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Magnetic domain walls in ultrathin fcc cobalt films

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The micromagnetic structure of 180°-domain walls in ultrathin cobalt films, grown on Cu(100), has been investigated by means of SEMPA. The comparison of our experimental data with one-dimensional micromagnetic calculations demonstrates that the magnetostatic energy has a pronounced influence on the domain-wall structure, even in the monolayer thickness range. Discrepancies between experimental observations and the one-dimensional model may be explained by a two-dimensional in-plane structure of the domain walls.

The recent development of the scanning electron microscope with spin-polarization analysis of the secondary electrons (SEMPA) (Ref. 1) has opened up a new branch of micromagnetic investigations, i.e., the experimental observation of domain structures in magnetic monolayer films, grown on nonmagnetic substrates.[2-4] The domain-structure investigations have shown that the domain pattern in ultrathin magnetic films are very complex. The domains are characterized by a very irregular shape even in cobalt films grown on Cu(100) with cubic in-plane magnetocrystalline anisotropy.[3,5-7] Recently, similar domain structures have been found in ultrathin cobalt films with uniaxial in-plane anisotropy.[8] Thus domains with irregular shape seem to be a typical feature of ultrathin cobalt films in contradiction to the highly symmetrical domain structure found in thicker films or bulk material.[9] As the domain shape is determined by domain walls and their minimum energy configuration, the domain-wall fine structure in ultrathin films is of essential importance for the understanding of the domain structure.

In this paper, we present an experimental study of the magnetization distribution within domain walls in ultrathin films. The experimental data are compared with numerical calculations, based on a one-dimensional micromagnetic description. Domain walls and their special behavior at surfaces and in thin films have been investigated theoretically and experimentally.[10-19] The experimental studies, however, were limited to films of a few 100-Å thickness (so called "thin films"), due to the limitations of the techniques[10,11,17] which have been used for investigations of domain walls previously. An important result of the theoretical studies for very small film thicknesses has been that the Néel-wall fine structure is well described by a one-dimensional model, where the magnetization orientation is only a function of one space variable.[12,15,16] Thus it is also reasonable to consider the magnetization within ultrathin films as homogeneous throughout the film, i.e., a one-dimensional description of the walls seems to be appropriate.

Figure 1 shows an experimental line scan across a 180°-domain wall, measured for a 5.5-monolayer cobalt film on Cu(100). In this plot the polarization, indicating the magnetization component parallel to the domain magnetization, is shown as a function of the lateral position. The experimental curve (× in Fig. 1) is characterized by a sharp core area, which represents a rapid rotation of the magnetization vector in the center of the wall. Remarkable features of this domain-wall profile are the long tails on either side of the center part. The lateral extension of these outer segments of the wall is surprisingly large, i.e.,

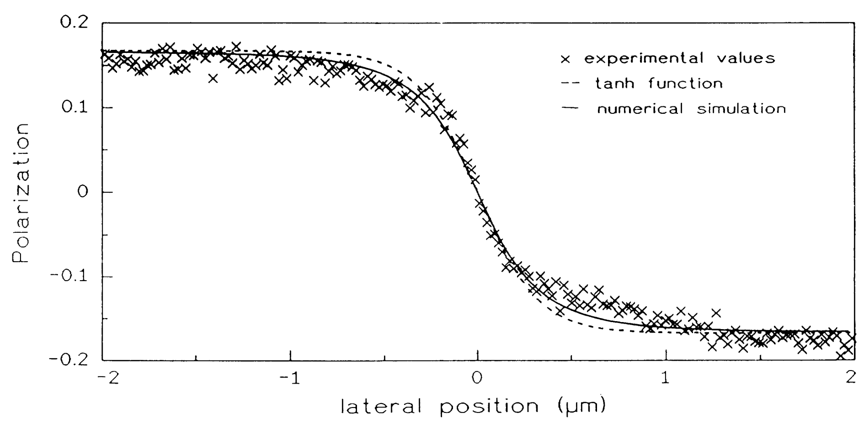

FIG. 1. Line scan across a 180°-domain wall for 5.5 monolayers Co/Cu(100). The experimental data points (×) are compared with a tanh function (dashed line) and the numerical calculation based on the one-dimensional micromagnetic description (solid line; $A=1.3\times10^{-6}$ erg/cm, $K=-2000$ erg/cm^3, $M_s=750$ emu, $b=1.0$ nm).

in the range of microns. The existence of the long domain-wall tails becomes much more obvious by a comparison of the experimental curve with the hyperbolic tangent (tanh) function (dashed line in Fig. 1), which is the analytical solution for uniaxial anisotropy without consideration of the magnetostatic energy. The tanh function has been fitted to the measured wall profile. The large lateral expansion of the domain-wall tails are obviously not described by the tanh function. Thus a more elaborated theoretical computation incorporating magnetostatic interactions has to be used to describe the domain-wall fine structure.

Our one-dimensional description is based on a discrete magnetization distribution within the wall (Fig. 2) first introduced by Brown and LaBonte for uniaxial films.[13] We have adapted this one-dimensional calculation to cubic magnetocrystalline anisotropy. Two-dimensional calculations with cubic anisotropy have been reported previously.[18,19] The energy density per wall area E of a 180°-Néel-like domain wall in a film of thickness b is given by

$$E=A\frac{N}{a}\sum_{l=1}^{N+1}\{(\alpha_{l+1}-\alpha_l)^2+(\gamma_{l+1}-\gamma_l)^2\}-K\frac{a}{N}\sum_{l=2}^{N+1}\alpha_l^2\gamma_l^2+\tfrac{1}{2}M_s^2b\sum_{I=2}^{N+1}\sum_{J=2}^{N+1}A_{IJ}\alpha_I\alpha_J$$

for a material with cubic magnetocrystalline anisotropy. The constant energy term which results from the transformation of the anisotropy energy term into the easy axis representation is omitted here. A, K, and M_s are the exchange constant, the first anisotropy coefficient for cubic symmetry, and the saturation magnetization of the material, respectively. α_l and γ_l are the direction cosines of the magnetization of slab l, with respect to the x and z axis, and the A_{IJ} describe the magnetostatic coupling between the slabs, which can be calculated analytically in this model. Magnetoelastic effects are not considered here.

The numerical computations are performed with an algorithm, derived from the minimization of the wall energy by Kirchner and Döring.[14] With this algorithm Néel walls and their long tails in thin films have been successfully described in opposite to the original work by Brown and LaBonte.[13] Due to the cubic magnetocrystalline anisotropy a much better accuracy of the computation is necessary than for uniaxial anisotropy to achieve the energy minimum for the 180°-domain wall. We have tested the validity of our calculations with the self-consistency parameter S, deduced by Aharoni and Jakubovics[18,20] which has to be $S=1$ for physically meaningful results. A detailed description of our computations and a discussion of the results is given elsewhere.[21]

The large lateral expansion of the domain-wall tails in

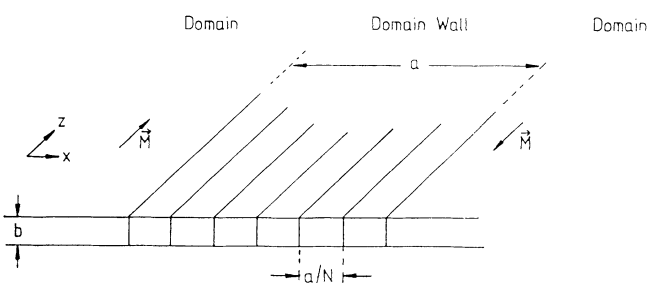

FIG. 2. Geometry of the one-dimensional 180°-domain wall description with discrete variation of the magnetization. The x and z axis are the easy axes of magnetization; b is the film thickness, and N the number of slabs. The magnetization direction is assumed to be $+e_z$ for $x<0$ and $-e_z$ for $x>a$. Each of the N slabs has a uniform magnetization M_s. The M_s orientation of the individual slabs is restricted to the x-z plane.

the micron range has to be attributed to a long-range interaction, e.g., the magnetostatic dipole-dipole interaction, which is demonstrated by Fig. 1. The solid line in Fig. 1 is a numerical calculation of the one-dimensional micromagnetic description, discussed above, including the magnetostatic energy term. The self-consistency parameter is $S=1+3.53\times10^{-4}$ in this case. For the exchange constant A, which has no influence on the tail structure,[22] we have used the bulk value of hcp cobalt $A=1.3\times10^{-6}$ erg/cm.[23] The film thickness [$b=5.5$ monolayers (ML)] was experimentally measured by the observation of MEED oscillations,[24] and the saturation magnetization $M_s=750$ emu can be deduced from the polarization value.[25] The anisotropy coefficient K is not exactly known for the ultrathin films. Thus it can be taken as a fit parameter. The calculated wall profile, presented in Fig. 1, has been obtained with $K=-2000$ erg/cm^3 and shows quite good agreement with the experimentally observed curve. From this correspondence of the experimental data and theoretical calculations, we conclude that the long tails of domain walls in ultrathin films are caused by the magnetostatic energy. These tails are produced by the magnetostatic field of the Néel wall itself and have been previously observed by Fuchs[10] and Feldtkeller[11] for much thicker permalloy films. Thus the magnetostatic energy term is essential for the description of domain walls even in the monolayer thickness range.

While the one-dimensional computations demonstrate the influence of the magnetostatic interaction on the domain-wall structure, two problems arise in detail. First, with the "fit" parameter K one obtains values which are orders of magnitudes too small compared with measured K values published for similar systems.[26] Second, remarkable deviations can be seen in the center of the wall profile between calculated and measured wall structure. To study the latter item in more detail the complete magnetization orientation within the wall has been measured for a 9-ML film. All three components of the magnetization are shown in Fig. 3. The asterisks (∗) in Fig. 3(a) give the polarization perpendicular to the surface. Within our experimental uncertainty, this polarization component is constant and is equal to zero in the whole domain-wall area. Thus for the ultrathin Co/Cu(100) films, the magnetization of a domain wall rotates within the film plane, demonstrating Néel-like behavior. The crosses (×) in Fig. 3(a) show the magnetization distribution of the same

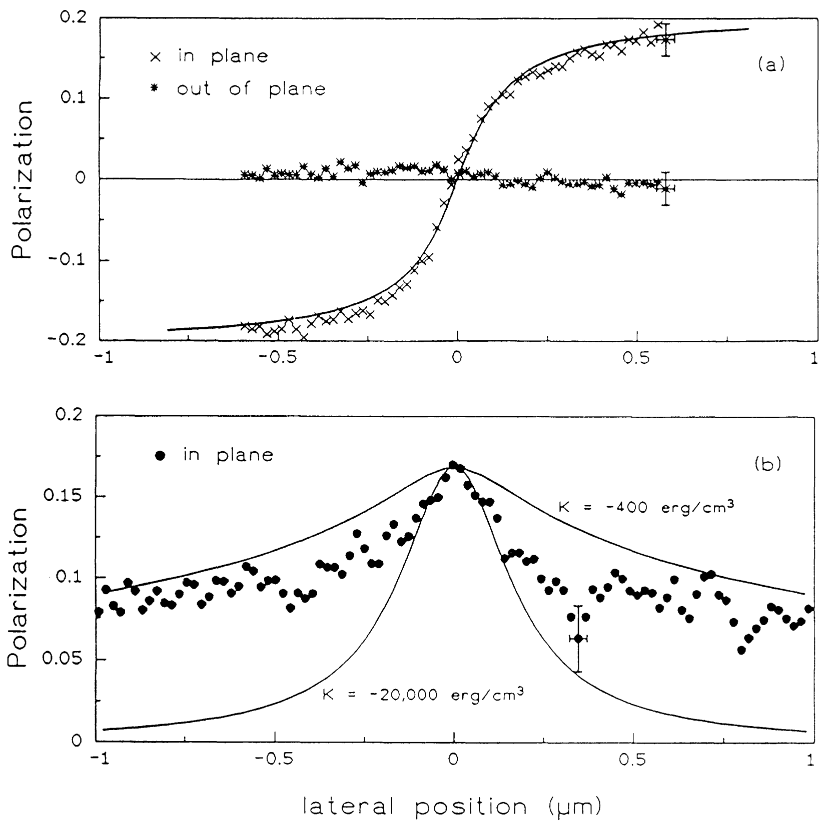

FIG. 3. Line scan across a 180°-domain wall for 9 monolayers Co/Cu(100). (a) The experimentally measured polarization components perpendicular to the film plane (∗) and the in-plane component parallel to the M_s orientation of the domains (×). The solid line represents the calculated wall profile based on the one-dimensional micromagnetic description ($A=1.3\times10^{-6}$ erg/cm, $K=-2000$ erg/cm^3, $M_s=900$ emu, $b=1.6$ nm). (b) The in-plane polarization component perpendicular to the domain polarization, measured (●) as well as calculated (solid line; $A=1.3\times10^{-6}$ erg/cm, $M_s=900$ emu, $b=1.6$ nm, K as indicated).

in-plane component as Fig. 1, exhibiting the same characteristics as the wall in the 5.5-ML film. The solid line in Fig. 3(a) is a numerical computation ($S=1-1.52\times10^{-4}$), using the same parameters as before, except the bigger film thickness ($b=9$ ML) and the also changed saturation magnetization ($M_s=900$ emu). The calculated curve exhibits once more qualitatively good agreement with the observed experimental data.

Figure 3(b) shows the second polarization component in the surface plane, perpendicular to the domain polarization. This component consists of a polarization maximum in the wall center and two long-tail areas, showing a slow decrease of the polarization with a lateral expansion of more than one micron. The maximum indicates that the magnetization rotates within the film plane crossing the perpendicular in-plane magnetization component, i.e., demonstrating the Néel-like wall structure. From the wall profiles in Fig. 3 it becomes obvious that the long tails are much more pronounced in the perpendicular in-plane component, shown in Fig. 3(b). Thus this component is more suitable for a quantitative comparison with the model.

The solid lines in Fig. 3(b) are both one-dimensional numerical computations with $K=-400$ erg/cm^3 ($S=1-2.63\times10^{-4}$) and $K=-20000$ erg/cm^3 ($S=1+1.87\times10^{-4}$). It is obvious that the whole experimental line scan cannot be described by one of our calculated curves. Due to the very slow polarization decrease the tails can only be described by a very small K value, even smaller than in the calculations of Fig. 3(a). In contrast to that, the inner part of the wall is extremely sharp and a K value nearly 2 orders of magnitude higher has to be chosen to obtain a qualitatively sufficient agreement. As the wall should center around a low K value position to achieve the lowest-energy configuration, the observed behavior cannot be attributed to a laterally varying K within the film. Thus we have to conclude that our one-dimensional calculations are not able to describe the detailed structure of domain walls in ultrathin cobalt films. It is important to note, however, that the wall center obviously reflects a high K value behavior of the films. Due to the inadequacy of the one-dimensional description a more accurate determination of the K value is not possible by the fit procedure. Hence we think that our results are not in contradiction to the K values found by other authors in similar Co films.[26]

The measured long tails of the domain walls lead to a reduction of the magnetostatic wall energy contribution. Moreover, indications for coupling of walls and varying wall profiles have been found.[21] Thus, the deviation of the calculated wall profiles from the experimentally observed line scans may be explained by the long-range magnetostatic interaction existing in a two-dimensional in-plane micromagnetic structure. This magnetostatic interaction might also influence the domain structure in ultrathin films showing irregular domain shapes.

In this paper we have presented an experimental study of domain walls in monolayer films. We have measured the magnetization distribution of 180°-domain walls in ultrathin cobalt films, grown on Cu(100). A Néel-like wall behavior has been found. The wall profiles exhibit long tails into the adjacent domains, with lateral expansions in the range of microns. With regard to one-dimensional calculations the tails can be attributed to magnetostatic interactions caused by the magnetic field of the internal Néel-wall fine structure. This demonstrates the strong influence of magnetostatic interaction even in the ultrathin films. The discrepancy between experiment and one-dimensional calculations in detail may be regarded as a first clue of a two-dimensional in-plane micromagnetic structure of domain walls in ultrathin cobalt films.

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