Magnetic microstructure of the (0001) surface of hcp cobalt

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The magnetic domain structure of the (0001) surface of a hcp cobalt crystal was investigated using scanning electron microscopy with polarization analysis (SEMPA). This is the first observation by SEMPA of both out-of-plane and in-plane magnetization components. The perpendicular magnetization imaged with SEMPA showed a branched structure very similar to that previously observed by magneto-optic Kerr microscopy. In addition, a previously unobserved in-plane magnetic substructure was measured. The in-plane magnetization is divided into well-defined submicron domains that appear to reflect the sixfold symmetry of the crystal surface.

The presence of a surface can have a major effect on the domain structure of a ferromagnetic material. The large magnetostatic energy associated with a magnetization component normal to the surface forces the magnetization near the surface to lie parallel to the surface. Closure domains are formed at a surface if an in-plane easy magnetization axis is available or if the magnetostatic energy associated with magnetization normal to the surface is greater than the cost in anisotropy energy for the magnetization to lie in plane. Even Bloch domain walls do not simply terminate perpendicular to the surface. Instead, the magnetization curls over parallel to the surface plane and forms a Néel wall.[1-3] The depth over which the magnetization is rotated parallel to the surface plane is of the order of the bulk domain wall width which is approximately 10 nm for a material like Co with magnetocrystalline anisotropy of about 10^6 erg/cm^3.

The tendency of the magnetization to lie in-plane at the surface is of particular interest for a technique such as scanning electron microscopy with polarization analysis (SEMPA), which is sensitive to only the outermost few atomic layers of the sample.[4] Of all the bulk ferromagnetic materials investigated by SEMPA to date, none has shown a perpendicular component of the magnetization. The purpose of this investigation of Co was to determine if there is any perpendicular component of magnetization at the surface which can be observed using SEMPA.

The Co (0001) surface was chosen for this investigation because cobalt is a prototypical uniaxial material with large magnetocrystalline anisotropy along the *c* axis, which in our experiment was oriented perpendicular to the surface. Magneto-optic Kerr measurements, which have a larger sampling depth, have shown perpendicular magnetization in the form of maze-like domain patterns.[5,6] In this letter we present SEMPA measurements which show a similar perpendicular magnetization. In addition, we also observe a large in-plane magnetization with a fine domain structure that seems to reflect a weak sixfold anisotropy within the surface.

A schematic of the SEMPA apparatus is shown in Fig. 1. The apparatus and polarization analyzers have been described in detail elsewhere.[4,7] Briefly, the incident beam of the scanning electron microscope creates secondary electrons whose spin polarization is directly proportional to the sample magnetization for transition metal ferromagnets. The secondaries are collected and transported to one of two polarization analyzers. One detector, the straight-through one in Fig. 1, can simultaneously measure the two in-plane components of the sample magnetization. The second detector, which is accessed by electrostatically deflecting the secondary electron beam by 90°, measures the out-of-plane magnetization component and a redundant in-plane component. The redundant in-plane measurement is used to make sure that both detectors have the same polarization sensitivity. By using two polarization analyzers the complete magnetization vector can therefore be resolved without having to rotate the specimen or detectors. This ensures that the in-plane and out-of-plane images will be well registered. Shifts due to mechanical and electronic drifts which occur between measurements are typically less than 50 nm and are easily accounted for by cross correlation techniques. Any false polarization signals due to apparatus asymmetries and sample-related trajectory effects can be corrected by also acquiring an image with a graphite target in place of the Au film in the analyzer.[8] This effectively turns off the spin sensitivity of the analyzer leaving only the false polarization signal to be removed.

The Co sample was prepared by mechanical polishing to within 0.5° of the (0001) surface followed by electropolish-

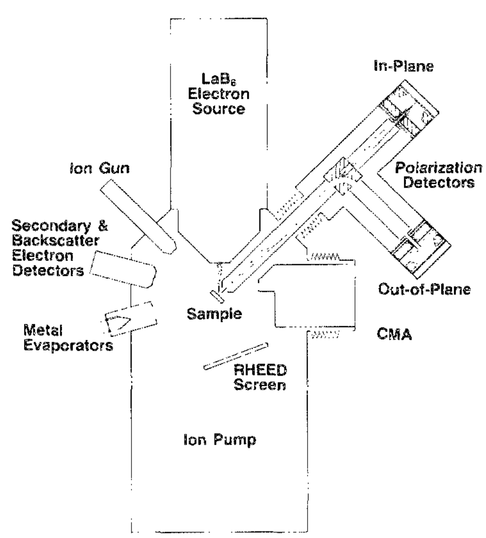

FIG. 1. Schematic of the SEMPA apparatus.

ing at which point good quality Kerr images could be obtained.[9] The sample was then cleaned *in situ* by 1–2 keV Ar ion bombardment followed by annealing to 400 °C. The cleaning cycles were continued until the carbon and oxygen Auger peaks were negligible. [The C(272 eV) and O(510 eV) peaks were less than 4% of the Co (53 eV) peak.] This cleaning procedure has previously been shown to produce well-ordered surfaces.[10] Subsequent heating to 500 °C caused the formation of small recrystallized regions with an in-plane *c* axis, but did not otherwise affect the domain structure.

An example of a domain pattern measured with SEMPA from the Co (0001) surface is shown in Fig. 2. The two in-plane magnetization components M_x and M_y and the intensity I were measured simultaneously with one spin analyzer. The out-of-plane magnetization M_z was measured with the other spin analyzer. The grey scale of the images maps positive magnetizations to white and negative to black. The direction of positive magnetization is toward the right, top, and out of the page in the M_x, M_y, and M_z images, respectively. A map of the in-plane magnetization direction,

$$\theta = \tan^{-1}(M_y/M_x)$$

is shown in Fig. 3.

FIG. 3. Map of the angle of the in-plane magnetization derived from Figs. 2(a) and 2(b). The color wheel gives the relationship between color and direction.

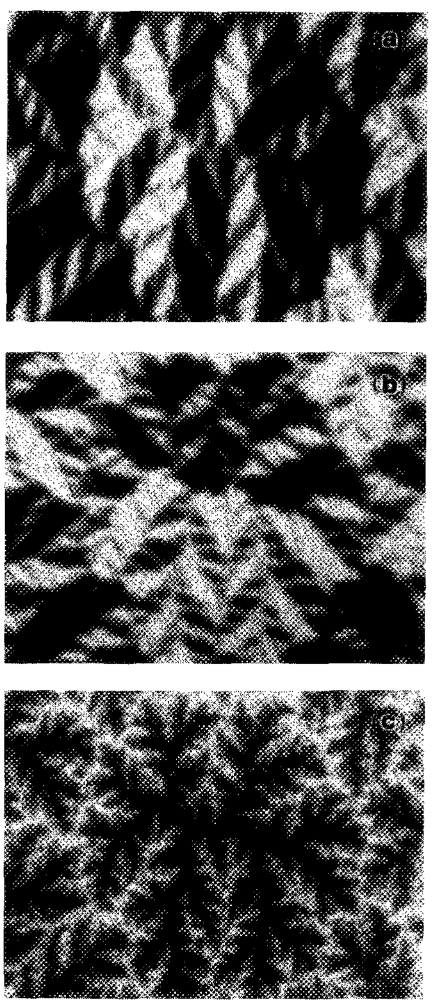

FIG. 2. SEMPA images of domains from the (0001) surface of cobalt showing measurements of the magnetization components (a) M_x along the horizontal and (b) M_y along the vertical in-plane directions, and (c) M_z in the out-of-plane direction. The images are 18 μm across.

By comparing the M_z and θ images one may begin to understand the complicated branched domain structure of the Co surface. The magnetization is found to flow out of the white regions and into the black regions of the M_z image. In between these magnetization sources and sinks the magnetization flows along the surface in well-defined in-plane domains. The magnetization does not have a fixed direction out of the surface but varies continuously. This can be seen by calculating the angle the magnetization makes with respect to the surface

$$\theta_\perp = \tan^{-1}[M_z/(M_x{}^2 + M_y{}^2)^{1/2}].$$

A histogram of the distribution of $\theta_\perp$ is shown in Fig. 4. The finite size of the electron probe, about 50 nm in this case, results in some averaging of the sharp perpendicular structure and consequently the histogram may be slightly biased towards zero degrees. One can see that the perpendicular component varies continuously and is generally smaller than the in-plane magnetization component.

Another interesting feature of the in-plane magnetization is that it is not random, but is fractured into well-defined

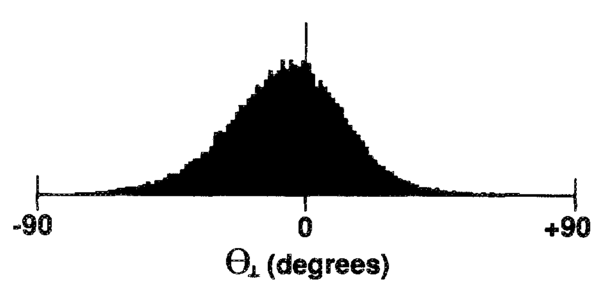

FIG. 4. Histogram of the angle $\theta_\perp$ the magnetization makes with the surface from the data in Fig. 2.

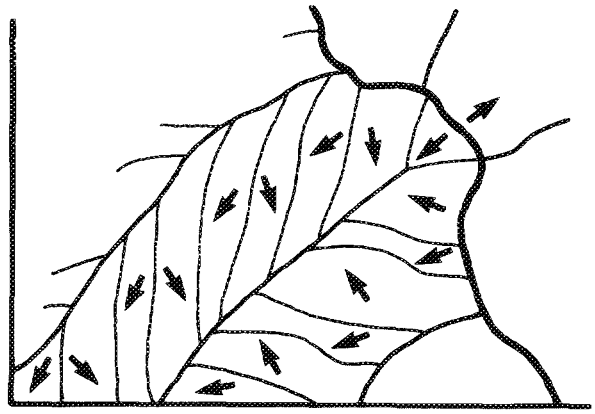

FIG. 5. Schematic of the in-plane domain structure from the lower left corner of Fig. 3.

submicron domains. A schematic of this domain structure taken from the lower left hand corner of the image in Fig. 3 is shown in Fig. 5. The in-plane magnetization does not rotate by a random angle in going from one domain to the next, but instead the changes appear to be quantized in roughly 60° increments. The domain walls occur in three types across which the magnetization either rotates by 180°, 120°, or 60°. We speculate that this symmetry of the in-plane domains is related to the weak sixfold magnetocrystalline anisotropy. We note that our measurements of polycrystalline SmCo samples, using SEMPA, show similar out-of-plane magnetization structure, but the in-plane magnetization varies smoothly without any domain microstructure.

In conclusion, we have used SEMPA to observe both in-plane and perpendicular magnetic domain structures in the Co(0001) surface. The perpendicular domain patterns were similar to ones observed previously with Kerr microscopy. Subsequent to our observation of in-plane magnetization using SEMPA, it was sought and observed using Kerr microscopy.[11] In our SEMPA measurements the in-plane magnetization was in general larger than the perpendicular component. In the Kerr measurements the reverse is true. Presumably this difference is related to the difference in probing depths between the two techniques (roughly 1 nm for SEMPA and 10 nm for Kerr microscopy). Future studies involving quantitative comparisons between the two probes may yield depth dependent information about the domain structure.

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