Spin-polarized scanning tunneling microscope for imaging the in-plane magnetization

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We present a spin-polarized scanning tunneling microscope (Sp–STM) for imaging the magnetic in-plane component of magnetic surfaces. Magnetic in-plane sensitivity is obtained by using a ferromagnetic ring as a Sp–STM tip. By periodically switching the magnetization of the ring, the spin-dependent tunneling current between the ring and a spin-polarized sample is measured. The topography and the spin polarization can be imaged at the same time. We resolved the 180° domain wall of Fe whiskers and antiferromagnetic coupled Mn layers on Fe(001). © *2003 American Institute of Physics.* [DOI: 10.1063/1.1606867]

During the last years, two different approaches to spin-polarized imaging with scanning tunneling microscopy (STM) have been developed, i.e., spin-polarized scanning tunneling microscopy (Sp–STM)[1] and spin-polarized scanning tunneling spectroscopy (Sp–STS).[2] The high lateral resolution of these techniques allow new insight into micromagnetism.[3,4] In the case of Sp–STS, W tips coated with ultrathin magnetic films were used. The magnetic contrast was obtained from spectroscopic data, which also contain information on the density of states. By using different materials for coating, the magnetic out-of-plane and one in-plane component was measured. In Sp–STM, the magnetization of a soft magnetic tip is periodically switched and the spin dependent tunneling current between the tip and the sample is measured. To periodically switch the magnetization of the tip, a small alternating current is applied through a coil wound around the Sp–STM tip. The spin dependent part of the current which is the difference in the tunneling current for opposite tip magnetizations (ΔI) is separated from the unpolarized part which is the average tunneling current ($\overline{I}$) with a phase sensitive lock-in amplifier. In this way, the topography and the spin polarization can be imaged at the same time. Up to now, only the magnetic out-of-plane component could be imaged in this way by using sharp magnetic tips.[4]

Here we present a method for imaging a well-defined magnetic in-plane component. In this case, the sharp STM tip is replaced by a ferromagnetic ring. The advantage of a ring is that the magnetization lies along the tangential direction. Therefore, using the ring as a Sp–STM tip, sensitivity to the magnetic in-plane component of the sample along its tangential direction is obtained following the ideas of Johnson and Clarke.[5] As the stray field of an ideal ring is zero, rings used as STM tips should have no or little influence on the sample magnetization.

The rings are electrochemically etched from a CoFeSiB foil (25 μm thick). The foil is of the same CoFeSiB amorphous material as in our previous work.[1,4] After etching, the rings were polished on their outer perimeter. The grain size of the polishing paste was stepwise decreased to a $\frac{1}{4}$ μm and the polishing was checked with scanning electron microscopy (SEM) [see Fig. 1(b)]. Some grooves could be found which originate from polishing which, however, should not influence the tangential magnetization. After these preparation steps, the rings were annealed to 620 K in H_2 atmosphere. A small coil was wound around the rings that enables the switching of the ring's magnetization. The modulation frequency of the ring magnetization was chosen between 15 and 30 kHz. To determine the current needed to saturate the ring, magneto-optical Kerr-effect measurements were performed. As depicted in Fig. 1(c) a small current of 4 mA is enough to switch the magnetization. In Fig. 1(a) an optical image of a ring with a small coil is shown. The ring is fixed to the scanner with a W wire. A necessary condition to perform Sp–STM measurements is a clean tip and a clean sample. Therefore, all measurements were carried out in UHV. After the transfer into the vacuum, the rings were cleaned by argon sputtering. Argon sputtering and evaporation of some monolayers (ML) Fe on the tunneling part of the rings improved the spin contrast. The sample, an Fe whisker, was cleaned by cycles of argon sputtering and annealing (720 K) until no contamination could be found with Auger electron spectroscopy and a perfect crystal structure was observed by low-energy electron diffraction. During the sputtering and annealing processes, the domain structure of an Fe whisker may change. Thus, we installed a Kerr-

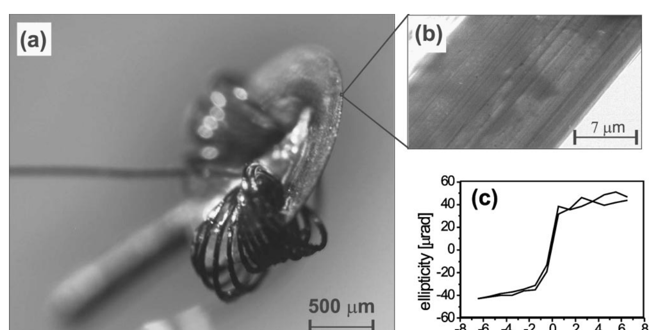

FIG. 1. (a) Optical image of a ring (outer diameter: 2 mm, inner diameter: 0.7 mm) with a small coil and a W wire, (b) SEM image taken at the outer perimeter of a ring, and (c) a Kerr loop of a ring.

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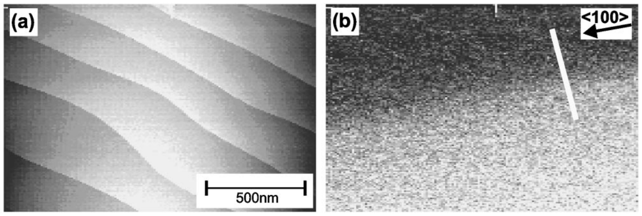

FIG. 2. Sp–STM image of (a) the topography and (b) the spin signal of an Fe whisker. Images were recorded at the same time at a bias voltage of 0.4 V and a feedback current of 1 nA.

microscope to crosscheck the domain pattern of the crystal in the UHV chamber. Some experiments were performed on Mn films grown on the Fe whisker. Mn was deposited by electron-beam evaporation with growth rates of 0.5 ML/min at 370 K. The evaporation rate of Mn was determined by medium-energy electron diffraction.

We chose Fe whiskers as test samples since they have been extensively studied in the past. Perfectly grown, defect free Fe whiskers have simple domain patterns,[6] i.e., 180° domain walls along ⟨100⟩ and 90° domain walls along ⟨110⟩. The magnetization at the surface of an Fe whisker lies in-plane and the domain walls at the surface are of Néel type. The domain pattern has been investigated with scanning electron microscopy with polarization analysis (SEMPA),[7] Kerr-microscopy,[6] and magnetic force microscopy.[8] Furthermore, Fe whiskers have flat surfaces (terrace sizes of several 100 nm) which is a necessary condition for imaging with a ring as a dull STM tip. Figure 2 shows the topography and the spin contrast of an Fe whisker, imaged with Sp–STM. In the topography, [Fig. 2(a)] monoatomic steps and terrace widths between 200 and 400 nm are visible. Tunneling with an ideal ring with an outer diameter of 2 mm should not result in high lateral resolution. The ring, however, shows small protrusions from polishing [see Fig. 1(b)] and possibly tips on the nanometer scale. Tunneling from these tips results in the observed high lateral resolution. In the image of the spin signal, clearly two domains separated by a 180° domain wall running along the ⟨100⟩ direction [Fig. 2(b)] can be seen. The spin signal contains no crosstalk of the topography and no magnetic structure of the 180° domain wall is found in the topography. A line profile across the domain wall obtained by averaging over 29 line scans is presented in Fig. 3

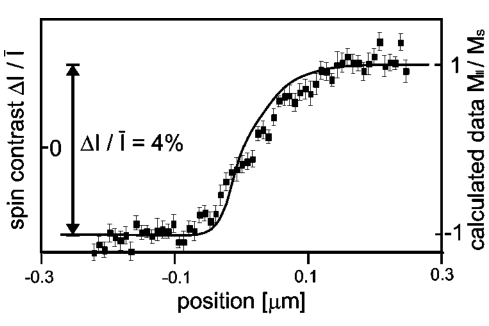

FIG. 3. Measured (squares) and calculated (solid line) (see Ref. 9) line profile across a 180° domain wall of an Fe whisker. The measured line profile is taken along the line indicated in Fig. 2(b). The error bars are the standard deviation of the mean of the 29 line scans.

(squares). The solid line represent the micromagnetically simulated line profile across the 180° domain wall.[9] It shows the in-plane component of the magnetization pointing along the domain wall ($M\|$) normalized to the saturation magnetization (M_s). The measured wall profile perfectly agrees with the calculated data within the lateral calibration error of the scanner (≈10%). Therefore, we indeed imaged the in-plane magnetization. The profiles are not always in such a good agreement. With some rings, the domain wall could be some 50 nm broader. This may be due to the very soft magnetic Fe whisker, where 1 Oe is enough to move an Fe whisker domain wall by some 100 nm. Therefore, the occasional broadening is likely due to a small residual stray field of some of the rings.

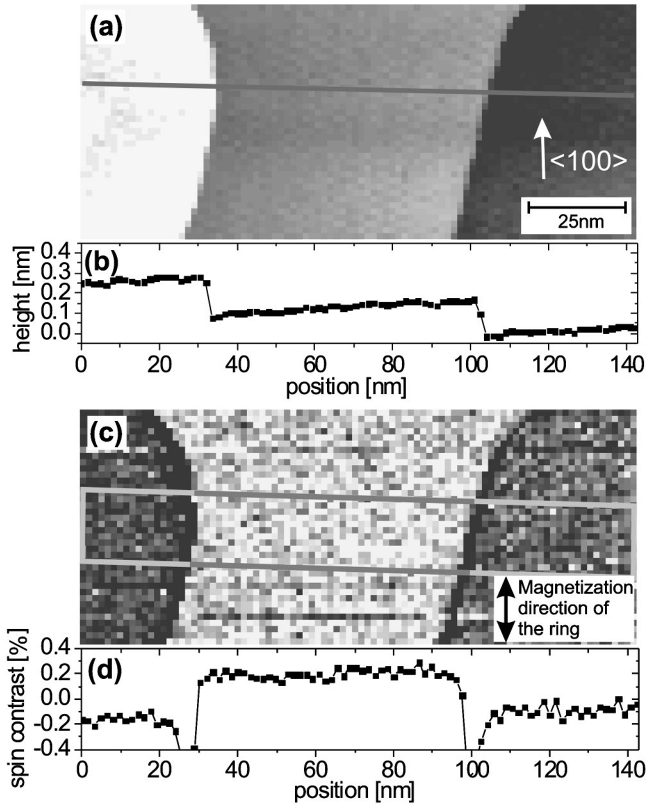

FIG. 4. Sp–STM image of (a) the topography and (c) the spin contrast of 7 ML Mn grown on Fe whisker. In the spin signal, the alternating contrast represents the antiferromagnetic coupling between adjacent Mn layers. (b) A line profile of the topography [line in (a)] and (d) a line profile of the spin signal averaged over 12 lines [rectangular in (c)]. The spin contrast is about 0.4%. Images were recorded at the same time at a bias voltage of 0.1 V and a feed back current of 3 nA.

Further, investigations were performed on the system Mn/Fe whisker. We studied the magnetic behavior of the topological antiferromagnetic Mn on a ferromagnetic substrate (Fe whisker). On this system, SEMPA and spin-polarized electron energy loss spectroscopy measurements showed that the Mn layers couple layer-wise antiferromagnetically.[10,11] We deposited 7 ML Mn on an Fe whisker at 370 K. The layer-by-layer growth of Mn on Fe whiskers changes to a layer-plus-island growth for layers thicker than 3 ML.[12] In Fig. 4, the topography and the corresponding spin signal are presented. Since we deposited 7 ML Mn, many levels are exposed on the surface. In Fig. 4(a), three different Mn layers on one Fe-whisker terrace are visible which are separated by monoatomic steps as seen from the line profile [Fig. 4(b)]. In the spin signal [see Fig. 4(c)], an alternating contrast between adjacent Mn layers can be seen. The spin signal of the first and third layer is the same but it is different from the one of the second layer [see line profile Fig. 4(d)]. The topography line profile shows that the signals derive from three different layers [Fig. 4(b)]. The alternating spin signal represents the antiferromagnetic coupling. The spin contrast on Mn strongly depends on the bias voltage; a high spin contrast was measured around 0.1 V. The two dips in the line profile [Fig. 4(d)] correspond to a crosstalk of the topography at the step edges. This may be due to the finite response speed of the feed back loop or due to nonperpendicular tunneling between the ring and the sample at the step edges. For this measurement the magnetization of the ring was along the ⟨100⟩ direction of the Fe whisker as indicated in the image. Hence, the measured spin signal corresponds to the spin component of the Mn along the ⟨100⟩ direction. Line profiles (not shown) across topologically enforced domain walls in the antiferromagnetic Mn layers revealed a lateral resolution of ≈ 1 nm similarly to the resolution obtained with the same method for the out-of-plane component of the magnetization.[4] Sp–STS measurements performed on the same system show a similar behavior of magnetic coupling between adjacent Mn layers.[13,14] However, no information on the direction of sensitivity could be obtained up to now by Sp–STS.

Comparing the method of Sp–STM presented here with Sp–STS,[2] the first has the advantage that the contrast is independent of the electronic structure and only sensitive to the spin, i.e., the electronic structure of the sample need not to be known and need not to be homogeneous. This allows to interpret the measured signal as a pure spin signal. Furthermore, using a ring as a Sp–STM tunneling tip the direction of sensitivity is known. In the case of SP–STS measurements, it has not been possible so far to determine the magnetization direction of the tunneling tip. Further, the contrast in Sp–STS contains mixed information on the spin and the total density of states.

In conclusion, we showed a simple way to image one well defined in-plane component of the sample spin polarization with a lateral resolution of 1 nm by using a ring as a Sp–STM tip. We demonstrated the capability of this method by resolving a 180° domain wall of a ferromagnetic Fe whisker and the antiferromagnetic coupling of Mn layers grown on an Fe whisker. Since the stray field of the rings is small, it was possible to image domain walls of a soft magnetic material. With all rings that showed easy magnetic switching [similar to the Kerr loop of Fig. 1(c)], we were able to obtain magnetic contrast after ring preparation by sputtering and/or Fe coating. Rings could be used for several months.

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