Effect of surface roughness on magnetization reversal of Co films on plasma-etched Si(100) substrates

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Co films ~970 Å thick were deposited, *simultaneously*, on ten plasma-etched Si(100) substrates with various etch times t. The surface morphologies and magnetic properties of the Co films were measured by atomic force microscopy (AFM) and magneto-optic Kerr effect (MOKE) technique. The analysis of the AFM images shows that as the etch time t increased from 0 to 100 min, the vertical interface width w increased from ~5 to ~1400 Å; the lateral correlation length ξ increased from ~300 to ~10 500 Å. The MOKE measurements provided the in-plane azimuthal angular dependence of the hysteresis loops and the change of loop shapes with the surface roughness. It was found that the magnetization reversal process changed with the surface roughness. Magnetization rotation dominated the magnetization reversal for the smoothest films. As the films roughened, the domain-wall pinning set in, eventually dominating the magnetization reversal for the roughest films. Additionally, the magnetic uniaxial anisotropy in the Co films disappeared as the roughness parameters increased. It was also found from MOKE that the surface roughness strongly affected the coercivity. © *1998 American Institute of Physics.* [S0021-8979(98)36911-X]

It is known that surface/interface roughness of magnetic thin films and of superlattices influences magnetic properties, such as magnetic anisotropy, coercivity, magnetoresistance, and magnetic domain structure.[1–3] Various works on the relationship between surface roughness and coercivity, of thin and ultrathin films, have been carried out.[4–6] For examples, Malyutin *et al.*[4] investigated the effect of surface roughness on the coercivity of chemically etched NiFeCo films (200–1000 Å thick) and found that the coercivity of the film increased with the increase of etch time. During the etching, the thickness of the magnetic film decreased and the surface roughness increased with etch time. Vilain *et al.*[5] investigated the dependence of coercivity on the surface roughness for electrodeposited NiCo alloy films. For ultrathin films, Jiang *et al.*[6] investigated the coercivity of ultrathin Co films on Cu(100) substrate versus substrate roughness. The coercivity of the 6–7 ML Co film increases from ~70 Oe for deposition on an atomically flat Cu substrate, to ~170 Oe for deposition on a Cu substrate roughened by Ar^+ sputtering to a (vertical) interface width of ~1.81 atomic-step heights. This demonstrates the sensitivity of coercivity on the surface roughness.

In addition to the surface roughness, it is known that the thickness, the composition, the crystalline structure of the magnetic film, and the preparation conditions also determine the magnetic properties of the films. Therefore, to understand the interrelationship between roughness and magnetic properties, other factors influencing the magnetic properties must be controlled. In the present study, we deposited ~970 Å Co films simultaneously (and thus identically) on ten plasma-etched Si(100) substrates by thermal evaporation in high vacuum and studied the effect of the surface roughness on the magnetic properties of ~970 Å Co films.

Ten n-type Si(100) substrates were etched by plasma-etching gases (CF_4 and 4% O_2) with an etch rate of 1500 Å/min to various degrees of roughness in a standard plasma-etching chamber. The etch times t were 0, 1, 5, 10, 20, 30, 40, 60, 80, and 100 min, respectively. The surface morphologies of these roughened Si(100) substrates were imaged by atomic force microscopy (AFM) with a Si_3N_4 tip. Then, these rough Si(100) substrates were arranged on a large supporting plate in another high-vacuum chamber. The Co atoms were thermally evaporated from a crucible onto these ten Si(100) substrates simultaneously. The base pressure was 5×10^{-7} Torr and the pressure increased to 5×10^{-6} Torr during deposition. A quartz crystal monitor indicated a deposition rate of ~0.8 Å/s and ~970-Å-thick Co films formed after about 20 min deposition. The starting substrate temperature was at the ambient temperature and the substrate temperature rose during the deposition due to the filament needed to heat the Co source. The characterizations were carried out in ambient air at room temperature. The surface morphology of the Co film was imaged by AFM. The hysteresis loops were measured by the magneto-optic Kerr effect (MOKE) technique.[7]

All of the AFM images from AFM measurements showed islandlike features with a wide distribution of sizes and separations. Figure 1 shows four typical AFM images of the ~970 Å Co films deposited on the plasma-etched Si(100) substrates. As illustrated by the increasing scan size for successive etch time t, the average size and separation of the features increased with increasing etch time t. For etch

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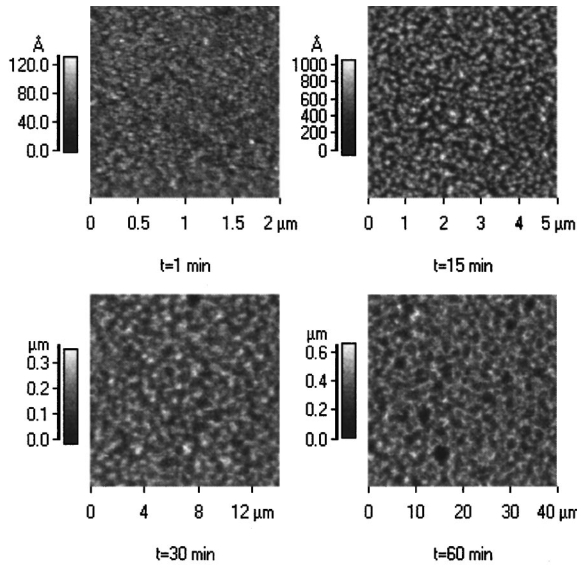

FIG. 1. Four grey-scale AFM images of ~970-Å-thick Co films deposited on Si(100) substrates etched for times $t=1$, 15, 30, and 60 min. Note, the scan size increases.

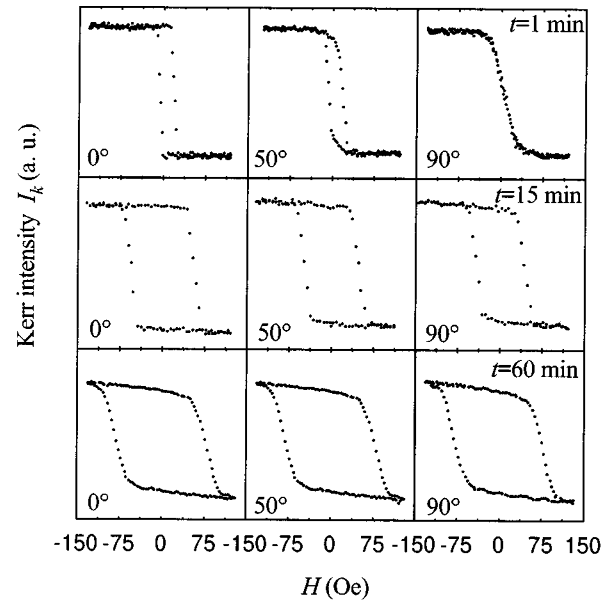

FIG. 2. MOKE hysteresis loops at three in-plane azimuthal angles (0°, 50°, and 90°) for three ~970-Å-thick Co films.

times longer than 20 min, the islandlike features connected to form a networklike morphology. The roughness parameters, the (vertical) interface width w, and the (lateral) correlation length ξ can be obtained by analyzing the height-height correlation function $H(r,t)$, which can be calculated from AFM images.[8] The vertical interface width w increased from ~5 to ~1400 Å; the lateral correlation length ξ increased from ~300 to ~10 500 Å. Table I lists the roughness parameters for different etch time t.

The longitudinal hysteresis loops were measured for all of the Co films using an external magnetic field amplitude $H_0=128$ Oe with a frequency $f=1.4$ Hz. For a given sample, the loop was measured as a function of in-plane azimuthal angle φ from 0° to 360°. The results indicate that the easy magnetization direction of the Co films lay in the film plane for all the samples studied here. There was in-plane uniaxial magnetic anisotropy in the Co films for etch times $t<60$ min, whereas there was no detectable in-plane magnetic anisotropy in the Co films with the etch time $t=60$ and 100 min.

The directions of the easy axis and the hard axis in the film plane were determined from the azimuthal angle dependence of the loop shape. Figure 2 shows the hysteresis loops at different azimuthal angles for three typical samples with etch time $t=1$, 15, and 60, min. For the samples with etch time $t\leqslant 5$ min, the shape of the loop changed from squarelike, to spindlelike, to almost a straight line as the in-plane azimuthal angle changes in the range of 0°–90°. The loop had a squarelike shape, a high coercivity H_c and a high squareness S when the magnetic field was applied along the easy axis. When the magnetic field was applied along the hard axis direction, however, the loop was almost reversible; as a result, both S and H_c were close to zero. This suggests that the magnetization reversal process was dominated by magnetization rotation, and that the contribution to the magnetization reversal from domain wall motion was negligible for samples with $t=0$, 1, and 5 min. The uniaxial magnetic anisotropy field can be easily obtained from the hysteresis loops.[9]

For samples with etch time $t=10$, 15, 20, 30, and 40 min, the twofold symmetry in the coercivity versus azimuthal angle still existed, but all of the loop shapes were squarelike. The squareness lost its twofold symmetry, becoming almost constant, independent of φ. Due to the increasing surface roughness, domain-wall pinning started to contribute to the coercivity. The magnetization reversal process was associated with both the domain wall motion and magnetization rotation. To make the magnetization reversal happen in these cases, the applied field H must overcome not only the domain-wall-pinning coercivity, H_{cw}, but also the component of the magnetic anisotropy field in the applied field direction, which is $H_a'=H_a\cos\varphi$. This means that the combined magnetic field should at least equal H_{cw}. Therefore, we have the following relation:

$$H_0^2=H^2+H_a'^2-2HH_a'\cos\varphi, \tag{1}$$

where φ again is the in-plane angle between the applied

TABLE I. The surface roughness parameters (vertical interface width w and lateral correlation ξ) of Co films vs etch time t.

t(min)	w (Å)	ξ (Å)
0	5±1.5	335±110
1	15±1.6	310±105
5	30±3	320±108
10	150±5	677±213
15	172±9	765±222
20	453±24	2009±695
30	485±15	2665±932
40	574±18	3207±1160
60	859±30	6795±2342
100	1376±15	10475±3884

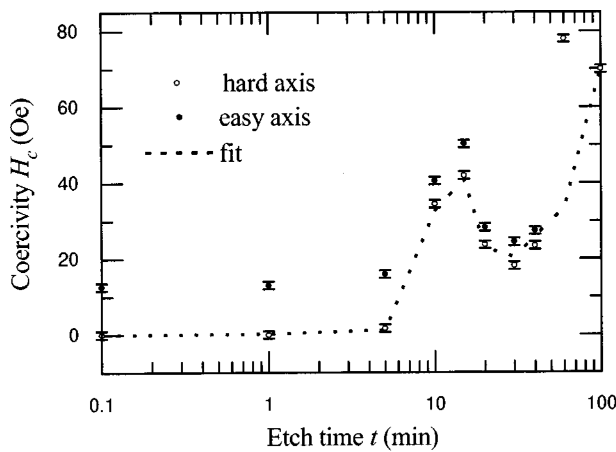

FIG. 3. The easy axis coercivity and hard axis coercivity vs etch time for ~970-Å-thick Co films. The dashed curve is the fit using $H_{cw}=aw^b/\xi^c$.

field and the easy axis of magnetization, and $H_a'=(2K_u/M_s)\cos\varphi$. Letting $H_0=H_{cw}$, and $H=H_c$, the magnetization reversal will occur, and we have

$$H_c=H_a'\cos\varphi+(H_{cw}^2-H_a'^2\sin^2\varphi)^{1/2}. \quad (2)$$

By using this equation, we fitted the measured angular dependence of H_c for samples with $t=10$, 15, 20, 30, and 40 min, and obtained the magnetic anisotropy field H_a and anisotropy coefficient K_u.

For the samples with $t>40$ min, the loop shape was squarelike, and there was no detectable in-plane magnetic anisotropy. At this point, the magnetization reversal was controlled mostly by the domain wall motion.

The results of MOKE hysteresis loop measurements suggest that the magnetization reversal process in these Co films depended strongly on the surface roughness. With the increase of the surface roughness, the magnetization reversal process changed from the magnetization rotation ($t<10$ min) to a combination of magnetization rotation and domain-wall motion ($10\ \text{min}\leqslant t\leqslant 40$ min), and then to domain-wall motion ($t>40$ min).

The coercivity determined from MOKE measurements is plotted in Fig. 3 versus etch time t and for samples with $t<60$ min, both the easy and hard axes coercivity are shown. The easy-axis coercivity H_c was, in general, a monotonically increasing function of the interface width, except for a dip around $t=30$ min. Specifically, the H_c increased slightly between 13 and 15 Oe for $t\leqslant 5$ min, peaked at ~50 Oe for $t=15$ min, came down to ~25 Oe for $t=30$ min, then increased again to ~80 Oe for $t=60$ min and ~70 Oe for 100 min. The hard-axis coercivity had a similar dependence on the etch time. The difference between easy axis coercivity and hard axis coercivity was due to the in-plane uniaxial anisotropy. The results indicated that H_c increased with the increase of the roughness. This is consistent with the prediction of H_c for a Bloch type of domain wall, for which H_c increases if the surface roughness increases for a given thickness.[9] The overall decrease of the absolute values of H_c for $t=20$ min and $t=30$ min samples, as compared with those of the $t=10$ min and $t=15$ min samples, might be due to the network formation (as in Fig. 1), which would make wall movements easier. As the etch time t increased further, the roughness increased and the H_c increased again for $t>40$ min. We fitted the hard-axis coercivity, i.e., the domain-wall pinning coercivity by using $H_{cw}=aw^b/\xi^c$, which is shown in Fig. 3 by the dashed line.[3] The roughness parameters used in the fit are the measured roughness parameters listed in Table I. The fit parameters obtained are $b=2.40\pm0.05$ and $c=1.00\pm0.01$. The value of fit parameter a was an order of magnitude different in two etch time ranges: $a=0.135\pm0.005$ for $t<20$ min and $a=0.019\pm0.005$ for $t\geqslant 20$ min. This change coincides with the formation of the networklike features in the morphology after a 20 min etch. This suggests a quantitative correlation between domain-wall coercivity and surface roughness. It is expected that, as the film thickness decreases, the enhancement of the coercivity due to surface roughness would be more dramatic.

The origin of the in-plane uniaxial magnetic anisotropy is not clear yet. It might be related to the stress built up during the film deposition[10] due to the different thermal expansion coefficients of the substrate and of the Co film. From MOKE measurements, the uniaxial magnetic anisotropy K_u decreased from 1.3×10^3 J/m^3 for $t=0$ min to 0 J/m^3 (no anisotropy) for $t=100$ min with the increase of the etch time. A possible reason for the decrease in K_u is that, when the surface became rougher, the stress between the Co film and the Si substrate was more easily relieved. Additionally, since the dispersion of the easy axis is expected to increase with the increase of the surface roughness, the uniaxial anisotropy would average out for differently oriented crystalline grains in a polycrystalline film. It is expected that when the magnetic thin film gets thinner, the effect of the surface roughness on the magnetic properties will be more dramatic and is worth further systematic studies.

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