Advances in high-precision and low-temperature scanning probe microscopy

Nijmegen, 28-30 July 2018

Abstract Book

Satellite meeting of the ICN+T 2018
Follow-up of the SPSTM-6 conference (Chiba, 2016)
SPSTM-7 & LTSPM-1 International Conference 2018
Advances in high-precision and low-temperature Scanning Probe Microscopy

28-30 July 2018

Satellite meeting of the ICN+T 2018
Follow-up of the SPSTM-6 conference (Chiba, 2016)

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- SPSTM1 (Hamburg, Germany, 2006)
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- SPSTM4 (Timmendorfer Strand, Germany, 2012)
- SPSTM5 (Ohio, USA, 2014)
- SPSTM6 (Japan, 2016)
The SPSTM-7 & LTSPM-1 conference will take place 28-30 July 2018 in De Lindenberg in Nijmegen.

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Program

Saturday, 28 July

8:30-9:25  Welcome and registration
9:25-9:30  Opening in Lindenbergzaal

9:30-10:10 Vidya Madhavan (University of Illinois, USA)  
STM studies on Iridates and Ruthenates

10:10-10:50 Tetsuo Hanaguri (RIKEN Center for Emergent Matter Science, Japan)  
Spectroscopic-Imaging STM Studies of Nematicity and Superconductivity in FeSe_{1-x}S_x

10:50-11:20 coffee break

11:20-12:00 Wulf Wulfhekel (Physikalisches Institut, KIT, Karlsruhe, Germany)  
Conventional or unconventional - what drives superconductivity in FeSe monolayers?

12:00-12:40 Yuanbo Zhang (Fudan University, China)  
Visualizing the electronic structure of thin layers of Bi2Sr2CaCu2O8+delta

12:40-15:00 Lunch and exhibition

15:00-15:40 Stefan Heinze (Christian-Albrechts-Universität, Kiel, Germany)  
Interplay of Dzyaloshinskii-Moriya and higher-order exchange interactions at Fe/Rh and Fe/Ir interfaces

15:40-16:20 Stefan Blügel (Forschungszentrum Juelich and JARA Germany)  
Potential of ultrathin films on (110)-oriented substrates as Skyrmion-Antiskyrmion racetrack memory

16:20-16:40 coffee break

16:40-17:20 Nadine Hauptmann (Radboud University Nijmegen, The Netherlands)  
Sensing atomic-scale noncollinear magnetism combining magnetic exchange and spin-polarized imaging

17:20-18:00 Christian Ast (Max Planck Institute for Solid State Research, Stuttgart, Germany)  
Single Channel Josephson Effect in a High Transmission Atomic Junction

18:00-22:00 Postersession / exhibition / dinner
Sunday, 29 July

9:00-9:40 Yoshiaki Sugimoto (University of Tokyo, Kashiwa, Japan)
*High resolution imaging of water molecules by non-contact atomic force microscopy*

9:40-10:20 Shigeki Kawai (National Institute for Materials Science, Tsukuba, Japan)
*High-resolution force measurements with a functionalized tip of atomic force microscope*

10:20-11:00 Harry Moenig (Westfälische Wilhelms-Universität Münster)
*High-resolution NC-AFM imaging with oxidized copper tips: Accessing quantitative bond lengths and intermolecular coupling*

11:00-11:30 *coffee break*

11:30-12:10 Franz J. Giessibl (University of Regensburg, Germany)
*High precision atomic force microscopy*

12:10-12:50 Marlou Slot (Utrecht University, Utrecht, Netherlands)
*Crafted atom by atom: realization and characterization of artificial lattices*

12:50-13:50 *Lunch*

13:50-14:30 Katharina Franke (Freie Universität Berlin, Germany)
*Yu-Shiba-Rusinov states in single atoms, dimers and chains on superconductors*

14:30-15:10 Ali Yazdani (Princeton University, New Jersey, USA)
*Spotting the elusive Majorana in atomic chains under the microscope*

15:10-15:50 Roland Wiesendanger (University of Hamburg, Germany)
*Bottom-Up Construction and Atomic-Level Characterization of Spin Chains on Superconducting Substrates for Topological Quantum Computation*

15:50-16:30 *coffee break*

16:30-18:30 *Lab tours*

18:30-22:00 *Excursion and conference dinner*
Monday, 30 July

9:00-9:40  Markus Morgenstern (RWTH Aachen University, Germany)  
Giant tuning of graphene's pseudospin polarization and valley splitting by a scanning tunneling microscope

9:40-10:20  Joseph Stroscio (National Institute of Standards and Technology, Gaithersburg, USA)  
Visualizing the Interplay between Spatial and Magnetic Confinement in Graphene Quantum Dots via Tunneling Spectroscopy

10:20-11:00  Matthias Bode (Universität Würzburg, Germany)  
STM investigations of topological materials

11:00-11:30  coffee break

11:30-12:10  Tim Wehling (University of Bremen, Germany)  
How to manipulate the electronic structure of correlated two-dimensional materials on the atomic scale?

12:10-12:50  Sebastian Loth (University of Stuttgart)  
Ultrafast electron dynamics in NbSe2 imaged with atomic resolution at femtosecond speeds

12:10-14:50  Lunch

14:10-14:50  Yujeong Bae (Center for Quantum Nanoscience, IBS, Seoul, S. Korea)  
Manipulating quantum states in engineered nanostructures using ESR-STM

14:50-15:30  Harald Brune (Ecole Polytechnique Fédérale de Lausanne, EPFL, Lausanne, Switzerland)  
The Smallest Permanent Magnets and Possibly Qubits

15:30-16:10  Jens Wiebe (Hamburg University, Germany)  
Emulation of Spin Systems via Artificial Arrays of Magnetic Atoms

16:10-17:00  Award ceremony / borrel / end of conference
Oral contributions
Correlated electron systems often exhibit emergent behavior and manifest unexpected properties that cannot be understood in within a single electron picture. Over the last few decades, Scanning Tunneling Microscopy (STM) and spectroscopy (STS) have emerged as powerful tools to study correlated electron systems. In this talk I will discuss our results on two interesting oxides, iridates and ruthenates. In the first part of the talk I will discuss the single-layered ruthenate Sr2RuO4 which has attracted a great deal of interest as a spin-triplet superconductor with an order parameter that may potentially break time reversal invariance and host half-quantized vortices with Majorana zero modes. While the actual nature of the superconducting state is still a matter of controversy, it has long been believed that it is condensed from a metallic state that is well described by a conventional Fermi liquid. In this talk I will show the first high resolution Fourier transform scanning tunneling spectroscopy (FT-STS) measurements on Sr2RuO4 obtained in the normal state. We use a combination of FT-STS and momentum resolved electron energy loss spectroscopy (M-EELS) to probe interaction effects in the normal state of Sr2RuO. Our high-resolution data show signatures of the β-band with a distinctly quasi-one-dimensional (1D) character. The band dispersion reveals surprisingly strong interaction effects that dramatically renormalize the Fermi velocity, suggesting that the normal state of Sr2RuO is that of a ‘correlated metal’ where correlations are strengthened by the quasi 1D nature of the bands. Another exciting new frontier in correlated systems is materials where both spin-orbit coupling and electron correlations are relevant. These materials manifest unexpected physical properties are predicted to host a range of novel topological phases. In the second part of the talk I will show STM data on the iridate Sr3Ir2O7 which show a range of interesting phenomena from Mott physics to density waves and pseudogaps and discuss what we have learnt about the physics of doped Mott systems based on our data.
Spectroscopic-Imaging STM Studies of Nematicity and Superconductivity in FeSe$_{1-x}$S$_x$

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Spontaneous breaking of lattice rotational symmetry in the electronic state, which is known as electronic nematicity, has been observed in various materials including unconventional superconductors such as iron-based materials. It has been argued that the relationship between superconductivity and nematicity is one of the keys to elucidate the mechanisms of high-temperature superconductivity [1]. A solid-solution FeSe$_{1-x}$S$_x$ is an important material to study this issue. The parent material FeSe undergoes tetragonal-to-orthorhombic transition at 90 K, which is a manifestation of the electronic nematic order. Superconductivity sets in at lower temperature of 9 K. The electronic nematic order is suppressed with increasing sulfur content $x$ and disappears above the nematic end point at $x \sim 0.17$ [2].

In order to study the relationship between superconductivity and nematicity, we performed low-temperature (1.5 K) spectroscopic-imaging STM on FeSe$_{1-x}$S$_x$ [3]. We have investigated the evolution of the band structure as a function of $x$ by analyzing the Fourier-transformed quasiparticle interference patterns (Fig., top row). We have found that anisotropy of the in-plane band structure diminishes with increasing $x$ but there is little change in the band parameters at the nematic end point. Superconducting gap is hardly affected by sulfur doping in the nematic phase but suddenly becomes smaller above the nematic end point (Fig., bottom row). This result indicates that there are two distinct superconducting pairing states depending on the presence or absence of nematicity.

This work has been done in collaboration with Prof. Shibauchi’s group at University of Tokyo and Prof. Matsuda’s group at Kyoto University.

Conventional or unconventional - what drives superconductivity in FeSe monolayers?

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Unconventional superconductivity is currently one of the most fascinating phenomena in solid state physics. The pairing mechanism in iron-based superconductors is believed to be unconventional, i.e. not phonon-mediated. The achieved transition temperatures Tc in these superconductors are still significantly below those of some of the cuprates, with the exception of single layer FeSe films on SrTiO3 showing a Tc of up to 100 K, i.e. an order of magnitude larger than in bulk FeSe. This enormous increase of Tc demonstrates the potential of interface engineering for superconductivity, yet the underlying mechanism of Cooper pairing is not understood. Both conventional and unconventional mechanisms have been discussed. Here we report a direct measurement of the electron-boson coupling in FeSe on SrTiO3 using inelastic electron scattering. We exclude strong electron-phonon coupling except for places near domain boundaries. Instead, the bosonic excitation spectrum is shown to be fully gapped below Tc in agreement with an electronic pairing mechanism.
Visualizing the electronic structure of thin layers of Bi2Sr2CaCu2O8+delta

Yuanbo Zhang
(Fudan University, China)

The role of dimensionality in high Tc superconductivity is an interesting issue: Many of the high Tc superconductor have layered atomic structures, and yet the link between the high Tc superconductivity and the two-dimensional nature of the crystal structure remains elusive. We fabricated atomically thin Bi2Sr2CaCu2O8+delta (Bi-2212) samples, and used scanning tunneling microscopy (STM) and scanning tunneling spectroscopy (STS) to investigate their electronic structure. In this talk, I will discuss our recent results on the superconducting gap, pseudogap and charge order in Bi-2212 in the 2D limit.
Interplay of Dzyaloshinskii-Moriya and higher-order exchange interactions at Fe/Rh and Fe/Ir interfaces

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The magnetic phase space of nanostructures at surfaces is complex due to the interplay of competing magnetic interactions. It has been demonstrated based on density functional theory (DFT) and spin-polarized scanning tunneling microscopy (SP-STM) that the competition of exchange and Dzyaloshinskii-Moriya interaction (DMI) plays a key role for spin structures of ultrathin films, clusters, or atomic chains at transition-metal surfaces [1-3]. The DMI originates from spin-orbit coupling and can occur in every system with broken inversion symmetry such as surfaces. The DMI can stabilize topologically non-trivial spin structures such as skyrmions [4,5].

Here, I will show that higher-order exchange interactions, which have received much less attention, can also be important in ultrathin film systems and lead to complex spin structures. In particular, interfaces of Fe/Rh and Fe/Ir display large effects. An example is the nanoskyrmion lattice in an Fe monolayer on Ir(111) [4] that is stabilized by the four-spin interaction. An Fe monolayer on the Ir(001) surface is an antiferromagnetic counterpart as our DFT calculations show. The interplay of anti-ferromagnetic nearest-neighbor exchange, DMI and four-spin interaction leads to an atomic-scale spin lattice with intriguing transport properties [6]. A similar scenario can be realized for an atomic Fe/Ir bilayer on the Rh(001) surface [7]. Surprisingly, the magnetic ground state of a Rh/Fe bilayer on Ir(111) depends on the Rh stacking as shown by DFT and SP-STM [8]. For fcc-Rh/Fe/Ir(111) we find a spin spiral ground state due to frustrated exchange interactions. For hcp-Rh/Fe/Ir(111) higher-order exchange interactions prevail and prefer a so-called up-up-down-down (↑↑↓↓) state [9]. Due to the competition with DMI a canted ↑↑↓↓ state becomes the ground state of hcp-Rh/Fe/Ir(111). These spin structures can be directly observed using SP-STM [8].

Potential of ultrathin films on (110)-oriented substrates as Skyrmion-Antiskyrmion racetrack memory

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In the past years the presence and importance of the Dzyaloshinskii-Moriya interaction (DMI) for the magnetic properties in ultra-thin magnetic films on substrates with large spin-orbit interaction was established. One of the most important consequences of the DMI is the formation of magnetic skyrmions, localized particle-like magnetic vortex-like spin textures. For the discovery of the DMI and the properties of skyrmions at the nanoscale the SPSTM played an essential role. So far almost all systems investigated have an (111) oriented interface with \( C_3 \) symmetry or higher exhibiting an isotropic DMI.

In this talk we will focus on (110) oriented ultrathin films, i.e. films with \( C_2 \) symmetry or lower exhibiting an anisotropic DMI. It is obvious this anisotropy provides a new degree of freedom to shape skyrmions. Extending micromagnetics from a scalar to tensor Dzyaloshinskii-Moriya (DM) interaction, we show that chiral magnets cannot only host skyrmions, but also antiskyrmions as least-energy configurations over all non-trivial homotopy classes. Antiskyrmions, are magnetic textures with a topological charge opposite to the one of skyrmions, which according to conventional wisdom are considered unstable in chiral film magnetism. We derive practical criteria for their occurrence and coexistence with skyrmions that can be fulfilled by (110) oriented interfaces in dependence of the electronic structure. An experimentally well-investigated system of this class is the double layer of Fe grown on a W(110) substrate. Combining density-functional theory calculations with spin-relaxation simulations employing a realistic atomistic spin model, we show that this system indeed hosts stable antiskyrmions rather than skyrmions \cite{Hoffmann2017}. Finally, we discuss the potential of (110) oriented films for the design of a race track memory based on the coexistence of skyrmions and antiskyrmions of the same energy as an alternative to the recently suggested skyrmions race-track memory.

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Sensing atomic-scale noncollinear magnetism combining magnetic exchange and spin-polarized imaging

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The ultimate goal of magnetic-based storage is to create ultra-high density memory based on energy-efficient manipulation of the remnant magnetization state of nanomagnets such as skyrmions. Spin-polarized scanning tunneling microscopy (SP-STM) is the most routinely used method to characterize nanomagnets on surfaces, but it poses limitations that can unintentionally reverse the magnetization, and convolute the magnetic, electronic, and structural properties.

We have developed a new combination of high-resolution magnetic detection utilizing SP-STM together with sensing magnetic exchange interactions (SPEX). We use SPEX to resolve the square skyrmion structure in a single iron layer on Ir(111) and demonstrate detection of different exchange regimes. We further show that the iron bilayer on Ir(111) is non-planar and use SPEX together with density functional theory calculations to decompose the real-space from the electronic/magnetic structure at the atomic level and the correlation with the spin-spiral ground state.

Mapping of the skyrmion lattice (8 x 6 nm²)
Single Channel Josephson Effect in a High Transmission Atomic Junction

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Andreev bound states lie at the heart of many phenomena involving scattering with superconductors, such as Yu-Shiba-Rusinov states, Majorana bound states, or the Josephson effect. In most cases it is sufficient to approximate the Josephson effect by an ensemble of many, nearly opaque transport channels. However, in scanning tunneling microscopy (STM), where only very few transport channels are realized and arbitrary transmissions can be achieved, this approximation may break down and the full energy-phase relation of the Andreev bound states has to be considered. Using the manipulation techniques available to STM, we exploit a single atom contact at high transmission to demonstrate the consequences of single channel transport for the Josephson effect. We demonstrate single channel transport through the analysis of multiple Andreev reflections at various transmission setpoints and discuss the transition from the tunneling approximation to the full Andreev bound state description in the dynamical Coulomb blockade regime.
High resolution imaging of water molecules by non-contact atomic force microscopy

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Non-contact atomic force microscopy (AFM) is a powerful tool for imaging organic molecules with high resolution. Although submolecular resolution can be obtained even at room temperature [1], conventional way is AFM observation under cryogenic temperature using CO terminated tips [2,3].

We use the same protocol for investigation of small molecules such as H₂O and NO on metallic surfaces [4-5]. One example is water chains grown on Cu(110) surface. Structure model was proposed as shown in Fig. (a) which was determined by scanning tunneling microscopy (STM), vibrational spectroscopy and theoretical calculations [6]. The water chain consists of fused pentagonal rings. In the pentagonal unit, one H₂O is bonded onto the hollow site in a vertical orientation relative to the surface. The other 4 H₂O lie on the atop site with almost flat configurations. In the STM image (Fig. (b)), the protrusions aligned along the chain direction in a zigzag manner are ascribed to vertical H₂O. Although the pentagonal bonding structure is hardly discriminated by STM, it can be clearly resolved by AFM as shown in Fig. (c). The water chain is observed as fused pentagonal rings in complete agreement with the model proposed previously. Force field data suggest that AFM image reflects the atomic position of O atoms, i.e. ‘Oxygen skeleton’.

Figure (a) Structure model of water network on Cu(110) surface. (b) STM image. (c) AFM image using a CO terminated tip.

High-resolution force measurements with a functionalized tip of atomic force microscope

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Recent progress in atomic force microscopy allows us to observe inner structures of molecules adsorbed on surfaces [1]. In such measurements, a reactive metal tip is usually terminated by a small molecule or an inert rare gas atom. Such high-resolution imaging is beneficial to study single and self-assembled molecules as well as chemical reactions. Besides high-resolution imaging, force measurements became more quantitative since the structure of the tip apex, at least the front-most-atom, can be controlled in experiment.

In this presentation, force spectroscopic measurements with different tips (i.e. Xe-tip for van der Waals force detection [2] and CO-tip for the intermolecular bond detection [3]) will be discussed (Fig. 1). Furthermore, we found that the CO tip is sensitive enough to resolve the differences of the interaction force between the CO tip and B/C/N atom embedded at the center of the graphene nanoribbon [4]. In such the measurement, the difference of the van der Waals radii is responsible for the elemental contribution in the force, yet the donation/acceptance of the electrons caused by the boron and nitrogen doping significantly appears in the apparent bond length.

Figure. Discrimination of multiple heteroatom doped into graphene nanoribbon with a CO tip of atomic force microscopy.

High-resolution NC-AFM imaging with oxidized copper tips: Accessing quantitative bond lengths and intermolecular coupling

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Imaging the bonding structure of organic molecules by noncontact atomic force microscopy (NC-AFM) has been a major breakthrough for a fundamental understanding of chemical processes in specific local environments. The methodology involves the atomic scale control of the tip termination by attaching single atoms or molecules (e.g. CO or Xe) to the metallic apex [1-5]. However, these probe particles are only weakly connected at the tip, which results in a considerable dynamic deflection in the experiments. As a consequence, such NC-AFM data show pronounced image distortions, a systematic overestimation of bond lengths, and artificial bond-like contrast features [4-8].

By combining NC-AFM- and scanning tunneling microscopy experiments with density functional theory, we developed an alternative approach of tip functionalization. By slightly indenting the probe tip into oxidized copper substrates and subsequent contrast analysis, allows for the verification of an O-terminated Cu tip. This copper oxide tip (CuOx tip) is chemically passivated and shows a high structural stability due to the tetrahedral configuration of the covalently bound terminal O atom [9,10].

It is shown that the rigidity of the CuOx tip allows to quantitatively determine bond lengths and to access bond order effects in molecular systems. Furthermore, it is demonstrated that artificial bond-like contrast features, as observed for flexible probe particles, can be neglected for the CuOx tip. This allows to study weak intermolecular interactions within self-assembled organic structures [11].

Combining this methodology with photoelectron spectroscopy, establishes this approach as a powerful tool for investigations of intermolecular coupling reactions on surfaces.

References
High precision atomic force microscopy

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The scanning tunneling microscope (STM), invented 1981 in Rüschlikon by Gerd Binnig and Heinrich Rohrer, has opened a new era of small things. STM relies on vacuum tunneling with an exponential increase of a tunneling current between two biased conductive electrodes at a factor of ten per Å (100 pm). If a tip has one atom that sticks out one Å more than all the others, this front atom carries ten times more current than the other atoms. The monotonic decrease of current with distance facilitates distance feedback and allows to scan the tip across a sample with atomic precision. In 1986, Binnig, Gerber and Quate introduced atomic force microscopy (AFM), a method that also images insulators by relying on forces. Unlike the current, the force between tip and sample is non-monotonic and includes long- and short range components. AFM has been inferior in resolution to STM for a long time. Today, AFM exceeds STM in spatial resolution by utilizing Pauli repulsion forces that change even stronger with distance than the tunneling current. That progress was enabled by advances in measuring small forces and by the isolation of chemical bonding forces from strong background forces. The special challenges of AFM lead to the invention of the qPlus sensor, a quartz force sensor that measures force gradients by frequency changes and was initially based on tuning forks used in Swatch wristwatches. Using the outstanding precision of frequency measurements, we can today measure the forces that act in atomic manipulation, measure exchange interactions with sub-pN sensitivity, image clusters and molecules with atomic resolution and single adatoms with subatomic resolution. Highest precision measurements require vacuum and low temperatures, and measuring the deflection of a force sensor usually introduces heat. Nevertheless, we could recently show that the tip of a qPlus sensor remains superconducting during its operation.

AFM image of a Fe trimer next to a Fe dimer on Cu(111). Inset: AFM image of a single Fe atom on Cu(111) [M. Emmrich et al., Science 348 308 (2015)].
Crafted atom by atom: realization and characterization of artificial lattices

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Geometry, whether on the atomic or nanoscale, is decisive for the electronic structure of a material. The honeycomb lattice of graphene, for instance, gives rise to Dirac cones in which charge carriers behave as effectively massless particles. Theoretical predictions are triggering the exploration of novel geometries that are not present in nature. One possible route to create and characterize electronic lattice geometries is by controlled patterning of the 2-D electron gas at the Cu(111) surface with adsorbed CO molecules, and investigate the lattice by scanning tunneling spectroscopy and wave-function mapping [1]. This concept of engineering electrons into well-defined geometries allows tuning of parameters that cannot easily be varied in real solid-state materials, while the design can readily be transferred to planar semiconductor electronics. In this talk, I will show how we use the geometry to tailor the lattice geometry itself, the dimension and the orbital degree of freedom of electronic artificial lattices [2,3].

Yu-Shiba-Rusinov states in single atoms, dimers and chains on superconductors

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Magnetic adatoms on a superconducting substrate act as a pair-breaking scattering potential for the Cooper pairs and induce Yu-Shiba-Rusinov (YSR) states inside the superconducting energy gap. Here, we show that individual Manganese (Mn) atoms give rise to a distinct number of YSR states, depending on the crystal field imposed by the adsorption site. The spatial extent of these states directly reflects their origin as the singly occupied d-states [1]. When the atoms are brought into sufficiently close distance, we detect the formation of symmetric and anti-symmetric combinations of the corresponding YSR wave functions [2]. In the limit of densely-packed atomic chains, the YSR states form extended bands. These inherit their spin-polarization from the spin-polarized d-bands at higher energies [3].

Spotting the elusive Majorana in atomic chains under the microscope

Ali Yazdani
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Ettore Majorana famously considered that there may be fermions in nature that are their own antiparticle — and then he mysteriously disappeared just after proposing the idea in 1938. In recent years, we have learned how to engineer materials that harbor quasiparticles that behave similar to fermions Majorana had envisioned. In particular, there has been a focus on one-dimensional topological superconductor that harbor Majorana zero modes (MZM) that can potentially be used to make fault-tolerant topological quantum computation possible. Recently, we have proposed and implemented a platform for realization of topological superconductivity and MZM in chains of magnetic atoms on the surface of a superconductor [1,2]. In this talk, I will describe this platform and the series of experiments we have performed to establish the presence of these exotic quasi-particle using spectroscopic mapping with the STM. [2-4] These include a recent study of the unique spin signature of MZM.[4] Finally, if there is time I will describe some ongoing experiment on realization of MZM in a platform based on chiral quantum spin Hall edge states.

Bottom-Up Construction and Atomic-Level Characterization of Spin Chains on Superconducting Substrates for Topological Quantum Computation

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A magnetic nanowire on the surface of a spin-orbit coupled s-wave superconductor is a fascinating platform, which has been proposed for observing the emergence of zero-energy Majorana bound states at the ends of the wires [1]. Majorana bound states can encode topological qubits and ultimately provide a new direction in topological quantum computation [2]. Most recently, evidences for topologically non-trivial end-states were experimentally found for self-assembled ferromagnetic Fe nanowires on superconducting Pb(110) substrates by using scanning tunneling microscopy and spectroscopy (STM/S) as well as non-contact atomic force microscopy methods [3-6]. However, self-assembled nanowires of Fe on Pb surfaces have unavoidable limitations, such as (1) intermixing of atomic species of the nanowire and the substrate during the annealing process, and (2) uncontrolled length, orientation and environment of the nanowires.

Here, we demonstrate the fully-controlled bottom-up fabrication of artificial 1D atomic chains from individual magnetic Fe adatoms on high spin-orbit coupled non-superconducting Pt(111) and superconducting Re(0001) substrates by utilizing STM-based atom-manipulation techniques at T=350 mK. Spin-polarized STM (SP-STM) measurements indicate the presence of non-collinear spin textures, i.e. spin spiral ground states, stabilized by interfacial Dzyaloshinskii-Moriya interactions [7] similar to self-assembled Fe chains on Ir(001) investigated earlier by our group [8]. The problem (1) of intermixing is avoided by the low-temperature fabrication of the chain and an appropriate choice of the substrate, while single-atom manipulation allows the construction of chains with a given number of atoms and orientation, thereby avoiding problem (2). Tunneling spectra measured spatially resolved on the Fe-atom chain on Re(0001) reveal the evolution of the local density of states (LDOS) inside the superconducting gap as well as the development of zero-energy bound states at the ends of the chain, which are distinguishable from trivial end states by systematically increasing the number of atoms within the Fe-atom chain. The experimental results will be compared with model-type calculations supporting the interpretation of the spectroscopic signatures at the ends of the chains as Majorana bound states [9].

Giant tuning of graphene's pseudospin polarization and valley splitting by a scanning tunneling microscope

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Graphene, the first two-dimensional material, provides two extra binary degrees of freedom, - sublattice and valley -, which are adequately described as a pseudospin. The sublattice pseudospin is chiral with respect to the Dirac-type momentum, such that it mimics the relativistic real spin completely. Here, I firstly show that application of large pseudomagnetic fields $B_{ps}$ ($\sim 1000$ T) can be used to polarize the sublattice pseudospin up to 40%. Therefore, the van-der Waals force of an STM tip is exploited, which locally lifts graphene from the SiO$_2$ substrate and, thus, induces huge strain gradients, i.e. $|B_{ps}|$ (Fig. 1, top). The resulting sublattice imbalance can be directly read from STM images and turns out to be in excellent agreement with analytic calculations based on molecular dynamics revealing the induced strain patterns [1].

Secondly, the valley degree of freedom is tuned using a quantum dot induced by the tip potential in combination with an external $B$ field (Fig. 1, bottom) [2]. The laterally changing orientation of graphene’s C atoms with respect to the B and N atoms on an angularly aligned BN substrate changes the valley splitting of the confined states continuously. This eventually leads to a tunable inversion of the valley splitting on nm length scales. Again, we provide excellent agreement with calculations, here, based on density functional theory combined with a tight binding model.

Visualizing the Interplay between Spatial and Magnetic Confinement in Graphene Quantum Dots via Tunneling Spectroscopy

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The quantization of energy due to quantum confinement, taking place when the particle’s de Broglie wavelength becomes comparable to the system’s length scale, is a striking manifestation of quantum coherence. Quantum dots (QD) offer an ideal platform for studying the interplay between quantum confinement, caused by spatial constraints or by large magnetic fields via cyclotron motion, and interaction effects. Historically, the majority of QD systems investigated have been based on semiconductor heterostructures. Recently, the ability to apply local nanometer scale gate potentials in graphene heterostructures has enabled the creation of QDs for Dirac quasiparticles. Graphene QDs are formed inside circular p-n junctions [1,2], where one has detailed control of electron orbits by means of local gate potentials and magnetic fields. We study the interplay between spatial and magnetic confinement using scanning tunneling spectroscopy measurements of the energy spectrum of graphene QDs as a function of energy, spatial position, and magnetic field. In zero field, the Dirac quasiparticles are confined by Klein scattering at large incident angle at the p-n junction boundary. The confined carriers give rise to an intricate eigenstate spectrum, characterized by radial and angular momentum quantum numbers, effectively creating a multi-electron artificial atom [1]. Applying a weak magnetic field results in a sudden and giant increase in energy for certain angular momentum states of the QD, creating a discontinuity in the energy spectrum as a function of magnetic field [2]. This behavior results from a π-Berry phase associated with the topological properties of Dirac fermions in graphene, which can be turned on and off with magnetic field. With increased applied magnetic field, the QD states are observed to condense into Landau levels, providing a direct visualization of the transition from spatial to magnetic confinement in these artificial graphene atoms. We determine the Landau level spatial properties, which show a “wedding cake” structure arising from interaction effects, as predicted by theory, and can now be directly mapped and visualized in a solid-state system for the first time [3]. With further increase in magnetic fields, an intricate interplay between Coulomb charging of compressible Landau levels separated by incompressible rings emerges, which we map as a function of energy, spatial position, and magnetic field utilizing the exceptional capabilities of scanning tunneling spectroscopy.

STM investigations of topological materials

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Topological insulators (TIs) have recently attracted considerable interest because they host linearly dispersing surface states that are strongly spin-orbit–coupled such that spin and electron momentum are tightly locked, thereby resulting in charge currents which are intrinsically tied to the spin. This property makes TIs promising candidates for spintronics applications. In this talk, I will describe how TIs respond to magnetic dopants that are deposited onto the surface [1,2] or into the bulk [3]. In particular, I will discuss various electronic scattering channels, which can be mapped by quasiparticle interference (QPI). In combination with local tunneling spectroscopy it allows for an extremely precise understanding of how topological states respond to magnetic impurities at the atomic scale. The combination of real and reciprocal space techniques elucidates a delicate balance between two opposite trends, that is, gap opening and the emergence of a Dirac node impurity bands, both induced by the magnetic dopants [3]. Finally, I will report on the discovery of a new type of one-dimensional (1D) electronic midgap states which exist at step edges of the topological crystalline insulator (TCI) Pb$_{1-x}$Sn$_x$Se [5]. The resulting conductive channels are only 10 nanometers wide and exhibit a surprising robustness against external perturbations.


(Top) Schematic representation of the atomic arrangement at double (left) and single (right) step edges on topological crystalline insulators with rock salt structure. Differently colored rectangles indicate the preservation and breaking of translational symmetry, respectively. (Bottom) Conductance map measured with a scanning tunneling microscope showing a strongly enhanced signal at the single step edge.
How to manipulate the electronic structure of correlated two-dimensional materials on the atomic scale?

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Coulomb and electron-phonon interactions largely shape the electronic structure of 2d materials. They affect band gaps in 2d semiconductors and lead to rich electronic phase diagrams including different metallic, insulating and superconducting phases. Here, we will analyze the interplay of short- and long-range Coulomb as well as electron-phonon interactions in monolayers of 2d materials and show that the combination of these interactions induces electronic correlations that are fundamentally different from what would be expected from the interaction terms separately [1]. We then study the competition of spin, charge and superconducting order in the family of metallic transition metal dichalcogenides and show that particularly the Nb-based compounds are at the verge between spin and charge order (c.f. Fig.1). Implications for atomic scale quantum engineering involving adatoms, alloying and coupling to substrates is discussed.

Fig 1. Magnetic susceptibilities of H-phase TMDCs. If interactions are taken into account (left panel) there is strong Stoner enhancement and magnetic order in the Nb and V-based compounds.

Ultrafast electron dynamics in NbSe$_2$ imaged with atomic resolution at femtosecond speeds

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Two-dimensional materials host a variety of electronic phases that can arise from increased electron-electron or electron-phonon interaction. Owing to the short-ranged nature of these interactions, such phases display heterogeneity on the nanometer to atomic scale and dynamics on the pico- to femtosecond scale.

I will outline the development of an ultrafast scanning tunneling microscope that uses a high-repetition rate THz source [1] to achieve approximately 100 fs time resolution. We apply this local pump probe spectroscopy technique to NbSe$_2$, a prototypic charge-density wave (CDW) material. We find that the tip-enhanced electric field of the THz pulse strongly excites the CDW under the STM tip and triggers rich dynamics that vary significantly on the length scale of 1 nm. The STM resolves the amplitude mode of the CDW which can also be observed by Raman spectroscopy [2] and an additional low-frequency mode in the vicinity of atomic defects which we attribute to a phase excitation in the pinning potential of the defects.

These first experiments demonstrate the feasibility of exploring the collective dynamics of electronic phases at the intrinsic length and time scales of the electron-electron interaction in one experiment. As this technique is STM-based it is extremely surface-sensitive and is particularly suited for resolving local dynamics in two-dimensional materials.

Manipulating quantum states in engineered nanostructures using ESR-STM

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Electron spin resonance (ESR) of individual atoms was recently achieved in a scanning tunneling microscope (STM) [1]. This new tool provides experimental access to individual spin centers to study their quantum states with nano-electron-volt resolution. In this talk, we demonstrate the use of ESR-STM to precisely control magnetic interactions of surface atoms and explore their quantum properties and local electronic structures.

We built dimers of hydrogenated titanium (Ti) atoms, which have spin of 1/2, on bilayer MgO via atom manipulation in STM. By controlling the atomic separation, interactions between two single-atom spins are tailored over a range from the dipole-dipole to the Heisenberg exchange coupling. Positioning two atoms closely to obtain the strongest coupling we can achieve, we create a two-level system composed of magnetic-field-independent states. Transitions between such states behave as ‘clock transitions’ and thus show enhanced spin coherence compared to other transitions in the dimer as well as in single atoms.

We also investigate the properties of nuclear spins for the isotopes of Ti atoms. We find the hyperfine splitting strongly depends on the binding configuration of Ti atoms on the MgO surface and the magnetic coupling with neighboring atoms.

Our work provides a powerful probe of the chemical environment and magnetic interactions of individual atoms and nanostructures. Additionally, the magnetic structures built using spin 1/2 atoms may serve as the smallest component for assembling custom spin chains and arrays for the exploration of quantum phases, spintronic information processing, and quantum simulation.

References:
The Smallest Permanent Magnets and Possibly Qubits

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Until two years ago, the smallest permanent magnets were single molecular magnets. They are promising candidates for magnetic information storage, molecular spintronics, and quantum bits (qubits) [1, 2]. Surface Science has opened up an alternative approach to this field in studying the magnetic properties of single atoms adsorbed onto surfaces. Spectacular properties such as very large magnetic anisotropies were reported, but until two years ago, all atoms were paramagnetic. Very recently a major breakthrough was achieved by identifying systems where a single surface adsorbed atom can indeed be a stable magnet. Ho atoms on two monolayer thick MgO(100) films grown on Ag(100) where found to exhibit magnetic remanence up to 30 K and relaxation times of at least one hour at 2 K [3]. This result was obtained from ensemble measurements using X-ray magnetic circular dichroism (XMCD). Spin-polarized scanning tunneling microscopy (STM) measurements demonstrated reading and writing of individual Ho atoms and confirmed their long magnetic lifetimes [4]. Very recent STM experiments show stable magnetization over two hours in external fields of 8 T that are applied opposite to the magnetization of the atoms and at temperatures of 30 K; the first spontaneous switching is observed at 45 K [5]. We have identified two more systems that exhibit permanent magnetism in single adatoms, namely Dy atoms graphene on Ir(111) [6] and Tb/MgO/Ag(100) [7]. These single atom magnets are all candidates for magnetic information storage; the combined coercitive field and thermal stability of Ho/MgO(100) outperforms the best single molecular magnets. Recently, electron paramagnetic resonance (ESR) has been realized on individual Fe atoms with the STM [8]. This gives access to the coherence time which is one of the benchmarks of qubits. We will elaborate on the possibility of single atom qubits.

Emulation of Spin Systems via Artificial Arrays of Magnetic Atoms

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A transition metal atom adsorbed to the surface of a solid state material can serve as the spin building block for the STM-tip based assembly of arrays of hundreds of atoms (see the image) that can emulate the properties of a large variety of spin systems. Possible applications which are in the focus of modern solid state physics range from few atom bits, over spin chains and Kondo lattices to topologically superconducting systems if the transition metal atom array is assembled on a superconducting substrate. The usage of magnetic STM-tips furthermore enables to read out the spin state and the excitations of every atom in such an array in order to do a one-by-one comparison with effective spin models and density functional theory calculations.

Here, I will focus on our recent work on arrays of magnetic atoms assembled on high-Z normal metal substrates, where we have been able to use the Dzyaloshinskii–Moriya component of the Ruderman–Kittel–Kasuya–Yosida (RKKY) interaction [1] in order to realize spin-spirals [2] in dilute chains of atoms, stable magnetic bits of only few densely packed atoms [3], and complexes of such bits and RKKY coupled atoms revealing intriguing dynamical properties [4].

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Posters
1. Quantifying the charge density wave properties of VSe$_2$

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We use scanning tunneling microscopy and spectroscopy (STS) to image the charge density wave (CDW) at the surface of VSe$_2$ and to probe its local density of states. Angle-resolved photoemission and tight-binding calculations are used to link the main features observed in STS spectra to contributions of the p-like and d-like bands of VSe$_2$. A transparent method to estimate the partial CDW gap based on STS spectra is introduced. The resulting, partial CDW gap of 26±6 meV is in good agreement with the transition temperature of VSe$_2$, pointing to weak electron-phonon coupling. This leads to the conclusion that the Peierls model of Fermi surface nesting is applicable in this material. The role of defects is investigated, which reveals that the partial gap in the density of states and hence the CDW phase itself is extremely stable, though the periodic modulation and amplitude of the CDW on the surface are strongly perturbed.

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2. Visualizing Magnon Excitation with Spin-Polarized Scanning Tunneling Microscopy

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Inelastic electron scattering plays a crucial role in spintronics devices concerning the spin lifetime of polarized electrons and the amount of spin transfer torque for switching magnetic configurations in magnetic tunnel junctions. One of the fundamental processes is magnon creation, which occurs when injected hot electrons induce spin-flip scattering with an electron in the Fermi sea of the magnetic material [1,2]. To image and address the magnetic origin of the excitations, we have performed low-temperature spin-polarized inelastic electron tunneling spectroscopy (IETS) on double layer (DL) Mn thin films formed on W(110) substrate.

The atomically-thin magnetic layer exhibits homogeneous spin spiral with antiferromagnetic coupling, which provides a good reference for spin-polarized scanning tunneling microscopy (STM) [3,4]. Characteristic peak-dip feature in IETS, as well as its correlation with the spin spiral, are acquired. Additionally, we have observed contrast reversal in the IETS intensity when the tip magnetization direction is flipped, indicating that the excitation is spin-dependent and thus presumably due to magnon creation. The spatial distribution of the magnon excitation and its energy dependence will be discussed in the presentation.

3. Tuning Spin Configuration of Single Magnetic Atom by Phthalocyanine Molecular Ligand Fields

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Direct observation, manipulation, and electron states of single atoms have captured human interest in the last decades after the invention of scanning probe microscopy. Since then, more researchers have focused on the super small “atom” in order to understand fundamental scientific concepts and to develop new generations of 1-nm-size devices.

One of the unique and important properties of the single atom electron states is that the states can be tuned by the local symmetry surrounding the atom, and produce a new electron state in the atom. Because of this, a single atom inside an organic molecule can have different electronic states depending on the ligand fields. In addition, scanning tunneling microscopy (STM) atomic manipulation enabled us to generate, observe and characterize nanoscale structures in a sequential manner. Figure 1 shows demonstration of STM atom manipulation.

In this study, we placed single magnetic atoms (Fe, Co) on a single phthalocyanine organic molecule using the STM tip, and investigated the dependency of the electronic structure of the magnetic atom on the adsorption site [1]. All experiments were performed with our home-built ultra-high vacuum low-temperature STM setups. The π-conjugated metal-free H2Pc phthalocyanine molecules were deposited on a clean and flat substrate [2,3], which was subsequently set into the STM and cooled down to 4.6 K, and then single magnetic atoms were deposited. Through our investigations combined with theoretical calculations, we have demonstrated that the splitting of the 3d orbitals of the magnetic atom is sensitive to the local ligand fields, and that leads to a different occupation of the orbitals and total spin angular momentum depending on the adsorption site.


![Figure 1](image-url)

Figure 1. (a) STM manipulation of single atoms on the atomically flat substrate, demonstrating a dimer fabrication. Typical STM images were obtained at the setpoint of 40 mV, 200 pA, while during the manipulation, the tip was moved closer to the target by increasing the current to 200 nA. (b) and (c) “N” and “S” with Fe single atoms.
4. Yu-Shiba-Rusinov states of magnetic adatoms on the quasi 2D superconductor 2H-NbSe$_2$

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A magnetic impurity adsorbed on a superconducting substrate yields so-called Yu-Shiba-Rusinov (YSR) states [1-3]. These are low energy bound states inside the superconducting energy gap locally induced by magnetic exchange scattering. 2H-NbSe$_2$ belongs to the class of transition metal dichalcogenides and is a layered van der Waals material with strong 2D character. In this material, superconductivity coexists with a charge density wave (CDW) at low temperatures.

Here, we investigate YSR states of single transition metal atoms adsorbed on the surface of 2H-NbSe$_2$ using low temperature scanning tunneling microscopy and spectroscopy. We observe variations in $d$ state resonances as well as in the YSR excitations. We can link these variations to the adsorption in two distinct atomic sites. Furthermore, the energy of the YSR states and their spatial extend appear to be influenced by the CDW.

5. Deposition and selective switching of a cationic Fe(III) compound on Au(111) and Cu2N

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Spin-crossover (SCO) complexes contain a transition metal ion that can be switched between a low-spin and a high-spin state by external stimuli. Investigations of single SCO molecules is challenging as the interaction with the substrate often leads to fragmentation or loss of functionality. So far, the focus was on Fe(II) based molecules, while SCO complexes with different metal ions (different oxidation states) would be desirable.

Using scanning tunneling microscopy, we evidence the first successful deposition of a cationic Fe(III) SCO complex, [Fe(pap)2]+ (pap = N-2-pyridylmethylidene-2-hydroxyphenylaminato), on Au(111) and Cu2N/Cu(100). The deposited Fe(III) SCO compound is controllably switched between three different states, each of them exhibiting a characteristic tunneling conductance. The conductance is therefore employed to readily read the state of the molecules [1,2].

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6. Magnetic structure of MnO$_2$ and FeO$_2$ chains on Ir(001) investigated by spin-polarized STM

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Low-dimensional systems are known to behave different from bulk properties. In particular, for monatomic 3$d$ transition metal chains unconventional magnetic ground states have been theoretically predicted [1]. Recently, a new self-organized growth method of transition metal oxide (TMO) chains on Ir(001) with a structural (3×1) unit cell has been reported [2]. DFT calculations predict a rather strong antiferromagnetic (AFM) coupling along MnO$_2$ and FeO$_2$ chains, but only a weak AFM interaction across the chains.

We performed low-temperature spin-polarized scanning tunneling microscopy (SP-STM) to unravel the spin structure of various TMO chains on Ir(001) at 5 K. Our results confirm an AFM coupling for MnO$_2$ and FeO$_2$ along the stripes. Surprisingly, we also find pronounced magnetic order in between adjacent chains. Whereas a ferromagnetic (FM) inter-stripe coupling leading to a (3×2) magnetic unit cell is found for FeO$_2$ in the SP-STM data of Fig. 1(b), MnO$_2$ chains show a complicated non-collinear ground state with a (9×2) magnetic unit cell shown in Fig. 1(d). Potential ordering mechanisms which may lead to this spin structure will be discussed.


Fig. 1: (a) Stripes of FeO$_2$ on Ir(001) as measured with a non-magnetic tip showing a (3×1) unit cell. (b) SP-STM image showing a doubling of the period along the row, indicative of an intra-chain AFM coupling. (c) Same as (a) but for MnO$_2$. (d) SP-STM data of MnO$_2$ on Ir(001) reveal a (9×2) magnetic unit cell.
7. Systematics of electronic and magnetic properties in the transition metal-doped quantum anomalous Hall platform Sb$_2$Te$_3$

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The quantum anomalous Hall effect (QAHE) has been reported to emerge in magnetically doped topological insulators. While its phenomenological description is quite clear, the microscopic origins are far from being completely understood and controlled.

Here, we provide a systematic characterization of the most prominent QAHE platform: transition metal-doped Sb$_2$Te$_3$. By combining complementary experimental techniques with ab-initio theory, we analyze how 3$d$ dopants (namely V, Cr, Mn, and Fe) impact the electronic and magnetic properties. On the one hand, to characterize the electronic structure we compare density functional theory (DFT) calculations for the density of states, for both bulk and surface, with scanning tunneling microscopy/spectroscopy and resonant photoemission measurements. On the other hand, we perform x-ray absorption spectroscopy and measurements of the magnetic hysteresis by means of x-ray magnetic dichroism. Experimental data are compared to results obtained by DFT calculations.

In summary, the combination of these complementary techniques yields a consistent picture of the bulk and surface magnetic properties of transition metal doped Sb$_2$Te$_3$, including anisotropies, easy axes, and induced and transition metal moments. Our results reveal that the fate of the topological surface state strongly depends on the specific character of the 3$d$ impurity. In particular, (i) the single-ion magnetic anisotropy, which controls the magnetic gap opening and its stability, can vary from in-plane to out-of-plane depending on the dopant; and (ii) the emergence of impurity resonances close to the Dirac point can give rise to new bands, which significantly alter the electronic structure of Sb$_2$Te$_3$ and prohibit the observation of a gap opening around the Dirac point [1]. Overall, our results provide general guidelines for the realization of a robust QAHE.

8. Visualizing the electronic structure of atomically thin high-T$_c$ cuprate crystals

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The role of dimensionality in high T$_c$ superconductivity is an interesting issue: after all, many of the high T$_c$ superconductor have layered atomic structures, and yet the link between the high T$_c$ superconductivity and the two-dimensional nature of the crystal structure remains elusive. Here, we fabricate few-layer Bi$_2$Sr$_2$CaCu$_2$O$_{8+x}$ samples, and use scanning tunneling microscopy (STM) and scanning tunneling spectroscopy (STS) to investigate the electronic structure, such as superconducting gap, pseudogap and charge order, in Bi$_2$Sr$_2$CaCu$_2$O$_{8+x}$ in the 2D limit.

If you have any questions, please contact us via: zhyb@fudan.edu.cn
Linear chains of magnetic 3d transition metal atoms on superconducting substrates have become of great interest in the last few years because of their promising ability to be topological superconductors and therefore host Majorana bound states at their ends [1, 2]. These states have been proposed to be suitable for fault-tolerant quantum computing. Most of the research on this topic investigated ferromagnetic chains on substrates such as Pb(110) in order to have strong spin-orbit-coupling which was shown to be able to induce topological superconductivity [3, 4]. However, these studies were all performed on self-assembled chains, whereas we aim to construct our chains by single atom manipulation. This technique allows us to perfectly control the geometric properties and chemical composition of the chains, which is crucial for the interpretation of scanning tunneling spectroscopy (STS) data on the chain’s ends. Single atom manipulation turned out to be impossible on Pb substrates which is why we use a superconducting Re(0001) surface.

In this study, we start by investigating the magnetism of single Mn, Co and Fe atoms adsorbed on Re(0001). We demonstrate that the magnetism of the adatoms strongly depends on the atom’s species and adsorption sites by studying spin excitations and the formation of Yu-Shiba-Rusinov (YSR) states – and find that our results are in good agreement with theoretical \textit{ab-initio} calculations. With single atom manipulation, we can continue to assemble larger nanostructures such as chains atom-by-atom and study the stepwise formation of YSR bands. We present STS measurements performed on chains of different lengths and compare the influence of the three adatom elements to the spectroscopic features obtained on the chains ends.

10. Spin-polarized STM study of the Fe monolayer on Rh(111)


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Skyrmions in thin magnetic films stabilized by the Dzyaloshinskii-Moriya interaction (DMI) have recently attracted considerable interest. Whereas Skyrmions are usually only stable in applied magnetic fields, the Fe monolayer on Ir(111) turned out to be unique as it exhibits a square lattice ground state of nano-skyrmions even without a field [1]. Here we report spin-polarized STM experiments performed on a monolayer Fe on Rh(111), a substrate that is isoelectronic and isostructural to Ir(111), but with Rh having a much smaller spin-orbit interaction than Ir and thus negligible DMI. In agreement with earlier calculations [2], which predicted a double-row-wise antiferromagnetic (↑↑↓↓) spin structure, we observe stripes oriented along ⟨110⟩-equivalent directions of the substrate (see Fig. 1). The periodicity of (1.0 ± 0.1) nm corresponds well with the expected value of 0.931 nm. These stripes exist in three orientational domains. Magnetic field-dependent data indicate that domain walls are associated with uncompensated magnetic moments that give rise to hysteresis effect due to domain wall movement.


Fig. 1: (a) Magnetic order of the 2Q spin spirals with \( q = M/2 \). In the green shaded triangles, the 4-spin-3-site interaction contributes by an energy of \(-6Y_1\), in the grey shaded triangles by \(+2Y_1\), where \( Y_1 \) is the strength of the interaction in the nearest neighbor approximation. Unit cells are indicated by thin lines. The Brillouin Zone is shown in the bottom part. (b) SP-STM image of the ML showing stripes along ⟨110⟩ directions of the substrate \((U = +0.3 \text{ V}, I = 1 \text{ nA})\). (c) Averaged line profile taken along the arrow. The periodicity between the stripes amounts to (1.0 ± 0.1) nm with a corrugation of (1.4 ± 0.1) pm. (d) Fourier transformation of (b).
11. Local Conduction in Transition Metal dichalcogenides: The Role of Stacking Faults, Defects and Alloying

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Understanding the electronic contact between transition metal dichalcogenides (TMD) and metal electrodes is vital for the realization of future TMD-based electronic devices. TMD materials have the drawback of a high density of defects and impurities. We have investigated, with high-spatial-resolution conductive atomic force microscopy [1], the effect of these defects on the local conduction of the TMD material [2]. We find that subsurface metal-like defects drastically decrease the metal/TMD Schottky barrier height as compared to that in the pristine regions, see Fig.1. The magnitude of the decrease depends on the contact metal and the TMD composition. The decrease of the Schottky barrier height is attributed to strong Fermi level pinning. In addition, we found that stacking faults, step edges and chemical heterogeneities form distinct two-dimensional (2D) and one-dimensional (1D) conduction paths on the TMD surface. In the case of TMD alloys, their conductivity has a strong localized nature, which exactly depends on the underlying chemical composition. Segregation to different phases during the growth process leads to large lateral variations of their conductivity, see Fig.1. These sites provide non-uniform conduction paths and could play a prominent role as the TMD-based devices decrease in size.

Figure 1: a) Top: Current map on a metal-like defect on MoS2. Bottom: Schottky Barrier Height (SBH) map at the same location. The defect reduces the SBH with the metal AFM tip at this particular location. b) SBH as a function of the tip’s work function on the pristine MoS2 surface (blue) and the defect sites (red). The defect sites have a much stronger Fermi level pinning (S=0.1) compared to the pristine regions (S=0.3). c) Current map of the MoWSe2 alloy surface. Large current variations are observed across the surface. This is apparent also from the recorded I(V) curves of panel (d), where large variations are observed.

12. An electrically controlled single atom magnetic switch on black phosphorus

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Single atoms at the surfaces of solids have demonstrated rich electronic\textsuperscript{1}, chemical\textsuperscript{2}, and magnetic\textsuperscript{3-5} properties. In this direction, we demonstrate that we can manipulate the orbital population of a single cobalt atom on a crystalline black phosphorus surface. Using the local electric field generated from an STM tip, individual cobalt atoms residing at the same hollow site can be reversibly switched between two stable states, which correspond to the different orbital configurations. The experimentally observed charge density of each configuration (fig. 1) is corroborated with density functional theory calculations, which reveal distinct high and low total magnetic moments for each state, as well as the electronic properties of the cobalt atom which locally dopes the black phosphorus. We investigate the stability of each configuration, as well as compare the experimentally measured impurity states with DFT calculations. Finally, we study the switching dynamics to determine the underlying mechanism and energy scale of the switching. This system opens up the horizon to explore complex memory based on both the orbital and spin degrees of freedom.

References:

\[ J_{\text{low}} \quad J_{\text{high}} \]

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig1.png}
\caption{Cobalt on graphene in $J_{\text{low}}$ and $J_{\text{high}}$ configurations.}
\end{figure}
A buffer layer formed by depositing $\frac{1}{2}$ monolayer (ML) of Sr on Si(001) is known to passivate the Si surface, while its surface structure constitutes an ideal template for the integration of various functional oxides with the existing Si platform [1]. This Sr buffer layer is conventionally grown using Molecular Beam Epitaxy (MBE), but the low deposition rate and difficult stoichiometry control of this technique makes it less suitable for the growth of functional oxides. A promising alternative that offers tunable growth rates and a well-controlled growth of complex oxides is Pulsed Laser Deposition (PLD). PLD-grown Sr/Si surfaces have already been studied by Reflection High Energy Electron Diffraction (RHEED) [2]: however, to gain information about the surface morphology, structure and surface defects at the local atomic scale, a new approach is needed.

In this contribution, the results of the first Low Temperature Scanning Tunneling Microscopy (LT-STM) of a PLD-grown $\frac{1}{2}$ ML Sr/Si(001) surface will be presented, and it will be shown that PLD can offer precise control for the growth of high quality Sr-buffer layers. These PLD-grown samples were transferred in ultra-high vacuum (UHV) conditions to a LT-STM system, where they were cooled to 60 K. The large-scale STM images show that the samples exhibit a smooth surface, with terraces composed of one-dimensional (1D) chains running along perpendicular directions on neighboring terraces. High-resolution STM images display a low amplitude corrugation along the 1D chains with a period of 0.39 nm, while the chains themselves are separated by 0.78 nm. The measured values agree well with the size of the (2×1) unit cell observed in similar MBE-grown surfaces [3]. Apart from the highly-ordered surface structure, the STM images reveal two types of surface defects, recognized as Sr vacancies and Sr adatoms. This interpretation of the surface defects is supported by simulated STM images based on DFT calculations. These results provide an important insight into the quality of a PLD-grown Sr-buffered Si(001) surface at a local level, which is crucial for controlled epitaxial integration of complex oxides with Si.

Here we study the transport behavior of SrR_{1-x}Ir_{x}O_3 series compounds with x = 0.0 and 0.1 of bulk polycrystalline materials. Without a change of orthorhombic structure of SrRuO_3, the lattice parameters increase by Ir doping. Both the compound shows ferromagnetic (FM) to paramagnetic (PM) phase transition and FM interaction decreases by Ir doping with decreasing Curie temperature (θ_p). The temperature dependent electrical resistivity, ρ (T) of SrRuO_3 shows metallic nature in the entire temperature range with kink around Tc and similar behavior also shows Ir doped sample with decreasing metallic nature. Above T_c, ρ (T) increases linearly while below T_c, sharp decrease of ρ (T) of both the compounds. By applying 8 T of the magnetic field, the ρ (T) decreases of both compound and show negative magnetoresistance.
15. Tunneling Spectroscopy in the superconducting state of 1T-TaSSe

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Close to the Mott insulating phase many emergent states have been found in the past, including high temperature superconductivity in the Cuprates. Interestingly, a Mott insulator to superconductor transition has recently also been found in the layered transition-metal dichalcogenide 1T-TaS₂ upon substitution with Se [1, 2, 3].

We studied superconducting 1T-TaSSe with optimal stoichiometry using Scanning Tunneling Microscopy (STM) and Spectroscopy (STS) below the critical temperature of 5K. Topography readily reveals domain structure consistent with previous reports [3] and similar to those in 1T-CuxTiSe₂ [4]. Spectroscopy measurements clearly show that Hubbard bands are preserved, but contrary to pure 1T-TaS₂, there is a finite density of states inside the Mott gap both in the domains and the domain walls. High resolution spectroscopy at lower temperatures (down to 1K) shows that a 5 meV “pseudo”-gap develops at the Fermi level. We report its temperature and spatial evolution and provide possible links to the superconducting state.

16. Coupling of Yu-Shiba-Rusinov states in a molecular lattice

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Magnetic impurities on a superconductor act as scattering centers for the Cooper pairs of the latter and thereby induce a bound state, called Yu-Shiba-Rusinov state, in their vicinity. The spatial extent of these Yu-Shiba-Rusinov states is of several nanometers which allows for hybridization between them.

Here, we observe the formation of a Kagome lattice after deposition of iron(III)-porphine-chloride molecules on Pb(111) and subsequent annealing. The lattice is composed of triangular units made of three iron-porphine molecules and one Cl adatom. By investigating small structures made of a few of these triangular units we can prove that the Yu-Shiba-Rusinov states induced by the molecules hybridize with one another within these structures. We are thus able to produce a two-dimensional coupled network by molecular self-assembly.
17. Applying SP-STM to Investigate Spin Polarization in Manganese Nitride, 2D-MnGaN, and Chromium (001) Surfaces

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Materials displaying high spin polarization, perpendicular magnetic anisotropy, and correlated magnetic and electronic properties are of high interest for technological applications related to spintronics. We find all of these properties within the transition metal nitrides including manganese nitride, chromium nitride, and manganese gallium nitride. Thin epitaxial layers of these materials are successfully prepared using nitrogen-plasma molecular beam epitaxy.

Samples prepared by UHV MBE are transferred to an in-situ UHV low-temperature SP-STM system for spin-polarized investigations. We first explore the structural and electronic properties of the surface, while at the same time using magnetic tips, searching for the magnetic properties. This presentation will focus on our most recent results. This includes first of all our recent report of highly spin-polarized and spin-split surface Mn states in a 2D-MnGaN alloy layer atop of semiconducting GaN.[1] The 2D system exhibits ferromagnetism with a bias-dependent spin polarization. Ferromagnetic domains are observed at both low temperature and room temperature along with magnetic rim states and magnetic switching events.

We have also investigated large, pancake-like, Ising domains formed in ultra-thin (9 nm thick) layers of ε-Mn₄N which is ferrimagnetic. Scanning by LT-STM shows a flat mesa-valley morphology, while $dI/dV$ maps reveal a magnetic field-dependent contrast between mesas and valleys. The $dI/dV$ contrast between the mesa and valley regions goes away above an out-of-plane applied field of ~ +2.5 kOe (field increasing), but contrast returns upon reducing the applied field from + 20 kOe to below ~ +10 kOe, and this behavior is mirrored at the opposite magnetic polarity. The results confirm perpendicular magnetic anisotropy in the ε-Mn₄N ultra-thin films, consistent with results from SQUID magnetometry.[2]

As a side project, we have also investigated magnetic anisotropies and layer-to-layer spin couplings for Cr (001) c(2×2) surfaces grown by UHV MBE.[3] We have developed a difference ratio technique which we apply to this sample system in order to quantitatively verify spin vector directions. This allows to determine at least 3 different surface in-plane magnetic anisotropy directions for our sample, and we clearly verify a model consisting of spins alternating terrace to terrace.

We are currently continuing to investigate spin polarizations for these and other related systems by using SP-STM as the ultimate tool for studying surface magnetic properties.

18. Spatially resolved magnetic anisotropy of Co islands on Au(111)
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In surface-supported islands, the magnetic anisotropy energy (MAE) can be modified in a controlled manner by varying the particle size, shape, and choosing appropriate substrate for inducing interface-driven effects [1]. The interfaces combining a 3d ferromagnet with its large spin moment and 4d or 5d metal with its large spin–orbit coupling offer a fertile platform to explore the mechanism of enhancements of MAE. Accounting for the precise structure-magnetic property correlation is essential to tune the MAE in such systems. Spatially averaging techniques, namely, magneto-optical Kerr effect, and X-ray magnetic circular dichroism, have been remarkably successful in revealing the magnetic properties such as magnetic moments and MAE in a monodisperse ensemble of surface-supported islands. However, for ensembles containing several species, unveiling the structure–magnetic property correlation, including the interface effects, demands a spatially resolved magnetic characterization technique. Here we report spatially resolved measurements of MAE of Co islands on Au(111) using a low-temperature spin-polarized scanning tunneling microscopy (SP-STM) technique [2].

The deposition of a submonolayer amount of Co onto clean Au(111) leads to the formation of bilayer high Co islands with a fraction of the third layer. We measure switching fields of individual Co islands with different size and different third layer coverage using SP-STM [3]. We extract the energy barrier, $\Delta E$, which separates two stable magnetization states, from the switching field for each Co island following the analysis of Ref. [4]. Using $\Delta E = K\times N$, where $K$ is the effective magnetic anisotropy and $N$ is the size of Co islands, we estimate the MAE for individual Co islands. Our analysis reveals that the MAE of bilayer islands depends strongly on the crystallographic stacking of the two Co layers. The MAE of Co atoms on Au(111) is enhanced by a factor of 1.75 as compared to that reported on Cu(111) [4]. Furthermore, we observe a strong reduction of MAE due to the nucleation of the third layer (Fig. 1), consistent with the trend of spin-reorientation transition reported in Co on Au(111) [5]. Our results highlight the strong impact of nanometer-scale structural changes in Co islands on MAE and emphasize the importance of spatially resolved measurements for the magnetic characterization of surface-supported islands [2].

19. Scanning probe microscopy at magnetic fields up to 34 T

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Up to now, low temperature Scanning Probe Microscopy (SPM) has been limited to a magnetic field strength of 18 T, as the majority of designs have been based on superconductor magnets. For some experimental applications – for example the study of fractal spectra in graphene superlattices, the room temperature quantum Hall effect and some metamagnetic transitions – higher fields are required. Static fields of more than 30 T can be generated in dedicated high-field facilities by water-cooled, resistive Bitter magnets or hybrid resistive-superconducting magnets. However, implementing SPM in a Bitter magnet is a major challenge, due to the high level of vibrational noise produced by the turbulent cooling water, in addition to the strong space constraints resulting from the small magnet bore.

We present a novel cryogenic Scanning Tunnelling Microscope (STM) designed to operate inside a water-cooled Bitter magnet, which can reach a magnetic field of 38 T. The performance of the STM is demonstrated through Landau level tunnelling spectroscopy of graphite, at 4.2 K in magnetic fields up to 34 T¹.

Additionally we show the design of a highly compact Atomic Force Microscope (AFM) for operation at cryogenic temperatures in an extremely high magnetic field. We present preliminary imaging data on the frustrated spinel CdCr₂O₄ at up to 30 T.

20. Local femtosecond dynamics of a Charge Density Wave Phase

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Niobium diselenide (NbSe₂) is a layered transition metal dichalcogenide (TMD) that features a charge density wave (CDW) phase below 33K in which the electrons order with a periodicity that is incommensurate with the atomic lattice. Studies using optical pump probe techniques showed a picosecond response of the CDW [1] and local scanning tunneling spectroscopy found a strong impact of pinning to atomic-sized defects [2]. Here we couple THz pulses to a scanning tunneling microscope tip [3] to probe the ultrafast dynamics of a CDW at individual atomic defects. The first pulse excites the CDW and the second one probes the response in the sample’s density of states with a time resolution better than 200 fs. We find that the CDW responds to an excitation on a timescale well below 1ps and exhibits rich dynamics with a spatial variation on the scale of one unit cell of the CDW.

21. Stability and lifetimes of magnetically coupled Fe nanostructures on Pt(111)

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Nanostructures composed of a few magnetic atoms are of great interest not only for studying the physics of magnetism at the atomic scale but also for possible use as magnetic bits or logic elements. Single Ho adatoms are found to be stable when decoupled using MgO from the Ag(001) surface [1], while Fe trimers are the smallest stable nanostructures on the metallic Pt(111) surface [2]. The properties of Fe trimers (and adatoms) on Pt(111) were found to depend strongly on how the magnetic atoms are stacked on the surface [2,3]. To understand and manipulating their magnetic stability, knowledge of the interactions with the surroundings, in particular other magnetic entities, is of paramount importance.

The magnetic interactions between Fe atoms on Pt(111) have been experimentally mapped and also extracted from first-principles calculations [4]. They comprise not only the isotropic Heisenberg exchange interactions but also chiral Dzyaloshinskii-Moriya interactions. In this contribution, we present our results for the magnetic interactions between several types of Fe nanostructures: adatom-dimer, adatom-trimer, dimer-dimer, dimer-trimer, and trimer-trimer. The influence of the stacking site is explored, as well as a so-far overlooked type of magnetic interaction, the anisotropic exchange or compass-type anisotropy. The dependence of the interactions not only on the distance but also on the relative arrangement of the nanostructures has a strong influence on the magnetic stability and the corresponding lifetimes of the magnetic states. This is borne out quantitatively via a newly developed scheme that combines data from first-principles calculations with a master equation based on an Anderson-Appelbaum-type model.

22. Observation of Quantum-Hall Wedding Cakes in Graphene Quantum dots

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Recently, the ability to embed nanometer-scale gate potentials in graphene heterostructures has enabled the creation of a new type of quantum dot (QD) for two-dimensional Dirac particles. Here, we use scanning tunneling microscopy and spectroscopy to characterize the local density of states in these novel quantum dots, under a perpendicular magnetic field. We observe an intricate spectrum of eigenstates, which at weak fields contains discontinuities unique to two-dimensional Dirac systems, and at increasingly strong fields gradually condenses into a series of distinct Landau levels. As the magnetic length becomes smaller than the length scale of electric confinement, partially occupied Landau levels begin to form compressible strips which screen the bare potential of the quantum dot, flattening the density of states profile into a series of plateaus similar to a wedding cake. We present detailed spectroscopic mapping of these structures in the local-density of states, as well as theoretical calculations, demonstrating the importance of electron interactions in confined graphene systems.
23. Quantum noise spectroscopy of magnetic atoms

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The stochastic noise of iron atoms on copper nitride is observed in the frequency domain with GHz bandwidth. Switching occurs spontaneously between different magnetic quantum states and, in contrast to pump-probe measurements [1], these intrinsic dynamics are accessible in the absence of large driving fields [2]. We add an oscillating electronic potential on the order of 100 V to the STM bias and thereby reveal the atom's dynamics. The dynamics hidden in mean variable measurements are extracted as effective occupation times and reveal the effect of the local environment on individual iron atoms. This technique can access picosecond-fast fluctuations and enables investigation of few-atom spin systems that have previously been considered static.

24. Electronic properties and transport mechanism in a 2D p-type InGaAs/InP (001) heterostructure

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By turning a 2-dimensional electron gas (2DEG) found in conventional III-V semiconductor heterostructures into a triangular antidot lattice, we are working on the realization and the characterization of a Dirac material. The first step was the study of the electronic properties and the transport mechanism of the confined structure. In order to obtain these information, combined low temperature scanning tunneling microscopy (LT-STM), spectroscopy (LT-STS) and in-line four-probe STM measurements under ultra-high vacuum (UHV) were performed in a thin InGaAs quantum well (QW) grown on an InP (001) substrate with molecular beam epitaxy (MBE). Tuning the surface structure to a (2x4) reconstruction, we further investigated the electronic local density of states (LDOS) of the QW. The results are in agreement with tight binding calculations, taking into account band-banding induced by Fermi level pinning. When the InP potential barrier was p-type doped, the differential conductance exhibited a clear step-like voltage dependence in the conduction band, in agreement with previous works, corresponding to the electron sub-bands formed in the InGaAs QW due to quantum confinement effects. In contrast, for an undoped potential barrier, the step-like features were not resolved at positive sample bias and the current saturated at negative sample bias. Based on these different behaviors and on the four-point probe transport measurements, we are able to explain the transport mechanisms that allow the establishment of a steady state current through the quantized states of the InGaAs QW at positive and negative sample voltages. Finally, the realization and the characterization of the nanoperofted structure, is under improvement.

![Figure 1: (on the left) SEM image of the InGaAs QW nanoperofted; (on the right) dI/dV spectrum acquired at a given point of the p-doped InGaAs QW surface. Inset: schematic of the InGaAs/InP (001) heterostructure grown by MBE.](image-url)
25. Nanofabricated tips as a platform for double-tip and device based scanning tunneling microscopy

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Here [1], we report on the design and fabrication of a new kind of smart tip for scanning tunneling microscopy (STM). By fully incorporating a metallic tip on a silicon chip using modern micromachining and nanofabrication techniques, we realize so-called smart tips and show the possibility of device-based STM tips. Contrary to traditional etched/grinded wire tips, these can be integrated in lithographically defined electrical circuits, photonic circuits and mechanical systems. We experimentally demonstrate that the performance of the smart tips is on par with conventional ones, both in stability and resolution. In situ tip preparation methods are possible and we verify that they can resolve the herringbone reconstruction and Friedel oscillations on Au(111) surfaces. In addition, these devices can be made to accommodate two isolated tips with sub-50 nm apex-to-apex distance to measure the two point propagator of the electron, providing new information on the transport of correlated electrons at the atomic scale. Smart tips can allow to considerably extend the range of STM, for example by enabling high-frequency tips to study noise on majorana zero modes, local gating using two tips or spin sensitive devices.

26. Crystalline chromium tips for spin-polarized tunneling

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I present a new method for the preparation of spin-sensitive STM tips from the antiferromagnetic material chromium. Repeated coating of crystalline chromium tips with a fresh chromium film leads to an epitaxial growth and unique structures of small dimensions at the tip apex. These structures do not only promise a high resolution but also the same structural properties as the core tip, resulting in a recovery of the tip magnetization direction. A once characterized tip can be used reliably over a long time. The performance of the produced tips in STM measurements is excellent in regard to a fixed spin-polarization, high resolution, and stability. I will show measurements with such prepared tips on the spin spiral in ultra-thin iron films on tungsten, illustrating magnetic contrast (in plane and out of plane), high spatial resolution in topographic maps, and even atomic resolution in differential conductance maps.
27. The noise of superconducting electrons

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The charge transport between two weakly coupled superconductors is rather unique. While in the case of metals the transferred charge simply stems from electrons tunneling, the transport in a superconductor-insulator-superconductor junction is much more diverse. At zero-bias, a pure dissipation-less current flows, carried by paired electrons, transporting twice the electron charge each. When a bias is applied various processes allow for transport of quasiparticles that can transfer multiples and/or fractions of elementary charge. We will present the developing of a noise-sensitive Scanning Tunneling Microscope to directly probe the effective charge that is transported in two weakly coupled superconductors. This opens a new route to study charge transport in quantum materials, like high-temperature superconductors.
28. Mapping the conductance of electronically decoupled graphene nanoribbons

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Recent developments in the field of on-surface chemistry have facilitated bottom-up fabrication of defect-free graphene nanoribbons (GNRs).[1] State of the art scanning tunneling microscopy (STM) techniques have highlighted the possibility of forming a molecular junction between a metallic substrate and the STM tip.[2-4] To counteract the strong electronic coupling to the metal surface, we developed a novel conductance measurement technique where we introduced intercalating layers of sodium chloride, allowing us to measure charge transport through single ribbons as a function of bias voltage and junction length. The reduction in current that is associated with the extra tunneling step through the NaCl also allows us to probe resonant transport, something which is difficult to do on the metal surface due to inelastic processes induced by the high currents involved. The thus-obtained conductance maps show fingerprints of the electronic structure of different types of graphene nanoribbons. This work presents a step towards the application of GNRs in molecular electronics.

29. Spin-spirals in bottom-up fabricated Fe chains induced by Dzyaloshinskii-Moriya interaction

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Magnetic atoms adsorbed on the surface of strong spin-orbit coupling materials experience indirect Dzyaloshinskii-Moriya interaction (DMI) [1]. DMI is an exchange interaction responsible for the stabilization of spin-spirals or Skyrmions by favoring perpendicular orientation of neighboring spins. By depositing single magnetic atoms on a surface and using the tip of a scanning tunneling microscope as a tool, those atoms can be moved to build bottom-up fabricated nanostructures [2].

Spin-sensitive measurements of such bottom-up fabricated chains enable the observation of the spin-state of each atom within the chain. So far, only collinear ferromagnetic [3] or antiferromagnetic [4] ground states have been observed. Here, we were able to measure DMI induced non-collinear ground states on chains of Fe atoms on Pt(111) of different lengths. By fixing the magnetization of the outermost atom in a 16 atoms long chain, we were able to stabilize a spin-spiral and investigate its properties by spin-polarized tunneling spectroscopy.

DMRG calculations corroborate our experimental findings and show how it is possible to tailor the spin-chain wavelength by tuning the ratio of Heisenberg- and DM-contributions in the Ruderman-Kittel-Kasuya-Yosida interaction regime using different interatomic distances within the chains.

30. Structural and electronic characterization of Sulfur-depleted monolayer VS$_2$

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Studies on bulk transition metal dichalcogenides (TMDCs) show a variety of electronic properties based on the specific combination of metal and chalcogen elements. Since it is possible to exfoliate or synthesize stable 2D versions of many TMDCs, they have attracted great attention for the opportunity to study reduced dimensionality in a variety of electronic systems.

VS$_2$ is of particular interest, as it has not yet been synthesized in monolayer form, and its magnetic ground state is unclear. Here, we present an investigation with low temperature scanning tunneling microscopy/spectroscopy (STM/STS) on the structural and electronic properties of sulfur-depleted single layer VS$_2$ on Au(111). Upon annealing as grown 1T monolayer VS$_2$, there is a structural phase transition to a sulfur depleted phase of VS$_2$, which exhibits reconstructed chain-like structures. Our results shed light on the atomic structure of single layer VS$_2$ as well as reveal a complex Fermi surface of striped phase. STS mapping at low temperature indicates the emergence of non-dispersive electronic ordering close to the Fermi level.
31. The complex magnetic structure of the Neodymium surface at 1.3 K

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Chiral magnetism has gained great attention due to its potential for magnetic storage devices or computing [1,2]. Following this development lanthanide metals shift into focus as they exhibit complex magnetic structures, e.g. helical/conical spin spirals or linear spin waves [3]. However, most investigations of lanthanides so far are based on magnetic neutron scattering experiments, lacking spatial resolution. Therefore, the nano-magnetic properties of lanthanides are poorly understood.

Neodymium shows the most complicated magnetic phase diagram among the lanthanides. It exhibits several magnetic phase transitions below its Néel temperature of 19.9 K, resulting in incommensurate multi-q magnetic order [4,5]. Until now, Nd(0001) surfaces have only been studied using STS, revealing the exchange-split $d_{xz}$-like surface state commonly observed on all trivalent Ln(0001) surfaces [6,7].

Here, we present first results and analysis of SP-STM measurements of Neodymium (Nd) bulk-like films on W(110) taken at 1.3 K. Various nanoscopic magnetic spin-spiral domains with single or multiple $q$ vectors are found, sometimes also overlapping. While we can retrieve some of the $q$ vectors found by previous neutron scattering studies, we discover additional vectors present at the Nd surface at 1.3 K.

High temperature superconductivity as it manifests in the cuprates was for long time suspected to be strongly related to the copper oxide layers, and therefore specific to only this family of materials. Using spectroscopic-imaging scanning tunneling microscopy, we visualize the electronic states of the iridate (Sr$_{1-x}$La$_x$)$_2$IrO$_4$ which is chemically radically different from the cuprates but also an effective Mott insulator. Above a certain doping threshold, we observe the emergence of a phase separated state, with the nucleation of pseudogap puddles and local charge order around clusters of dopant atoms [1]. At lower doping, we measure fully gapped Mott spectra, with a gap value that is in disagreement with photoemission and optical experiments. We find that this is evidence for poor electronic screening in the lightly doped iridates, and we develop an algorithm able to extract the intrinsic value of the gap, reconciling our measurement with literature and illustrating the importance of considering field penetration when performing STM experiments on poorly screened quantum materials [2].

33. The Center for Quantum Nanoscience

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In this poster presentation, we will describe the concept, members, and the facilities of the new Center for Quantum Nanoscience (QNS) in Seoul. QNS aims to combine the research interests of the nanoscience and quantum science communities with the goal of establishing a unique research effort in this area. One particular focus of QNS lies in the utilization of scanning probe techniques to study the quantum properties of atoms and molecules on and near clean surfaces.

As part of this effort, Ewha Womans University is currently in the process of building a customized research building including a special low-vibration facility and some clean rooms for optics and other experiments. A Helium recovery and liquefier system will be installed. This building is scheduled to be operational in Spring 2019.

The scanning probe microscopy team is currently operating a RHK closed-cycle STM/AFM operating at 10K. In addition, a Unisoku He-3 high field STM will be delivered before September of this year. Four home-built systems operating at temperatures below 4K and in high fields will join this effort during this year, however, some of those will become fully operational only in the new building. Advanced sample growth systems will become available this year as well as low temperature STM systems optimized for good optical access.

The scanning probe part of QNS consists of several PI researchers, postdocs and students with about half Korean and half international team members and is organized in relatively small teams.

We have a few positions available at all levels and we look forward to hearing from you and visiting us in Seoul.

Website: www.qns.science
Contact: heinrich.andreas@qns.science
34. Extending Cu$_2$N(100): Towards micron sized nitride islands for atomic assembly

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The study of thin insulating layers is of great interest in the field of scanning tunnel microscopy (STM), as they provide an anisotropic crystal field for atoms deposited on them$^1$. In addition they decouple said adatoms from conduction electrons from the metal substrate, which can give rise to long lived spin states$^2$.

Copper nitride, Cu$_2$N(100), has been shown to be a very successful insulating thin layer, as it well suited for manipulation of adatoms with atomic precision. This enables the leveraging of its uniaxial anisotropy to engineer spin structures with a controlled coupling$^3$, and study the interaction between them$^4$.

The main limitation of Cu$_2$N(100) is the small size of the islands that can grow on the Cu(100) surface, around 25 nm$^2$, as they are strained-limited by the mismatch in lattice parameter between the Cu$_2$N layer and the Cu(100) substrate. Some progress has been made by saturating the Cu(100) surface with nitrogen, leading to 400 nm$^2$ islands$^5$.

Here we present our approach to remove this limitation by reducing the mismatch between the Cu$_2$N layer and the substrate by using a Cu$_3$Au(100) alloy instead of a pure Cu(100) crystal. Our results at lower temperatures show 2500 nm$^2$ islands with straight edges, indicating influence of the strain in island growth. For higher temperatures islands approaching 1 um$^2$ with less regular edges, and thus no strain-limit indication, have been obtained.

35. Exploring magnetic frustration in atomically engineered closed chains

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Modelling quantum systems with a large number of degrees of freedom can be a daunting task from a computational standpoint. Scanning Tunneling Microscopy (STM) offers an alternative path, by enabling atom-by-atom engineering and probing of such systems. Spin Polarized STM (SP-STM) can provide direct insight into a system’s spin configuration, while at the same time providing a tunable interaction parameter. This enables the study of frustrated spin systems, which pose a particular modelling challenge as they are governed by a delicate balance of competing interactions.

Here we present the study of such a frustrated spin system, consisting in D-shaped chains of single iron atoms assembled on a single nitride layer grown on Cu3Au(100). As in the similar Cu2N system, the nitride layer provides a uniaxial framework with different ferromagnetic and antiferromagnetic interatomic couplings depending on the relative position on the lattice. This allows us to assemble closed loop chains with an odd number of antiferromagnetic couplings, leading to frustration. We explore the role of an external magnetic field, interatomic exchange, as well as the exchange interaction with the spin polarized tip in the stabilization of the resulting spin configuration.

36. Resolving Picosecond Magnetic Lifetimes via Distortion-Compensated Pump Probe Spectroscopy

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Applying electric current pulses [1] to a tunnel junction is a powerful technique for the characterization of fast magnetic surface dynamics using scanning tunneling microscopy. The microscope’s signal line is strongly attenuating in the sub-nanosecond domain [2,3,4,5], limiting the achievable time resolution. We present an in-situ technique for the quantitative measurement of the signal line’s transfer function, both in phase and amplitude. In this way, the effective bandwidth of the instrument can be improved by at least one order of magnitude. Distortion-compensated pulses allow spin relaxation times of individual atoms; often well under a nanosecond, to be measured. This pulse correction technique opens the door to revealing a wide range of ultra-fast phenomena at the atomic scale.

We present initial studies of a two-dimensional graphene device using simultaneous measurements of atomic force microscopy (AFM), scanning tunneling microscopy (STM) and electrical transport. This combination allows for the investigation of exotic ground states and edge channels within the 2D graphene electron system. Initial measurements on a back gated graphene Hall bar device will be presented.

A newly constructed microscope (Figure 1) uses a self-sensing quartz tuning fork (qPlus) sensor and operates in an ultra-high vacuum (UHV) environment inside a dilution refrigerator (DR) with a base temperature of 10mK and magnetic fields up to 15T [1]. Radio frequency (RF) filtering of all signal lines entering the UHV chamber and improved home built RF powder filters at low temperatures were implemented to produce an improved energy resolution in tunneling spectroscopy. Low noise preamplifiers for the sensor deflection [2] and the STM current signal [3] were implemented at the 4K stage within the DR. This allows for reduced Johnson noise of the amplifier feedback resistors and a relatively short distance (1.2m) between amplifier and the STM/AFM module where the sensor is operating. As cable capacity between sensor and amplifier adds noise, a special cable with a capacity of merely 30pF/m has been designed and implemented.

Figure 1: left: CAD model of the microscope module; right: qPlus quartz tuning fork sensor mounted in the microscope above a sample.

38. Large Tunneling Anisotropic Magnetoresistance mediated by Surface States

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We investigated the tunneling anisotropic magnetoresistance (TAMR) in thick hcp Co films at cryogenic temperatures using scanning tunneling microscopy. Around −350 mV, a strong TAMR up to 30% is found with a characteristic voltage dependence and a reversal of sign. With the help of ab initio calculations the TAMR can be traced back to a spin-polarized occupied surface states of $J=5/2$ character that experiences strong spin-orbit interaction. It selectively hybridize with bulk bands of $J=5/2$ and $J=3/2$ character depending on the magnetization direction.
Interplay between Yu-Shiba-Rusinov states and spin-flip excitations on magnetic impurities on superconducting NbSe$_2$ substrate

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Yu-Shiba-Rusinov (YSR) states have become very important in artificial designer structures, e.g. in atomic iron chains on a superconducting substrate that gives rise to Majorana modes [1]. It has been demonstrated that the strength of the magnetic coupling $J$ between the impurity spin and the underlying superconducting substrate can be tuned by introducing molecular spacers. In this case, the YSR states migrate close to the main superconducting coherence peaks and new symmetric features with respect to $E_F$ appear outside the superconducting gap [2,3]. In this work, we experimentally and theoretically investigate the spectral evolution arising from the interplay between the YSR states and spin inelastic tunnelling in different spin systems (M—phthalocyanine molecule with M: Co,Mn,Cu,Fe) on NbSe$_2$ surface. By controlling the distance between the central ion and the NbSe$_2$ substrate through approaching the STM tip to the ion, we can tune the exchange coupling strength $J$ over the spin inelastic tunnelling, and demonstrate the spectral crossover from the YSR states to the intrinsic quantum spin states. The results pave the way to a detailed understanding of the low-energy quantum states and quantum phase transition induced by molecular flexibility. Our results further demonstrate that the structural flexibility of the molecular biased system can help to realize novel functionalities in nanostructures.

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40. Mapping the Hubbard Energy with Submolecular Resolution

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In developing models of electronic and optoelectronic properties of novel materials, we often start with the ground-state electronic structure. In reality, the properties we are interested in are a result of excitations. In cases where the electronic (dielectric) screening is low, excitations may give rise to distinct states, e.g. excitons and other quasiparticles/correlated states. In the case of orbital half-filling where charges are poorly screened, electron addition and removal is typically described by an on-site electrostatic repulsion, characterized by the Hubbard U [1]. This provides one of the simplest examples of how the ground state electronic structure does not fully capture the physics behind excitations of the system needed for transport and other charged excitations of the system.

Previously, we investigated clusters of the prototypical organic semiconductor 3,4,9,10-perylenetetracarboxylic dianhydride (PTCDA) on bilayer NaCl islands on Ag(111) to examine the effects of electronic polarization [2]. We observed a significant influence of molecular geometry on the electron addition and removal spectrum measured with pixel-by-pixel STS. Here, we use STS simultaneously alongside EFS to characterize the local charge distributions and charging energies for clusters and isolated molecules of PTCDA. By spatially resolving the charging events to generate “Hubbard maps” with sub-molecular resolution, we find that the initial local charge distribution strongly influences the charge injection energy and site. The ability to probe both the charge distribution and charging energy on angstrom length scales gives new insight into on-site and nearest-neighbour interactions that give rise to strongly correlated systems.

References

41. Tuneable topological domain wall states in engineered atomic chains

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The main goal of material science is to search for new materials. One way is to study naturally occurring materials. On other hand, we can also create materials artificially from their fundamental building blocks arranged in different lattice geometries. Artificial materials are an ideal platform to study various novel and exotic electronic band structures, which are not easily available in Nature [1,2]. Here, we report engineering of the topological domain wall states in one-dimensional trimer and coupled dimer chains constructed using chlorine vacancies in a chlorine monolayer on a Cu(100) surface [2,3]. We have used a low-temperature scanning tunneling microscope to fabricate these chains with various domain walls by atomic manipulation. The characteristic electronic properties of the domain wall states are mapped using scanning tunneling spectroscopy. The experimental findings are further supported by tight binding calculations using the parameters extracted from the experiment. These results are important steps on the path towards designer quantum materials with tailored properties.

42. Scanning Tunneling Microscopy of encapsulated 2D materials

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Recent results have shown that air-sensitive atomically thin crystals produced in the controlled atmosphere of a glove box can be exposed to ambient if encapsulated between chemically inert 2D materials, and used in different types of experiments. Experimental studies, however, have remained mainly limited to basic transport and optical measurements. To explore whether scanning tunneling microscopy (STM) and spectroscopy (STS) can be performed on encapsulated layered van der Waals materials, here we report on systematic STM measurements that we have performed on a model system consisting of a thin exfoliated NbSe2 crystals encapsulated by an overlaying MoS2 monolayer. We show that the results depend strongly on the relative angle between the NbSe2 and MoS2 lattices. For well aligned lattices, the interaction between MoS2 and NbSe2 appear to be strong and the measured properties of MoS2 capping layer are not simply related to the properties of the constituent material. However, when the two lattices are strongly misaligned the measured properties of MoS2 seem to be unaffected. Energy dependent STS can be performed successfully to detect the known properties of NbSe2 (e.g., the presence of the superconducting gap at low-temperature). Our results show that encapsulation does not prevent STM and STS investigations of new 2D materials, and clearly demonstrate how the properties of the encapsulated material remain unaffected even in the case of well align lattices, where strong interaction between layers occur.

Scanning tunnelling microscopy and spectroscopy of encapsulated NbSe2. a) STM topographic image of MoS2 ML/NbSe2 heterostructure. Fast Fourier Transform of the former image, showing the points corresponding to the atomic lattice of MoS2 ML, NbSe2 and the superstructure formed by the MoS2 ML/NbSe2 heterostructure. c) Superconducting gap of capped NbSe2.
43. Reversible, crystalline hydrogenation of graphene by STM field dissociation

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The interaction with atomic hydrogen is of considerable interest for tuning graphene’s electronic, magnetic, and chemical properties for a variety of applications. Crystalline ordering would help in identifying the intrinsic properties of hydrogenated graphene (H-Gr) and mitigating effects of disorder on, for example, carrier mobility in electronic transport. We have developed a novel method for crystalline hydrogenation of graphene on the nanoscale [1]. Molecular hydrogen was physisorbed at 5 K onto pristine graphene islands grown on Cu(111) in ultrahigh vacuum. Field emission local to the tip of a scanning tunneling microscope dissociates H2 and results in hydrogenated graphene. At lower coverage, isolated point defects are found on the graphene and are attributed to chemisorbed H on top and bottom surfaces. Repeated H2 exposure and field emission yielded patches and then complete coverage of a crystalline \( \sqrt{3} \times \sqrt{3} \text{ R30°} \) phase, as well as less densely packed 3x3 and 4x4 structures. The hydrogenation can be reversed by imaging with higher bias voltage.

44. First-principles study of metal adatoms on Mn/W(110)

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Single magnetic atoms on surfaces are intriguing systems for experimental and theoretical studies. A monolayer of Mn on W(110) with its noncollinear magnetic spin spiral ground state offers an interesting choice of surface in this kind of applications. The surface presents a cycloidal spin spiral ground state [1] with an angle of 173° between neighboring spins. It allows quasi-continuous control of spin directions for the adsorbed adatom. The manipulation of spin directions of adsorbed Co atoms on this surface have been reported in the literature [2,3]. In a recent theoretical work, Caffrey et al. [4] have reported the tunneling anisotropic magnetoresistance (TAMR) effect of Co, Rh, and Ir adatoms on Mn/W(110) surface. In contrast to the tunneling magnetoresistance effect, the TAMR offers an alternative approach towards the spintronic applications as TAMR effect requires single magnetic electrode.

In this work, using first-principles calculations based on density functional theory as implemented in the VASP code [5], we investigate the series of the 3d metal adatoms from V to Ni adsorbed on Mn/W(110) and compare their electronic and magnetic properties. We study whether the orbital symmetry effect allowing to determine the spin direction of Co adatoms on Mn/W(110) [2,3] is also present for other 3d transition-metal atoms. Using spin-orbit coupling, we also investigate the magnetization direction dependent changes in the electronic structure. We find quite high values of TAMR from our calculations which can be even measurable in STM experiments using a non-magnetic tip.

45. Realistic Description of Competing Interactions in Metallic TMDCs

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Two-dimensional transition metal dichalcogenides constitute a prominent showplace for competing many-body instabilities such as superconductivity [1], charge-density waves [2] and magnetism [3]. In this study, we show that even though the observed phase diagrams are complex, the underlying mechanisms are captured by a compact unifying theoretical framework. We apply the constrained random-phase approximation (cRPA) [4] and constrained density-functional perturbation theory (cDFPT) [5] to the metallic monolayers H-MX$_2$ with M ∈ {V, Nb, Ta} and X ∈ {S, Se} and summarize the material specifics with a small number of representative Coulomb and electron-phonon interaction parameters. Both cRPA and cDFPT imply a separation of the electrons into a correlated subspace, here an isolated metallic band, and the rest. We find that all relevant physics emerges from interactions within this subspace. Beyond that, the materials can be well described by very similar tight-binding and mass-spring models.

46. Upgrade of a low temperature STM for single atom electron spin resonance experiments

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The range of experiments now possible due to the recent demonstration STM enabled electron-spin resonance (ESR) [1] provide good arguments to add high-frequency lines to existing STM facilities. Here we describe our upgrade of a helium-3 low temperature, 2D vector-field STM into an ESR compatible device. An RF transmission line was added to the system, capable of feeding RF power at frequencies larger than 25 GHz to the tip. A relay allows us to choose between a DC or low bandwidth modulated tunnel voltage from the STM control electronics or to apply fast voltage pulses generated by a pulse pattern generator for pump-probe spectroscopy or used for reading out of Rabi oscillations. Either mode allows simultaneous RF excitation, which is added via a bias-tee to the bias voltage path. For ESR, sweeping the magnetic field at constant RF frequency, or keeping the field constant and sweeping the RF frequency can be chosen. We characterize the transmission function [2], illustrate some performance numbers, and show preliminary ESR data on the model system of Ti/MgO/Ag(100) [3].

47. The role of tip reactivity in intramolecular imaging of organic molecules in NC-AFM

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Noncontact atomic force microscopy (NC-AFM) is now routinely capable of obtaining submolecular resolution, readily resolving the carbon backbone structure of planar organic molecules adsorbed on metal substrates. However, normally this resolution requires functionalisation of a metal tip by a carbon monoxide (CO) molecule or similar passivating group, which limits the technique to liquid helium (i.e. 5K) temperatures.

In this work, we show that the same resolution may also be obtained for molecules adsorbed on a reactive semiconducting substrate, and that surprisingly, this resolution is routinely obtained without the need for deliberate tip functionalization. We investigate the reactivity of silicon clusters at the end of a scanning probe tip both experimentally via “inverse imaging” of the silicon adatoms of the Si(111)-7x7 surface, and via density functional theory DFT calculations.

Counter to intuitive expectations, we find that many silicon terminated tips do not react strongly with the adsorbed organic molecules, and we find that only specific highly oriented clusters have sufficient reactivity to break open the existing carbon-carbon bonds. Our results suggest a wide range of tips may be capable of producing intramolecular contrast for molecules adsorbed on semiconductor surfaces, and at liquid nitrogen (78K) temperatures, leading to a much broader applicability for submolecular imaging protocols [1,2].

48. Probing and Tuning Interactions between Landau quantum liquids in Graphene Quantum Dots


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The charge of a conductor isolated from particle reservoirs by tunnel junctions is quantized in units of the elementary charge, a phenomenon known as Coulomb blockade. In our experiment, we created graphene QDs with fixed build-in potentials inside circular p-n junctions by ionizing impurities in the boron nitride underlying insulator. In these small nanometer sized circular resonators the quasi-bound resonances can be confined further by the application of a perpendicular magnetic field forming quantized Landau levels (LL) inside the graphene QD. The LLs at high magnetic fields form a series of metallic rings, separated by highly insulating incompressible rings, allowing tunnel barriers to be created between the LL quantum liquids and the sample bias electrode. The isolated LL metallic rings are then accessible by Coulomb blockade spectroscopy between the STM probe and graphene sample. Using scanning tunneling spectroscopy we provide direct spatially and spectroscopically resolved measurements of the formation of the LL rings and their charging characteristics. We investigate the addition energy spectrum of the LL rings and analyze their charging characteristics in terms of capacitances and QD energy level structure.
49. Controlled spin switch in a nickelocene molecular junction

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One of the main challenges in molecular spintronics is to achieve an active control of a molecular spin. This is possible through the modification of the molecular structure either by chemical doping or by external stimuli. Here we investigate the effect of varying the electrode-electrode distance in a controlled way in a single nickelocene molecular junction using a low-temperature scanning tunneling microscope. The molecule, when attached to the metallic tip of the microscope, exhibits spin excitations in the tunneling regime, while a Kondo ground state emerges upon contact with a Cu(100) surface, causing then an order of magnitude change in the zero-bias conductance. First principle calculations show that nickelocene reversibly switches from a spin 1 to 1/2 between the two transport regimes.

50. Tunable glassiness on a two-dimensional atomic spin array

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We demonstrate that a two-dimensional periodic array of spins coupled via RKKY-like exchange can exhibit tunable energy landscapes ranging from robust double-well toward spin glasses. We characterize the magnetic ground states and energy landscapes of such arrays, by the distribution of low energy states, energy barriers, aging relaxation dynamics and the size of the basins of attraction. We identify three phases resulting from singularly varying the RKKY period: a double well phase, a spin glass phase and a multiwell phase. The spin glass behavior results from self-induced glassiness, which is driven by the incommensurability of the RKKY period and the periodic array. We argue that the tunable complexity of these spin arrays can function as an associative memory (Hopfield network) at the atomic scale.
51. Spin signatures of Majorana zero mode in atomic chain and on quantum spin hall edge

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A wide class of one dimensional system can be engineered to host topological superconductivity and Majorana zero mode (MZM). In particular, atomic chains of magnetic atoms on a superconducting substrate have been proven to be a valuable platform for harboring MZM[1-3]. In this poster, I will present how spin polarized measurements allow us to distinguish MZM from trivial Bogolubov quasiparticles in the atomic chains[4]. In the second part, I will discuss our ongoing efforts on localizing MZM on a quantum spin hall edge[5] including the role of spin.

52. Band engineering in artificial electronic lattices


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Artificial electronic lattices, created atom by atom in a scanning tunneling microscope, have emerged as a highly-tunable platform to realize and characterize the lowest-energy bands of novel lattice geometries. Here, we show that artificial electronic lattices can be tailored to exhibit higher, $p$-like bands. Experimentally and theoretically, we report $p$-like bands in a four-fold and three-fold rotational symmetric lattice and we lift the degeneracy of the $p_x$-and $p_y$-bands. The lattices were formed by confined surface state electrons of Cu(111) in structures of carbon monoxide molecules, a platform that was previously used to construct i.a. molecular graphene [1] and an electronic Lieb lattice [2]. The ability to engineer higher-energy electronic bands in artificial quantum systems paves the way to exploring $p$-band physics in novel geometries in a controlled way.


Crafting a Topological Insulator Atom-by-Atom

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Artificial electronic lattices, created atom by atom in a scanning tunneling microscope, have emerged as a highly-tunable platform to study quantum matter. Here, we show that this approach can be extended to create topological insulators, atom-by-atom. In a honeycomb lattice with alternating hopping strengths, a gap in the energy dispersion is opened [1]. Depending on the ratio of the hopping parameters, the so-called Kekulé lattice is either topologically trivial or non-trivial. The topologically non-trivial lattice should exhibit a protected edge-state, whereas the trivial version does not. Here, we realize two Kekulé lattices through the coupling of artificial atoms, created by the careful arrangement of electron scatterers (carbon monoxide molecules) on a 2D electron gas (Cu(111) surface state) [2]. The electronic properties were probed using scanning tunnelling spectroscopy and differential conductance mapping. We show that the topologically non-trivial lattice indeed features a robust edge state whereas the trivial equivalent does not. The experimental outcomes align well with results from tight binding and muffin tin calculations.

References
54. Image states and energy dissipation on Bi2Te3 (0001) surface

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Small amount of energy is dissipated when bodies separated by few nanometers gap are in relative motion [1]. Non-contact friction can be measured by highly sensitive cantilever oscillating like a tiny pendulum over the surface [2]. Dissipation mechanisms in a broad spectrum of physical systems and media attracted great interest among fundamental scientific and applied communities. Non-contact friction phenomena have been studied in many systems revealing structural and electronic phase transitions [3, 4], quantum dots [5] and graphene devices [6]. Understanding the origin of various dissipation (non-contact friction) mechanisms is still wide open problem. Such frictional nature on layered systems is yet another exotic playground.

Here we study electronic nature of Bi2Te3 (0001) surface and its effect on frictional response of the crystal by means of combined pendulum AFM/STM. While quantized image potential states were observed with STM, AFM data show huge dissipation peaks due to population of those states by the oscillating tip. Energy dissipation peaks are localized at relatively large voltages as expected for image states and observed to be shifted to even higher voltages as tip-sample distance increase. Their relation was investigated in more detail by simultaneously operating STM and AFM.

In this presentation, image potential states (IPS) and non-contact energy dissipation spectra on Bi2Te3 (0001) measured by means of combined pendulum AFM/STM system will be shown. Effect of image potential states on non-contact friction due to charge fluctuations and electrostatic friction will be discussed.

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- KNAW
- Nanoscore
- NWO
- Pfeiffer Vacuum
- Radboud University/IMM
- Scienta Omicron
- Sigma-Surface-Science GmbH
- Specs GmbH