

## O 105: Scanning Probe Techniques II: Method Development (joint session O/CPP)

Time: Thursday 10:30–12:45

Location: WIL C107

O 105.1 Thu 10:30 WIL C107

**Identifying the atomic configuration of the tip apex using STM and FM-AFM with CO on Pt(111)** — ●OLIVER GRETZ, ALFRED J. WEYMOUTH, and FRANZ. J. GIESSIBL — Institute of Experimental and Applied Physics, Department of Physics, University of Regensburg, 93053 Regensburg

We investigated individual CO molecules adsorbed on Pt(111) with a metal tip using scanning tunneling microscopy (STM) and frequency-modulation atomic force microscopy (FM-AFM). When tips terminate in multiple atoms, the individual atoms are visible not only in the FM-AFM image but also in the raw STM image. This is in contrast to CO on Cu(111), where individual atoms cannot be identified in the raw STM image [J. Welker and F. J. Giessibl, *Science* 336, 444 (2012)]. We consider the mechanisms behind the higher spatial resolution on Pt, and rule out the increase stiffness of the adsorbed CO, concluding that CO bending does not strongly affect the STM image on either Cu or Pt.

O 105.2 Thu 10:45 WIL C107

**Atomic Force Microscopy study of the complex surface unit cell of CaF<sub>2</sub>(111) with a CO-terminated tip** — ●ALEXANDER LIEBIG<sup>1</sup>, PROKOP HAPALA<sup>2</sup>, ALFRED J. WEYMOUTH<sup>1</sup>, and FRANZ J. GIESSIBL<sup>1</sup> — <sup>1</sup>Institute of Experimental and Applied Physics, University of Regensburg, Universitätsstraße 31, D-93053 Regensburg, Germany — <sup>2</sup>Department of Applied Physics, Aalto University, 00076 Aalto, Espoo, Finland

A chemically inert tip apex of an atomic force microscope (AFM), such as a carbon-monoxide (CO) molecule, allows to enter the repulsive interaction regime without destroying tip or sample. Imaging in a gentle repulsive regime has led to unprecedented spatial resolution of organic molecules [1] and opened the way for numerous results on different sample systems [2,3]. Here, we probe the ionic CaF<sub>2</sub> (111) surface with a CO-terminated tip over a range of distances, starting from a regime, where short-range electrostatics dominate the AFM contrast, down to distances, where Pauli repulsion and CO bending lead to a complete reversal of the atomic-scale contrast. By comparing the data to simulations, we demonstrate that a mechanical model using the overlap of electron densities [4] as well as the Lennard-Jones potential [5] is reproducing experimental AFM images even at tip-sample distances, where strong lateral forces cause strong lateral deflection of the CO molecule at the tip apex. [1] L. Gross et al., *Science* 325, 1110 (2009). [2] P. Jelínek, *J. Phys.: Condens. Matter* 29, 343002 (2017). [3] F. Huber et al., *Science* 366, 235 (2019). [4] M. Ellner et al., *ACS Nano* 13, 786 (2019). [5] P. Hapala et al., *PRB* 90, 085421 (2014).

O 105.3 Thu 11:00 WIL C107

**Tip induced configuration change of a CO molecule on a copper surface** — ●NORIO OKABAYASHI<sup>1</sup>, THOMAS FREDERIKSEN<sup>2,3</sup>, and FRANZ J. GIESSIBL<sup>4</sup> — <sup>1</sup>Kanazawa University — <sup>2</sup>Donostia International Physics Center — <sup>3</sup>Basque Foundation for Science — <sup>4</sup>University of Regensburg

Live coverage of a reaction process between the two atomic scale objects is one of the central goals in nanoscience. This can be achieved by combining atomic force microscopy to measure the potential energy between the tip apex and a molecule on a surface and inelastic electron tunneling spectroscopy (IETS) to measure the vibrational state of the molecule in the force field [1,2]. Here we demonstrate that the configuration change of a CO molecule in the force field produced by the tip can be traced with unprecedented quality by combining these two techniques and density functional theory (DFT). We found that when the tip is located laterally just above the CO molecule with upright configuration on a copper surface and approaches to the molecule, the CO molecule keeps the upright configuration from the attractive force regime to the beginning of the repulsive force regime; with further approaching the tip, the CO molecule suddenly changes its configuration from upright to tilted with the angle of 20 degree from the surface normal. This scenario is confirmed by IETS with adopting isotope <sup>13</sup>C<sub>16</sub>O and <sup>12</sup>C<sub>18</sub>O molecules. [1] N. Okabayashi, A. Peronio, M. Paulsson, T. Arai, and F. J. Giessibl, *PNAS* 115, 4571 (2018). [2] A. Peronio, N. Okabayashi, F. Griesbeck, and F. J. Giessibl, *Rev. Sci. Instrum.* (in press)

O 105.4 Thu 11:15 WIL C107

**Nonequilibrium Bond Forces in Single-Molecule Junctions** — JONATHAN BRAND<sup>1</sup>, SUSANNE LEITHERER<sup>2</sup>, NICK R. PAPIOR<sup>3</sup>, ●NICOLAS NÉEL<sup>1</sup>, YONG LEI<sup>1</sup>, MADS BRANDBYGE<sup>2</sup>, and JÖRG KRÖGER<sup>1</sup> — <sup>1</sup>Institut für Physik, Technische Universität Ilmenau, D-98693 Ilmenau, Germany — <sup>2</sup>Center for Nanostructured Graphene, Department of Physics, Technical University of Denmark, DK-2800 Kongens Lyngby, Denmark — <sup>3</sup>Department of Applied Mathematics and Computer Science, Technical University of Denmark, DK-2800 Kongens Lyngby, Denmark

Passing a current across two touching C<sub>60</sub> molecules imposes a nonequilibrium population of bonding and antibonding molecular orbitals, which changes the equilibrium bond character and strength. A current-induced bond force therefore contributes to the total force at chemical-bond distances. First-principles calculations and scanning probe experiments exploring currents and forces in a wide C<sub>60</sub>-C<sub>60</sub> distance range consistently evidences the presence of current-induced attraction that occurs when the two molecules are on the verge of forming a chemical bond. The unique opportunity to arrange matter at the atomic scale with the atomic force and scanning tunneling microscope tip has enabled closely matching molecular junctions in theory and experiment. The findings consequently represent the first report of current-induced bond forces at the single-molecule level and further elucidate the intimate relation between charge transport and force.

O 105.5 Thu 11:30 WIL C107

**Electrostatic Force Separation in Electrochemical Strain Microscopy** — ●SEBASTIAN BADUR<sup>1</sup>, DIEMO RENZ<sup>2</sup>, THOMAS GÖDDENHENRICH<sup>1</sup>, BERNHARD ROLING<sup>2</sup>, and ANDRÉ SCHIRMEISEN<sup>1</sup> — <sup>1</sup>Institute of Applied Physics, Justus-Liebig University Gießen, Germany — <sup>2</sup>Philipps-University Marburg, Germany

In electrochemical strain microscopy an AC voltage is applied to a conductive SPM tip in contact to a mixed conductor. Detection of a few picometer of Vegard-strain allows characterization of electrochemical processes on the nanoscale. However, electrostatic contributions conceal the small displacements and thus are the major challenge to be overcome. Here, we present a novel compensation method, where the frequency dependence of Vegard-strain is utilized in a low and a high frequency regime in order to separate the electrostatic contribution and quantify electrochemical strain on mixed conducting Cu<sub>2</sub>Mo<sub>6</sub>S<sub>8</sub> under ultra high vacuum conditions.

O 105.6 Thu 11:45 WIL C107

**Sensing with an ultra-sensitive cantilever** — ●MARC-DOMINIK KRASS, URS GROB, RAPHAEL PACHLATKO, ALEXANDER EICHLER, and CHRISTIAN DEGEN — ETH Zürich, Solid State Physics, Switzerland

Magnetic resonance force microscopy (*MRFM*) is a scanning probe technique capable of detecting nuclear magnetic resonance (*NMR*) signals from nanoscale sample volumes. The sample is attached to the cantilever tip and is brought in close proximity to a sub-micrometer sized magnet which provides a magnetic field gradient. Periodic spin inversions synchronized with the cantilever frequency generate an oscillatory force at the tip apex.

The forces generated by nuclear spins in a nanometer-sized volume are on the order of 10 aN and detection requires very compliant cantilevers (spring constant below 10<sup>-4</sup> N/m). Though mounted in pendulum geometry, strong interactions between the magnet and the cantilever lead to snap-in distances of tens of nanometers, resonance frequency shifts over one order of magnitude, and significant changes of the effective spring constant even for small scan ranges.

We present our latest setup improvements in order to obtain an artifact-free 3D magnetic resonance image on nanometer scale. This includes the correction of static cantilever deflections as well as the determination of the instantaneous dynamic spring constant, and real-time adjustments of feedback damping parameters.

O 105.7 Thu 12:00 WIL C107

**Coupling broadband single-cycle THz pulses from a spintronic emitter to an STM junction** — ●MELANIE MÜLLER<sup>1</sup>, NATALIA MARTÍN SABANÉS<sup>1,2</sup>, SAROJINI MAHAJAN<sup>1</sup>, and MARTIN WOLF<sup>1</sup> — <sup>1</sup>Fritz Haber Institute, Berlin, Germany — <sup>2</sup>Freie Universität Berlin, Berlin, Germany

THz-gated Scanning Tunneling Microscopy (THz-STM) combines sub-molecular spatial with femtosecond temporal resolution, as first impressively demonstrated in 2016 [1]. Combined with plasmonic enhanced optical excitation THz-STM provides a powerful platform to study the atomically-resolved dynamics of photoexcited surfaces. We have developed an ultrahigh-vacuum STM for broadband excitation from the VIS through the THz spectral range. In particular, we employ an ultra-broadband (1-30 THz) spintronic THz emitter (STE) as source of single-cycle THz pulses to modulate the junction bias. To characterize the bandwidth, phase and voltage amplitude of the THz near-field, we sample the tip-enhanced THz waveform via THz-induced modulation of photocurrents [2]. Careful comparison to the far-field waveform allows us to investigate the antenna properties of the STM tip. Considering strong tip-induced low pass filtering, frequencies up to 10 THz can be detected in the near-field. We further demonstrate versatile phase and polarity control of the THz waveform via the STE excitation conditions, and show that THz transients with a half-cycle period of 115 fs and several Volts amplitude can be achieved in the current setup. References: [1] Cocker T., et al, Nature 539, 263-267 (2016); [2] Yoshida S., et al, ACS Phot. 6, 1356-1364 (2019)

O 105.8 Thu 12:15 WIL C107

**Single Asperity Sliding Friction across the Superconducting Phase Transition** — WEN WANG, ●DIRK DIETZEL, and ANDRE SCHIRMEISEN — Institute of Applied Physics, Justus Liebig University Giessen, 35392 Giessen, Germany

In sliding friction, different energy dissipation channels have been proposed, including phonon and electron systems, plastic deformation, and crack formation. However, the details of how energy is coupled into these channels is heavily debated, and especially the relevance of the electron system for energy dissipation often remains elusive. Here, we present contact mode AFM friction experiments of a single asperity sliding on a high  $T_c$  BSCCO-superconductor in a wide temperature

range from 40 K to 300 K. Overall, friction decreases with temperature as expected based on thermally activated friction models, but we find an unexpected large peak around  $T_c$  of 95 K. We model these results by a superposition of different energy dissipation channels, where the influence of electronic contributions vanishes when cooling below the superconducting phase transition  $T_c$ . Our experiments thereby unambiguously link electronic friction effects to the number of normal state electrons in the superconducting phase below  $T_c$ , allowing us to quantify the relative importance of the electron system to overall friction.

O 105.9 Thu 12:30 WIL C107

**Non-contact heat transfer between metallic surfaces** — ●PAUL PHILIP SCHMIDT and CARSTEN HENKEL — Universität Potsdam, Institut für Physik und Astronomie

The heat transfer at distances beyond contact can be described by fluctuating electrodynamics developed by Rytov [1]. Recent experiments provide deviations from the theoretical predictions. In the measurements, a flat gold surface was approached by a gold-coated probe tip, the distance between the two being less than 10nm [2,3]. In this work we model the measured data in a phenomenological way. The basic assumption is that at a critical distance, the heat flow between flat surface elements saturates, proportional to the number of transport channels. When combined with the proximity force (Deryagin) approximation, this “snap-in model” is in good agreement with the experimental data [4].

[1] D.V.H.M. Polder and M. Van Hove, PRB **4** (1971) 3303.

[2] K. Kloppstech, N. Köhne, S.-A. Biehs, A. W. Rodriguez, L. Worbes, D. Hellmann, and A. Kittel, Nature Commun. **8** (2017) 14457.

[3] L. Cui, W. Jeong, V. Fernández-Hurtado, J. Feist, F. J. García-Vidal, J. C. Cuevas, E. Meyhofer, and P. Reddy, Nature Commun. **8** (2017) 14479.

[4] C. Henkel and P. P. Schmidt, JOSA B **36** (2019) C10.