mode that increases the averaging time for small currents, enabling fast and high-resolution spectroscopy. Additionally, the AC excitation of our method can be used to dramatically increase the dynamical current range by exactly and deliberately suppressing the large amplitude, low order harmonics that would otherwise saturate the preamplifier stage.

O 16.3 Mon 15:30 H25

Dynamics on the atomic-scale: Use and limitations of stochastic resonance spectroscopy — •Nicolaj Betz[1,2], Vivek K. Rajathilakam[1], Laëtitia Farinacci[1,3], Susan N. Coppersmith[4], Susanne Baumann[1], and Sebastian Loth[1,2] — [1]University of Stuttgart, Institute for Functional Matter and Quantum Technologies, Stuttgart, Germany — [2]Center for Integrated Quantum Science and Technology (IQST), University of Stuttgart, Stuttgart, Germany — [3]Carl-Zeiss-Stiftung Center for Quantum Photonics Jena-Stuttgart-Ulm, Germany — [4]School of Physics, University of New South Wales, Sydney, Australia.

Stochastic dynamics offer valuable insight into the internal structure of a system and its interactions with the environment. However, in atomic-scale systems investigated using scanning tunneling microscopy, comprehensive and accurate characterization is often a significant challenge. In this talk, we discuss a new type of measurement technique, stochastic resonance spectroscopy (SRS), that provides comparatively large signals over a wide range of timescales down to the picosecond range. It uses the effect of stochastic resonance, where the system's state synchronizes with an external harmonic drive. This encodes information about the dynamics in a time-independent signal. Such drive-induced imprinting of time-independent signals can alter the system's dynamics, but this limitation can be mitigated in SRS by its ability to identify and even tune these drive-induced dynamics. This enables targeted investigation of driven quantum systems on the atomic scale.

O 16.4 Mon 15:45 H25

From experiments to insights: processing tool for SPM images with periodic pattern — •Farzin Irandoost[1], Fillippo Federici Canova[2], Tobias Dickbreder[3], Franziska Sabath[3], Angelika Kühnle[3], and Adam S. Foster[1,4] — [1]Department of Applied Physics, Aalto University, Helsinki, Finland — [2]Nanolayers Research Computing Ltd., London, England — [3]Physical Chemistry I, Bielefeld University, Germany — [4]Nano Life Science Institute (WPI-NanoLSI), Kanazawa University, Kanazawa, Japan

Big datasets of Scanning Probe Microscopy (SPM) images are potentially valuable, but robust algorithms are required for preprocessing them due to the high levels of defects and noise introduced during experiments. These issues often render many images unusable, especially for in-liquid SPM studies.

As part of a study on hydration patterns using a dataset of in-liquid calcite, we developed a versatile workflow to clean the data and extract features for further analysis. This workflow automatically corrects non-linear defects, ensuring the outputs closely resemble ideal periodic patterns. Consequently, many previously discarded raw images can be recovered to prepare a large, clean dataset ready for analysis. Afterward, the features of interest could be extracted using pattern decomposition facilitated by Fourier transforms.

This approach provides access to invaluable information about the lattice and hydration patterns for our study. Additionally, it offers a versatile tool for broader analyses of images with periodic structures.

O 16.5 Mon 16:00 H25

True Alternating Current Scanning Tunneling Microscope (ACSTM): tunneling on insulators — •Marcel Rost[1] and Milan Allan[1,2] — [1]Leiden Institute of Physics (LION), Leiden, NL — [2]University of Munich (LMU), Munich, Germany

Scanning Tunneling Microscopy has revolutionized our atomic scale understanding of surfaces and accelerated progress in nanotechnology. This technique, however, is restricted to metal or semiconducting samples, as it requires a tiny current to stabilize the tip-sample distance with atomic scale precision.

We developed a new imaging and feedback method that relies on true alternating current (AC) without any direct current (DC) component. This technique does not only enable the imaging on non-conducting surfaces with atomic resolution, like (thin) glass and oxides, it provides also access to high-frequency electronic sample information. We demonstrate that it is possible to measure on 22nm thick silicon oxide with 10 MHz tunneling current.

O 16.6 Mon 16:15 H25

STM-induced luminescence with a parabolic mirror - millions of counts — •Yannis Hilgers, Andreas Reutter, Mike Stummvoll, Markus Etzkorn, and Uta Schlickum — Institute of Applied Physics - LENA, TU Braunschweig, Germany

In recent years, scanning tunneling microscopy-induced luminescence (STML) has become a powerful technique allowing to record topography with atomic resolution and simultaneous spatially resolved photon count maps. We have built a Photon STM with a large parabolic mirror which was specifically designed for high photon collection efficiency. With this system we detected so far unreached photon counts of about 6 million photons per second at 1 nA tunnelling current that result from the decay of plasmon-polariton excitations between a Ag(111) surface and a Ag tip. Considering losses due to geometry, shadowing, optical components and detectors, we estimate a yield of approximately $5 \cdot 10^{-3}$ photons per tunnelling electron. This is scratching on the theoretical predictions by Johansson et al. [1], Persson and Baratoff [2] and others who all reported conversion factors in the range of 10^{-4} to 10^{-3} at most. In this talk we discuss these results, the instrumental calibrations and assumptions necessary for this estimation and speculate about possible explanations of the high observed excitation efficiency.

1 P. Johansson, R. Monreal, P. Apell - Phys. Rev. B 42, 9210 (1990)
2 B.N.J. Persson, A. Baratoff - Phys. Rev. Lett. 68, 3224 (1992)

O 16.7 Mon 16:30 H25

Momentum-polarized microscopy with van der Waals scanning probe tip. — •Abhisek Kole[1,2,4], Frank Stefan Tautz[1,2,4], Markus Ternes[1,2,3], Jose Martinez Castro[1,2,3], and Felix Lüpke[1,2,5] — [1]Peter Grünberg Institut (PGI-3), Forschungszentrum Jülich, Germany — [2]Jülich Aachen Research Alliance, Fundamentals of Future Information Technology, Germany — [3]Institut fur Experimentalphysik II B, RWTH Aachen, Aachen, Germany — [4]Institut fur Experimentalphysik IV A, RWTH Aachen, Aachen, Germany — [5]II. Physikalisches Institut, Universität zu Köln, Cologne, Germany

Van der Waals materials are celebrated for their remarkable 2D physics, which includes correlated phenomena and topological effects. In this work, we present momentum-polarized microscopy using a van der Waals scanning probe tip. We developed and implemented a novel fabrication method to fabricate van der Waals scanning tunneling tips from exfoliated graphite flakes. The fabricated tips were characterized by atomically resolved scanning tunneling microscopy (STM) on an Ag(111) surface, where differential conductance measurements provided direct evidence of tunneling through the zigzag edge states of graphene. In addition, Friedel oscillations on the Ag(111) surface revealed clear signs of momentum-dependent tunneling, manifesting as anisotropic tunneling conductance. To further validate and investigate the momentum selective properties of the zigzag graphene tips, we have resolved the momentum dependent superconducting gap on FeSe lattices.

O 16.8 Mon 16:45 H25

Image-to-molecule translation for high-resolution SPM images — •Lauri Kurki[1], Jie Huang[1], Niko Oinonen[1,2], and Adam S. Foster[1,3] — [1]Aalto University, Finland — [2]Nanolayers Research Computing Ltd., UK — [3]WPI-NanoLSI, Kanazawa University, Japan

Scanning tunnelling microscopy (STM) and atomic force microscopy (AFM) functionalized with a CO molecule on the probe apex capture sub-molecular level detail of the imaged sample [1]. However, the produced images are often difficult to interpret due to complex tip-sample interactions. To accelerate image analysis, we propose machine learning tools to extract sample properties directly from SPM images.

In recent years, there has been rapid development in image analysis methods in SPM in general and in particular for extracting atomic positions from AFM and STM images [2,3,4]. We build upon these models and achieve improved chemical and physical sensitivity compared to previous results [2]. Additionally, we explore equivariant neural networks [5] and compare their data efficiency and accuracy to traditional deep learning models.

[1] Cai et al., J. Am. Chem. Soc. 2022, 144, 44, 20227-20231 [2] Kurki et al., ACS Nano 2024, 18, 17, 11130*11138 [3] Alldritt et al., Sci. Adv. 2020; 6 : eaay6913 [4] Carracedo-Cosme et al., Nanomaterials 2021, 11, 1658. [5] Cesa et al., arXiv:1911.08251

O 16.9 Mon 17:00 H25

Scanning Quantum Microscopy for 2D Superconductors — •Ruoming Peng[1], Malik Lenger[1], Sreehari Jayaram[1], and Joerg Wrachtrup[1,2] — [1]3. Physikalisches Institut, University of Stuttgart, 70569 Stuttgart, Germany — [2]Max Planck Institute for Solid State Research, 70569 Stuttgart, Germany

Visualization of nanoscale dynamics in 2D superconductors provides critical insights into pairing mechanisms and topological electronic responses. Using state-of-the-art scanning quantum microscopy based on nitrogen-vacancy (NV) centers in diamonds, we investigate the local magnetic behavior of the 2D superconductor 2H-NbSe2 with high sensitivity and spatial resolution. This approach enables the first spatial-temporal measurements of vortex dynamics in thin exfoliated 2H-NbSe2, revealing a strong correlation between vortex arrangements and geometric confinement. We observe the melting transition of vortex solids near the critical temperature, alongside cooling-rate-dependent vortex rearrangements across thermal cycles. Additionally, through local magnetic noise probing via spin coherence time (T2) measurements, we uncover unexpected supercurrent fluctuations in reduced dimensionality. These findings highlight the potential of scanning quantum microscopy in advancing our understanding of vortex physics and emergent phenomena in 2D superconducting systems.

O 16.10 Mon 17:15 H25

A high-throughput ESR-STM setup at mK temperatures — •Máté Stark, Jonas Arnold, Luise Renz, Johannes Schwenk, Christoph Sürgers, Wolfgang Wernsdorfer, and Philip Willke — Physikalisches Institut (PHI), Karlsruhe Institute of Technology, Karlsruhe, Germany

Characterizing and controlling single spins using Electron Spin Resonance Scanning Tunneling Microscopy (ESR-STM) [1] benefits from ultra-low temperatures, minimal noise, and efficient RF transmission to the junction. This work details upgrades to an ESR-STM system operating at mK temperatures within a compact dilution refrigerator under UHV conditions. We achieved an electronic temperature below 200 mK while maintaining effective RF transmission up to 40 GHz. In addition, we developed a compact UHV chamber with an automated sputter-annealing stage, allowing for efficient sample preparation and quick exchange of samples with various atoms and molecules atop. In combination with the fast cooldown of the dilution refrigerator, these upgrades greatly streamline the experimental workflows allowing for rapid and high quality ESR-STM measurements. [1] Baumann, S. et al., 350(6259), 2015.

O 16.11 Mon 17:30 H25

Molecular Identification via Molecular Fingerprint extraction from Atomic Force Microscopy images — •Manuel González Lastre[1], Pablo Pou[1,2], Miguel Wiche[3,4], Daniel Ebeling[3,4], Andre Schirmeisen[3,4], and Rubén Pérez[1,2] — [1]Departamento de Física Teórica de la Materia Condensada, Universidad Autónoma de Madrid, E-28049 Spain — [2]Condensed Matter Physics Center (IFIMAC), Universidad Autónoma de Madrid, E-28049 Madrid, Spain — [3]Institute of Applied Physics, Justus Liebig University Giessen, Giessen, Germany — [4]Center for Materials Research, Justus Liebig University Giessen, Giessen, Germany

Previous works have already shown that deep learning (DL) models can retrieve the chemical and structural information encoded in a 3D stack of constant-height HR–AFM images, leading to molecular identification.

In this work, we overcome their limitations by using a well-established description of the molecular structure in terms of topological fingerprints, the Extended Connectivity Fingerprints, which provide local structural information of the molecule. In this work, we train a DL model to extract this optimized structural descriptor from the 3D HR–AFM stacks and use it, through virtual screening, to identify molecules from their predicted ECFP4 with a retrieval accuracy on theoretical images of 95.4%. This approach, unlike previous DL models, assigns a confidence score, the Tanimoto similarity, to each of the candidate molecules, thus providing information on the reliability of the identification.

O 16.12 Mon 17:45 H25

The Josephson effect in the dynamical Coulomb blockade regime with high energy resolution — •Xianzhe Zeng[1], Janis Siebrecht[1], Haonan Huang[1], Sujoy Karan[1], Klaus Kern[1,2], and Christian R. Ast[1] — [1]Max-Planck-Institut für Festkörperforschung, Heisenbergstraße 1, 70569 Stuttgart, Germany — [2]Institut de Physique, Ecole Polytechnique Fédérale de Lausanne, 1015 Lausanne, Switzerland

The Josephson effect can be used as a good quantitative indicator of the energy resolution of scanning tunneling microscopy (STM). Recently we have upgraded our mK-STM with low-temperature filtering on our scan head. We measured the Josephson current and found an improvement of the energy resolution by almost an order of magnitude. The high resolution allows us to measure several spectroscopic features in detail, including the superconducting coherence peaks with extreme sharpness and the environmental resonances in the Josephson current at low frequency due to the dynamical Coulomb blockade.