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New insights into nano-magnetism by spin-polarized scanning tunneling microscopy

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ABSTRACT

We study the magnetization reversal and the position dependence of the spin-dependent electronic properties of nm small bilayer Co islands on Cu(1 1 1) by spin-polarized scanning tunneling microscopy in magnetic fields at low temperatures of 8 K. The analysis of the energy barrier of magnetization reversal from measurements of the switching field suggests a crossover of the magnetization reversal mode with increasing island size around 7500 atoms from exchange-spring behavior to domain wall formation. The quantitative analysis of the island size dependence of the energy barrier indicates an inhomogeneous magnetic anisotropy of the island. The island rim is magnetically soft, whereas the center shows a pronounced effective anisotropy of 0.148 meV/atom. We speculate that this inhomogeneity of the magnetic anisotropy might be a consequence of the spatial dependence of the spin-dependent electronic properties. We measure a spin-polarization and a tunnel magneto resistance ratio of opposite sign at the rim as compared to the island center.

1. Introduction

At first sight the magnetization reversal of nm small structures seems to be well understood in nanomagnetism [1–3]. One is tempted to assume that as long as the particle dimensions are smaller than the width of a domain wall, reversal occurs by coherent rotation of all spins in a so-called macrospin model [4]. In the macrospin model, all spins of the structure are coupled by the exchange interaction, and the reversal can be described in the Néel–Brown model of thermally assisted reversal [5,6]. It is expected that in larger particles, magnetization reversal occurs by domain nucleation and growth, or by other reversal mechanisms. Note however, that in any case the macrospin description is a model, and more complicated reversal modes are conceivable [2,7–10].

Both fundamental research and applications show a tremendous interest in the understanding of the crossover between different reversal modes. This opens the way to modify the decisive parameters and to tune this transition as wished. A key parameter in this respect is the magnetic anisotropy energy density K. A large anisotropy favors stable magnetization directions against thermal agitation. This is required for example in magnetic data storage [11,12], where a sufficiently large ratio of the magnetic anisotropy energy KV, V: volume of the magnetic entity, over the thermal energy k_BT of order 60 is called for to ensure stable data storage.

However, the magnetic anisotropy changes dramatically when the dimensions of a particle are reduced to the nm scale in one or more dimensions. Lattice strain, its relaxation and the increasing relative number of surface and interface atoms induce a dramatic deviation of the magnetic anisotropy from its bulk values [13–17]. Also, structural [18,19] and electronic relaxations at the boundary of a nano structures [20] lead to distinct deviations of the atomic positions and the electronic structure on the nm scale. It is a priori not clear how the magnetic properties respond to this. Our work aims at providing experimental reference data for this largely unresolved issue.

To this end, we are striving for an understanding of the peculiar magnetic properties of a nanostructure on the electronic level. We exploit the unsurpassed spatial resolution of spin-polarized scanning tunneling microscopy [21–23] to investigate magnetization reversal and spin-dependent electronic properties of individual nano structures by scanning tunneling spectroscopy at low temperatures (8 K) in magnetic fields. In this work we focus on bilayer Co islands on Cu(1 1 1), which serve as a model system, as many structural [19], and electronic, including magnetic properties [20,24,25] have been established.

In Section 2 we address some experimental aspects of spin-polarized scanning tunneling microscopy. In Section 3 we present data on the magnetization reversal of individual bilayer Co islands on Cu(1 1 1). We find evidence for a spatial variation of the magnetic anisotropy, where the rim atoms of the Co islands are

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magnetically soft. We reveal in a combined experimental and theoretical study the spatial variation of the spin-polarization and of the tunnel magneto resistance which we present in Section 4. These studies identify a pronounced difference in the electronic structure of the rim region as compared to the center region. In the outlook we speculate about the interplay between magnetic anisotropy and electronic structure near the rim region of Co islands.

2. Experimental aspects: spin-polarized scanning tunneling microscopy at low temperature in magnetic field and tips for its use

Scanning tunneling microscopy (STM) has developed into a powerful experimental technique to characterize magnetic nano structures over a wide size range from single atoms up to continuous films. Its strengths are manifold: atomic manipulation for the creation of artificial nano structures with atomic precision [26–28] and unsurpassed spatial resolution in imaging and spectroscopy on the atomic scale [29–31], including single spin excitation spectra [32].

The use of spin-polarized tips opens the way to characterize spin-dependent properties of nano structures by exploiting the dependence of the tunnel current $I(V)$ and of the differential conductance $dI/dV(V)$ on the relative orientation of the magnetization of tip and sample [21–23,33–35]. This technique is called spin-STM for short. By this technique, the spin-structure of antiferromagnetic surfaces [36,37] and of skyrmion lattices [38] has been resolved, and magnetic domain imaging [39,40] has been performed. Also, inelastic tunneling spectroscopy has been successfully applied to study magnons [41,42]. We note that also non-spin polarized tips have been discussed to reveal magnetic contrast as the electronic density of states above the sample surface depends on its magnetization state [43].

The strength of scanning tunneling spectroscopy is that the resulting data are related to the local electronic density of states of the tip-sample system [44,45], and this allows contact with calculation of the electronic density of states. Thus, a comparison between spin-dependent differential conductance measurements and calculated spin-resolved electronic density of states is possible and is applied in the discussion of the results in Section 4.

Still, there are some caveats when it comes to the application of spin-STM for magnetic characterization. Spin-STM is not a magnetometry technique. The link between the magnitude of the signal in spin-STM and the magnitude of the magnetic moments at tip and sample is not rigorously established. Presently it appears that micro-squid is the only technique capable of quantifying magnetic moments of individual nano structures [2]. Although the determination of the magnitude of the magnetic moment of a nano structure by spin-STM remains illusive, the relative orientation between the magnetization of tip and sample can be reliably established [46,47]. This requires an external magnetic fields to enforce a well defined magnetic reference state, which is often given by a parallel alignment of tip and sample magnetization at high magnetic fields. Therefore, spin-STM develops its full potential only in combination with sizable magnetic fields. Typically superconducting magnets are used to deliver fields of several T at the STM. This magnitude of magnetic field is typically required to manipulate the magnetization of nano structures and possibly that of the tip.

Note that also secondary electron microscopy with spin analysis (SEMPA) allows to image magnetic domains at surfaces [48–52]. It offers the benefit over spin-polarized scanning tunneling spectroscopy that it may give all components of the spin polarization of the secondary electrons emerging from the surface region of the nanostructure. The spatial resolution of SEMPA in the magnetic contrast mode is of order 5 nm [50]. A lateral resolution of order 10 nm in magnetic imaging is also possible by spin-polarized low energy electron microscopy, as described in Ref. [53].

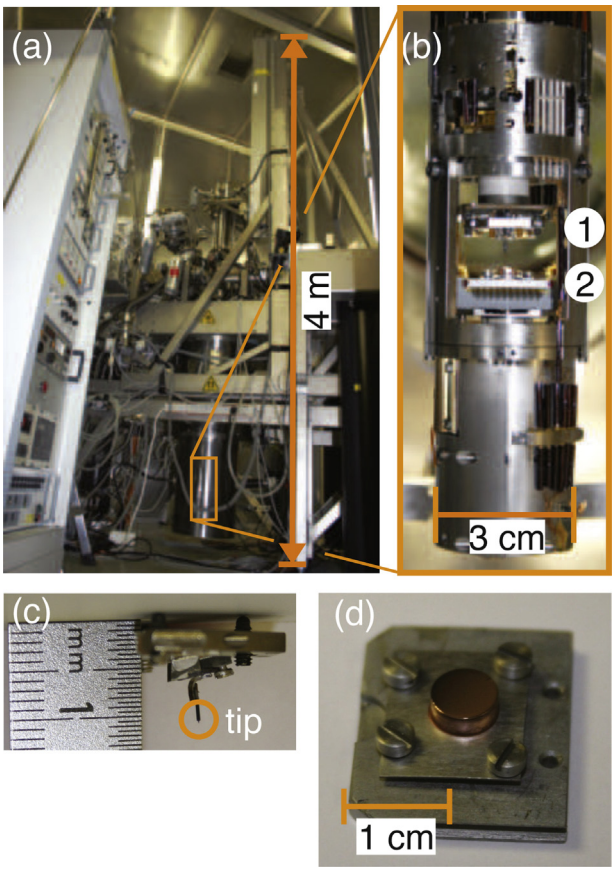

Fig. 1. (a) Side-view of Omicron cryogenic STM. The STM head (b) is located at the bottom end of the cryostat (orange rectangle). (b) The tip holder 1 mounted at the x, y coarse motion, the sample holder 2 is attached to the z-coarse motor and scanning piezo. (c) Side view of the tip holder, where the tip is spot welded to its support. (d) Cu(1 1 1) crystal, diameter 6 mm, mounted to the sample plate with Mo foils. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

2.1. LT-STM and superconducting magnet

Fig. 1 shows selected aspects of our low temperature STM with magnetic field [54]. The STM is a so-called top loader, where the STM head is lowered from the top into the cryostat. Loading of tip and sample into the STM is done in the UHV chamber above the cryostat at room temperature. The setup is fairly tall (4 m), as indicated in Fig. 1(a) to provide the necessary vertical travel.

The cryostat [55] contains concentric tanks for the cryo liquids. An outer liquid nitrogen surrounds an inner liquid helium (LHe) tank, which contains a superconducting magnet at its lower end. This magnet produces a magnetic field of up to 7 T along the vertical axis, normal to the sample surface. The STM is cooled by pressing the STM heat exchanger to a LHe cooled part within the UHV section of the cryostat by applying a contact force with the vertical lift. The lowest temperature is of order 7–8 K, as verified by calibrated sensors at the STM head.

Fig. 1(b) shows the STM head with the central opening for the insertion of tip (1) and sample holder (2). The tip can be positioned by a piezo coarse motion by ±5 mm horizontally in x- and y-directions. The sample is mounted on the scanner piezo which gives a scan range of order 1 μm at 7 K. The scanner piezo is mounted at the z-coarse motion which gives a vertical travel of up to 10 mm.