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Ultra sharp domain walls in the closure domain pattern of Co(0001)

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Abstract. – We present high-resolution measurements on the closure domain pattern of Co(0001) obtained with spin-polarized scanning tunneling microscopy. Besides the well-established wide surface domain walls we find ultra sharp sections of the wall. The width of these walls is only 1.1 nm, an order of magnitude less than previously observed in bulk Co. The ultra sharp domain walls are explained on the basis of a micromagnetic model taking into account the competition of exchange energy and magnetic anisotropy.

Magnetism on the sub-micrometer scale has attained increasing attention in recent years. Not only in commercially available data storage devices recording density has increased immensely so that bit lengths below 40 nm have been demonstrated, but also in the field of patterned media [1–5] and magnetic non-volatile memory cells, magnetic structures on the nanometer scale are aimed at. Unfortunately, not many experimental facts are known about the magnetic structure on length scales set by the magnetic exchange, *i.e.*, well below 10 nm, due to lack of lateral resolution in surface-sensitive magnetic imaging. However, the knowledge about the magnetic structure on these small scales is believed to be crucial for the fundamental understanding of micromagnetism and the controlling of magnetic media and devices of the future. Even the seemingly simple question, how sharp a domain wall —one of the elementary building blocks of micromagnetism— can possibly be in hard magnetic materials, could not be adequately addressed with standard magnetic imaging techniques but was only accessible by theoretical modelling, so far.

In this letter we report on spin-polarized scanning tunneling microscopy (Sp-STM) measurements on the closure domain structure of Co(0001). For the first time the closure domain structure is resolved with a resolution well below the exchange length. Surprisingly, sharp sections in the domain walls are found that at first glance seem to contradict common knowledge about domain walls in bulk magnetic materials.

The Sp-STM experiments were performed in ultra-high vacuum ($p = 5 \times 10^{-11}$ mbar). The vacuum chamber was equipped with an Auger electron spectrometer (AES), low-energy electron diffraction (LEED) and a Sp-STM [6, 7]. The Co(0001) bulk single crystal was electrochemically polished and was cleaned *in situ* by cycles of sputtering with 1 keV Ar^+ ions

and annealing to 570 K. Annealing to higher temperatures was avoided to stay below the well-known hcp-fcc phase transition of Co at ≈ 690 K. No traces of contaminations could be found in AES. LEED images showed the expected sixfold diffraction pattern with sharp spots and low background intensity. After sample preparation, topographic STM images revealed an atomically flat surface with terraces of the width of ≈ 500 nm separated by single atomic steps. Due to the limited annealing temperature, the surface remained with a low concentration of small defects —either sputter defects or local fcc or mis-oriented hcp areas as has been observed also by others [8].

Magnetic tips of the Sp-STM were etched from amorphous CoFeSiB wires and cleaned *in situ* by sputtering with 1 keV Ar^+ ions. During scanning, an alternating current of 40 kHz 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 magneto-tunnel effect [9]. These variations were detected with a phase-sensitive lock-in amplifier to separate the magnetic information from the topographic information. The ac component of the tunneling current is related to the magnetic structure of the sample and the dc component to the topography. For a more detailed description of the technique please see [6, 7]. The technique offers a high magnetic contrast and fast data acquisition times in the range of ms/pixel and is an alternative approach to the techniques used by Wiesendanger and coworkers [10, 11]. To minimize the influence of the stray field of the tip on the magnetic structures under investigation, sharp tips of conical shape obtained by slow etching of a 130 μm diameter magnetic wire were used [12]. The pointed shape of the tips ensures a magnetization along the tip axis which leads to a sensitivity of the Sp-STM to the perpendicular component of the magnetization of the sample [13]. Note that in our previous work we used poorly defined tips cut from an amorphous foil [6, 7] insted of etched tips. With cut tips, the lateral resolution was limited to about 10 nm and, due to the unknown shape of the tip apex, the direction of magnetization of the apex was unclear. This may lead to an in-plane magnetic contrast showing different domain patterns on Co(0001) [6].

Hcp cobalt displays a uniaxial magnetocrystalline anisotropy with the easy axis along the *c*-axis, *i.e.*, perpendicular to the selected (0001) surface. Due to the minimization of the stray field energy, the single domain state is unstable and splits up into a Lifshitz closure domain pattern [14]. Since for Co the magnetic anisotropy and the dipolar energy are of the same order of magnitude [15], no perfect and simple closure domain structure occurs on the (0001) surface. Instead, a complex dendritic structure is observed, where the magnetization of most areas of the surface of the closure domains is strongly rotated away from the surface normal as observed, *e.g.*, with scanning electron microscopy with polarization analysis (SEMPA) [8]. We use Sp-STM with its intrinsically high lateral resolution to study this complex structure. Figure 1a depicts the perpendicular magnetization component of the complex closure domain pattern as seen with the Sp-STM on a scale of $4 \times 4\,\mu m^2$. It is similar to the pattern observed with SEMPA [8] when broadening with its resolution function, or similar to images obtained by magnetic force microscopy (MFM). For a detailed comparison between MFM and Sp-STM images of the very same sample please see [16]. The magnetization flows out of the white regions into the black regions. The magnetization does not have a fixed out-of-plane component but varies continuously. As SEMPA measurements have shown, the perpendicular component varies between almost fully perpendicular orientation in the center of the branches to an in-plane orientation in the grey regions between the branches. When zooming into the ends of the fractal branches, sharp features in the otherwise smooth contrast can be observed as shown in fig. 1b. The contrast across these sharp features resembles domain walls (see fig. 1c) and is much less than the full contrast observed on larger scales in the closure pattern. The sharp domain walls are, however, not related to topographical defects on the surface.

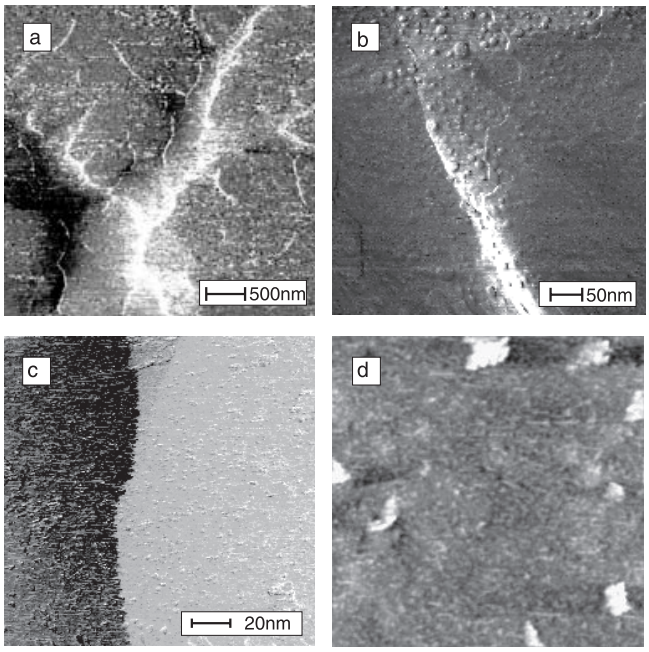

Fig. 1 – Sp-STM images of the fractal perpendicular magnetic structure of Co(0001) on the large scale (a), the end of a branch in higher magnification with a wall-like feature (b) and detail of a sharp domain wall at an end of a branch in even higher magnification (c). (d) shows the topography of the surface taken at the same time and same area as the magnetic image of (c). No correlation between magnetic and topographic information is observed. Sample bias: 0.2 V; tunneling current: 0.5 nA.

As depicted in fig. 1d, the topography of the sample surface taken at the same time as the magnetic image on the same area as fig. 1c shows no traces of defects [17]. Note that, due to the contrast mechanism of Sp-STM, the spin-polarization of the density of states at the Co surface is used for imaging the magnetization. In principle, by varying the sample bias, different states can be imaged. However, the general appearance of the observed walls does not change with bias voltage. A more detailed report on the voltage dependence of the magnetic contrast will be given in a forthcoming publication [18].

The relatively low contrast across the sharp wall can be realized, when having a look at the measured perpendicular magnetization component across the wall in comparison to that of the large-scale domain pattern. Figure 2a displays a line scan between two points of maximal contrast, *i.e.*, between two points that are located in the center of the branches. As can be seen, the perpendicular component varies continuously along several micrometers between the two extrema. Across the domain wall at the end of a dendritic branch, the contrast changes abruptly on a length scale of ≈ 2 nm; however, not between the minimum and maximum value but only by $\approx 20\%$ of the maximal contrast centered just in the middle between the extrema. Taking the maximal observed contrasts as perpendicular up and down magnetization, one can estimate a maximum angle of rotation across the wall of only 20° centered around the in-plane direction. To estimate the wall width w, we fit the line profile $m_z(x)$ with the standard wall profile for uniaxial systems [15]:

$$m_z = \tanh\left(\frac{2x}{w}\right), \tag{1}$$

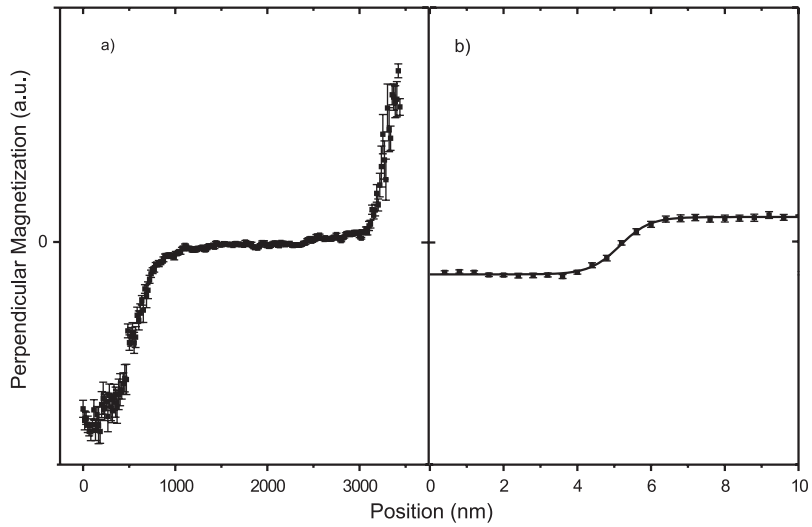

Fig. 2 – Line scan through points of maximal perpendicular magnetization component (a) and line scan across ultra sharp domain wall at an end of a dendritic branch including the fitted wall profile of 1.1 nm width (b). The line scans are plotted with identical scales to allow direct comparison of the perpendicular magnetization component.

resulting in the width of $w = 1.1 \pm 0.3$ nm. At first sight, this ultra narrow width seems to be unphysical and to contradict common knowledge about domain walls. The wall of fig. 2b is one order of magnitude narrower than the Bloch wall in bulk Co of ≈ 11 nm [15] and a factor of five narrower than the magnetic exchange length of Co. This is very surprising, since the walls observed on the surface originate from domains that penetrate into the bulk of the crystal. To exclude instrumental reasons for the observation of such sharp walls, we take the following consideration. One mechanism that could cause sharper walls would be a nonlinear response of the instrument to the perpendicular component of the magnetization, *e.g.*, a response like a step function. Theoretically, we can exclude such a nonlinear response since the magneto-tunnel effect is a linear effect with magnetization [19]. Also experimentally we can exclude a step-like response function since we observe sharp and smooth contrasts in one and the same image, while a step-shaped response function would result in entirely sharp contrasts for all structures, including even the line scans of fig. 2. An alternative scenario could be that we pick up the domain wall with the magnetic tip due to magnetostatic interaction and drag it along during scanning until it snaps off. In that case a sharp transition would be

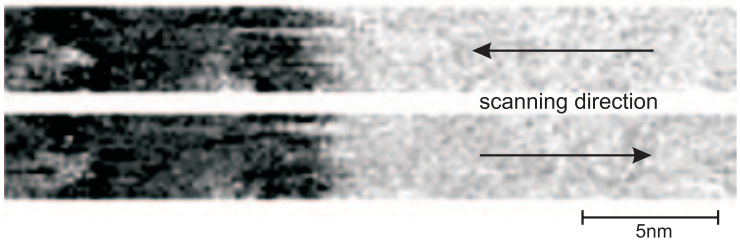

Fig. 3 – Detailed Sp-STM images of an ultra sharp domain wall scanning from the right to the left (top) and from the left to the right (bottom). Sample bias: 0.2 V; tunneling current: 0.5 nA.

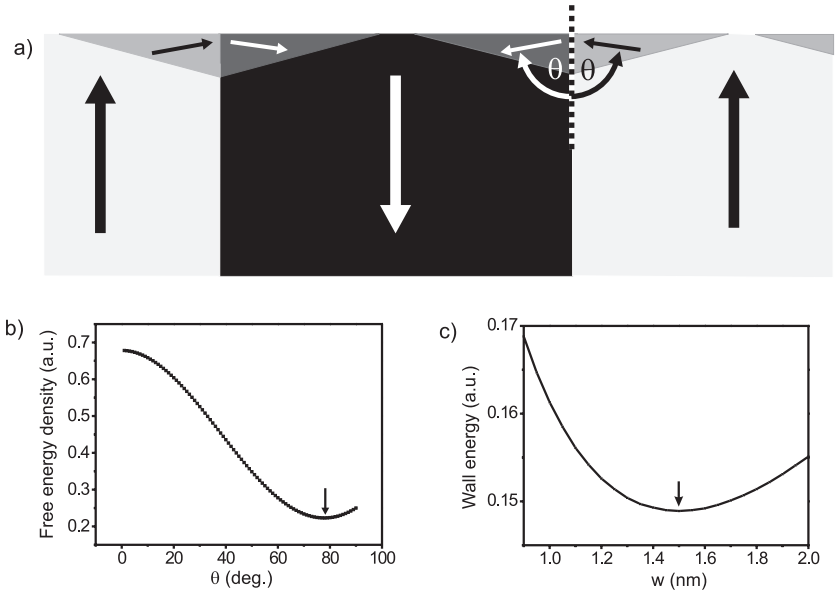

Fig. 4 – Schematic cross-section of the closure domain pattern of Co with tilted surface domains (a). Free-energy density of the tilted closure domain configuration as a function of the tilting angle θ (b), and energy density as a function of width of a 20° domain wall (c).

observed at the point of snapping-off. To test for this mechanism, we recorded the wall while scanning from the right to the left and from the left to the right (see fig. 3). If the wall were dragged along and snapped off, an opposite displacement of the wall for scanning in the two directions should be seen. However, the domain wall appears at exactly the same position for both directions (see fig. 3), ruling out any significant dragging. Finally, by measuring the magnetic susceptibility [7] locally on the position of the wall, we checked for higher-order magnetostatic interactions. No significant influence could be detected. Hence, the observed ultra-sharp domain walls are real and need a physical explanation.

To understand the origin of the specific type of 20° wall and to calculate its expected width, we again focus on the closure domain pattern of Co(0001). In Co(0001) the magnetocrystalline anisotropy favors a magnetization along the surface normal. To reduce the stray field energy of the sample, domains of opposite magnetization along the normal separated by 180° domain walls are formed in the bulk of the crystal (see fig. 4a). This magnetization configuration reduces the overall stray field, but still produces a large number of surface charges, since the flux is not kept inside the crystal. As Hubert *et al.* [20] suggested, the system can reduce the amount of surface charges by a partial flux closure with tilted surface domains. In these surface domains, the magnetization rotates away from the magnetocrystalline easy direction, which costs energy. However, the system saves dipolar energy due to the flux closure. For Co, the ratio between magnetocrystalline and dipolar energy is $Q = 0.4$. From this value, one can easily calculate the angle θ, the magnetization is tilted from the surface normal in the surface domains by minimizing the free energy of the tilted partial closure domain configuration [20]. As depicted in fig. 4b, we find a clear minimum of the energy at a large angle of $\theta \approx 80°$, *i.e.*, the flux closure is obtained by almost in-plane magnetized surface domains. Hence, under the condition that there are well-defined domains, one expects to find 20° domain walls on the surface in agreement with our Sp-STM observations. Next, we calculate the expected

domain wall width of such a 20° domain wall in a one-dimensional model by minimizing the sum of the magnetic exchange energy and anisotropy energy in the wall [15, 21]. We neglect contributions of the dipolar energy in our calculation, since they only give a small correction to the wall energy. Figure 4c shows the wall energy as a function of the wall width w. For the calculations, we took the exchange constant of Co $A = 1.5 \times 10^{-11}$ J/m and the first-order magnetic anisotropy $K_u = 5 \times 10^5$ J/m^3 [15]. The minimum of the energy is found at a wall width of only 1.5 nm. This agrees well with the experimentally observed wall width of 1.1 ± 0.3 nm. The small deviation of the wall widths might be due to the neglected dipolar fields or higher-order anisotropies and surface anisotropies of Co(0001). This shows that the observed ultra sharp domain walls are also theoretically expected. There is the possibility that a domain wall is much narrower than the magnetic exchange length $\sqrt{A/K_u}$ without violation of micromagnetic rules, but only if the angle of rotation across the wall is small. A similar wall width can also be estimated by a rule-of-thumb argument. A 180° domain wall has a width of ≈ 11 nm in bulk Co [15]. A 20° domain wall should have a width of a fraction of 20/180 of this. Hence, the observed ultra-narrow walls can be explained by a domain wall where the magnetization direction is changed by only $\approx 20°$. The finding of sharp domain walls on the surface of Co(0001) also gives some experimental evidence for the theoretical predictions of Hubert and Rave that sharp wall-like transitions can be formed at the surface of a closure domain pattern [22], especially when higher-order in- or out-of-plane anisotropy terms are present, as is the case for Co(0001). Why the sharp walls are only observed close to the ends of the dendritic branches of the closure domain pattern remains an open question. Possibly only at these special points the magnetic flux is compensated in such a way that the total anisotropy term becomes stationary [20, 22] and well-defined domains may form.

In conclusion, we present measurements of the closure domain pattern of Co(0001) with nm resolution, that show that the magnetic structure in magnetic materials can be much finer than the magnetic exchange length without violating micromagnetic rules. It is shown that domain walls can be much sharper than previously thought as long as they are walls of low angles.

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