Influence of the Surface on Magnetic Domain-Wall Microstructure

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The magnetization orientations in domain walls at the surfaces of an Fe crystal, a ferromagnetic glass, and a Permalloy film, measured by scanning electron microscopy with polarization analysis, exhibit asymmetric surface Néel wall profiles which (1) are at least twice as wide as interior Bloch walls in bulk and (2) are described quantitatively by our micromagnetic calculations without assuming any special surface parameters. Misinterpretation of domain-wall widths, Bitter patterns, and magnetic-force-microscopy images can result from overlooking the extreme effect of the surface on magnetic microstructure.

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The surface of a ferromagnetic material has a profound effect on the final magnetization configuration, that is, the magnetic microstructure, resulting from the energy minimization which takes place by formation of domains and domain walls. A detailed knowledge of surface magnetic microstructure is of great importance to our understanding of many fundamental properties of magnetic materials as well as to our understanding of the ultimate limitation on information density in magnetic storage technology. Although there has been intense study of magnetic microstructure for many years, there is still considerable uncertainty about the behavior of a domain wall at the surface, specifically the relative width of domain walls at the surface and in the interior. In this Letter, we present the first quantitative comparison of the measured magnetization orientation in surface domain walls and the predictions of micromagnetic theory. Excellent agreement is found between the calculated and measured profiles for three materials, an Fe single-crystal whisker, a ferromagnetic glass, and a Permalloy film, without invoking surface anisotropy or surface exchange parameters different from the bulk. Having verified this application of the micromagnetic theory, we show that the domain-wall width at the surface is significantly greater than that in the bulk. The depth of the surface-induced modification of the domain wall is found to be on the same order as the width of the bulk Bloch wall. Our results provide new insight into the interpretation of relative wall widths[1] and have important implications for other methods used to observe magnetic microstructure, the Bitter technique and magnetic force microscopy.

The surface of a solid breaks the translational symmetry normal to it. This has a large effect on the magnetostatic energy. In an infinitely extended ferromagnet, the boundary between antiparallel domains would be a 180° Bloch wall, in which the magnetization rotates in the plane of the wall. If a Bloch wall were terminated by a surface, the magnetization would point out of the surface causing a large, energetically unfavorable stray field. This surface magnetostatic energy is sufficient to cause the magnetization to rotate totally in the plane of the film in thin films, forming what is called a Néel wall. For thicker films, there are a number of different wall configurations. Hubert[2] and LaBonte[3] recognized that in a thickness range of twenty to a few hundred nanometers a wall configuration, known as an asymmetric Bloch wall, that has a vortex structure in the interior with a Néel-type wall at the surface is energetically favorable. Evidence for this model has been obtained from transmission electron microscopy by measuring the integrated effect (through the film) of the wall magnetic field on an electron beam.[4,5] The predicted Néel wall at the surface has been observed in measurements using magneto-optic Kerr effect[6] and scanning electron microscopy with polarization analysis (SEMPA).[7,8] A surface Néel wall profile was also measured in a recent high-resolution SEMPA investigation.[1] We observe surface Néel wall profiles that are in excellent agreement with our calculations. Lowering the surface magnetic energy by the formation of surface Néel walls appears to be a widespread phenomena found for a number of different materials.

The quantitative profiles of domain walls at surfaces which we report here were obtained from high-resolution SEMPA images such as those shown in Figs. 1(a)–1(c). The familiar SEM images which show surface topography, as in Fig. 1(d), are obtained by measuring the secondary-electron intensity as the focused high-energy electron beam rasters the specimen surface. An image of the magnetic microstructure is obtained if, in addition, the spin polarization of the secondary electrons is measured. The SEMPA technique has been developed over the last few years and is described in detail elsewhere.[7,8] The projection of the sample magnetization along two orthogonal axes lying in the specimen surface are shown in Figs. 1(a) and 1(b), respectively. The linear intensity scale uses white (black) for the maximum value of the magnetization component pointing along the positive (negative) direction.

The measurements in Fig. 1 are from a zero-mag-

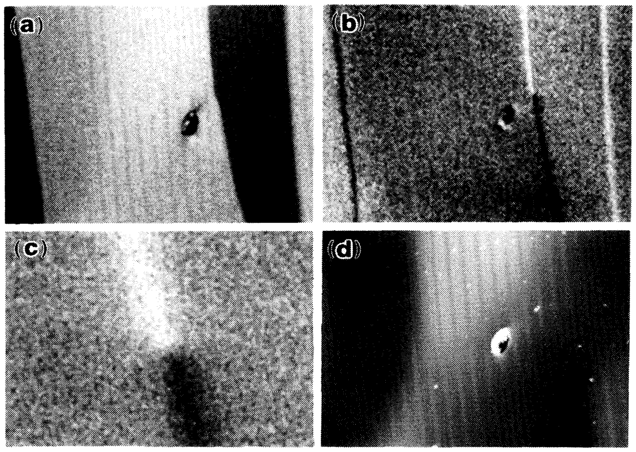

FIG. 1. SEMPA images of a Co-based ferromagnetic glass showing components of the magnetization along the (a) vertical and (b) horizontal directions. The images are 70 μm across. (c) A higher-resolution, 5 μm across, magnetization image of the central region of (b). (d) The intensity image showing the topography corresponding to images (a) and (b).

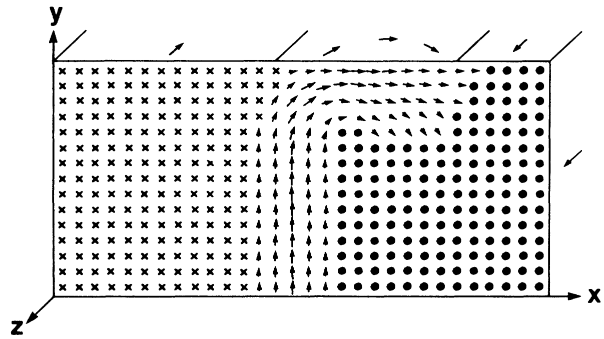

FIG. 2. Schematic representation of the calculated magnetization distribution in the upper 0.2 μm of the cross section through an Fe sample.

netostriction Co-based ferromagnetic glass (Allied 2705M, $Co_{69}Fe_4Ni_1Mo_2B_{12}Si_{12}$). In Fig. 1(a), one sees parts of four domains with magnetization nearly aligned with the vertical axis. The magnetization within the domain walls is seen in Fig. 1(b) to be along the horizontal direction, perpendicular to the wall. This demonstrates that, at the surface, the domain wall is a Néel wall with the magnetization rotation occurring in a clockwise direction in the surface plane. A high-magnification image of the middle of the wall in the region where the Néel wall changes direction is shown in Fig. 1(c). Note that the black and white segments of the wall are slightly offset from each other.

Our calculations of domain-wall configurations employ the nonlinear micromagnetic equations.[9] The magnitude of the magnetization is constant and only its direction is varied in order to minimize the total magnetic energy consisting of contributions from the exchange, anisotropy, and magnetostatic energies. Our calculation follows that of LaBonte[3] in which the continuous magnetization is approximated by dividing the ferromagnet into a finite number of cells, each with a discrete magnetization. The magnetization in each cell is affected by that of the nearest-neighbor cells through the exchange interaction and by that of all the other cells through the long-range magnetostatic interaction. In each cell, the direction of the magnetization is varied iteratively to minimize the energy (until the change in the magnetization direction cosine is less than 0.2%). Although this energy-minimization procedure is computer intensive (a typical calculation takes 5 to 10 min on a supercomputer), it has the advantage that the equilibrium low-energy magnetization is reached without a model-dependent initial configuration. This phenomenological calculation has as input the material parameters, e.g., the exchange constant A, the anisotropy constant K (cubic for Fe and uniaxial for Permalloy and the ferromagnetic glass), and the saturation magnetization M_s, and such geometrical parameters as the thickness and the associated boundary conditions. The output is the orientation of the magnetization at each cell and the values of each energy contribution to the total energy.

The results of the calculation of the magnetization distribution for an Fe single crystal are shown schematically in Fig. 2 for the top half of a cross section through the sample (the x-y plane). The magnetization is uniform in the z direction, which is appropriate for the situations discussed here. The strong vertical magnetization of the Bloch wall in the middle of the sample turns over and into the surface plane leading to the surface Néel wall. This results from minimizing the magnetostatic energy. Note that the center of the Bloch wall in the interior is displaced in the x direction from the center of the surface Néel wall. This distance, between the peak of M_y in the interior and the peak of M_x at the surface, is Δ. The shift is quite evident in Fig. 1(c); the distance between the center of the black and white walls in the image is 2Δ. We take as a working definition of surface Néel wall width, W_S, the distance between the 10% points of the surface M_x distribution and that of the interior Bloch wall width, W_B, as the distance between the 10% points of the bulk M_y distribution.[10] The calculated and measured values of W_S and Δ are compared in Table I which also gives the calculated values of W_B and the parameters used in the calculation. For Fe, it was found that the structure of the interior Bloch wall was completely developed for a film thickness of 0.4 μm. Increasing the thickness did not alter the surface Néel wall, but merely extended the length of the interior Bloch wall.

The comparison between the calculated and measured asymmetric Néel wall profiles of the three specimens is shown in Figs. 3(a)–3(c). The asymmetry of the wall profile is clearly apparent; for example, in Fig. 3(a),

TABLE I. The input parameters used in the calculations for the three materials and a comparison of the calculated and measured domain-wall widths and shifts.

Material	M (emu/cm^3)	K (erg/cm^3)	A (erg/cm)	Calculated W_B (nm)	Calculated W_S (nm)	Calculated Δ (nm)	Measured W_S (nm)	Measured Δ (nm)
Fe(100)	1714	4.7×10^5	2×10^{-6}	104	234	50	225	50.5
Ferromagnetic glass	557	2×10^4	1×10^{-6}	310	660	80	665	78
Permalloy	800	1×10^3	1×10^{-6}	...	2450	...	2360	120

there is a steep rise on the right which is in the surface region directly above the interior Bloch wall. The surface domain wall profiles which we analyze here were obtained by averaging several scans from an image over a length of the wall. The agreement between the calculations and the measurements is striking for these three very different magnetic systems. The magnetocrystalline anisotropy varies over 2 orders of magnitude in going from Fe to Permalloy which is reflected in the order-of-magnitude variation in wall width displayed in Fig. 3. In the 20-μm-thick Fe whisker and the 25-μm-thick ferromagnetic glass sample examined experimentally and simulated by the calculation, the interior Bloch wall and surface Néel wall are both well developed because the sample thickness is several times the bulk Bloch wall width. However, in the 1.5-μm-thick Permalloy specimen, our calculation shows that the surface Néel wall is inseparable from the vortex structure of the asymmetric Bloch wall; i.e., no distinct interior Bloch wall has formed for this thickness of Permalloy.

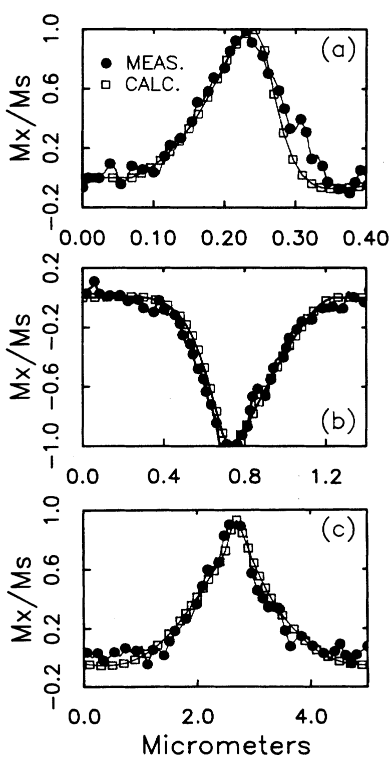

FIG. 3. (a)-(c) Comparison of calculated and measured profiles of the magnetization component perpendicular to the wall for (a) an Fe(100) single crystal, (b) a $Co_{69}Fe_4Ni_1Mo_2B_{12}Si_{12}$ metallic glass, and (c) a 80Ni-20Fe Permalloy film. The scatter in the solid points gives a measure of the experimental uncertainty.

Generally, the exchange energy, which tends to make the wall wider is counteracted by the anisotropy energy which is lowered when the magnetization varies rapidly in order to return to a direction along an easy axis. In a cubic crystal such as Fe with an easy axis in the plane of the wall and normal to the domain magnetization, textbook arguments[11] suggest that magnetostriction must be considered to avoid a 180° wall being comprised of two infinitely separated 90° walls. This argument is only true in an infinite crystal. The presence of the surface constrains the wall width. The magnetostatic interaction causes the energy-favorable configuration to be the 180° Bloch wall. The wall is "held together" by the magnetostatic energy which is significantly larger than the magnetostrictive energy, thus again showing the important influence of the surface.

The surface Néel wall widths are uniformly wider than the Bloch wall widths in the interior as determined from the calculations. There are no experimental determinations of the Bloch wall width in bulk samples. Transmission Lorentz electron microscopy measurements in Fe films up to 0.3 μm thickness yield Bloch wall widths which increase to a maximum for thicknesses of 0.2 to 0.3 μm.[4] Since transmission electron microscopy senses the integrated effect of the magnetic field in the thin film, it is incorrect to identify wall widths determined in this way with the interior Bloch wall width unless the film is thick enough (>0.4 μm for Fe) not to be in the vortex region of an asymmetric Bloch wall. Although a difference between domain wall widths at the surface and in the interior has been predicted previously,[12] this first detailed comparison, and the agreement obtained between measured and calculated surface Néel wall profiles, provides a new underpinning to the conclusions which can be drawn from micromagnetic calculations. Overlooking the extreme effect of the surface has led to the incorrect conclusions that surface Néel and bulk Bloch wall widths in Fe are the same[1] and that bulk Bloch walls in Fe are ≈ 200 nm wide.[13,14]

Our results also have important implications for other techniques which seek to determine magnetic microstructure. The asymmetric Néel wall reduces the external field from the interior Bloch wall and causes the external field maximum to be displaced from the position of the Bloch wall in the interior. The widely used Bitter technique for imaging domain walls, and the newer technique of magnetic force microscopy, do not simply respond to the bulk Bloch walls. Rather, they respond to the resultant field from the interior Bloch and surface Néel walls, and in the case of magnetic force microscopy, to a possibly reconfigured surface magnetization distribution in the presence of a magnetic tip.

In the systems we have considered, the surface affects the magnetization distribution over a length scale comparable to a Bloch wall width. Because of this, even though our measurements probe only the top several layers, there is excellent agreement between our micromagnetic calculation and the experimental profiles without introducing any special surface parameters. A surface micromagnetic length scale comparable to a bulk Bloch wall width is supported by observations of the surface Néel walls by the magneto-optic Kerr effect[6] which has a probing depth on the order of 10 nm. Thus we expect similar images of domain walls obtained with SEMPA or the Kerr effect, within the resolution limitations of each technique, for most magnetic materials. Kerr observations also rule out a surface monolayer effect being responsible for the observed surface Néel walls.

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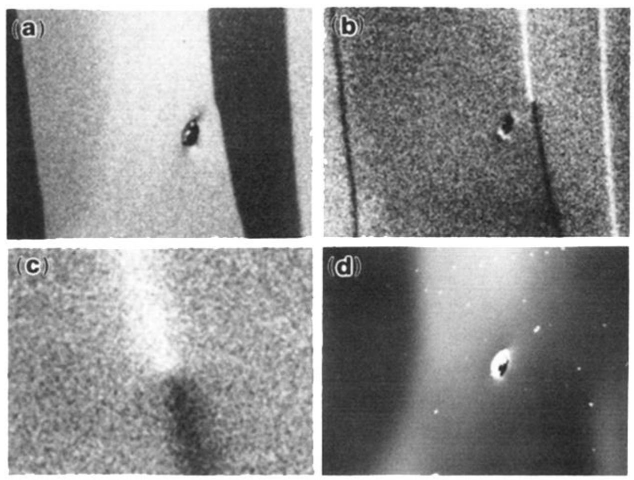

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