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Amorphous, low magnetostriction tips for spin-polarized scanning tunneling microscopy

W. Wulfhekel*, R. Hertel, H.F. Ding, G. Steierl, J. Kirschner

Max-Planck-Institut für Mikrostrukturphysik, Weinberg 2, 06120 Halle, Germany

Abstract

Ferromagnetic CoFeSiB tips of low coercivity were used in a scanning tunneling microscope to achieve high-resolution magnetic imaging. Magnetic sensitivity is obtained on the basis of local tunneling magnetoresistance between the tip and the sample while the magnetization of the tip is switched periodically. For this method it is crucial to ensure a single-domain configuration at the end of the tip and to avoid mechanical vibrations of the tip due to magnetostriction. We present micromagnetic calculations that show that at the end of the tip only two magnetic states are possible and relate these theoretical expectations with the experiment. Further we demonstrate, that with the proper choice of materials, the magnetostriction can be suppressed well below the noise limit of the experiment and present domain wall profiles of Co(0 0 0 1) with a lateral resolution of at least 1 nm.

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1. Introduction

In the last decades, magnetic imaging has experienced several boosts of the lateral resolution [1–4]. With the invent of spin-polarized scanning tunneling microscopy (Sp-STM) that enables to image the topography as well as the magnetic structure of a sample at the same time [5–8], the lateral resolution finally reached the intrinsic length scale of magnetism, the magnetic exchange length of the order of 10 nm or below. In principle, this allows to image the magnetic structure of a sample in all detail. Magnetic imaging with a resolution below the exchange length is not only desirable from the fundamental point of view. Also in commercially available data storage devices, recording density has increased immensely so that bit lengths of 35 nm have been demonstrated. For further development of recording media, it is extremely useful to have an imaging technique at hand that is able to resolve the inner structure of the bits on the medium.

2. Experimental setup

In our approach to Sp-STM, we use a soft magnetic tip as the tip of the STM. The longitudinal magnetization of the tip is switched periodically by the magnetic field induced by a

*Corresponding author.

E-mail address: wulf@mpi-halle.mpg.de (W. Wulfhekel).

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small coil wound around the tip [6]. Magnetic contrast is obtained by locally measuring the tunneling magnetoresistance [9] between the magnetic tip and the surface of the specimen. The whole volume of the tip is ferromagnetic so that the field of the coil at the back side of the tip switches the magnetization of the tip apex, between the two well-known energetically favored states of opposite magnetization, as will be discussed in detail below. For optimal performance we used a tip etched from a wire of CoFeSiB metallic glass of vanishing magnetostriction ($<10^{-8}$), low saturation magnetization (≈ 0.5 T) and low magnetization losses at high frequencies. These parameters allow a rapid switching of the magnetization of the tip apex without significant magnetization losses up to 80 kHz. It is important for the functionality of the method that during the switching process of the tip the sample–tip distance is kept constant. Primary, this is necessary to avoid crashing of the tip, which is positioned only a few Å in front of the sample during STM operation. Secondary, one has to avoid changes of the tunneling current due to distance changes in order not to cover the small changes of the tunneling current due to the tunneling magnetoresistance. The extremely low magnetostricticton of the amorphous CoFeSiB [10] is essential to keep mechanical vibrations low during switching. The amorphous magnetic tips were first prepared in air. The tips were electrochemically etched from specially designed thin wires ($d \approx 130$ μm) produced by M. Vázquez by the in-rotating-water quenching technique [11]. This kind of wires shows a soft magnetic behavior associated with a high initial susceptibility. As etching agent, a diluted mixture of HCl and HF was used that was suspended as a thin liquid film in a Pt ring by surface tension during etching. The pH value was selected so that the formation of silica from the Si in the amorphous wire was prevented. Using low etching currents of the order of 250 μA, especially sharp and pointed tips are created, as can be seen in Fig. 1. The opening angle of the tip is typically around 12–15° and the radius of curvature can be as low as 20 nm. These tips were then fixed with a conducting glue to a non magnetic tip shaft ($d \approx 500$ μm), around which the magnetic coil (inner diameter ≈ 600 μm) was wound. The coil was mechanically fixed to the shaft by insulating glue to avoid vibrations. The coil is used to switch the longitudinal magnetization of the tip apex. The STM experiments were performed in an ultrahigh vacuum chamber system ($p = 5 \times 10^{-11}$ mbar) equipped with standard surface sensitive techniques like Auger electron spectroscopy (AES) and low-energy electron diffraction (LEED). Further, a modified commercially available room temperature STM[1] was installed. Care was taken in the STM design to avoid magnetic parts in the sample stage and scanning unit to allow the operation of the STM in an applied magnetic field. After the introduction of a tip to the STM, the tips were cleaned in situ by sputtering with 1 keV Ar^+ ions to remove the native oxide at the apex. A paramagnetic Cu(0 0 1) and a ferromagnetic Co(0 0 0 1) crystal were prepared in vacuum by Ar sputtering followed by annealing up to 800 K for Cu and 570 K for Co. No traces of contaminations on the samples could be found in AES spectra and LEED images showed sharp diffraction patterns with a low

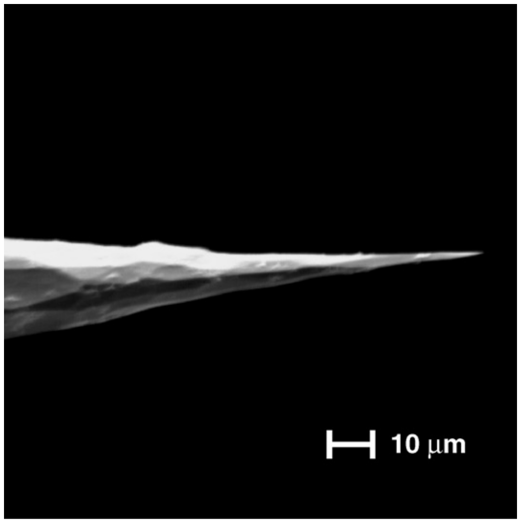

Fig. 1. Scanning electron microscopy image of the end of magnetic tip etched from a 130 μm amorphous wire.

[1] Micro-STM, Omicron Vakuumphysik GmbH, Idsteiner Street 78, 65232 Taunusstein, Germany.

background intensity. After sample and tip preparation, tunneling images of the topography as well as the magnetization were recorded at room temperature.

3. Magnetic configuration and reversal of the tip apex

First, we investigate the magnetic configuration at the end of the tip and how it can be switched by applying magnetic fields with a coil at the back side of the tip. For this, we performed micromagnetic calculations of the end of the tip to find the stable domain configuration. The simulations have been performed with a micromagnetic finite element algorithm based on direct energy minimization. The boundary element method is applied to accurately calculate the dipolar field [12]. The shape of the tip is approximated with a cone of an aperture angle of 12°, capped at its end with a hemisphere of 30 nm diameter. This rather complicated geometric structure can be modeled well by means of finite elements. Since the whole magnetic tip is too large (2 mm) to be modeled completely in the framework of numerical micromagnetism, we analyzed only the last 500 nm of the end of the tip. This, however, is well above the single-domain particle size so that the end of the tip is free to form domains in the volume that is included in the simulations. As the stable configuration, we found the single-domain state with a homogeneous magnetization pointing along the axis of the tip (see Fig. 2) in agreement with simple micromagnetic rules based on the shape factor of an elongated object [13]. Closure domains at the end of the tip are not stable in contrast to the domains found at the cylindrical ends of amorphous wires [14]. This is entirely due to the small diameter of several 10 nm at the pointed end of the tip. The apex of the tip is free from vortices and on the outer surface of the cone shaped tip, the magnetization points along the axis of the tip as well and hence does not lie in the surface of the tip. Evidently, the homogeneous configuration is energetically favorable compared to a structure without surface charges. This is not only so because of the almost vanishing exchange energy

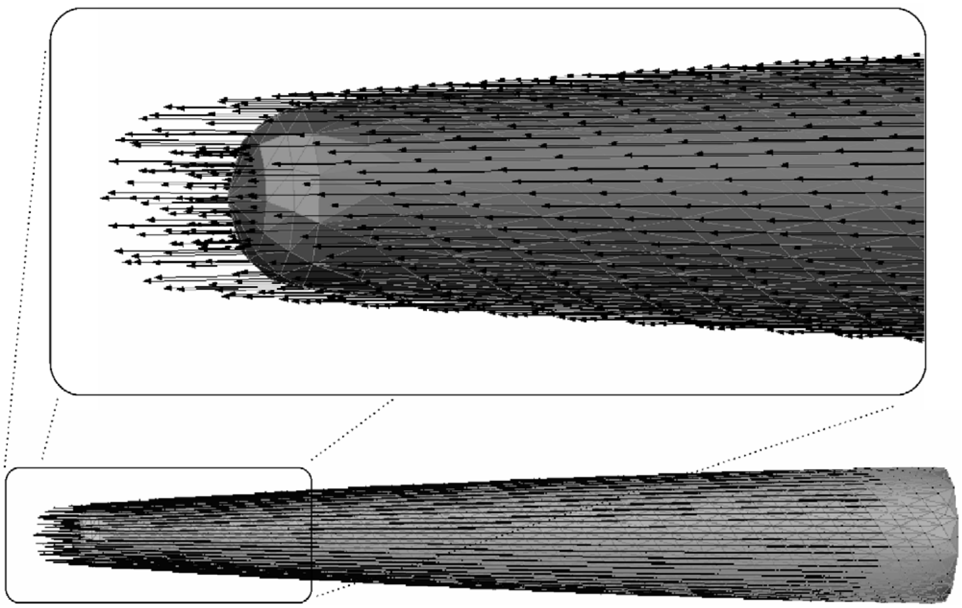

Fig. 2. Energetically lowest magnetic configuration of the end of the tip. The inset shows the apex in higher magnification and reveals that the magnetization on the outer cone surface (depicted as arrows) points along the tip axis. The total length of the simulated tip is 500 nm.

of the homogeneous arrangement, but also because an inhomogenous magnetic structure would lead to magnetic volume charges $\nabla \cdot M \neq 0$, so that stray fields could not be avoided. The necessary leaking by the geometrically required amount keeps the magnetization exactly along the tip axis on the outer surface of the cone-shaped tip. Due to reasons of symmetry, the configuration with opposite magnetization as depicted in Fig. 2a has the same energy, i.e., there are only two stable configurations. Hence, the end of the tip shows a bistable behavior.

The switching of the magnetization of the tip, however, is a more complex process. As has been shown with Kerr microscopy, the non-magnetostrictive wires show a multidomain structure and lack a single, large Barkhausen jump [15]. Nevertheless, due to their extreme magnetic softness, they display a high magnetic susceptibility. As a consequence, when a magnetic field is applied by the small coil at the back side of the tip, the created flux is dragged into the needle shaped tip. Applying a small field below saturation results in the movement of the internal domain walls and that the flux induced by the coil is fully kept inside the tip. Magnetostatically, it is unfavorable for the flux to leak out at the side of the tip and instead is guided to the apex. It is then only the direction of the flux that determines which of the two single-domain configurations of the end of the tip is the more stable one. If switching of the end of the tip is not hindered, e.g. by pinning of a domain wall, it is efficiently switched between the two states just by the collected flux from the back side of the tip. We checked for this switching behavior of the tip by micromagnetic simulations. For this, we chose as initial configuration for the simulation a tip with a 180° domain wall to mimic a domain of opposite magnetization induced on the back side by the applied field. This domain on the back side induces magnetic flux that drives the magnetic domain wall due to the conical shape of the tip towards the apex as can be seen in Fig. 3. The simulations, however, are not fully dynamic but represent the pathway of the magnetization during the approach towards the state of lowest energy. During the wall propagation along the conical tip, the total magnetic energy is constantly reduced and no energetic barrier is found. This implies that once a 180° domain wall is formed, it is driven out to the end of the tip and no pinning is observed due to the particular geometry of the tip. Therefore, the apex of the tip indeed is switched by applying a field to the back side of the tip in contrast to the cylindrical ends of full diameter of the amorphous wires, where closure domains have been observed [14].

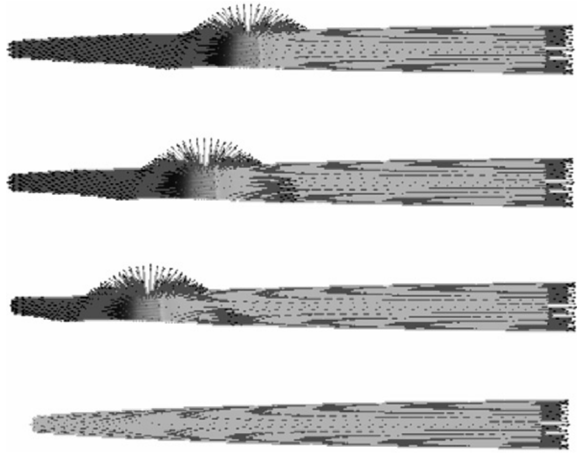

Fig. 3. Simulation of the switching of the apex of the tip. The magnetization component along the tip axis was coded as the brightness. Black (grey) represents magnetization to the left (right). Additionally, arrows point along the magnetization direction. The total length of the tip is 1000 nm.

4. Magnetostriction and mechanical vibrations

A priori, it was not clear if stable tunneling could be obtained while the magnetisation of the tip is rapidly switched. Magnetostriction in the tip possibly causes mechanical vibrations that may prevent imaging the surface. To check for these effects, we performed test measurements of the Sp-STM setup on a non-magnetic Cu(0 0 1) sample. Fig. 4a displays the topography of a Cu(0 0 1) crystal as obtained with a CoFeSiB tip, while applying an alternating field of ≈ 1 mT. Terraces separated by atomic steps are clearly visible. Obviously, vibrations due to magnetostriction are small enough to get stable STM images. Note

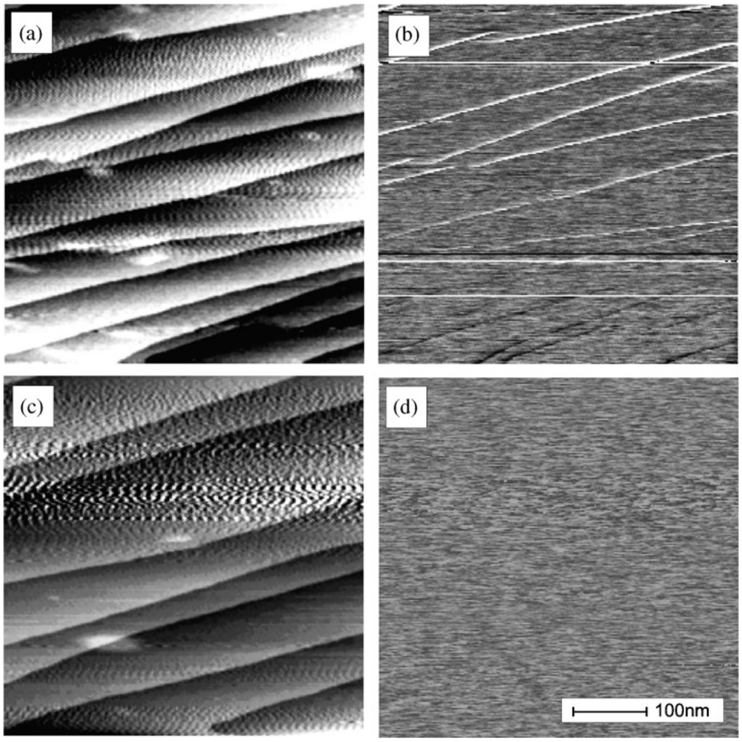

Fig. 4. STM scans of the topography (a,c) and the spin signal (b,d) of the same areas (a,b and c,d) of Cu(0 0 1). During scanning an alternating magnetic field of 20 kHz was created by the coil around the tip. The field was set to 1.1 mT (a,b) and 100 μT (c,d). For the higher field, mechanical vibrations of the tip are observed causing a cross-talk from the topography into the spin signal. Both spin images (b,d) are normalized to a black and white contrast corresponding to 0.3% of the tunneling current.

that the weak vibrations visible as ripples in the topography are not related to the switching of the tip but are due to insufficient damping of vibrations of the building. In the signal obtained from the lock-in amplifier; however, one observes a weak contrast at the step edges (see Fig. 4b). This cross-talk from the topography is of the order of 0.3% of the tunneling current and is due to small mechanical vibrations of the tip caused either by magnetostriction or other forces (e.g. forces due to eddy currents) acting on the tip in the alternating field of the coil. These vibrations can be avoided, when the exciting field is reduced by one order of magnitude (see Fig. 4c and d). The lock-in signal in this case is zero and does not show any cross-talk from the topography while the magnetization of the end of the tip is still switched, as will be discussed below. Hence, vibrations due to magnetostriction can be excluded down to the sensitivity of the lock-in detection of $<0.1\%$ of the tunneling current. Taking the well-known dependence of the tunneling current on the distance (see, e.g. Ref. [16]) with a tunneling voltage of 0.2 V, a tunneling barrier height of 3 V and a tunneling current of 1 nA, one can estimate the vibration in the narrow frequency band around the modulation frequency. The lock-in signal corresponds to distance changes between tip and sample of less than 5×10^{-4}Å, i.e., mechanical vibrations due to magnetostriction of the tip can safely be neglected.

This is also in agreement with the theoretical expectations for the magnetostriction in the tip. Switching of the tip proceeds by domain wall formation and/or domain wall movement and not by coherent rotation of the entire magnetization of the tip. As a consequence, magnetostriction only acts in the magnetic domain walls. Thereby, the length of the tip is changed by the magnetostriction of the wall, when a domain wall exits (or enters) the apex of the tip. The width of a 180° domain wall at the end of the tip can be estimated from simple micromagnetic rules [13] and is given by $2\sqrt{A/K}$, where A is the magnetic exchange and K the magnetic anisotropy that has to be overcome in the wall. We take the magnetic exchange of crystalline Co of $\approx 10^{-11}$ J/m as an upper limit for A. The dominant anisotropy term in the wall is given by the stray field energy of the wall of $K = \pi M_s^2$, i.e., the shape anisotropy of tip. With these values one gets an estimation for the domain wall width of 20 nm in good agreement with the full micromagnetic simulations from above (see Fig. 3). Together with the low magnetostriction constant of the material of 10^{-8}, this results in an undetectable distance change of the order of 10^{-5} Å in agreement with the experimental finding.

5. Imaging capabilities of Sp-STM

In magnetic imaging, the lateral resolution is given by the extension of area that is used for the physical interaction responsible for the contrast. In magnetic force microscopy, the magnetic volume at the end of the tip is responsible for the contrast formation and by this the lateral resolution is limited by the size of the magnetostatically interacting areas. These are usually of the order of several 10 nm [4]. In Sp-STM using a ferromagnetic tip the contrast is, however, due to the tunneling magnetoresistance effect of the tunneling electrons. The resolution is determined only by the shape of the very end of the tip. Under fortunate situations, the tip can be atomically sharp and only the the last atom of the tip carries a significant tunneling current such that very high resolutions can be achieved [17]. After Ar sputtering of the magnetic tips, the end of the tip is usually not atomically sharp, as can be deduced from a limited lateral resolution of the topographic STM images. However, by applying gap voltages above 4 V, field evaporation of atoms at the tip apex can be induced and by this, the tip can be sharpened and lateral resolution can be improved significantly. Using tips that have been sharpened by this method, we studied the closure domain pattern of Co(0 0 0 1) [18] and found extremely sharp domain walls. A line scan across such a sharp domain wall is depicted in Fig. 5. To estimate the wall width $w = 2\delta$, we fit the profiles with the standard wall profile for uniaxial systems [19]:

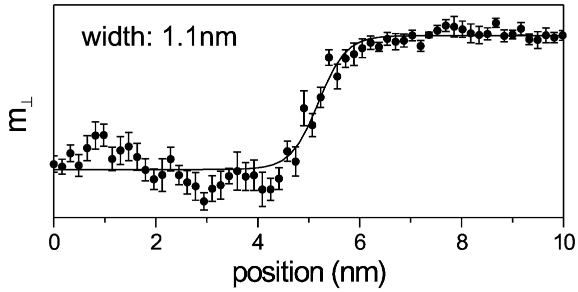

Fig. 5. Line profiles across an ultrasharp domain wall at the surface of Co(0 0 0 1) including the statistical errors and a fit with the standard wall profile (solid line).

$$m_z = \tanh\left(\frac{x}{\delta}\right) \quad (1)$$

resulting in a width of 1.1 ± 0.3 nm. From the magnetic contrast across the wall, the wall was identified as a 20° domain wall [20]. The width of this type of domain wall, can be calculated straightforward. Following the standard procedure for the calculation of domain wall widths by minimizing the sum of exchange and the anisotropy energy [13,19], one obtains a width of $w = 1.5$ nm in fairly good agreement with the experimentally observed width. This finding illustrates that the resolution one can obtain in Sp-STM with amorphous CoFeSiB tips is of the order of 1 nm or better. Using this specific material for the tips, lateral resolutions can be obtained that are much superior to those reported for MFM.

6. Summary

In conclusion, we have shown how amorphous CoFeSiB wires can be used as tips in Sp-STM due to their unique magnetic properties. The end of the etched tip shows a bistable magnetic configuration with a magnetization along the tip axis. It can be switched by rather low magnetic fields due to the high magnetic susceptibility of the material. During switching, magnetostrictive changes of the tip length can safely be neglected due to the small magnetostriction of the material. With CoFeSiB tips, a lateral resolution of 1 nm was obtained in the magnetic contrast.

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