180° surface domain wall magnetization profiles: Comparisons between scanning electron microscopy with polarization analysis measurements, magneto-optic Kerr microscopy measurements and micromagnetic models

M. R. Scheinfein, P. J. Ryan,[a] J. Unguris, D. T. Pierce, and R. J. Celotta
National Institute of Standards and Technology, Gaithersburg, Maryland 20899

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We compare measurements of magnetization profiles across a 180° surface domain wall in a 0.24-μm-thick of Permalloy ($Ni_{81}Fe_{19}$), obtained with scanning electron microscopy with polarization analysis (SEMPA) and longitudinal magneto-optic (MO) Kerr microscopy with the predictions of a bulk micromagnetic theory. Both measurement techniques yield wall profiles in accordance with the predictions of micromagnetic theory. We conclude that for micromagnetic structure with relevant length scales on the order of tens of nanometers, SEMPA and MO Kerr microscopy yield equivalent quantitative micromagnetic information within the transverse spatial resolution limits of each technique. Near-surface effects such as enhanced surface moments, weakened surface exchange, and surface anisotropy are not important in determining the surface domain wall profiles that we observe.

The surface of a ferromagnetic material is important in determining the equilibrium micromagnetic structure which results in the formation of domains and domain walls. Important fundamental properties of magnetic materials as well as the ultimate limitations imposed on the density of information stored in magnetic media may be revealed by a study of surface magnetic microstructure. Clues to the underlying bulk magnetic structure may also be gleaned from observation of surface magnetic microstructure.

The technique of scanning electron microscopy with polarization analysis (SEMPA) has been developed as a means of obtaining high spatial resolution quantitative maps of the surface magnetization of ferromagnets (e.g., Refs. 1, 2) using electrons as a probe. From such measurements one can obtain the profile of the magnetization across a domain wall at its intersection with the surface.[3,4] Longitudinal magneto-optic (MO) Kerr microscopy is an optical method for extracting surface magnetization information from ferromagnets[5,6] from which domain wall profiles may be also be extracted.[7]

While both techniques produce signals which are proportional to the magnetization of the sample being probed, we would like to emphasize two differences between SEMPA and MO Kerr microscopy. First, the transverse spatial resolution of SEMPA is limited by aberrations in the probe forming electron optical column while the resolution of MO Kerr microscopy is limited by diffraction at optical wavelengths. Transverse spatial resolutions can approach 10 nm in SEMPA and 200 nm for MO Kerr microscopy. Second, the depth from which information is extracted by these two techniques occurs over two distinct length scales. We will characterize the depth sensitivity for extracting information from within the sample by an attenuation length. In SEMPA, this attenuation length is on the order of 1 nm,[8] while in MO Kerr microscopy this length, approximately equal to the electromagnetic skin depth, may be as long as 8 nm in Ni.[9] Thus we expect that SEMPA measurements are more characteristic of the near-surface (top several atomic layers) magnetic microstructure while MO Kerr microscopy should yield more bulk-like (top several tens of atomic layers) information. The aim of this letter is twofold. First, we will show that for the case of quantitative analysis of surface domain walls in Permalloy, both techniques yield the same domain wall magnetization profiles within the transverse spatial resolution available with each technique. Second, we show that both measurements produce results which verify micromagnetic models which use only bulk parameters.

In SEMPA,[1,2] a finely focused beam of unpolarized medium energy (5–50 keV) electrons is rastered across a sample's surface exciting secondary electrons. The secondary electrons scattered out of the surface maintain their spin orientation, which is characteristic of the net spin density in the solid for a wide variety of ferromagnetic materials. Surface magnetization maps are generated by spin analyzing the emitted secondary electrons, point by point, as the incident beam rasters the sample surface. The SEMPA images used for this study are comprised of 256 by 192 square pixels. The dwell time per pixel was 30 ms, for a total image acquisition time of 24.5 min. The two in-plane magnetization images, together with the standard secondary intensity image, were acquired simultaneously and are therefore registered exactly.

In order to extract quantitative information from our domain wall measurements, we characterized the instrument function of our probes. We have measured the probe diameter for our scanning electron microprobe in the SEMPA mode. The incident electron beam distribution was assessed from line scan profiles across a cleaved GaAs crystal edge oriented orthogonal to the beam scan direc-

[a]Seagate Technology, 7801 Computer Ave., Bloomington, MN 55435

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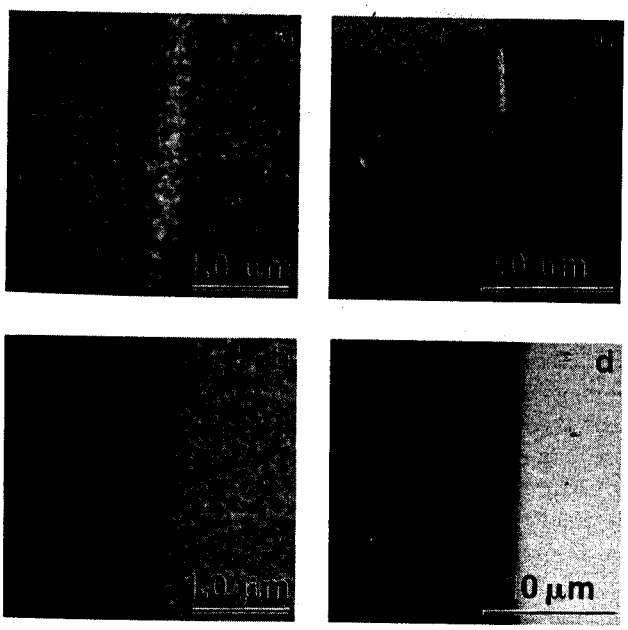

FIG. 1. Magnetization images of a surface domain wall in 0.24-μm-thick Permalloy. The SEMPA images of the (a) x component and (b) y component of the magnetization are shown with the corresponding MO Kerr microscopy images of the (c) x component and (d) y component of the magnetization for the same film.

tion. The secondary intensity images of the cleaved edges were acquired through the SEMPA transport optics. All possible beam broadening effects, such as those caused by mechanical or electrical instabilities, are included.[10] The probe size in an electron microprobe depends on various electron lens excitations and angle-limiting apertures in the electron optical column. For the SEMPA magnetization profiles presented here, data were acquired with a relatively high current, and hence a lower spatial resolution than ultimately attainable in our instrument. The Gaussian fit to the probe profile had a full width at half maximum (FWHM) of 0.210 μm.[10]

SEMPA images of the surface magnetization from a region near a 180° surface domain wall in a 0.24-μm-thick Permalloy ($Ni_{81}Fe_{19}$) film are shown in Figs. 1(a) and 1(b). These images are 3 μm across. Both SEMPA magnetization images show positive (negative) magnetization as white (black). In Fig. 1(a), the image of the x component of the magnetization, M_x, is shown where positive magnetization (white) points to the right. In Fig. 1(b), the image of the y component of the magnetization, M_y, is shown where positive magnetization points upward. Both M_x and M_y are in the plane of the page. We measured no out-of-plane component of the magnetization M_z for this surface domain wall magnetization profile.

The MO Kerr microscopy wall measurements were taken directly from 256×256 pixel digitized images acquired through a video-enhanced magneto-optic microscopy. The system is comprised of a polarized light microscope, video vidicon camera, and high-speed image processor with 16-bit resolution. A strain-free 100× objective, an oil-immersion lens with a numerical aperture of 1.25 is used for all domain wall measurements. Magnetic image contrast is accomplished by the longitudinal Kerr effect with the optic plane of incidence parallel to the measured magnetic moment orientation.[5] A polarized mercury light source is used for illumination and directed obliquely to the sample plane through a Berek prism. The reflected signal is passed through a polarization analyzer, an adjustable compensator, and enhanced further by electronically differencing and averaging multiple magnetization states to boost contrast.

Using the Rayleigh criteria, the anticipated minimum measurable spatial resolution of our MO Kerr microscope using a Hg lamp of a wavelength of 546 nm and an oil immersion lens is 0.2 μm. However, because it is necessary to use an off-axis optical configuration to obtain the oblique incidence critical for detecting a longitudinal Kerr rotation, the absolute spatial resolution is actually somewhat diminished. The resolution of this instrument was also measured from edge profiles from cleaved GaAs. The resolution extracted from these edge profiles had a FWHM of 0.44 and 1.0 μm for measuring the x and y components of the magnetization, respectively.

MO Kerr microscopy images of the surface magnetization from a region near a 180° surface domain wall in the same 0.24-μm-thick Permalloy ($Ni_{81}Fe_{19}$) film are shown in Figs. 1(c) and 1(d). These images are 23.25 μm across. As in the SEMPA images, both MO Kerr magnetization images show positive (negative) magnetization as white (black). The Kerr images are not acquired simultaneously, as it is necessary to rotate the sample by 90° to acquire the second component. The x component of the magnetization is shown in Fig. 1(c) and the y component of the magnetization is shown in Fig. 1(d). Figures 1(c) and 1(d) are characteristic of the MO Kerr microscopy images from which we extract surface domain wall magnetization profiles.

We calculate the micromagnetic structure present in domain walls by following the methods used by Brown and La Bonte,[11] La Bonte,[12] Hubert,[13] and Aharoni.[14] The equilibrium configuration of domain walls in ferromagnetic materials results from the minimization of a system's total magnetic energy. The system is composed of mean field exchange, bulk magnetocrystalline anisotropy, surface magnetocrystalline anisotropy, and self-magnetostatic and external magnetostatic energies. We solve for the magnetization distribution in a domain wall by considering a boundary value problem in two spatial dimensions with the constraint of constant magnetization.[10] The minimum energy state is found iteratively using a relaxation scheme.

The experimental surface domain wall profiles extracted from SEMPA data, solid points, for a 0.24-μm-thick Permalloy film are compared to the results of micromagnetic theory, solid line in Fig. 2(a). The experimental data are the result of averaging several line scans across the wall. The error bars give the standard deviation about the mean for the averaged line scans. The theoretical curve has been convoluted with the measured instrument function to yield the solid line in Fig. 2(a). The parameters used in the simulations are the accepted bulk value of $A = 1.05\times10^{-6}$ erg/cm,[15–17] and the measured values of $M_s = 813$ emu/cm^3 and $K = 1743$ erg/cm^3. A region of the film 1.2 μm