Atomic-Scale Magnetic Domain Walls in Quasi-One-Dimensional Fe Nanostripes

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Fe nanostripes on W(110) are investigated by Kerr magnetometry and spin-polarized scanning tunneling microscopy (SP-STM). An Arrhenius law is observed for the temperature dependent magnetic susceptibility indicating a one-dimensional magnetic behavior. The activation energy for creating antiparallel spin blocks indicates extremely narrow domain walls with a width on a length scale of the lattice constant. This is confirmed by imaging the domain wall by SP-STM. This information allows the quantification of the exchange stiffness and the anisotropy constant.

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In the past micromagnetic models assuming continuous material properties have successfully been used to describe magnetization structures in samples with extended dimensions [1]. The nonlinear angular dependence of the energy stored in a pair of spins with different orientation is the main reason why spins change their directions gradually inside a domain wall. Usually, a domain wall extends over numerous lattice constants and sample dimensions are even larger. In this case continuum models are well justified. However, the same micromagnetic models mentioned above have been applied to predict magnetization structures in nanostructures, too, although it is not at all clear whether these models can be applied to systems with lateral dimensions of only a few atoms where the discontinuous atomic structure of matter may play an important role [2]. Because of potential applications like high density recording [3], low-dimensional magnetic nanostructures have recently attracted considerable interest, both experimentally [4–8] and theoretically [2,9].

Nowadays, the preparation of elongated, one-dimensional (1D) nanostructures with lateral restrictions of only a few lattice periods in the other two dimensions by self-organized growth on vicinal single crystal surfaces is an established technique [4,10]. However, only in few experiments hints of a 1D behavior of magnetic properties were found [5,6,10]. For our study we have chosen pseudomorphically grown Fe/W(110). From previous studies it is known that due to its large in-plane uniaxial anisotropy the ferromagnetic phase transition of an Fe monolayer (ML) grown on *flat* W(110) can be described within the two-dimensional (2D) Ising model [11,12]. If, however, a *vicinal* surface is used as a substrate, the Fe ML as well as the double layer (DL) grow in a step-flow mode at elevated temperature thereby forming narrow stripes parallel to step edges of the substrate [8]. These narrow stripes are good candidates to show the theoretically predicted one-dimensional behavior.

In this Letter we show that the susceptibility of Fe nanostripes on W(110) exhibits a thermodynamical behavior which has been predicted by Monte Carlo simulations within the 1D Ising model [9,13]. A detailed analysis reveals that the activation energy for the creation of a spin block is close to the exchange energy between nearest-neighbor atoms pointing to extremely narrow domain walls with a width on a length scale of the lattice constant. This is indeed confirmed by spin-polarized scanning tunneling microscopy (SP-STM) showing a ML domain wall width $w = 0.6 \pm 0.2$ nm. The wall profiles of these are compared with micromagnetic theory at the most simple model feature, i.e., a 180° domain wall in the well defined Fe nanostripe system [8]. The information gathered by both experimental techniques allows the determination of absolute values of the magnetic anisotropy K as well as the exchange stiffness A.

The experiments have been performed in two different UHV systems for Kerr magnetometry (MOKE) and SP-STM. In both systems the Fe films were prepared by molecular beam epitaxy at pressures $p < 5 \times 10^{-10}$ torr and characterized structurally and chemically using low energy electron diffraction, Auger spectroscopy, and scanning tunneling microscopy (STM). The Kerr ellipticity ϵ_K of the longitudinal Kerr effect was measured in longitudinal fields applied along $[1\bar{1}0]$ (magnetic easy axis of the monolayer). Using a compensation technique, ϵ_K could be measured in absolute units. Temperatures were measured with a relative accuracy of 1 K and an absolute accuracy of about 10 K using a thermocouple fitted to the sample holder. MOKE measurements presented in this study were done during slowly warming up with a rate of about 1 K/min. SP-STM measurements have been performed at $T = 14 \pm 1$ K. Details of the SP-STM setup can be found elsewhere [14].

How can the domain wall energy be determined from the magnetic susceptibility of the stripe system? The magnetic

susceptibility χ of the 1D Ising model is given by

$$k_B T\chi \propto \exp(2J/k_B T), \quad (1)$$

with J being the exchange energy between nearest-neighbor spins. We emphasize that the exponential behavior is characteristic for the 1D case while power laws are expected for two- and three-dimensional systems. The exponential behavior can be understood as an Arrhenius law for the creation or annihilation of two "domain walls" limiting a group of spins pointing antiparallel to the rest of the spin line. Because of the restriction to nearest-neighbor interaction, the domain wall consists of a pair of antiparallel spins and the domain wall energy is J. Thus the activation energy e_W for an antiparallel spin corresponds to $2J$. The same 1D behavior can be calculated for a model system of W parallel rows of spin sites [9,15] as long as the temperature is below the Curie temperature T_C of the corresponding 2D system. In this case fluctuating spin blocks are formed with nearly homogeneous magnetization across the stripe. Albano *et al.* [15] showed that for such a quasi-1D system the susceptibility is given by

$$k_B T\chi \propto |\epsilon|^{2\beta} \exp(2JW/k_B T), \quad (2)$$

with $\epsilon = (T - T_C)/T_C$ being the reduced temperature and $\beta = 1/8$ the critical exponent of the 2D Ising model. Note that the temperature dependent prefactor $|\epsilon|^{2\beta}$ results from the fact that the spin average taken across the stripe is smaller than the absolute value of a single spin because of single spin fluctuations. Using Monte Carlo calculation Sen *et al.* [9] confirmed Eq. (2).

In order to test Eq. (2) experimentally, we determined the initial slope of magnetization curves as indicated in the inset of Fig. 1. According to Eq. (2) we define an effective susceptibility

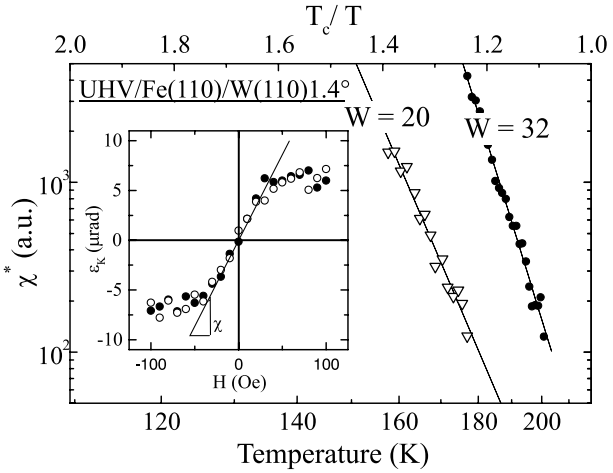

FIG. 1. Magnetic susceptibility $\chi^*(T)$ as defined in the text for averaged stripe widths $W = 20$ and $W = 32$ atomic rows. The linear dependence of the susceptibility observed in this Arrhenius plot confirms the 1D behavior. The inset shows an example of the magnetization curves ($T = 195.3$ K, $W = 32$) used for the determination of the susceptibility.

$$\chi^* \propto \chi \frac{k_B T}{|\epsilon|^{2\beta}} \propto \exp(2e_W/k_B T), \quad (3)$$

with e_W the (generalized) activation energy for the creation of a spin block as described above. Figure 1 shows the experimental data in a typical Arrhenius plot for two different stripe widths. The linear dependence confirms the expected Arrhenius law for χ^*, indicating the 1D behavior. The temperature interval in which this behavior can be observed is limited: at a temperature considerably above the Curie temperature $T_C = 225$ K of the Fe ML on flat W(110), the correlation length of spin fluctuations is too short to feel the stripe geometry. Hence, one should observe a transition to a 2D behavior, which is not possible in our case because of the rapidly decreasing signal to noise ratio. At temperatures below a mean field critical temperature T_C^{MFM} the dipolar coupling between adjacent stripes stabilizes any fluctuations, thus resulting in a spontaneous order as has been discussed in Ref. [8]. T_C^{MFM} strongly depends on the stripe width (see Table I). At temperatures slightly above T_C^{MFM} the influence of the dipolar coupling vanishes rapidly due to the exponential behavior of χ. The slope observed in the Arrhenius plot (Fig. 1) results in a value for the activation energy e_W. As expected from Eq. (3) the slope increases with increasing stripe width. Experimental values for different stripe widths are listed in Table I. Obviously, the activation energy per atomic row is almost constant for different stripe widths W with an average value of $2e_W/W = 15.2 \pm 1.4$ meV. Is this a large or small quantity? For the two-dimensional Ising model on a square lattice J is related to the Curie temperature by $k_B T_C = 2.22J$ [15], resulting in $J = 8.7$ meV for the monolayer Fe on W(110) [8]. Surprisingly, $2J = 17.4$ meV is in close agreement with the experimental value for the activation energy (see Table I), indicating that the magnetization changes its orientation on a length scale of the lattice constant. Generalizing from the Ising model with antiparallel spins in a domain wall we identify e_W with the domain wall energy of an extended wall.

This domain wall should be observable by SP-STM, a magnetically sensitive technique with a lateral resolution down to the atomic scale [16,17]. Because we are interested in the domain structure of the Fe ML on W(110) which exhibits an in-plane easy axis we have to choose a suitable STM tip being sensitive to the in-plane component of the magnetization. Recently, we have shown that

TABLE I. Values of activation energies $2e_w$ for different stripe widths resulting from Arrhenius plots. The activation energy per atomic row is almost constant for different stripe widths. The average value is $e_W/W = 7.6 \pm 0.7$ meV.

W	T_C^{MFM} (K)	$2e_W$ (meV)	$2e_W/W$ (meV)
20	159.6	313	15.7
24	169.1	405	16.9
28	175.1	413	14.8
32	179.2	433	13.5

this condition is fulfilled for W tips coated with 5–10 ML Fe [18,19]. As a consequence, no domain contrast can be achieved for the perpendicularly magnetized Fe DL on W(110). Only within DL domain walls does the magnetization of the DL locally possess an in-plane orientation to which the Fe-coated tip is sensitive. Figure 2 shows the topography (a) and the magnetic dI/dU signal (b) of 1.25 ML Fe/W(110) grown at $T \approx 500$ K [20]. Several domain walls separating dark and bright domains of the Fe ML can clearly be recognized in the overview of Fig. 2(b). Since the total Fe coverage exceeds 1 ML, DL stripes have formed along the step edges of the substrate [16]. Because of their different electronic properties, the DL stripes appear dark at this particular sample bias, i.e., $U = +130$ mV (cf. Ref. [16]). Approximately in the center of the white box in Fig. 2(b), a bright spot shows up which is caused by a domain wall in this particular DL. The inset of Fig. 2(b) shows this location at higher magnification. Averaged line sections drawn along the white lines across domain walls in the ML and the DL are plotted in Fig. 2(c) bottom and top, respectively. Obviously, the ML domain wall is much narrower than the DL wall. The inset of Fig. 2(c) shows the data in the vicinity of the ML domain wall in more detail revealing a domain wall width $w < 1$ nm.

In order to allow a more quantitative discussion we have fitted the measured data with a theoretical tanh function of a 180° wall profile [1]. It can be extended to an arbitrary angle between the magnetization axis of tip and sample ϕ by

$$y(x) = y_0 + y_{\mathrm{sp}} \cos\left\{\arccos\left[\tanh\left(\frac{x - x_0}{w/2}\right)\right] + \phi\right\}, \tag{4}$$

where $y(x)$ is the dI/dU signal measured at position x, x_0 is the position of the domain wall, w is the wall width, and y_0 and y_{sp} are the spin-averaged and spin-polarized dI/dU signal, respectively. In this case we work with an Fe coated tip which exhibits in-plane sensitivity. Therefore, we have to use $\phi_{\mathrm{DL}} = \pi/2$ and $\phi_{\mathrm{ML}} = 0$. The best fit to the wall profile of the DL is achieved with $w_{\mathrm{DL}} = 3.8 \pm 0.2$ nm [16]. It turns out that the profile of the ML domain wall is much narrower. If the fit procedure is performed over the full length of the line section we find $w_{\mathrm{ML}} = 0.50 \pm 0.26$ nm, while $w_{\mathrm{ML}} = 0.66 \pm 0.18$ nm is found if the fit is applied to the data in the inset of Fig. 2(c), thereby confirming the result of the analysis of the magnetization curves, i.e., an almost atomically sharp domain wall. However, we emphasize that the excellent agreement between the measured data (black points) and the fit (gray curve) has to be interpreted with some care. First, at this length scale the spatial resolution of the instrument certainly plays a role. The lateral resolution of STM has been estimated to $[(2\ \text{Å})(R + d)]^{1/2}$, where R is the tip radius and d is the width of the vacuum gap between tip and sample [21]. Even under the assumption

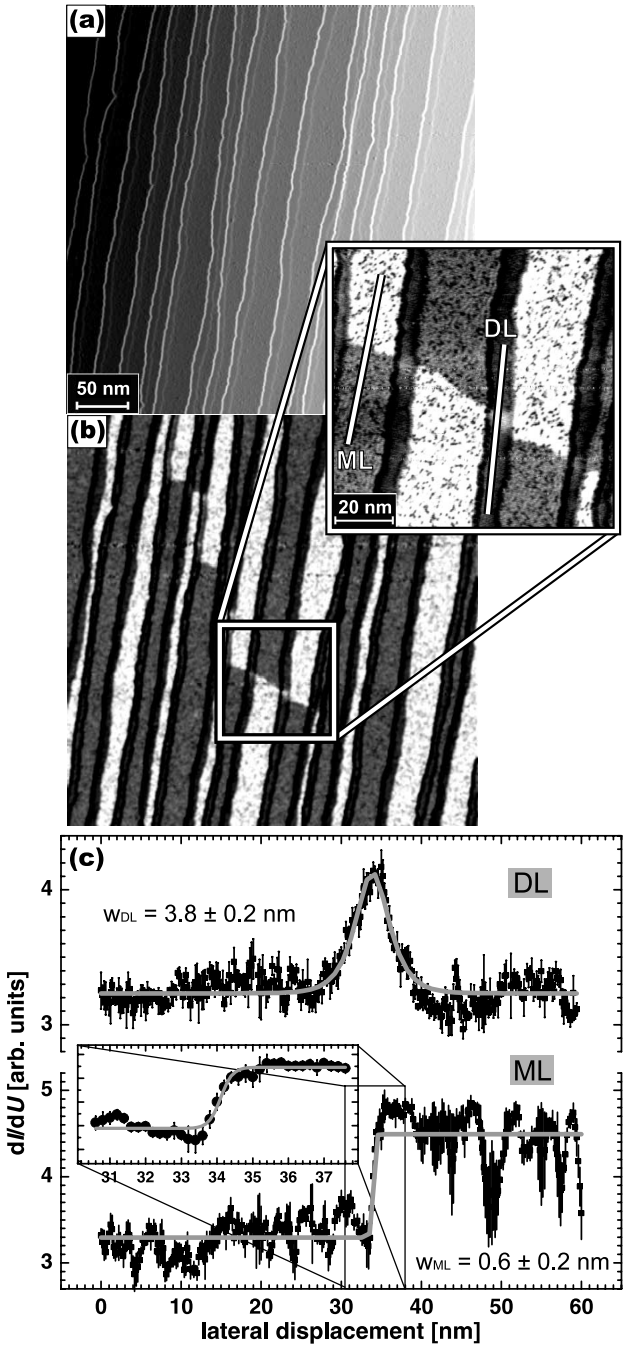

FIG. 2. (a) Topographic and (b) spin-resolved dI/dU image showing the in-plane magnetic domain structure of 1.25 ML Fe/W(110) (tunneling parameters: $I = 0.8$ nA, $U = +130$ mV). Several ML and DL domain walls can be recognized in the higher magnified inset. (c) Line sections showing domain wall profiles of the ML (bottom) and the DL (top). The inset reveals that the ML domain wall width is on the atomic scale, i.e., $w_{\mathrm{ML}} = 6 \pm 2$ Å. In spite of this fact the data can be nicely fitted by micromagnetically calculated wall profiles (for details see text).

of an atomically sharp tip and a gap width $d = 7$–10 Å the lateral resolution is approximately 4–5 Å; i.e., the measured wall width $w_{\mathrm{ML}} = 0.6 \pm 0.2$ nm represents an upper limit only. Second, the fact that the magnetization

direction changes by 180° over a lateral distance of only one or two atomic sites implies that a basic assumption of micromagnetic theory, i.e., a small angle between adjacent Heisenberg spins, is no longer valid. It remains to be investigated in how far the itinerant nature of the Fe $3d$ electrons allows treating the spin rotation in terms of continuum micromagnetism. In this context it would be interesting to measure domain wall profiles in localized moment magnets as, e.g., rare-earth metals.

By combining the results of both experimental methods we are able to determine A and K quantitatively [22]. In classical continuum micromagnetics domain wall energy σ_W and width w is given by $\sigma_W = e_W/S = 4\sqrt{AK}$ and $w = 2\sqrt{A/K}$, respectively. The area of the domain wall S is given by $S = W(a/\sqrt{2})^2$ ($a = 0.316$ nm for tungsten). From the product and quotient of the two experimental values e_W and w for monolayer stripes we finally obtain values for the exchange stiffness $A = 1.8^{+1.1}_{-0.7} \times 10^{-12}$ J/m and anisotropy $K = 20.3^{+13.0}_{-7.4} \times 10^6$ J/m^3 (4.2 meV/atom), respectively. Because of its extremely large value the anisotropy energy of the Fe ML on W(110) could not be determined by conventional magnetometry in the past [10,12]. The value of A is about 1 order of magnitude smaller than the bulk value which was reported to be between $A_{\text{bulk}} = 0.8 \times 10^{-11}$ J/m (as derived from domain wall structures) and $A_{\text{bulk}} = 2 \times 10^{-11}$ J/m (from spin wave excitations at low temperatures) [1]. However, the fact that $A \ll A_{\text{bulk}}$ can already be estimated in the framework of the 2D Ising model on a square lattice which gives $A = JS^2/2a_{\text{nn}} = 3.8 \times 10^{-12}$ J/m, with the nearest-neighbor distance a_{nn} and the exchange integral $J = 8.7$ meV [the latter estimated from T_C of the extended ML (see above)]. We emphasize that at those extreme values A is no longer a universal parameter. Instead, the length scale on which A has been determined is important: as long as the magnetization direction changes on a lateral scale >10 nm, the angle between adjacent Heisenberg spins is small and micromagnetic theory can be applied. This is, however, not valid if the magnetization rotates on a scale of a few atoms. Therefore, the result obtained on the basis of an analysis of magnetic nanostructures — as performed here — cannot be compared with results obtained by neutron diffraction at low-energy (long wavelength) spin wave excitations.

In conclusion, we have shown that a quasi-1D temperature dependence of the magnetic susceptibility can be observed in an Fe nanostripe array grown on stepped W(110). An analysis of the data suggests extremely narrow domain walls with a width on a length scale of the lattice constant. This is confirmed by imaging the domain wall by SP-STM. This information allows the quantification of the exchange stiffness and the anisotropy constant.

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