Abstract — This paper describes the use of Scanning Electron Microscopy with Polarization Analysis (SEMPA) to quantitatively image the magnetic structure of permalloy magnetic memory elements. During ion milling the surface composition is monitored by Auger spectroscopy and SEMPA can directly measure the magnetization magnitude and direction. The problem is that polarization analyzers measure the three components of the magnetization vector rather than the vector itself. Therefore, while relative measurements of a single magnetization component are sufficient to image the magnetic domains, the determination of the total magnetization vector requires measurements of each magnetization component with all of the non-magnetic, instrumental and sample-related contributions to the polarization removed.

INTRODUCTION

By measuring the spin polarization of secondary electrons generated in a scanning electron microscope, Scanning Electron Microscopy with Polarization Analysis (SEMPA) can directly measure the magnitude and direction of the magnetization with sub-micron spatial resolution. The high spatial resolution capability of SEMPA has been demonstrated for several systems. Quantitative measurements of the total magnetization magnitude and angle, however, have only been successful in systems where the magnetization was already well understood. The problem is that polarization analyzers measure the separate components of the magnetization vector rather than the vector itself.

We accomplish the latter by using two scattering targets in our SEMPA apparatus; a gold film target which is spin sensitive and a low-Z graphite target which has all the same instrumental asymmetries as the gold but is without the spin dependent contrast.

EXPERIMENTAL

A schematic of the SEMPA apparatus is shown in Figure 1. The apparatus consists of an ultra-high vacuum Auger probe and scanning electron microscope to which two orthogonal polarization analyzers were added. The analyzers have been described in detail elsewhere. Briefly, the analyzers work by first accelerating the secondary electrons to 1500 eV and transporting them through electron optics which prepare them for scattering from a gold film. Deflection plates within the electron optics are coupled to the scan of the electron microscope so that any motion of the secondary electron trajectories due to surface topography or scanning of the incident electron beam. Intrins
Note how the background nonmagnetic Si substrate appears to have the same magnetization as the permalloy.

Figure 1: SEMPA apparatus schematic.

spectroscopy, an ion gun for cleaning and depth profiling samples, metal evaporators and a Reflection High Energy Diffraction (RHEED) screen for monitoring film structure during evaporation. The samples were cleaned by sputtering with 1 keV Argon ions. Surface cleanliness and chemical composition were monitored by Auger analysis. The permalloy elements were about 40 nm thick and were deposited upon a silicon substrate.

RESULTS

Figure 2 shows an example of single SEMPA measurement of a typical permalloy element. The intensity, I, and the two in-plane magnetization components, $M_x$ and $M_y$, were simultaneously measured using one detector. Also shown are the magnitude of the in-plane magnetization, $M$, and the angle, $\theta$, which were calculated from

$$M = \sqrt{M_x^2 + M_y^2} \quad \theta = \tan^{-1}(M_x/M_y)$$

(3)

In this case the instrumental asymmetry was determined by assuming that both the instrumental asymmetry and the total magnetization were constant throughout the image. There still appears to be some missing magnetization at the domain walls. This is an instrumental effect, however, caused by the incident electron beam averaging over domain walls where a magnetization component changes sign in a region smaller than the beam diameter. The beam diameter for these images was about 100 nm. Since the amount of missing magnetization is directly related to the sharpness of the wall, this image shows that the domain walls that make up the arms of the y-domain are thinner than the wall that forms the leg. There is also the indication of a sharp singularity at the junction of the walls. No perpendicular magnetic component was observed for any of the elements either within the domains or at the domain walls. A problem with the method of instrumental asymmetry removal used in this image is that the absolute values of the total magnetization cannot be determined.

Figure 2: SEMPA image of memory element showing in-plane horizontal ($M_x$) and vertical ($M_y$) magnetization components, intensity ($I$), total magnetization magnitude ($M$) and direction ($\theta$). The gray map key for the $\theta$ image is shown.

Figure 3: Same measurements as in Fig. 2, but the graphite measured instrumental asymmetry has been removed.
Figure 3 is an example of a SEMPA measurement in which the instrumental asymmetries were determined by using the detector with a spin-independent target as a reference. Four memory elements are imaged with the magnetization of the two elements on the right going around the element in a clockwise sense as opposed to counter-clockwise for the two on the left. Polarizations were first measured using the usual gold film target. The images were then repeated using a graphite target. The difference between the gold and graphite measurements are shown as $M_x$ and $M_y$, as well as the calculated magnitude and angle of in-plane magnetization. In this case, not only is the magnetization uniform over the entire element, but the value is also significant. The non-magnetic substrate polarization is zero while the permalloy polarization is about 13%. The main problems associated with this method are that the signal-to-noise is decreased by $\sqrt{2}$ and, if the two images are not exactly aligned before subtraction, the topographic polarization contrast from sharp edges increases rather than decreases.

Figure 4 is an example of how SEMPA can be used as an in situ magnetic imaging technique during thin film preparation. In this case, the film is being ion milled using a stationary ion beam off to the side of the image. From the Ni Auger map (c) one can see that the permalloy has been removed from the right hand side of the image and is still intact on the left hand side. The thickness of the thinned elements in the middle of the picture is unknown, since the Auger electron depth sensitivity is only about 5 nm. One component of the in-plane magnetization, $M_x$, is shown both with (b) and without (a) the graphite target image subtracted. As the material is removed the domains are observed to change from the standard y-domain configuration to a two domain pattern which bisects the element across its width. Note that in the graphite corrected data the polarization of the elements with no permalloy present is zero, in contrast to the uncorrected data where some instrumental polarization is observed.

CONCLUSION

Two methods of determining and eliminating spurious apparatus asymmetries in SEMPA measurements were successfully used to image the vector magnetization in permalloy memory elements. The first relied on assumptions about the symmetry of the domain pattern to establish the polarization zero. In general, this produced accurate maps of the magnetization direction as long as false asymmetries due to surface topography were not important. The second method used the spin-independent scattering from a graphite target as a reference. This method eliminates the instrumental and topographic asymmetry, and is preferred for absolute, quantitative magnetization measurements. Both methods permit one to measure the angle of the magnetization vector to within $\pm 10$ deg.

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