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Magnetization Reversal and Magnetic Anisotropy in Co Network Nanostructures

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***Abstract*—The magnetization reversal and magnetic anisotropy in Co network structures have been studied using magneto-optic Kerr effect (MOKE). An enhancement of the coercivity is observed in the network structures and is attributed to the pinning of domain walls by the hole edges in the vicinity of which the demagnetizing field spatially varies. We find that the magnetization reversal process is dominated by the intrinsic unaxial anisotropy ($2K_u/M_s \approx 200$ Oe) in spite of the shape anisotropy induced by the hole edges. The influence of the cross-junction on the competition between the intrinsic uniaxial anisotropy and the induced shape anisotropy is discussed using micromagnetic simulations.**

***Index Terms*—Coercivity, magnetic anisotropy, network structures.**

I. INTRODUCTION

The intense interest in ferromagnetic mesoscopic structures derives both from the development in lithography and pattern transfer techniques, and from the opportunity for exploring novel magnetic phenomena. A number of studies on micron- and nanometer-sized dot, hole (or antidot), and wire structures [1]-[7] have been recently carried out. On reducing the lateral size to dimensions comparable to physical length scales, e.g., the domain wall width or the exchange length, the questions of how finite lateral size affects the magnetic reversal behavior, magnetic anisotropy, and domain configurations are of great relevance. A detailed understanding of the magnetization reversal processes in small ferromagnetic elements is significant in the design of high density storage media, miniature read heads, and magnetoelectronic devices [1]-[7].

In previous work [4], we demonstrated that the demagnetizing field introduced by the edges of holes leads to a spatially variant shape anisotropy field, which competes with the intrinsic uniaxial anisotropy of a permalloy continuous film and gives rise to magnetically easy regions with respect to an applied field. The easy regions could be used as individual data storage bits. We also found that significant changes in the coercivity and remanence are observed with hole size in a permalloy film [5]. In an earlier work [6], Barnard *et al.* fabricated magnetic 'networks' by sputtering ferromagnetic films onto the surface of porous nanochannel alumina substrates. They found that coercivity enhancement in the networks is due to the obstruction of wall motion by the pores. Very recently, Liu and Chien [7] reported that ferromagnetic films sputtered onto nanopored alumina membranes show a large increase of coercivity and unusual magnetoresistance behavior due to the impediment of domain wall formation and motion in the networks. In previous studies [6], [7] on network structures, the reversal behavior and coercivity depend upon the film thickness and pore size of the substrate.

In the present work, as an extension of our earlier work [4], [5], we have investigated the magnetization reversal process and magnetic anisotropy in lithographically defined Co network structures using the magneto-optic Kerr effect (MOKE). An enhancement of the coercivity with respect to that of the continuous film is observed in the network structures, which can be explained by the pinning of domain walls due to the hole edges in the vicinity of which the demagnetizing field is significant. We discuss the coercivity data in terms of the competition between the intrinsic uniaxial anisotropy of the continuous film and the induced shape anisotropy. Finally, we present a model of the magnetic anisotropy in the network structure based on numerical micromagnetic simulations.

II. EXPERIMENTS

A continuous polycrystalline Co film structure of 30Å Cu/200ÅCo/700ÅCu/Si(100) was grown at room temperature in an ultrahigh vacuum (UHV) system with a base pressure of $\sim 3\times10^{-9}$ mbar. The Co layer was deposited at an evaporation rate of ~2 Å/min. There was no annealing so that the stress-induced anisotropy would be preserved [8]. MOKE measurements exhibit a uniaxial anisotropy ("intrinsic anisotropy"). High voltage electron beam lithography has been utilized to define the network structures in 0.5 μm thick polymethylmethacrylate (PMMA). After resist development the sample was exposed to an oxygen plasma for 2 min to remove any remaining materials at the exposed surface. Lift-off was carried out in acetone for 2 min with ultrasonic agitation.

The network structures consist of square arrays of square holes with a repeat distance of 1.5 μm and the hole width (w) varies from 0.5 to 1.2 μm: thus hole width (w) + separation (s)=1.5 μm (see Fig. 1). The network structures were patterned to have the diagonal direction parallel to the intrinsic easy axis of the continuous film. In Fig. 1, we present (a) a SEM image showing the network structure with w=1.2 μm (s=0.3 μm) and (b) schematics of the patterned network structures and magnetic anisotropy axes in the continuous film. Magneto-optic Kerr effect (MOKE) hysteresis loops were obtained using the unfocused laser beam (0.2 mm area) to probe the samples by scanning Kerr microscopy.

III. RESULTS AND DISCUSSION

MOKE studies have been carried out to assess the magnetization reversal behavior in both the continuous film as a reference sample and the network structures. Fig. 2 displays MOKE hysteresis loops of the continuous film for fields applied along the easy and hard axes. It is clearly seen that the continuous film has an intrinsic uniaxial anisotropy field (H_a) of ~ 200 Oe and a coercivity, H_c=30 Oe. The intrin-

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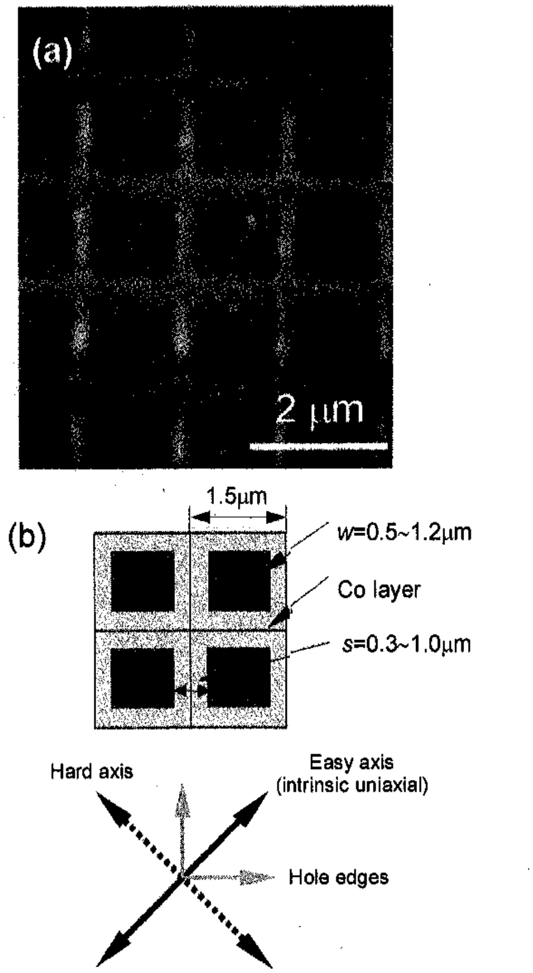

Fig. 1 A SEM image (a) showing a network structure with w=1.2 μm (s=0.3 μm) and schematics (b) of the patterned network structures and the directions of intrinsic magnetic anisotropy and hole edges in the Co continuous film.

sic uniaxial behavior can arise from stress or from the nanoscale morphology for example [8]. The continuous film has a much lower coercivity compared with that of epitaxial *fcc* Co in Cu/Co/Cu/Si(100) layers (H_c=100 Oe) [9] and epitaxial *hcp* Co in Au/Co/Au/MoS_2 sandwiches with perpendicular magnetic anisotropy (H_c=400 Oe) [10]. The network structures, however, are magnetically 'hard' in comparison to the continuous film. Fig. 3 shows the variation in the coercivity with the hole width (w) in the network structures, measured when the applied field was swept along the diagonal direction (intrinsic easy axis) and the edge direction in the network structures. A striking increase in the coercivity is observed as the hole width (w) increases, or the separation (s) decreases for both the diagonal direction and the edge direction. The enhancement of the coercivity in the network structures can be explained by the pinning of domain walls due to the hole edges in the vicinity of which the local demagnetizing field is significant [4], [5]. Our results are also similar to the results of previous work [6], [7] on ferromagnetic transition metal network structures, in which the domain wall formation is impeded and wall motion is pinned due to the pores of the substrates. In previous work [5] we reported

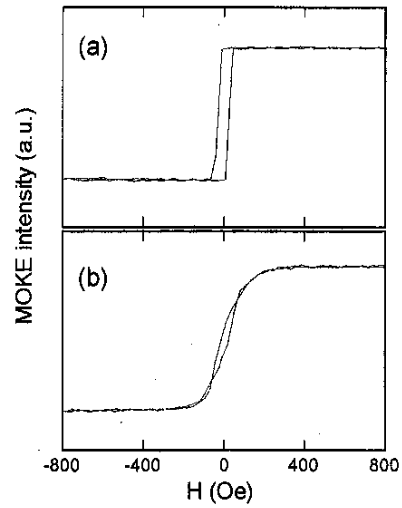

Fig. 2 MOKE hysteresis loops of the Co continuous film for magnetic fields applied along the easy (a) and hard (b) directions. The uniaxial behavior is clearly seen.

a linear dependence of the coercivity on the inverse hole width, $1/w$ at fixed ratio of $s=2w$ in pattered permalloy antidot structures in qualitative agreement with theoretical models [11]. The variation in the coercivity with the hole width (w) in the Co network structures is different from that in the permalloy antidots, since the ratio of s/w varies from 0.25 to 2 in the Co network structures.

In the present work, it is of interest to study the effect of the competition between the intrinsic uniaxial anisotropy and the induced shape anisotropy. It can be expected that the network structure has a cubic shape anisotropy with a strength dependent on the separation (s). The variation in the coercivity with separation (s) for the two field orientations (the diagonal and edge direction) reveals that the cubic shape anisotropy is in competition with the intrinsic uniaxial anisotropy. For the network structure with $s \geq 0.3$ μm ($w \leq 1.2$ μm) the intrinsic uniaxial anisotropy is found to be still do-

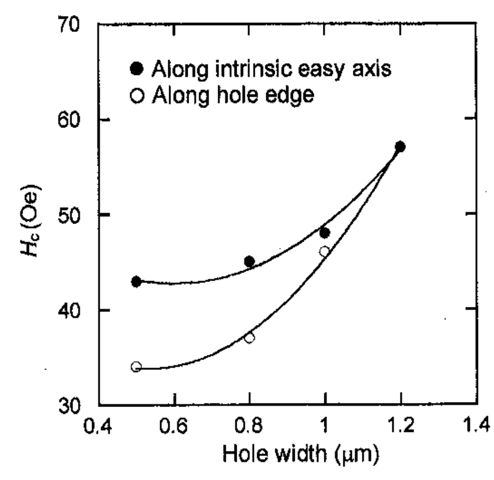

Fig. 3 The variation in the coercivity with hole width (w) in the network structures for field orientations parallel to the intrinsic easy axis and the hole edge direction.

minant due to the high anisotropy field (H_a=200 Oe), resulting in a lower coercivity along the hole edge. This result is in contrast to the previous results on permalloy antidots [5]. For such structures the edge-induced shape anisotropy completely dominated the intrinsic uniaxial anisotropy (H_a=10 Oe) with w=1 μm (s=2w) [5].

In Fig. 4, we present MOKE loops for the Co network structures for field applied along the diagonal direction (intrinsic easy axis). The loops are rather noisy due to optical diffraction associated with the edges of the structures. It is, however, obvious that all network structures show almost rectangular hysteresis loops confirming that the easy axis is still along the diagonal direction of the structures in spite of the expected shape anisotropy. For the network structure with w=1.0 and 1.2 μm [Fig. 4 (c) and (d)], the detailed shape of the loops is attributed to the presence of the cubic shape anisotropy. On the other hand, we found that the hysteresis loops for fields along the edge direction evolve to a rectangular shape due to the cubic shape anisotropy with a strength dependent on the separation (s). The magnetic reversal behavior for the edge direction depends upon the competition between the intrinsic uniaxial anisotropy and the induced shape anisotropy. A crossover of the coercivities for the two directions was found in the network structure with s=0.3 μm (w=1.2 μm) as shown on Fig. 3. For the range of w measured, H_c for H parallel to the edge is lower than H_c for H parallel to the diagonal. This indicates that magnetization reversal process is predominantly influenced by the intrinsic uniaxial anisotropy in spite of the shape anisotropy induced by the hole edges. For larger values of w, we expect the shape anisotropy to dominate.

A numerical micromagnetic calculation was performed in order to investigate the magnetic anisotropy behavior of the network structure using a finite difference method. Fig. 5 shows the magnetization configurations of a cross-junction in the equilibrium state for the network structure with s=0.5 μm, in which it is assumed that there is no uniaxial anisotropy parallel to the diagonal direction. It is seen that, as expected, the magnetization is aligned parallel to the edge directions due to the cubic shape anisotropy. However, we found that the magnetization components at the cross-junction lie along the diagonal direction. The simulation shows that the intrinsic uniaxial anisotropy is still dominant in the network structure

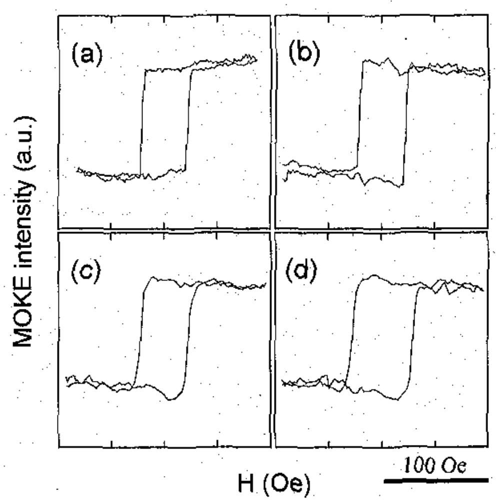

Fig. 4 MOKE hysteresis loops for the Co network structures with w=0.3 μm (a), w=0.8 μm (b), w=1.0 μm (c), and w=1.2 μm (d) for field applied along the diagonal direction (intrinsic easy axis).

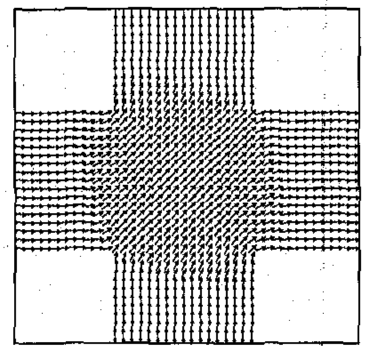

Fig. 5 Magnetization configurations of a cross-junction in the equilibrium state for the network structure with s=0.5 μm.

with s=0.5 μm (w=1.0 μm) in spite of the cubic shape anisotropy as observed. Further simulations on the cross-junction in the network structure are underway.

IV. Conclusion

An enhancement of the coercivity in Co network structures is observed with increasing hole width. This can be explained by the pinning of domain walls due to the hole edges in the vicinity of which the demagnetizing field is significant. The magnetization reversal process in the network structures is dominated by the intrinsic uniaxial anisotropy in the width range 0.5≤w≤1.2 μm in spite of the shape anisotropy induced by the hole edges. For larger w values, our results indicate that the shape anisotropy is dominant. The competition between the intrinsic uniaxial anisotropy and the induced shape anisotropy leads to a crossover in the values of the coercivity with hole width.

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