Scientific Profile of Prof. Dr. Roland Wiesendanger

Revealing spin structures with atomic resolution is of central importance to many fields of modern condensed matter physics and spin-based technologies, e.g. nanomagnetism and spin-electronics, spin structures in high-Tc superconductors, or spin textures in quantum Hall ferromagnets. In the past twenty years a fascinating technique was developed and continuously further improved by Roland Wiesendanger and his team members at the Universities of Basel (Switzerland) and Hamburg (Germany), which allows for the first time the atomic-scale visualization of spin structures and the investigation of the spin- and spatially-resolved electronic structure down to the atomic level. As a result, structural, local electronic, *and magnetic* properties of condensed matter can now be correlated down to the atomic scale. Moreover, Roland Wiesendanger and coworkers could recently demonstrate the first all-spin logic operations on the atomic scale (Science 332, 1062 (2011)).

The technique developed by Roland Wiesendanger is based on vacuum tunnelling of spin-polarized electrons in a scanning tunnelling microscope (STM) operated with (ferro- or antiferro-)magnetic probe tips offering a high degree of spin polarization. In a pioneering experiment in 1990 a ferromagnetic CrO_2 thin film tip was used to probe the topological antiferromagnetism of the Cr(001) surface consisting of alternately magnetized ferromagnetic terraces separated by monoatomic steps (PRL 65, 247 (1990)). While the early experiment was performed in the constant-current mode of STM, significant improvements were achieved by introducing a spectroscopic mode of the spin-polarized (SP)STM (PRL 81, 4256 (1998)) leading to high-contrast images of the surface spin structure of Cr(001) crystals even in the presence of screw dislocations (PRL 85, 4606 (2000)).

By using SP-STM in the constant-current operation mode atomic-scale imaging of ferrimagnetic crystals (Science 255, 583 (1992)) as well as of 2D antiferromagnetic spin structures of single atomic layers of Mn or Fe atoms on W(110) or W(001) substrates, respectively, was demonstrated (Science 228, 1805 (2000) and PRL 94, 087204 (2005)). Though the existence of 2D antiferromagnetic order in single atomic layers of transition metals was theoretically predicted, the experimental verification remained a scientific challenge due to the lack of sensitivity and spatial resolution of established analysis techniques. Moreover, SP-STM has allowed the first atomic-scale study of antiferromagnetic domain walls in ultrathin films (Nature Materials 5, 477 (2006)).

The spectroscopic mode of SP-STM was applied to study magnetic domain and domain wall structures in several ultathin film systems and nanostructures of transition metals and rare-earth metals. For instance, the dipolar antiferromagnetic coupling of Fe nanowires being only two atomic layers high and a few nanometers wide could directly be visualized with sub-nanometer-scale spatial resolution (PRL 84, 5212 (2000)). Subsequently, the magnetization and remagnetization processes of arrays of such magnetic nanowires in an external magnetic field have been studied by SP-STM allowing the determination of magnetic hysteresis loops at the single-digit nanometer length scale (Science 292, 2053 (2001)). Remarkably, atomic-scale magnetic domain walls were discovered in quasi-1D Fe nanostripes being only one atomic layer high (PRL 87, 127201 (2001)). The orientation of magnetic domain walls in magnetic nanowires was studied and was found to be closely linked to particular

crystal lattice directions in contrast to expectations based on continuum micromagnetic theory (PRL 92, 077207 (2004)).

Considerable progress in the application of SP-STM to magnetic nanostructures came along with the use of antiferromagnetically coated probe tips which exclude a disturbing influence of the tip's magnetic stray field on the magnetic state of the system to be investigated due to the lack of magnetic dipolar interaction in this case (PRL 88, 057201 (2002)). As a consequence the intrinsic width of magnetic vortex cores in Fe nanostructures could quantitatively be determined for the first time using such antiferromagnetic tips (Science 298, 577 (2002)). Furthermore, the spin- and spatially-resolved electronic structure of Co nanostructures on Cu(111) substrates could be studied as a function of an external magnetic field (PRL 92, 057202 (2004) and PRL 96, 237203 (2006)).

By combining SP-STM with time-resolved studies the magnetization dynamics of individual nanoparticles could be revealed with sub-nanometer-scale spatial resolution (PRL 92, 067201 (2004)). In particular, the shape dependent thermal switching behaviour of superparamagnetic iron nanoislands being only one atomic layer thick could be investigated in detail, and different microscopic processes of the magnetization reversal of irregularly shaped and compact nanoislands were identified (PRL 103, 127202 (2009)). Additionally, magnetization reversal processes induced locally by spin currents from a SPSTM tip were demonstrated, thereby paving the way towards a combined atomic-scale spin manipulation and spin read-out scheme (Science 317, 1537 (2007) and PRL 107, 186601 (2011)). More recently, the transition between classical und quantum dynamical behaviour of the magnetization of few-atom-iron clusters on a copper substrate has been revealed by time-resolved SP-STM techniques (Science 339, 55 (2013)).

The spectroscopic mode of SP-STM has also been applied to study the spin-dependent scattering of electrons on iron surfaces at single oxygen impurities (PRL 92, 046801 (2004)). The spatially anisotropic scattering states directly revealed the d-orbital nature of the electronic states of Fe involved. A clear difference in the scattering strength for spin-minority and spin-majority electrons of Fe(110) was observed, thereby providing a direct real-space visualization of the microscopic origin of magnetoresistance effects caused by atomic impurities.

Most importantly, SP-STM has led to new discoveries of complex magnetic order at the nanoscale, such as a surprising chiral magnetic order in Mn monolayer films on W(110) (Nature 447, 190 (2007) and PRL 108, 087205 (2012)) and in bi-atomic iron chains on Ir(001) (Phys. Rev. Lett. 108, 197204 (2012)), or the interface-driven skyrmion lattice in a monolayer Fe film on Ir(111) (Nature Physics 7, 713 (2011) and Nature Nanotechnology 9, 1018 (2014)). More recently, SP-STM has allowed the first direct observation and controlled manipulation of individual skyrmions in ultrathin magnetic films and heterostructures, thereby paving the way towards skyrmion-based memory and logic devices (Science 341, 636 (2013), Nature Nanotechnology 10, 1039 (2015) and Nature Communications 6, 8455 (2015)).

Another important application of SP-STM has been the magnetism of individual atoms and molecules, including the spin-dependent interactions among them. By introducing the novel method of single-atom magnetometry (Science 320, 82 (2008) and Nature 467, 1084 (2010)), the magnetic moments and magnetic anisotropies of

individual atoms on metal and semiconductor surfaces could be determined quantitatively for the first time. Moreover, the oscillatory nature of indirect magnetic exchange coupling between individual magnetic adatoms could be studied for the first time (Nature Physics 6, 187 (2010)).

By combining spin-sensitive imaging of individual atoms with single-atom manipulation techniques (Nature Nanotechnology 5, 350 (2010)), Roland Wiesendanger and coworkers have recently demonstrated the first all-spin logic operations on an atom-by-atom basis (Science 332, 1062 (2011)). This most impressive experimental breakthrough paves the way towards an all-spin-based information and communication technology at an ultimately small length scale. Additionally, Roland Wiesendanger and coworkers have recently achieved an atom-by-atom engineering of tailored nanomagnets (Nature Physics 8, 497 (2012) and Nature Nanotechnology 10, 958 (2015)) being the first demonstration of an atomically tailored material design based on the knowledge of the fundamental magnetic interactions between individual magnetic atoms.

As another outstanding application of the SP-STM technique, Roland Wiesendanger and coworkers have revealed for the first time spin-split molecular orbitals of single-molecule magnets directly in real space (Nature Communications 3, 953 (2012)). To observe spin structures at surfaces of insulators at atomic resolution, a novel technique, called Magnetic Exchange Force Microscopy (MExFM), has been developed by Roland Wiesendanger and coworkers (Nature 446, 522 (2007)). Using that technique, it has become possible to observe the atomic-scale surface spin structure of NiO(001) and to study complex spin states in materials exhibiting metal-insulator transitions.

The highly demanding experimental studies described above demonstrate the power of SP-STM and MExFM for revealing atomic-scale spin configurations of nanomagnets and thin films as used in magneto- and spin-electronics. Moreover, fundamental studies of magnetism at the level of individual atoms and molecules as well as unprecedented insight into complex spin structures of condensed matter have become possible. As most outstanding technological application of that development, the SP-STM technique has proven to provide the basis for all-spin-based logic and memory devices being ultimately small and fast, while simultaneously requiring low energy consumption only.