Spin-Polarized Scanning Tunneling Microscopy with Antiferromagnetic Probe Tips

A. Kubetzka,* M. Bode, O. Pietzsch, and R. Wiesendanger

Institute of Applied Physics and Microstructure Research Center, University of Hamburg, Jungiusstrasse 11, D-20355 Hamburg, Germany

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We have performed low temperature spin-polarized scanning tunneling microscopy (SP-STM) of two monolayers Fe on W(110) using tungsten tips coated with different magnetic materials. We observe stripe domains with a magnetic period of 50 ± 5 nm. Employing Cr as a coating material we recorded SP-STM images with an antiferromagnetic probe tip. The advantage of its vanishing dipole field is most apparent in external magnetic fields. This new approach resolves the problem of the disturbing influence of a ferromagnetic tip in the investigation of soft magnetic materials and superparamagnetic particles.

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Imaging magnetic structures at the single digit nanometer scale is an important issue with respect to basic research as well as technological applications [1]. Recently, a number of different nanomagnetic systems have been investigated with spin-polarized scanning tunneling microscopy (SP-STM) [2–5], a technique which allows a lateral magnetic resolution down to the atomic scale [6,7]. In these studies the tunnel magnetoresistance effect between a ferromagnetic (FM) tip and a ferro- or antiferromagnetic (AF) surface has been exploited for domain imaging. Despite the fact that the magnetic dipole interaction between the sample and the tip is considerably reduced for FM ultrathin film coatings on a nonmagnetic tip in comparison to thicker coatings [2,8] or even bulk FM tips [9,10], a remaining influence cannot be ruled out which might play an important role for magnetically soft or superparamagnetic samples. Pareek and Bruno stated that this interaction "cannot be avoided" [11]. A straightforward and experimentally feasible solution, however, is the use of an AF coated or bulk AF tip. It should exhibit no significant stray field since opposite contributions compensate on an atomic scale. Nevertheless, it is suitable for SP-STM due to a nonvanishing spin polarization near the Fermi level [12]. Furthermore, the tip is insensitive to external fields, which allows one to directly access intrinsic sample properties in field dependent studies.

In this Letter we report on SP-STM measurements of two monolayers (ML) Fe on W(110) at $T = 14$ K. Employing in-plane and out-of-plane magnetized FM tips we investigated the magnetic structure of the sample: We observe dense stripe domains with a defined sense of magnetic rotation. This leads to the formation of numerous 360° walls in applied perpendicular fields. A direct comparison between a GdFe- and a Cr-coated tip reveals that the remagnetization of these walls occurs in external fields which are 200–300 mT higher when a Cr tip is used than for the GdFe tip case, which is a direct consequence of the Cr tip's vanishing stray field. This experimental result illustrates the importance of using AF probe tips in quantitative studies of nanoscale magnetic systems.

The experiments were performed in a UHV system with different chambers for surface analysis, sample preparation, metal vapor deposition, and cryogenic STM [13], with a base pressure in the low 10^{-11} torr range. The W(110) single crystal has a miscut of 0.5° which leads to an average terrace width of ≈25 nm. Fe is deposited onto the clean substrate at $T = 500 \pm 50$ K with a rate of ≈0.5 ML/min, resulting in an almost perfectly closed double-layer (DL) film at $\theta = 2.0$ ML. The W tips were flashed *in vacuo* at $T = 2300$ K, coated with magnetic material, and subsequently annealed at $T \approx 550$ K for 4 min. We used four different kinds of coating: (i) 10 ± 1 ML Fe, (iiA) 7 ± 1 ML Gd and 0.5 ML Fe, (iiB) 14 ± 2 ML Gd and 1 ML Fe, and (iii) 35 ± 10 ML Cr. The alloy films were prepared by coevaporation. Maps of the differential conductance dI/dU ("magnetic signal") were recorded simultaneously to the constant current images (topography) by adding a modulation voltage of $U_{\mathrm{mod}} = 20\ \mathrm{mV_{rms}}$ to the sample bias U and detecting the dI/dU signal by a lock-in technique.

In the first experiment we investigated the sample's initial state with FM tips. Figure 1(a) displays a 3D composite of a constant current image and the simultaneously acquired dI/dU map of 2.0 ML Fe/W(110), recorded with a type A GdFe tip (top view shown in the inset). Since the tip has a magnetization perpendicular to the surface, the dI/dU map is an image of the z component of the surface magnetization. We observe stripe domains with a period of 50 ± 5 nm and the domains roughly oriented along $[1\bar{1}0]$. Adjacent terraces are exchange coupled across the step edges. A number of dislocation lines with [001] orientation can be seen which, however, have no detectable influence on the domain structure. The lower panel of Fig. 1(a) displays a line section taken as indicated in the inset. It can be fitted by three winding 180° Bloch walls [14], using a standard wall profile, $\sin(\varphi(x)) = \tanh[(x - x_0)/(w/2)]$ [15], with a wall width of $w = 7$ nm and a distance between wall centers of 23 nm. To verify that indeed all walls exhibit the same sense of magnetic rotation ("winding" case in Ref. [14]) we employed probe tips with in-plane

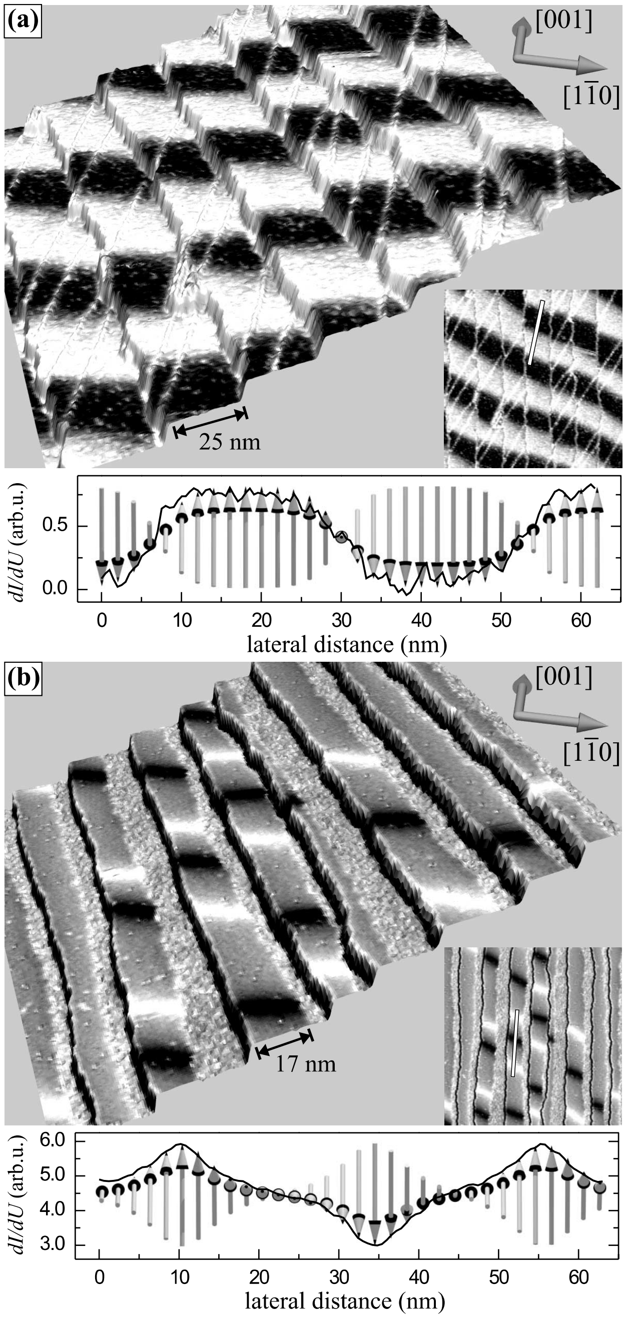

FIG. 1. (a) Constant current topograph of 2.0 ML Fe on W(110) colorized with dI/dU map ($I = 0.3$ nA, $U = -0.45$ V), recorded with a GdFe tip (out-of-plane contrast) at 14 K. Stripe domains are observed with a magnetic period of 50 ± 5 nm and the domains roughly oriented along $[1\bar{1}0]$. A line section is compared to a proposed magnetic configuration (side view). (b) 1.6 ML Fe/W(110) imaged with an Fe tip (in-plane contrast) at $I = 0.3$ nA, $U = -0.1$ V. Domain walls appear alternately bright and dark. A second line section is compared to the same magnetic configuration (top view).

sensitivity. Figure 1(b) shows an image of 1.6 ML Fe/W(110) recorded with an Fe tip. In the DL areas the domain walls now appear alternately bright and dark without exception, indicating an opposite magnetization direction within the centers of neighboring walls, in agreement with the assumption made above. This is a general property of the DL domain structure which we also observe on the closed 2.0 ML Fe film (not shown). To further illustrate this point, we took a line section from an area which also contains three domain walls like the section in Fig. 1(a). It can be reproduced by the same formula as above if one allows for a rotation of 90° to take the different magnetization direction into account. The two line sections therefore represent one and the same magnetic configuration within our measurement accuracy. Note, however, that since we have no means of controlling or knowing the azimuthal angle of the tip's magnetization the Bloch type character of the walls cannot directly be inferred from our measurements but follows from the fact that the $[1\bar{1}0]$ direction is a magnetic easy axis for the extended DL at higher temperatures [16,17]. In comparison to Fig. 1(a) the distances between walls have locally increased with decreasing structural width of the DL and the walls are distributed more irregularly. We regard this domain structure as an intermediate state between the fully developed stripe domains at $\theta = 2.0$ ML and the dipolar antiparallel coupled nanowires observed on substrates with narrower terraces [3,14,18,19].

In the second set of measurements we investigated the response of the system to an applied perpendicular magnetic field. Figure 2(a) displays a series of dI/dU maps of 1.95 ML Fe recorded with a type B GdFe tip. Figure 2(a)(i) shows an overview of the initial state. Dislocation lines appear as bright lines along [001], because they locally change the electronic properties. The domain structure is similar to the one in Fig. 1(a), except that the exchange coupling across the step edges is significantly reduced. A second image 2(a)(ii) is taken at higher resolution as indicated by the frame in 2(a)(i). Because of the coverage being slightly below $\theta = 2.0$, narrow ML areas can be seen, appearing bright at the chosen bias voltage. These ML areas efficiently decouple DL regions on adjacent terraces. At 350 mT [2(a)(iii)] the domain distribution is asymmetric: bright domains have grown and dark domains have shrunk which is equivalent to a formation of 360° walls [20]. In some places the magnetic contrast changes abruptly from one horizontal scan line to the next (see arrows), a result of a rearrangement of the sample's magnetic state during the imaging process. At 700 mT [2(a)(iv)] the sample has reached saturation within the field of view, except for two walls at the lower right. However, it becomes obvious in the overview image, recorded at the same location in zero applied field [2(a)(v)], that this field value does not reflect intrinsic sample properties. A large fraction of dark domains has survived outside the region which was scanned previously at 700 mT. We conclude that the superposition of the applied field and the additional field emerging from the magnetic coating of the tip is much more efficient in the remagnetization of 360° walls than the applied field alone.

Figure 2(b) shows an analogous series of images of a sample, which was prepared identically, but imaged with

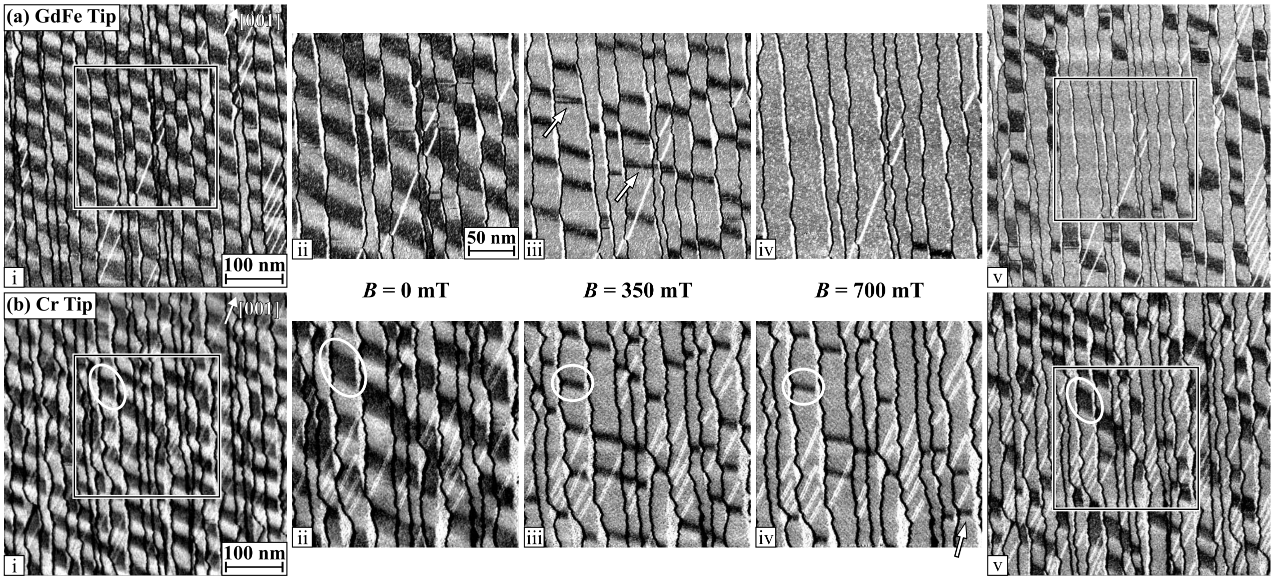

FIG. 2. (a) dI/dU maps of 1.95 ML Fe/W(110) recorded with a GdFe tip (out-of-plane contrast) at $I = 0.3$ nA, $U = -0.22$ V: (i) 500×500 nm^2 overview of magnetic initial state. (ii) 250×250 nm^2 zoom-in. (iii) Asymmetry at $B = 350$ mT: Dark domains are compressed and form 360° walls. (iv) Saturation is observed within the field of view. (v) The influence of the tip's stray field becomes obvious in the overview recorded at $B = 0$ mT. (b) Analogous series of an identically prepared sample, recorded with a Cr-coated tip at $I = 0.8$ nA, $U = -0.5$ V: (i),(ii) Magnetic initial state. (iv) A large fraction of walls has survived at 700 mT, in contrast to (a). (v) The scanned area exhibits no significant difference in comparison to its surrounding.

an AF Cr-covered tip. It exhibits an out-of-plane sensitivity like the GdFe tips. We have marked a dark domain as an example to be recognized in all five images. The domain structure in Fig. 2(b)(i)–2(b)(iii) displays no significant difference to the corresponding ones in 2(a). Since a rearrangement of the domain structure during imaging is not observed throughout this series, the occurrence of such events in 2(a) can be attributed to the GdFe tip's stray field. Alternative explanations like thermally or tunnel current activated wall motion can be excluded by a comparison with 2(b). As in Fig. 2(a)(iii), the dark domains are compressed at 350 mT and rotated away from the $[1\bar{1}0]$ direction, thereby reducing their lengths. These are two processes which proceed at 700 mT. At this field value and in contrast to 2(a) a large fraction of dark domains has survived. In the overview image 2(b)(v) taken in zero applied field, the previously scanned area exhibits no significant difference in domain distribution in comparison to its surrounding, a result demonstrating the advantage of a stray field free tip. A closer inspection of Fig. 2(b)(v) reveals two details: While the dark domains have again increased in size from 2(b)(iv) to 2(b)(v) they retain their number. The imbalance of bright and dark areas means that the sample is in a remanent state. Second, dark domains have vanished preferentially in regions with dislocation lines.

To estimate the effect of the GdFe tip's stray field we further increased the field in steps of 50 mT (not shown), in order to reach a magnetic state which is equivalent to Fig. 2(a)(iv). At 900 mT only a single dark domain is left, which we marked by an arrow in Fig. 2(b)(iv) [21]. We conclude that the effect of the GdFe tip's stray field is equivalent to an additional homogeneous perpendicular field of 200–300 mT. Even though this value is considerably below the highest value possible at a Gd surface, $B_{\max} = \mu_0 M_s/2 \approx 1.3$ T, it seems to be inconsistent with the rather weak tip-sample interaction observed in the absence of an applied field. To clarify this issue we calculated the tip's stray field using formulas derived in Ref. [22]. We model the tip by two parts: a smooth thin film on a half sphere, magnetized normal to its surface, and a cone on its apex as a nanotip being responsible for the tunneling process, magnetized along its axis. Using $M_s = 2.13 \times 10^6$ A/m for Gd and a radius of $r = 500$ nm [23] we calculate the field of the thin film to be of the order of 1 mT per nm coating thickness s for $s \ll r$ at a distance of 1 nm from its surface. This contribution is much too weak and too homogeneous to explain the strength and locality of the tip-sample interaction observed in Fig. 2(a)(v) [24]. We assume the nanotip to be a triangular pyramid with an aspect ratio of bulk hcp Gd ($h/a = 2.89/3.64$), which we approximate by a point sharp cone of the same height h and the same volume ($h/r \approx 2.14$). Figure 3 displays the perpendicular and in-plane components of the stray field of such a cone at tunneling distance (1 nm) vs lateral distance x for heights $h = 1$–3 nm [25] with the ratio h/r kept constant. These fields are highly localized, and their strength increases monotonously with the cone's size. We argue that, for the given sample, such inhomogeneous fields arising from the STM tip's roughness are sufficient to locally trigger remagnetization processes at external fields close to the sample's coercivity, but do not seriously alter the magnetic state in the absence of an external field, due to the small interaction

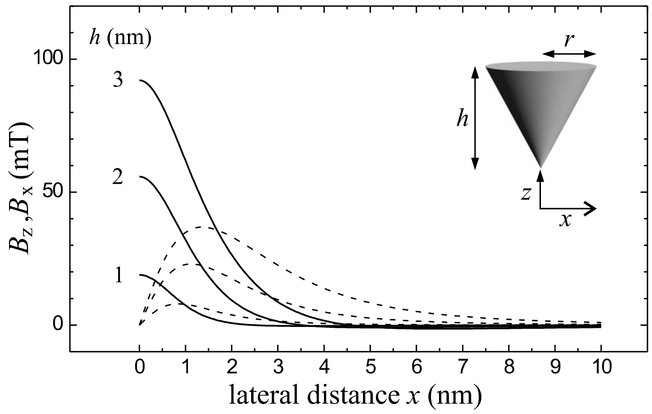

FIG. 3. Perpendicular stray field component B_z (solid line) and in-plane component B_x (dashed) of a cone vs lateral distance x from its axis, calculated at $\Delta z = 1$ nm.

area. The latter might, however, not be the case for magnetically softer substrates or superparamagnetic particles.

To shed some light onto the remagnetization process and to estimate whether the former assumption is quantitatively reasonable we performed micromagnetic calculations [26] for a single 360° wall in an isolated DL section, the details of which will be published elsewhere. In addition to the perpendicular [110] easy axis, we introduced a second uniaxial anisotropy K_h, with the hard axis along [001], which stabilizes these walls in applied perpendicular fields [20,27]. With increasing field the wall reduces in size until at a critical field B_c a breakdown process occurs, where the uniform state is reached by a rotation via the hard axis. For a given set of reasonable magnetic parameters [28] the experimentally determined critical field $B_c = 900$ mT can be reproduced by choosing $K_h \approx -2.1 \times 10^6$ J/m^3. It turns out that at 700 mT a localized field of only 40 mT along the hard direction is sufficient to initiate the remagnetization at the DL boundary. It is thus the in-plane component of the tip's stray field B_x which is most effective in the remagnetization process. Furthermore, since B_c scales down with decreasing K_h, the observed reduced stability of 360° walls in areas with dislocation lines can be explained by a reduced value of K_h. This is plausible, since dislocations locally distort the lattice, thereby lifting the in-plane symmetry of the film.

In summary, we have investigated the magnetic structure of two monolayers Fe on W(110) with SP-STM at $T = 14$ K. We observe dense stripe domains with a defined sense of magnetic rotation, which leads to the formation of numerous 360° walls in applied perpendicular fields. The influence of an FM probe tip's stray field onto their remagnetization has been investigated in detail. The advantage of a stray field free AF probe tip is demonstrated by a direct comparison. This new approach might play an important role in the investigation of a number of magnetic materials and processes which require a well defined, stray field free environment.

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*Email address: kubetzka@physnet.uni-hamburg.de

[1] F. J. Himpsel *et al.,* Adv. Phys. **47**, 511 (1998).
[2] M. Bode, M. Getzlaff, and R. Wiesendanger, Phys. Rev. Lett. **81**, 4256 (1998).
[3] O. Pietzsch, A. Kubetzka, M. Bode, and R. Wiesendanger, Phys. Rev. Lett. **84**, 5212 (2000).
[4] M. Kleiber, M. Bode, R. Ravlic, and R. Wiesendanger, Phys. Rev. Lett. **85**, 4606 (2000).
[5] A. Kubetzka, O. Pietzsch, M. Bode, and R. Wiesendanger, Phys. Rev. B **63**, 140407 (2001).
[6] S. Heinze *et al.,* Science **288**, 1805 (2000).
[7] D. Wortmann *et al.,* Phys. Rev. Lett. **86**, 4132 (2001).
[8] R. Wiesendanger *et al.,* Phys. Rev. Lett. **65**, 247 (1990).
[9] R. Wiesendanger *et al.,* Science **255**, 583 (1992).
[10] W. Wulfhekel and J. Kirschner, Appl. Phys. Lett. **75**, 1944 (1999).
[11] T. P. Pareek and P. Bruno, Phys. Rev. B **63**, 165424 (2001).
[12] Note that the inverse configuration with an AF surface and an FM tip was realized in Refs. [4,6,8].
[13] O. Pietzsch *et al.,* Rev. Sci. Instrum. **71**, 424 (2000).
[14] O. Pietzsch, A. Kubetzka, M. Bode, and R. Wiesendanger, Science **292**, 2053 (2001).
[15] A. Hubert and R. Schäfer, *Magnetic Domains* (Springer, Berlin, Heidelberg, New York, 1998).
[16] H. J. Elmers *et al.,* Phys. Rev. Lett. **75**, 2031 (1995).
[17] D. Sander *et al.,* Phys. Rev. Lett. **77**, 2566 (1996).
[18] J. Hauschild, U. Gradmann, and H. J. Elmers, Appl. Phys. Lett. **72**, 3211 (1998).
[19] M. Bode, A. Kubetzka, O. Pietzsch, and R. Wiesendanger, Appl. Phys. A **72**, 149 (2001).
[20] E. Magyari and H. Thomas, Phys. Scr. **T44**, 45 (1992).
[21] We emphasize that an overview scan taken after field removal did not show any indication of tip-sample interaction.
[22] A. Wadas and H. J. Hug, J. Appl. Phys. **72**, 203 (1992).
[23] M. Bode *et al.,* J. Electron Spectrosc. Relat. Phenom. **114–116**, 1055 (2001).
[24] Note that a radially magnetized sphere or a perpendicularly magnetized and infinitely extended film does not exhibit any external stray field [15].
[25] Since the coating thickness is ≈4 nm, much bigger nanotips are unrealistic.
[26] We used the OOMMF program, release 1.2 alpha 2 (http://math.nist.gov/oommf/).
[27] H. B. Braun, Phys. Rev. B **50**, 16 485 (1994).
[28] Exchange: $A = 1.5 \times 10^{-11}$ J/m; magnetization: $M_s = 2.0 \times 10^6$ A/m; easy axis anisotropy: $K_e = 3.5 \times 10^6$ J/m^3.