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Spin-polarized scanning tunneling spectroscopy study of Fe nanomagnets on W(001)

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We have studied the magnetic states of self-organized Fe islands on W(001) by means of spin-polarized scanning tunneling spectroscopy (Sp-STS). Single-domain and vortex states in the nanoscale islands have been observed. The high-resolution magnetic images enable to experimentally determine the boundary between the single-domain and vortex states. The single-domain state was always found below a thickness of 6 nm and a diameter of 120 nm in Fe islands. The boundary directly observed with Sp-STS is consistent with theoretical predictions. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1687276]

Studying magnetism of nanoscale magnets is not only of fundamental interest but is also important for the development of high-density magnetic storage devices and magnetic random-access memory.[1–4] In soft-magnetic nanoscale particles, micromagnetic calculations predict that various stable or metastable magnetic states exist, e.g., single-domain, vortex, flower, and *C* state.[5–10] In the small particles, the exchange interaction dominates and the structure is mostly homogeneous, i.e., single domain, whereas in the larger particles the tendency to reduce the stray field dominates and flux-closure patterns are formed. While the phase diagram of magnetic states in nanometer thick elements has been well studied from the theoretical approach,[6,8–13] the direct observation of the single-domain limit has been out of reach of standard magnetic imaging techniques.[14] Recently, the vortex core in Fe islands on W(110) has been resolved using spin-polarized scanning tunneling spectroscopy (Sp-STS).[15] Sp-STS offers the necessary lateral resolution to fully resolve the details of the magnetization state. As Stroscio *et al.* mentioned,[16] spin-dependent contrast in STS on Fe(001) may be acquired by using a spin-polarized surface state.[17–20] In this paper we present the direct study on the single-domain to vortex state transition using high-resolution Sp-STS.

The experiments were performed in an ultrahigh vacuum chamber system for sample and tip preparation and characterization as well as cryogenic scanning tunneling microscopy. For imaging, we used chemically etched polycrystalline W tips and followed the method of Bode.[17] After flashing the tip to ≈ 2200 K, we deposited ≈ 10 ML Fe onto the tip followed by annealing. As has been reported,[19] these tips have an in-plane magnetization. The magnetic nanostructures were prepared by deposition of 4.7–6.5 ML (monolayers) of Fe on W(001), followed by annealing to ≈ 800 K. This results in the formation of nanometer sized Fe islands.[21] During the annealing, the magnetization of the Fe islands thermally fluctuates and is most likely frozen in the ground state in the following cooling. The size of the Fe island can be controlled by changing the amount of deposited Fe. The surface cleanliness of substrate and film were confirmed by Auger electron spectroscopy and low-energy electron diffraction. During magnetic imaging, the sample was held at ≈ 25 K. Magnetic contrast was obtained with tunneling spectroscopy using a lock-in technique. In this technique, differences in the density of states of minority and majority electrons lead to a spin-dependent differential conductance when measured with a spin-polarized tip.[17] On electroncially homogeneous isalnds, i.e., islands with a flat top, the relative orientation between tip and sample magnetization can be concluded from the differential conductance. The presented magnetic images were obtained with a modulation voltage of 30 mV at a frequency of 6.7 kHz.

In order to acquire spin-sensitive dI/dU images, we chose the spin-polarized surface state of Fe(001).[16] For this, STS spectra of an Fe whisker with well-defined Fe(001) single crystal surfaces have been recorded. The spectra were measured near the top side and down side edges of the Fe whisker corresponding to the areas of opposite magnetization due to the flux closure in the whisker [see Fig. 1(a)]. The peak of the surface state in both spectra is seen at the same energy $U = 0.13$ V as shown in Fig. 1(b).[16,22,23] The intensities of the peaks, however, differ significantly. This difference is due to spin-dependent tunneling since (i) the peak originates from *d*-like surface state of minority spin[16] and (ii) the relative orientation of magnetization is reversed going from one to the other side of the whisker. We used the same surface state in the Fe nanostructures as they display the

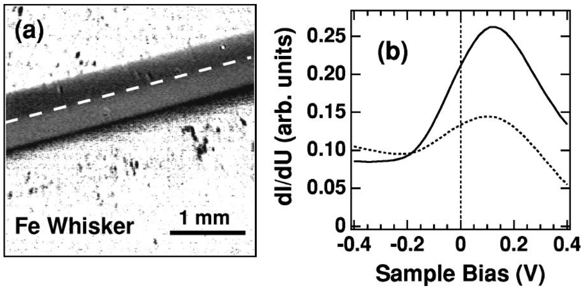

FIG. 1. (a) Magneto-optical Kerr microscope image of Fe whisker. The broken line denotes the magnetic domain wall. (b) STS spectra of the same Fe whisker. Solid/dotted lines show spectra with parallel/antiparallel orientation between the in-plane component of the magnetization of the tip and the whisker.

same electronic structure due to their thickness of several nanometers. Maps of dI/dU were taken at an applied voltage of 0.15 or 0.20 V, i.e., close to the peak maximum of the surface state. One may observe a contrast in island free areas which is due to the thin pseudomorphic carpet of Fe covering the W(001) surface. This contrast is not of magnetic origin but is due to the totally different density of states in few ML thin pseudomorphic Fe films. For the magnetic interpretation of the islands we restrict ourselves to well defined islands with *atomically* flat surfaces that have a homogeneous electronic structure.

Figures 2(a) and 2(b) show the topographic and magnetic dI/dU images of an Fe island on W(001) measured by Sp-STS with Fe-coated W tip. The major and minor axes and height of the island are about 250, 150, and 10 nm, respectively. Although next to the island one sees the atomic steps as black lines, on the top of the island one can see no atomic step, i.e., the island has an atomically flat top. Therefore, the observed dI/dU contrast on the flat top of the island does not originate from topographic structures or extrinsic tip-sample interactions but it reflects the magnetic state, i.e., the in-plane magnetization of the sample.[19] The magnetic configuration of the island is a vortex as concluded from the bright, dark, and intermediate areas that can be clearly seen in Fig. 2(b). Note that the edge of the islands in the topographic and dI/dU images shows a strong black (white) contrast due to rapidly shrinking (extending) of the piezo during scanning across the edges. This contrast is not of magnetic origin.

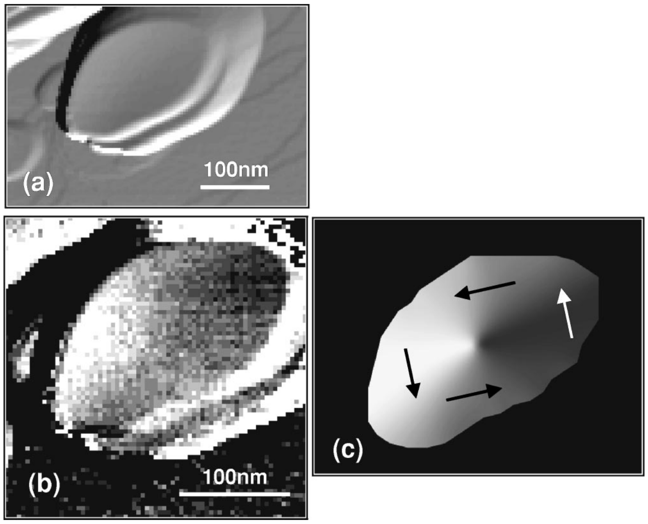

FIG. 2. (a) Topographic image of an Fe island on W(001). The image is differentiated to make the edge of the island and atomic steps clearer. The differentiation leads to an illumination of the islands from the bottom right. (b) Magnetic dI/dU ($U=0.15$ V) image of the Fe island showing a vortex state. (c) Calculated vortex state for the Fe island. The arrows schematically illustrate the orientation of the magnetization. The sense of rotation of the vortex is unknown since the absolute orientation of the tip magnetization is not known.

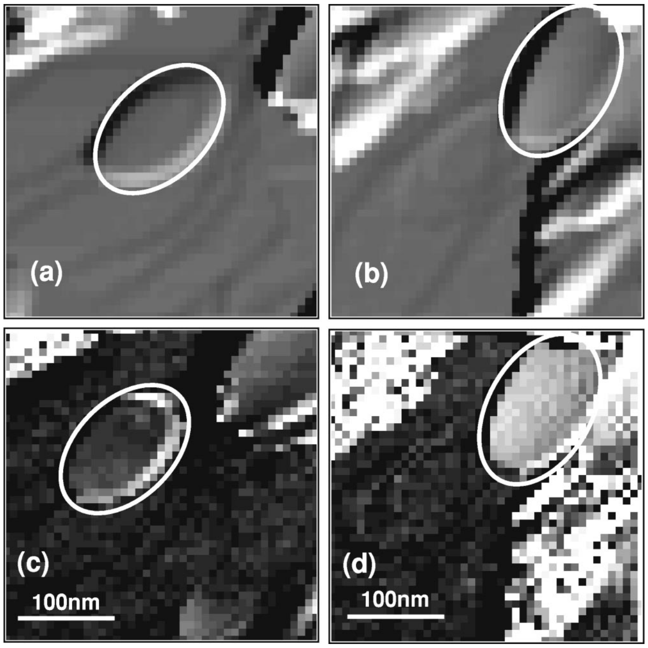

FIG. 3. Topographic (a), (b) and magnetic dI/dU (c), (d) images of Fe islands (marked by ellipses) with magnetic single-domain states on W(001) ($U=0.20$ V).

We have further calculated the magnetic structure of this island with micromagnetic simulations. The micromagnetic code is based on the finite element method,[24] which allows to generate a fine mesh according to the topologic image of the Fe island. This allows a direct comparison of the experimental and simulated domain patterns. A more detailed description of the code is given in Ref. 25. According to the simulations, there are two possible candidates of magnetic stable or metastable state, i.e., single-domain or vortex state. However, the single-domain state yields not only a higher total energy but also a much different dI/dU image compared to the experimental one. The calculated vortex state is shown in Fig. 2(c). Although the contrast close to the vortex core in the calculation is not found in the experiment, the calculated contrast agrees well with the experimental one. Obviously, the vortex core is not imaged with full resolution, possibly due to a weak magnetostatic interaction between the tip and the sample.[20] The observed magnetic state is in qualitative agreement with the calculations, predicting that the votex state, not the single-domain state, is the ground state.

Smaller islands, like those displayed in Figs. 3(a) and 3(b), never showed a vortex state but always a homogenous contrast as shown in Figs. 3(c) and 3(d). The dI/dU signal of the two Fe islands is remarkably different, indicating a dif-

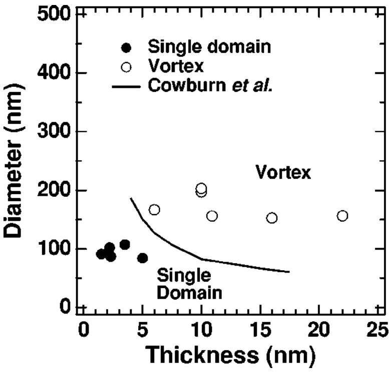

FIG. 4. A phase diagram of the magnetic states for different diameters and thicknesses of the Fe islands on W(001). Solid and open circles show the single-domain and vortex states, respectively. The solid line is the dividing line following calculations by Cowburn *et al.*[13]

ferent direction of magnetization. Therefore, we can conclude that the magnetization of one island is nearly antiparallel to that of the other island and both islands are in the single-domain state.

From the magnetization pattern of a set of islands observed with Sp-STS, the experimental magnetic phase diagram shown in Fig. 4 was obtained. The single-domain state was always found below a thickness of 6 nm and an average diameter of 120 nm. The average diameter of the island is defined as $(a+b)/2$, if the island has an elliptic shape with a and b as the two axes. The directly observed experimental boundary between the single-domain and vortex states is well reproduced by analytical and numerical calculations by Cowburn *et al.* and others.[13] In the self-organized nanostructures, we observed aspect ratios up to 2. For these aspect ratios, calculations show no shift of the single-domain limit.[11] For more elliptical particles, however, the single-domain limit is slightly shifted towards smaller islands as numerical simulations indicated.[11]

In conclusion, we present in-plane magnetic images of single-domain and vortex states of self-organized Fe nanostructures on W(001) by means of spin-polarized scanning tunneling spectroscopy with Fe coated W tips. The experimentally found single-domain limit is well reproduced by previous theoretical calculations. The single-domain limit of elliptical islands with aspect ratio below 2 obtained experimentally is consistent with the results of calculations by Cowburn *et al.* and by Ha *et al.* for circular islands, indicating a weak dependence on the shape.

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