SURFACE MAGNETIC MICROSTRUCTURE

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The way in which a magnetic solid minimizes its energy through the formation of domains and domain walls is strongly influenced by the presence of the surface. At the surface, a bulk Bloch wall may change into a Néel wall in order to reduce the magnetic stray field energy of the ferromagnetic system. We present high spatial resolution images of surface magnetic microstructure obtained by scanning electron microscopy with polarization analysis (SEMPA). Quantitative domain wall profiles at surfaces have been measured for a wide variety of ferromagnetic materials which display asymmetric surface Néel walls for bulk-like thicknesses. We have calculated the magnetic moment configuration at the surface using bulk magnetic parameters and an iterative micromagnetic energy minimization scheme. The calculated profiles are compared qualitatively with experimental surface magnetization profiles. The surface magnetic microstructure of a surface magnetic topological singularity is observed and an upper limit on the size of the singularity is determined.

1. Scanning Electron Microscopy With Polarization Analysis (SEMPA)

Scanning Electron Microscopy with Polarization Analysis (SEMPA), in which the spin polarization of the secondary electrons is measured, is unique in domain imaging techniques using electron microscopy in that the image is directly proportional to the magnetization. In this sense it is like the magneto-optic Kerr effect without the transverse spatial resolution of the technique being limited by diffraction at optical wavelengths. The sampling depth of the SEMPA probe is limited by the escape depth for spin-polarized secondary electrons, which is estimated to be on the order of 10 to 20 angstroms. This property of SEMPA, coupled with the high transverse spatial resolution attainable with focused electron beams, makes SEMPA ideal for observing surface magnetic microstructure.

In the SEMPA experiment, a beam of high (5 to 60 keV) energy electrons is rastered point-by-point across the surface of a ferromagnetic sample generating spin-polarized secondary electrons at each point [1]. The polarized electrons are efficiently extracted from the locale of the sample surface, and focused into an electron-spin polarization analyzer. Most electron-spin polarization analyzers separate electrons of differing spin orientation via the spin-orbit interaction in the scattering of the polarized electron beam with a high-Z target, such as Au. We utilize a new type of spin analyzer,which is exceptionally compact and efficient, developed explicitly for experiments of this type [2,3]. A map of the surface electron spin-polarization is generated as the focused beam scans the sample surface and the polarization of the emitted secondary electrons is anlayzed.

In a 3d ferromagnetic transition metal such as Fe, Co or Ni, the magnetization M is directly proportional to the net spin density, $n_\uparrow - n_\downarrow$

$$M = -\mu_B (n_\uparrow - n_\downarrow) \qquad (1)$$

where $n_\uparrow (n_\downarrow)$ are the number of spins per unit volume parallel (antiparallel) to a particular quantization direction and μ_B is the Bohr magneton. Spin polarized electron spectroscopies such as SEMPA depend on extracting electrons from the solid without loss of any information. One then measures the degree of spin polarization P of the extracted beam,

$$P = (N_\uparrow - N_\downarrow)/(N_\uparrow + N_\downarrow) \qquad (2)$$

where $N_\uparrow (N_\downarrow)$ are the number of electrons with spins parallel (antiparallel) to some quantization direction. Low energy secondary electrons are primarily the result of electron-hole pair creation and thus reflect the net spin density of the valence band. The secondary electron spin polarization can be estimated as $P=n_B/n$, where n_B is the magnetic moment per atom and n is the number of valence electrons per atom; one estimates net electron spin-polarizations of 28%, 19%, and 5% for Fe, Co, and Ni respectively.

In our implementation of SEMPA, we simultaneously measure the total secondary electron intensity, characteristic of topographic and work-function related contrast, and two perpendicular components of the electron spin-polarization. In this way we are able to determine, for example, both components of the in-plane magnetization or one in-plane and the out-of-plane magnetization simultaneously. This is useful when forming maps of the magnetization angle in the surface of the specimen because the two-components of the in-plane magnetization are measured simultaneously, thus eliminating registration problems arising from sample drift.

2. Magnetic Microstructure

We would like to emphasize here the profound effect that the surface has in determining the magnetic microstructure. Detailed studies of surface magnetic microstructure are of both fundamental and technological importance. Although there has been intense study of magnetic microstructure for years, there is still considerable uncertainty about relative wall widths, wall profiles and the magnetization distribution about topological singularities. This is due primarily to a lack of a sufficiently high resolution probe to examine the magnetic microstructure experimentally. Fundamental studies will further impact the development of magnetic storage technology, as device densities will ulimately be limited by the spatial extent of the magnetic microstructure.

The principal effect that a surface has on a solid is breaking the translational symmetry in a direction normal to it. This effects the magnetostatic energy of the system in a fundamental way. The presence of the surface forces the magnetization in the sample into the surface plane, thereby minimizing the stray magnetic field energy that would result if the magnetization vector pointed out of a surface. In an infinitely extended ferromagnet, the boundary between anti-parallel domains would be a 180 degree Bloch wall. If the ferromagnet is cut so that the Bloch wall intersects the surface, a large stray magnetic field and an unfavorable energy configuration results. Instead, the magnetization vector rotates within the plane of the surface between anti-parallel domains forming a Néel wall. The internal structure of domain walls between anti-parallel domains varies as a function of the film thickness. For extremely thin films, the magnetization vector rotates in the plane of the film forming Néel walls. For thick, or bulk-like films, the magnetization forms Bloch walls in the interior and Néel walls at the surfaces. For intermediate thicknesses, a number of different wall configurations are possible as first realized by Hubert [4] and LaBonte [5]. These wall configurations, known as asymmetric Bloch walls, are vortex like structures which have Néel walls at the surfaces, but no well developed wall in the interior. Evidence for this model has been obtained from transmission electron microscopy using Lorentz contrast [6] and a newer differential phase contrast technique [7]. The surface Néel walls predicted by micromagnetic models have been observed by magneto-optic Kerr effect [8] and SEMPA [1,9-11]. Lowering the surface magnetic energy of a ferromagnetic by formation of surface Néel walls appears to be a widespread phenomena for relatively soft magnetic materials.

In Fig. 1, an example of a typical SEMPA image in shown of domains and domain walls found at the (100) surface of an Fe single crystal. The surface of this and other samples described here were prepared by gentle sputtering with a 1 keV Ar ion beam. This sample was re-annealed at 700° C after sputtering. In Fig. 1a, the horizontal component of the in-plane surface magnetization distribution is shown. The image is 14 μm across. White (black) indicates that the surface magnetization vector points to the right (left). The horizontal component of the magnetization vector is M_x. In Fig. 1b, the vertical component of the in-plane surface magnetization distribution M_y, is shown. Here, white (black) indicates that the magnetization vector points up (down). This convention will be used thoughout. Clearly visible in these images are three large domains. The two largest domains, white and black in Fig. 1a, are separated by a 180 degree Bloch wall in the bulk and a 180 degree Néel wall at the surface. The Néel wall is the broken horizontal black-white band in Fig. 1b. There are two topological singularities clearly visible in Fig. 1b. The first, is at the junction of the small white arrow domain on the left and the black surface Néel wall. This singularity has the magnetization circulating in the clockwise sense about it [12]. The locus of magnetization vectors about the singularity forms an ellipse. The second singularity is at the junction of the black and white surface Néel walls in the center of Fig. 1b. This singularity is of another type, where the locus of magnetization vectors forms hyperbolas. The type of magnetic microstucture found on this Fe sample is indicative of that found on bulk samples with in-plane magnetocrystalline anisotropy, namely, large domains separated by surface Néel walls.

Our micromagnetic simulations solve the coupled, non-linear equations derived by Brown [13]. In this model, the magnitude of the magnetization vector is constant and equal to the saturation magnetization M_s, while the direction of the magnetization vector may vary. The approach is to minimize the energy of the system subject to the constraint that the magnitude of the magnetization is fixed. The micromagnetic contributions to the total energy of the system are: the nearest neighbor exchange interaction characterized by the bulk exchange coupling constant A; the magneto-crystalline anisotropy energy characterized by the bulk anisotropy constant K_v; the surface magneto-crystalline anisotropy energy characterized by the surface anisotropy constant K_s; and the long range magnetostatic field energy derived from the self-fields generated by the magnetic charges where there is a finite divergence in the magnetic substructure. Our two dimensional simulation follows that of LaBonte [5], and the three dimensional simulation follows Schabes and Bertram [14]. We divide the ferromagnet into finite sized rods or cubes. The energy and effective magnetic field (the effective magnetic field results from all of the energy terms) is calculated for each discretized magnetization element. The angle of each pixel is adjusted so that it points in the direction of the effective magnetic field. As the system relaxes, the magnetization vector at each element will point in the direction of the effective magnetic field, and the local minimum in the energy distribution is reached. Although the energy minimization scheme is computer intensive, taking up to 10 minutes on a supercomputer for a modest grid of 2000 elements, the equilibrium magnetization distribution arises without any ad hoc assumptions which may be model dependent. This phenomenological calculation has as input the magnetic parameters A, M_s, K_v, K_s and the thickness and boundary conditions. The output of the program is the magnetization direction at each pixel and the various contributions to the total energy.

The hard-direction magnetization configuration in a cross-section (the x-z plane) of a 180° wall in a bulk, zero magnetostriction, Co based ferromagnetic glass is shown in Fig 2a. The magnetization is assumed to be uniform in the y direction, which is appropriate for the situation discussed here. Note how 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. The parameters used in the simulation for the Co based ferromagnetic glass are $A = 1 \times 10^{-6}$ erg/cm, M_s = 557 emu/cm^3 and K = 20000 erg/cm^3. For bulk samples, we determined the critical thickness, such that any further increase in thickness resulted in elongating the interior Bloch wall without modifying the structure of the surface Néel wall profiles. For Fe, for example, it was found that the structure of the interior Bloch wall was completely developed for a film thickness of 0.4 μm. The width of the Bloch wall calculated at the center of the 0.4 μm film is identical to that of an infinite crystal calculated using periodic boundary conditions to eliminate surface effects.

The profiles of the surface Néel wall are shown in Fig. 2b by plotting the components of the surface magnetization. The asymmetry of the surface Néel wall is most easily seen by examining M_x, the surface magnetization component perpendicular to the wall. It clearly falls much more sharply on the left and rises more slowly on the right. The profiles of the bulk Bloch wall, formed by taking a trace through the wall in a direction perpendicular to it, are shown in Fig. 2c. M_z is the vertical component of the magnetization directed normal to the surface plane. The asymmetry so clearly seen in the surface profiles is no longer evident in bulk. The width of the calculated surface Néel wall is about twice the width of the bulk Bloch wall.

Note in Fig 2a 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 can also be seen by comparing the position of the maximum of M_x in Fig. 2b with the position of the maximum of M_z in Fig. 2c. This distance, between the peak of M_z in the interior and the peak of M_x at the surface is Δ.

The measurements in Fig. 3 are from a zero magnetostriction Co based ferromagnetic glass (Allied 2705M, $Co_{69}Fe_4Ni_1Mo_2B_{12}Si_{12}$). In Fig 3a, an image of M_y, one sees parts of two domains with magnetization nearly aligned with the vertical axis. The magnetization within the domain walls, as seen in the M_x image in Fig 3b, lies in 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 counter-clockwise direction in the surface plane. These images are about 9 μm across. The point at which the Néel wall changes direction is a magnetic topological singularity on the surface. Note that the black and white segments of the wall are slightly offset from each other. The shift is quite evident in Fig 3b; the distance between the center of the black and white walls in the image is 2 Δ. This is the offset which was predicted in the simulations.

The widths of the surface Néel walls are consistently wider than the corresponding Bloch wall in the bulk. There is no experimental observations of bulk Bloch walls for bulk samples. Transmission electron Lorentz microscopy studies [6] of Fe films of up to 0.3μm thickness show wall widths consistent with our models. However, these walls are in the asymmetric Bloch wall regime, having no well developed Bloch wall in the interior. If reasonable electron transmission through Fe films of thicknesses greater than 0.6 μm could be achieved, with for example, a 1 MeV transmission electron microscope [15], one would be able then to measure a Bloch wall width close to that in bulk. Since the vortex wall structure of the asymmetric Bloch wall is still present in Fe films up to 0.3 μm, it is incorrect to identify the walls measured in this case with bulk Bloch walls.

Shown in Fig. 3c is the magnitude of the in-plane magnetization as calculated from adding the magnetization of Fig. 3a and 3b in quadrature. A black dot is clearly visible against the nearly constant background which corresponds to a drop in the magnitude of the in-plane magnetization. This point coincides with the location of the magnetic topological singularity at the surface. The missing magnetization is due to a finite sized probe (60 nm) being convolved with a magnetization distribution which is changing sign on length scales on the order of the probe diameter. When this occurs, the probe samples regions of magnetization with the opposite sign, resulting in a cancelation of some of the signal. In this case, the measured full width at half maximum of the hole in Fig. 3c is approximately 270 nm in diameter. Shown in Fig. 3d is the magnetization direction profile in the surface near the singularity derived from our data. The boxed in regions represent the light and dark regions of the surface Néel walls of Fig. 3b. The swirl pattern is clearly visible. We attempted to measure the out-of-plane component of the magnetization near the singularity, but although it was present in some images, it could not be measured repeatedly. With this limitation, we can safely put an upper limit on the radius of the singularity in this Co based ferromagnetic glass at 130 nm. This is still about six times as large as the core of the singularity calculated by Hubert [12].

In summary, we find surface Néel wall widths in bulk samples are at least twice those of interior Bloch walls. Our micromagnetic calculations provide a good qualitative description of asymmetric surface Néel walls, and predict correctly that the surface wall is offset from the interior Bloch wall at the intersection of a Bloch wall with the surface. SEMPA clearly provides a powerful means for the experimental investigation of surface magnetic microstructure.

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Figure Captions

Fig. 1. SEMPA images of an Fe <100> oriented single crystal showing components of the magnetization along the horizontal (a) and vertical (b) directions. The images are 14 micrometers across.

Fig. 2.(a) The calculated magnetization distribution in the upper 0.4 micrometers of the cross section through a Co based ferromagnetic glass sample. (b) Calculated surface domain wall profiles for each component of the magnetization distribution shown in (a). (c) Calculated bulk domain wall profiles for each component of the magnetization distribution shown in (a).

Fig. 3.(a) The vertical component of the magnetization M_y in a Co based ferromagnetic glass. The horizontal extent of the image is 9 μm. (b) The horizontal component of the magnetization recorded simultaneously with (a). (c) The magnitude of the in-plane magnetization. (d) The surface swirl pattern near the Bloch line singularity at the juction of the two surface Néel walls.