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High-resolution study of magnetization and susceptibility by spin-polarized scanning tunneling microscopy

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We present static measurements of the domain structure and dynamic results on domain wall motion and local susceptibility obtained by spin-polarized scanning tunneling microscopy. The topography and the magnetic structure of the sample are recorded simultaneously with down to 10 nm resolution. With this technique, domain wall movement on Co(0001) is studied *in situ*. In some cases, the magnetization of the sample is locally influenced by the stray field of the tip. Measuring higher harmonics in the tunneling current allows one to quantify this influence and measure magnetic susceptibilities on similar scales. © *2000 American Institute of Physics.* [S0021-8979(00)19908-6]

It is one of the challenges of experimental micromagnetism to image magnetic structures down to scales below the exchange length. With techniques like scanning electron microscopy with polarization analysis (SEMPA), spin-polarized low-energy electron microscopy (SPLEEM) or magnetic force microscopy (MFM) resolutions of several 10 nm have been achieved. These resolutions, however, are not sufficient to study hard magnetic materials like Co(0001) in that detail. Additionally, SEMPA and SPLEEM do not allow dynamic studies due to long acquisition times or limitations in the use of an applied magnetic field. An alternative scanning technique that intrinsically offers atomic resolution is scanning tunneling microscopy (STM). By using a spin-polarized tunneling current, STMs high topographic resolution can be extended to spin sensitivity to the sample electrons as has been reported by several groups.[1–7] However, in most of these experiments, no magnetic images were obtained and only in the work of Suzuki *et al.*[5,6] and Bode *et al.*,[7] lateral imaging with a contrast due to tunneling was reported. However, no rigorous proof for a magnetic origin of the contrast was given and in some cases, an optical contrast could not be excluded.[5,6] In this work, we use a magnetic tip to image the sample in the spirit of Johnson and Clarke.[1] We separate the spin-dependent part of the tunnel current by rapidly changing the magnetization of the tip and detecting the variations in the tunnel current due to the magnetotunnel effect[8] with a lock-in amplifier.[9] This technique offers a high spin contrast, fast data acquisition times in the range of ms/pixel and allows dynamic studies. Even magnetic susceptibility can be measured when an appropriate tip sample combination is used.

Experiments were performed in an ultrahigh vacuum chamber ($p = 5 \times 10^{-11}$ mbar) equipped with an Auger electron spectrometer (AES), low-energy electron diffraction (LEED), and a room-temperature STM. To allow the operation of the STM in an applied magnetic field, magnetic parts in the sample stage and scanning unit were avoided. The Co(0001) sample as well as magnetic tips were cleaned *in situ* by argon sputtering. The sample was annealed afterwards by heating to 570 K. In AES spectra, no traces of contaminations could be found. LEED images showed the expected sixfold diffraction pattern with sharp spots and low background intensity. After sample and tip preparation, tunnel images of the topography were recorded at room temperature. During imaging, an alternating current of frequency f was passed through a small coil wound around the magnetic tip to periodically switch the longitudinal magnetization of the tip. This results in variations of the tunnel current due to the magnetotunnel effect,[8] that were detected with a lock-in. To allow a rapid switching of the magnetization of the tip without mechanical vibrations due to magnetostriction, magnetic forces or magnetization losses, the tip material was chosen to have a low coercivity, vanishing magnetostriction and a low saturation magnetization.[9] The frequency f was set to 40–80 kHz, i.e., well above the cutoff frequency of the feedback loop, to avoid reactions of the z control on the magnetically induced variations of the tunneling current.[9] Tests of the setup on paramagnetic Cu(100) showed no variations of the tunneling current due to vibrations or magnetostriction. Since the tip is magnetized along its axis and perpendicular to the sample surface, sensitivity mainly for the perpendicular magnetic component of the sample is obtained. However, the geometry of the very end of the tip is unknown and a small sensitivity to in-plane components cannot be excluded. Hence, the output signal of the lock-in is mainly proportional to the perpendicular component of the magnetization.

Figure 1(a) displays the topography of the Co(0001) surface. Due to a slight and practically unavoidable miscut of the sample, steps are present on the surface that bunch during annealing to form step bunches 1–2 nm high separated by

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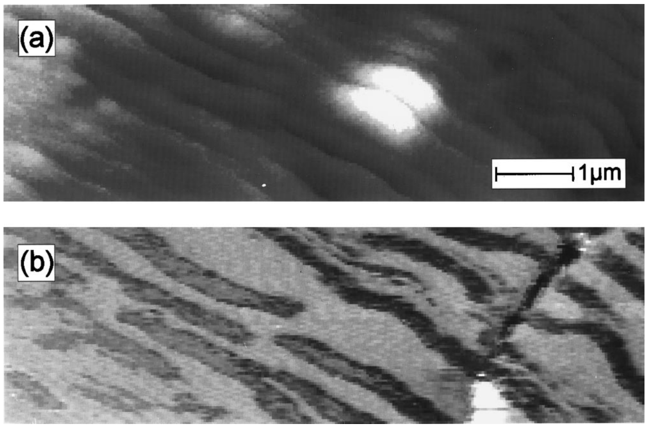

FIG. 1. STM images of (a) the topography and (b) the magnetic closure domain structure of the same area of Co(0001). Sample bias: 0.2 V, tunneling current: 0.5 nA, (a) height variations 4 nm, (b) spin contrast: 3.6%.

flat terraces ≈500 nm wide. This leads to some roughness of the surface. Keeping in mind that the presented scans extend over several μm, i.e., are rather large for a high-resolution technique like STM, the observed roughness of few nm still corresponds to a very flat surface. Figure 1(b) shows the magnetization of the very same area of the sample, as seen with the spin-polarized STM. The expected closure domain pattern with domains of the order of 500 nm is observed.[10,11] Many of the closure domains are pinned at the step bunches giving alternating magnetization on adjacent flat regions of the sample. The influence of the topography on the local arrangements of closure domains is not unknown and has been reported for structures on larger scales.[10] However, there are also domains that are not correlated to the morphology [upper right corner of Fig. 1(b)]. The contrast in the magnetic image, i.e., the tunneling magnetoresistance, is mostly smaller than that corresponding to tunneling experiments.[12,13] This is probably due to the fact that the majority of surface domains on Co(0001) show only a small perpendicular component[11,14] and are oriented almost in-plane giving a small projection of the magnetization onto the tip axis.

To estimate the lateral resolution of the spin signal, we focus on the observed domain walls. Figure 2 displays a linescan across a domain wall separating two domains of opposite contrast. The scan (raw data) reveals a wall width of ≈17 nm which is in good agreement with the estimated width of a 180° Bloch wall for Co of 15.7 nm.[15] However, one has to keep in mind that in the closure domain pattern of Co(0001), many different types of walls of lower angles are present[11,14] that might modify the domain wall thickness. The linescan reveals a lateral spin resolution of about 10 nm.[16] This high lateral resolution is obtained in combination with a high contrast and low data aquisition times (3 ms/pixel). The resolution in the topography channel, however, is better (≈1 nm) and in principle, the magnetic resolution should be of similar size. Unfortunately, magnetic domain walls are usually much broader than that. Hence, the demonstrated resolution is basically limited by the sharpness of the available magnetic structures.

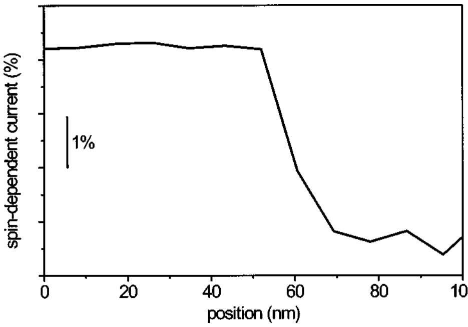

FIG. 2. Linescan across a domain wall between two domains of opposite contrast on Co(0001) revealing a resolution of ≈10 nm.

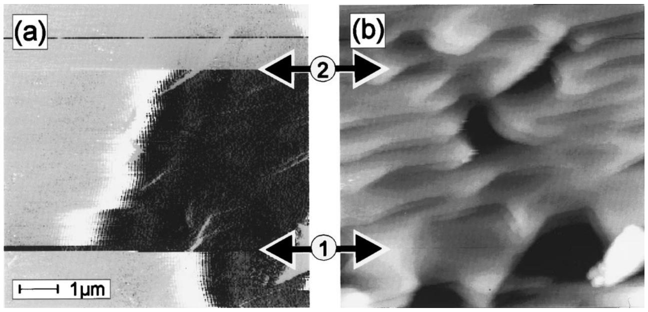

FIG. 3. STM image of (a) the domain structure and (b) topography of the same area of the surface of Co(0001). When applying external magnetic field pulses of 50 Oe during scanning (indicated by the arrows), the domain wall can be moved to the left (1) or right (2), depending on the direction of the field. No movement is observed in the topography.

The observation of a contrast in the magnetic channel, even if the expected domain structure is seen, is no rigorous proof for a magnetic origin of the signal. To exclude all other origins, we did a proper magnetic experiment. We carried out dynamic measurements and studied the influence of a magnetic field on the features in the spin signal. On Co(0001), the observed features show only minor changes even after extended scanning of the same area over hours. When applying a short pulse of a homogeneous magnetic field of the order of 50 Oe perpendicular to the sample surface as indicated by the arrows in Fig. 3, the observed domain wall can be moved a couple of μm during scanning [see Fig. 3(a)], while no movement is observed in the topographic image [see Fig. 3(b)]. This unambiguously proves the magnetic origin of the spin signal. The observed structures are indeed magnetic domains and domain walls on the surface. Additionally, this illustrates that spin-polarized STM can be used to study the domain wall movement dynamically during scanning.

Spin-polarized STM using a ferromagnetic tip poses some constrains on the shape of the tunneling tip. To obtain a good and possibly atomic resolution, the very end of the tip has to be atomically sharp. This also determines the magnetic resolution. When imaging domain walls or soft magnetic materials, however, the stray field of the magnetic tip cannot be neglected, since it might influence the structures under investigation. Freshly prepared tips that are also sharp on the mesoscopic scale produce a rather localized stray field; the domain walls of hard magnetic materials are not

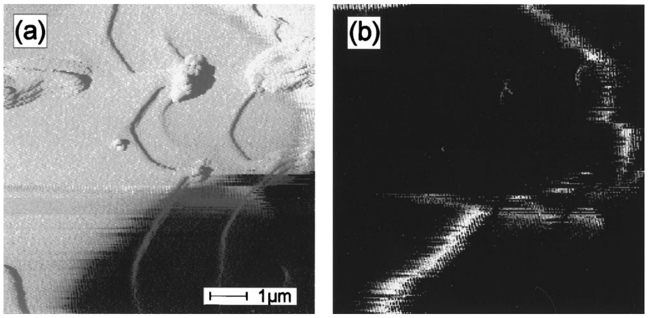

FIG. 4. STM images of (a) the magnetic domain structure and (b) magnetic susceptibility of the same area on Co(0001).

effected and are resolved with high resolution like in Fig. 1. When a dull tip is used,[17] however, domain walls are smeared out like in Fig. 3 or Fig. 4(a). This is due to a periodic domain wall movement induced by the alternating field of the tip. The walls rapidly vibrate with the magnetization frequency f, such that the resolution is limited to $\approx 1000\,\text{nm}$ [see Fig. 4(a)]. However, this interaction can also be used to locally measure the magnetic susceptibility of a sample. Since the magnetization cannot follow instantaneously the stray field of the tip, a phase difference between the magnetization of the tip and the sample exists and due to the nonlinearity of the magnetization process, higher harmonics in the tunneling current are produced that can also be detected with a lock-in amplifier. This mechanism may be used to obtain domain wall contrast as shown in Fig. 4(b) ($2f$ signal). From the observed width of the susceptibility signal around the wall and the switching frequency f, a local domain wall speed of $\approx 10\,\text{cm/s}$ can be estimated. This technique in combination with higher switching frequencies might even allow the local study of the switching behavior of individual magnetic nanostructures.

In conclusion, we have demonstrated that spin-polarized STM using a magnetic tip is a suitable technique to image hard magnetic structures with superb resolution. We have presented dynamic observations of domain wall movement and by this unambiguously proven the magnetic origin of the observed contrast. Further, magnetic susceptibility can be recorded simultaneously together with the magnetization and the topography. This technique might be used to study the switching behavior of individual magnetic nanostructures and allows the investigation of the local susceptibility in soft magnetic materials or domain walls.

[1] M. Johnson and J. Clarke, J. Appl. Phys. **67**, 6141 (1990).
[2] R. Wiesendanger, H. J. Güntherodt, G. Güntherodt, R. J. Gambino, and R. Ruf, Phys. Rev. Lett. **65**, 247 (1990).
[3] S. F. Alvarado and P. Renaud, Phys. Rev. Lett. **68**, 1387 (1992).
[4] M. W. J. Prins, R. Jansen, and H. van Kempen, Phys. Rev. B **53**, 8105 (1996).
[5] Y. Suzuki, W. Nabhan, and K. Tanaka, Appl. Phys. Lett. **71**, 3153 (1997).
[6] Y. Suzuki, W. Nabhan, R. Shinohara, K. Yamaguchi, and T. Katayama, J. Magn. Magn. Mater. **198–199**, 540 (1999).
[7] M. Bode, M. Getzlaff, and R. Wiesendanger, Phys. Rev. Lett. **81**, 4256 (1998).
[8] M. Julliere, Phys. Lett. **54A**, 225 (1975).
[9] W. Wulfhekel and J. Kirschner, Appl. Phys. Lett. **75**, 1944 (1999).
[10] D. Craik and R. S. Tebble, in *Ferromagnetism and Ferromagnetic Domains*, edited by E. P. Wohlfahrt (North-Holland, Amsterdam, 1965), p. 119.
[11] J. Unguris, M. R. Scheinfein, R. J. Celotta, and D. T. Pierce, Appl. Phys. Lett. **55**, 2553 (1989).
[12] Y. Lu, X. W. Li, G. Xiao, R. A. Altman, W. J. Gallagher, A. Marley, K. Roche, and S. Parkin, J. Appl. Phys. **83**, 6515 (1998).
[13] J. S. Moodera, J. Nowak, and R. J. M. van de Veerdonk, Phys. Rev. Lett. **80**, 2941 (1998).
[14] A. Hubert and R. Schäfer, in *Magnetic Domains* (Springer, Berlin, 1998), p. 321.
[15] E. Kneller, in *Ferromagnetismus* (Springer, Berlin, 1962), p. 293.
[16] We define the resolution by the length over which the contrast in a domain wall changes by 67% of the total contrast of the wall.
[17] The tip used in this experiment is dull on the mesoscopic scale due to several severe tip crashes.