O 72: Scanning Probe Techniques I: STM-ESR and Method Development (joint session O/CPP)

Time: Wednesday 15:00–17:30 Location: TRE Ma

O 72.1 Wed 15:00 TRE Ma

Dynamics in spin excitation spectroscopy measurements — •Luigi Malavolti[1,2], Max Hänze[1,2], Gregory McMurtrie[1], and Sebastian Loth[1,2] — [1]University of Stuttgart, Institute for Functional Matter and Quantum Technologies, Stuttgart, Germany. — [2]Max Planck Institute for Solid State Research, Stuttgart, Germany.

Spin excitation spectroscopy has proven to be an essential tool for the investigation of magnetic phenomena at the atomic scale [1] forming the basis for RF-STM investigation of both electron spin resonance and spin dynamics [2]. However, certain spin dynamic phenomena can also be transduced directly via standard dIdV(V) measurements [3]. Here, the contribution of spin dynamic effects to static spectroscopy measurements is presented using a combined theoretical and experimental approach. Understanding these phenomena allows the behavior of spin systems with long-lived excitations to be anticipated, offering a fast and reliable way to access spin dynamics with standard STM techniques. [1] R. Wiesendanger, Rev. Mod. Phys. 81, 1495 (2009) [2] Loth S., Science, 329, 1628, (2010) [3] Rolf-Pissarczyk S., PRL, 119, 217201, (2017)

O 72.2 Wed 15:15 TRE Ma

Electron paramagnetic resonance of single Ti and Fe atoms with an out-of-plane magnetic field probed by STM — •Tom S. Seifert[1], Stepan Kovarik[1], Dominik Juraschek[1,2], Nicola A. Spaldin[1], Sebastian Stepanow[1], and Pietro Gambardella[1] — [1]ETH Zurich, Switzerland — [2]Harvard University, USA

Combining the sub-atomic resolution of scanning tunneling microscopy (STM) with the spectral resolution of electron-paramagnetic resonance (EPR) allows for sensitive probing magnetic interactions of single atoms on a surface [1]. However, the experimental requirements for driving the EPR transitions are still under debate [2,3]. In-depth understanding of what drives these spin rotations is mandatory to explore novel material systems and optimize the sensitivity of this technique. Here, we acquire EPR spectra of single Fe and hydrogenated Ti atoms on bilayer MgO on Ag using a radio frequency (RF) antenna close to the STM junction with a magnetic field applied perpendicular to the surface [4]. We investigate in a systematic way the impact of RF excitation strength and tunneling parameters on the EPR signal with emphasis on the electric and magnetic fields present at the tunnel junction. This analysis is supported by density functional calculations of the electronic and phononic density of states of the probed systems.

[1] S. Baumann et al., Science **350** (2015) [2] K. Yang, et al., PRL **122** (2019) [3] P. Willke et al., Nano Lett. **19** (2019) [4] T. S. Seifert et al., ArXiv 1908.03379 (2019)

O 72.3 Wed 15:30 TRE Ma

Electron spin resonance of an individual atom at mK temperature in a vector magnetic field — •Manuel Steinbrecher[1], Werner v. Weerdenburg[1], Jan W. Gerritsen[1], Niels v. Mullekom[1], Fabian D. Natterer[2], and Alexander A. Khajetoorians[1] — [1]Institute for Molecules and Materials, Radboud University, 6525 AJ Nijmegen, The Netherlands — [2]Department of Physics, University of Zurich, CH-8057 Zurich, Switzerland

It was recently shown that electron spin resonance (ESR) can be combined with spin-resolved scanning tunneling microscopy (STM) to quantify the resonant excitations of individual 3d transition metal atoms [1]. The combination of atomic-resolution and ultra-high energy resolution, compared to standard scanning tunneling spectroscopy, has e.g. enabled quantification of the hyperfine coupling of individual atoms at temperatures near 1K [2]. Nevertheless, probing small absolute energy scales down to MHz frequencies requires the implementation of this method at much lower temperature. We will present ESR performed in a home-made dilution refrigerator (T = 30mK) based spin-polarized STM including a vector magnet [3]. The ESR was recorded on individual atoms on a thin insulating film of MgO over a whole frequency range from several hundred MHz to tens of GHz. A vector magnetic field was applied and allowed ESR experiments in different crystallographic directions.

[1] S. Baumann *et al.*, Science **350**, 417 (2015)
[2] P. Willke *et al.*, Science **362**, 336 (2018)
[4] H. v. Allwörden *et al.*, RSI **89**, 033902 (2018)

O 72.4 Wed 15:45 TRE Ma

Electron spin resonance in scanning tunneling microscopy — •Andreas Heinrich — Center for Quantum Nanoscience, Seoul, Korea

The scanning tunneling microscope is an amazing tool because of its atomic-scale spatial resolution. This can be combined with the use of low temperatures, culminating in precise atom manipulation and spectroscopy with several microvolt energy resolution. In this talk we will apply these techniques to the investigation of the quantum spin properties of magnetic atoms sitting on thin insulating films. We will explore the superposition of quantum states which is inherent to spin resonance techniques. About 5 years ago it was demonstrated that electric field driven electron spin resonance (ESR) can be combined with STM on single Fe atoms on MgO (Science 2015). This technique combines the power of STM of atomic-scale spectroscopy with the unprecedented energy resolution of spin resonance techniques, which is about 10,000 times better than normal spectroscopy. We will give an update on recent advances in our team including pulsed ESR on Ti atoms on MgO (Science 2019).

O 72.5 Wed 16:00 TRE Ma

Transfer Function Compensation for High Frequency Radiation into an STM Tunnel Junction — •Maximilian Uhl, Piotr Kot, Robert Drost, and Christian R. Ast — Max-Planck-Institut für Festkörperforschung, Stuttgart

Creating constant amplitude radiation of varying frequencies in the tunnel junction of a scanning tunneling microscope is an important condition for probing the interaction of matter and electromagnetic waves at the nanoscale, such as for electron paramagnetic resonance [1]. The transfer function describes the transmission of an AC signal to the tunnel juntion and depends highly non-linearly on the frequency. A known transfer function can be compensated by a frequency dependent signal power. Reaching non-zero constant amplitudes at frequencies $> 40\,\mathrm{GHz}$ has remained a challenge. Our setup makes this possible for frequencies up to 90 GHz. So far, transfer functions have been measured by plasmonic light emission [2] and rectification at current-voltage non-linearities [3]. Here, a new technique based on the Tien-Gordon equation [4] is demonstrated. It allows to probe even small AC voltages in the μV range, requiring only a single measurement point per frequency. For that, we use the coherence peak of a superconductor-insulator-superconductor junction. Generally, the technique can also be used with other peak types in the current-voltage derivative.

[1] S. Baumann et al.: Science **350** (6259), 417 (2015)
[2] C. Grosse et al.: Appl. Phys. Lett. **103**, 183108 (2013)
[3] W. Paul et al.: Rev. Sci. Instrum. **87**, 074703 (2016)
[4] G. Falci, V. Bubanja, G. Schön: Z. Phys. B **85**, 451 (1991)

O 72.6 Wed 16:15 TRE Ma

Hyperfine fields of magnetic adatoms on ultrathin insulating films — •Sufyan Shehada, Manuel dos Santos Dias, Filipe Souza Mendes Guimarães, and Samir Lounis — Peter Grünberg Institut and Institute for Advanced Simulation, Forschungszentrum Jülich & JARA, 52425 Jülich, Germany

Individual nuclear spin states can have a very long lifetime and could in principle be used as qubits. A promising step in this direction was the recent detection of the hyperfine interaction between the atomic nucleus and the surrounding electrons for single Fe and Ti adatoms on MgO/Ag(001) [1]. Here, we report on systematic first-principles calculations of the hyperfine fields of magnetic transition metal adatoms (from Ti to Cu) placed on different ultrathin insulators, such as MgO, NaCl, CuN and hBN. We analyze the trends and the dependence of the computed hyperfine fields on the filling of the magnetic d-orbitals of the adatom and on the type and strength of the bonding with the substrate, and what is the impact of an underlying metallic surface. We also identify promising candidates for future experimental investigation with scanning probe techniques.

This work was supported by the Palestinian-German Science Bridge BMBF program and the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme

(ERC-consolidator Grant No. 681405-DYNASORE).

[1] P. Willke *et al.*, Science **362**, 336–339 (2018)

O 72.7 Wed 16:30 TRE Ma

Mapping the perturbation potential of metallic and dipolar tips in tunneling spectroscopy on MoS_2 — •Christian Lotze, Nils Krane, Gaël Reecht, Nils Bogdanoff, and Katharina J. Franke — Freie Universität Berlin, Germany

Single layer molybdenum disulfide (MoS_2) features a direct band gap and strong spin-splitting of the valence band at the K-point, which make it an interesting material for optoelectronic applications.

We grow a single layer of MoS_2 epitaxially on a Au(111) surface, adopting a recipe from [1], and employ its decoupling properties for high resolution scanning tunneling spectroscopy of single molecules [2]. Because of the band gap and small electron-phonon coupling strength of MoS_2, it is possible to resolve spectral features down to few meV. Differential conductance spectra of 2,5-bis(3-dodecylthiophen-2-yl)thieno[3,2-b]thiophene (BTTT) molecules exhibit a multitude of sharp characteristic peaks, originating from vibronic states. Indeed, these allow even for an identification of different rotamers [2].

Here, we make use of these vibronic fingerprints to investigate the influence of the tip potential on the apparently shifted molecular states along the extended molecular backbone of BTTT. Our analysis further allows us to distinguish between the inhomogeneous shape of the bias potential in the junction and possible intrinsic tip dipoles [3].

[1] Sørensen, *et al.*, Langmuir, 31, 35, 9700 (2015)
[2] Krane, *et al.*, ACS Nano, 12, 11, 11698 (2018)
[3] Krane, *et al.*, Phys. Rev. B, 100, 035410 (2019)

O 72.8 Wed 16:45 TRE Ma

Fast quasiparticle interference mapping through traveling salesperson and sparse sampling optimization — •Jens Oppliger and Fabian D. Natterer — Department of Physics, University of Zurich, Switzerland

STM investigations are slow and render complex measurement tasks, such as QPI mapping, impractical. Conventionally, QPI patterns are composed from a Fourier-transform of hundreds of thousands of point-spectra that encode LDOS modulations from which the scattering space is inferred. Yet, despite this measurement complexity, we rely heavily on QPI since it provides insight into materials that are experimentally inaccessible to ARPES. Surprisingly, QPI patterns contain only little information, despite their origin from many data-points. Since sparsity is one key-ingredient for compressive sensing, we use it here to fundamentally speed-up QPI mapping [1]. In view of the incoherent measurements required for CS, we sparsely sample LDOS at randomly selected locations using constant and varying probability density. To that end, we move the STM-tip according to a traveling salesperson and ultimately achieve a 5-50 times faster QPI mapping.
[1] J. Oppliger and F.D. Natterer, arXiv 1908.01903

O 72.9 Wed 17:00 TRE Ma

Development of a Variable-Temperature High-Speed Scanning Tunneling Microscope — •Zechao Yang, Leonard Gura, Jens Hartmann, Heinz Junkes, William Kirstädter, Patrik Marschalik, Markus Heyde, and Hans-Joachim Freund — Fritz-Haber-Institut der Max-Planck-Gesellschaft, Berlin, Germany

Scanning probe microscopy allows for resolving the atomic structure of crystalline and vitreous thin oxide films on metal substrates. For understanding the structural transition of these films as a function of temperature in real space and at real time, we developed a variable-temperature high-speed scanning tunneling microscope (STM).

The experimental setup consists of a two-chamber ultra-high vaccum (UHV) system including a preparation and a main chamber. The preparation chamber is equipped with standard preparation tools for sample cleaning and film growth. The main chamber hosts the STM that is located within a continuous flow cryostat for counter-cooling during high-temperature measurements. The microscope body is compact, rigid, and highly symmetric to ensure vibrational stability and low thermal drift. We designed a scanner made of two independent tube piezos for slow and fast scanning, respectively. Here we have decided to implement non-conventional spiral geometries for high-speed scanning. A Versa Module Eurocard bus system enables the fast scan control and is implemented in the EPICS software framework.

With sprial scans, we atomically resolved diffusion processes within an O(2x2) coverage on Ru(0001) and achieved a time resolution of 25 milliseconds per frame.

O 72.10 Wed 17:15 TRE Ma

Integrated Electrodes in H:Si(001) for Scanning Gate Microscopy — •Matthias Koch, Alex Kölker, Leonid Shupletsov, Takashi Kumagai, and Martin Wolf — Fritz-Haber-Institut der Max-Planck-Gesellschaft, Berlin, Germany

Single atoms or molecules can not only be characterized but also manipulated by exploiting the incredible high spatial resolution of the scanning tunneling microscopy. However, often the electrical characterization is limited by the experimental setup which consists of only two electrodes (tip and sample). Although multi-tip setups or scanning gate microscopes exist their operation is often demanding [1].

Here, we demostrate a sample system, compatible to most commercial low-temperature SPMs, equipped with multiple integrated electrodes. These in-plane electrodes, which are in close proximity to the surface, act as drain or gate contacts. We realize the *m-large electrodes by ultra-shallow ion-implantation in an otherwise highly resistive silicon crystal [2]. Notably, even after high-temperature treatment to prepare atomically flat silicon, the electrodes behave ohmic. The optimal distance between two electrodes is determined by in-situ transport measurements. Furthermore, the applicability of our sample system is demonstrated by first gating experiments. In future it will be used to study lateral nano-circuits in-operando with the SPM tip as a mobile electrode.

[1] B. Voigtländer et. Al, Rev. Sci. Instrum. 89, 101101 (2018)
[2] A.N. Ramanayaka et. al Scientific Reports 8, 1 (2018)