Dynamics of Domain Structure in Magnetic Multilayers

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Abstract **— We use a new method for visualization and direct experimental study of dynamic magnetization processes and for nondestructive characterization of the defect structure of magnetic multilayers. The method utilizes a transparent indicator ferrimagnetic magneto-optic film with in-plane anisotropy. An example of its application to the investigation of the magnetization reversal by domain wall motion in electrochemically produced CoNiCu/Cu multilayers which exhibit a giant magnetoresistance effect is described.**

I. Introduction

Nanostructured magnetic multilayers exhibit effects such as giant magnetoresistance (GMR) and are being extensively studied [1,2]. A knowledge of the in-plane magnetic domains is important to understanding the GMR [3]. Several techniques have been used to study the magnetic domain structure of such materials, each with its advantages and disadvantages. With our new magneto-optical indicator film (MOIF), technique, observation of domains can be performed directly on the as-prepared material using a simple apparatus, and provides rapid direct observations of the domain structure and its dynamics as the field or temperature is varied. The effect of defects on the magnetization process is readily observed. The resulting Faraday "portrait" of the multilayer's stray fields is imaged in a polarized light microscope.

II. Experimental

The MOIF technique was initially developed [4] for magnetic flux visualization in superconductors. The indicator film a ~2 μm thick Bi-substituted iron garnet, with in-plane anisotropy, is laid on top of the sample. The magnetization vector in the garnet film, which lies in the plane in the absence of external fields, develops an out-of-plane component if a normal field is present. Polarized light passes through the indicator film and is reflected back through the indicator film by an Al underlayer. Normal components of the magnetic field due to the sample are observed through the magneto-optical Faraday effect created in the garnet film. The domain patterns from the garnet itself are distinctive and, in any case, can be readily distinguished by moving the garnet with respect to the sample. The resulting Faraday "portrait" of the multilayer's stray magnetic fields is imaged in a polarized light optical microscope. The location and intensity of the light and dark areas are used to determine the direction of the magnetization in the sample under study and provide a means for estimating the characteristics of the magnetostatic field. Image analysis may be used to produce maps of the vertical component of the magnetic field intensity. In the images presented in the figures, white represents areas where the magnetic field has a component vertically up (flux leaving the sample), and black areas with a component vertically down (flux entering the sample).

The specimen studied here is a multilayer which was electrodeposited on a circular disk of (100) copper single crystal from a sulfamate electrolyte containing Co^{2+}, Ni^{2+} and Cu^{2+} ions in a single cell, with the cathode potential pulsed between -1.8 V for deposition of the NiCo layer and -0.26 V for copper deposition. A small amount of copper is codeposited with the CoNi, and the magnetic layer composition is estimated by x-ray fluorescence to be $Co_{64}Ni_{31}Cu_5$. The copper layers are almost pure Cu. The thickness of the magnetic layers is ≈2 nm. The Cu layers are 1 nm thick. There were 200 bilayers. The structure and periodicity of the film was confirmed by high-angle x-ray diffraction. A few MOIF images were reported on this specimen earlier [5]. Giant magnetoresistance measurements were reported [6] on similar polycrystalline specimens with the Cu substrate stripped off.

III. Results and Discussion

A hysteresis loop of the multilayer, measured in a SQUID magnetometer with an in-plane magnetic field of ±25 mT applied along the easy direction, is shown in Fig. 1. For the easy-direction loop, there is a sharp break in the curve at about 6 mT and a coercive field of about 8 mT. Both these values would be larger for a full major loop. The hard-direction loop (not shown) has a larger coercivity and requires a much higher field to saturate. (The shape demagnetization factor is nearly identical in the two directions.) The presence of an easy and hard direction is presumably related to anisotropy in the radial and azimuthal directions created during the electrodeposition of the multilayer.

The MOIF micrographs from this multilayer displayed here were always taken with the applied magnetic field close to the easy direction. Fig. 2 shows the magnetostatic field image of a portion of the CoNiCu/Ni multilayer, as the magnetization

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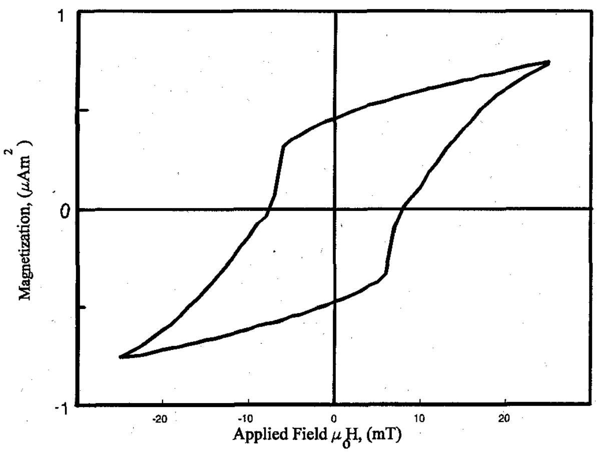

Fig. 1 Hysteresis loop of the multilayer.

is changed from near positive saturation (Fig. 2a) to near zero (Fig. 2b), and to near negative saturation (Fig. 2c). Note the polarity differences in Figs. a and c at the edges of the sample on the top and on the right, as indicated by the dark and bright lines in these regions. These polarities are in agreement with the magnetization directions shown, and with the direction of the saturating field. The long line across the center of the sample, due to a surface ridge on the sample, also has dark and bright regions where flux leaves (bright) and enters (dark) the sample. Fig. 2d shows an example of image enhancement

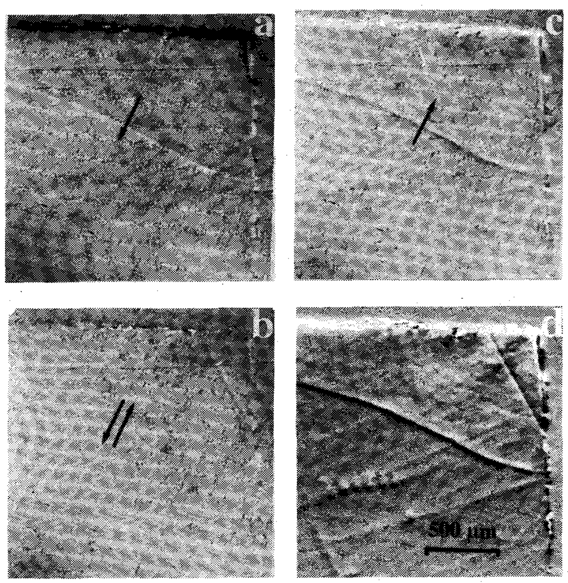

Fig. 2 MOIF images of multilayer: (a) Positive magnetizing field (H=25 mT); the dark line near the top is due to flux entering the film edge. The arrow represents the magnetization, which is in the + H direction. (b) Almost zero magnetization state (H=-10 mT); no flux is seen entering or leaving the film. (c) Negative magnetizing field (H=-25 mT); the bright line near the top is due to flux leaving the film edge. (d) Image of (c) with (b) subtracted; multilayer surface defects are clearly seen.

obtained by a subtraction technique (the image of 2b was subtracted from 2c). The imperfections on the multilayer are much more evident in Fig. 2d.

Magnetization reversal by domain wall motion is investigated in more detail in Fig. 3. All images in Fig. 3 have been processed by subtracting the image of Fig. 2a obtained when the sample is saturated in the positive direction. During subtraction the intensities of the images are adjusted slightly in order to retain the maximum information. The sample was first saturated with a positive (+) applied field. When the field is changed to H=-4 mT, Fig 3a, most of the sample magnetization is still oriented in the + direction, but the nucleation of a new domain can be seen in the upper right hand corner and along the upper edge. As the field is made more negative, (H=-5 mT in Fig 3b, H=-5.5mT in Fig 3c) that domain grows to cover a larger region along the upper edge of the film. In Fig 3d (H=-5.7 mT), the nucleation of an additional domain can be seen in the middle, while some pinning center has retarded the progress of the growth of the large edge-nucleated domain. In Fig 3e

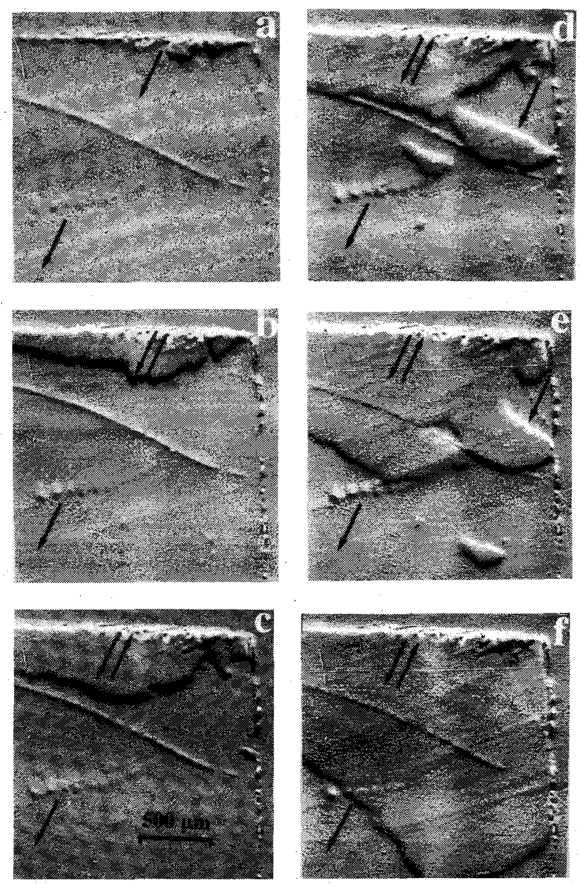

Fig. 3 Series of magneto-optical indicator film micrographs from an electrodeposited $[Co_{64}Ni_{31}Cu_5/Cu]_{200}$ multilayer. The sample is first saturated in the + direction: the micrographs show the remagnetization process in the - direction. (a) -4mT (b) -5mT (c) -5.5mT (d) -5.7mT (e) -6mT (f) -6.3mT. Arrows indicate the direction of domain magnetization.

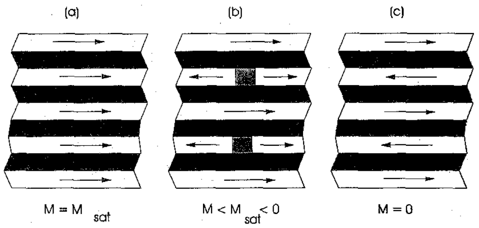

Fig. 4 Schematic of proposed magnetization structure when sample is (a) saturated, (b) magnetized between saturation and M=0, and (c) with M=0.

(H=-6 mT), the small domain nucleated in the center of Fig 3d has become part of the larger domain, while another small domain has nucleated near the lower right hand corner. With the field magnitude corresponding to the sharp break in the hysteresis curve, Fig 3f (H=-6.3 mT), only two smaller regions remain magnetized in positive direction. The response of the indicator film is very rapid and Barkhausen jumps can be observed.

One possible set of domain structures for the multilayer, consistent with our MOIF observations, is shown in Fig. 4. In the saturated state, all magnetic layers spins are pointing in the same direction (Fig. 4a). When the field is changed to a value where the magnetization is between the saturation value and 0, moments in alternating layers begin to form domain boundaries (shown as tail-to-tail in Fig. 4b), producing flux leakage at the sample surface. When the coercive field is reached and M=0, the layers are alternately magnetized forming an antiferromagnetic-like structure (Fig. 4c).

As illustrated in Fig. 3, tail-to tail and head-to-head walls are observed to nucleate at the edge of the sample and then to move across the sample during the magnetization reversal process (i.e. in quadrants 2 and 4 of the hysteresis loop of Fig. 1.) Consistent with the observed magnetization behavior (e.g., Fig. 1), our MOIF studies of the present sample did not detect the multiple step spin-flop processes suggested by Dieny et. al [7,8]. Instead, our observations are more consistent with the simpler spin flip transition illustrated by them [7,8]. The spin-flop process may be suppressed (or may be below the detection limits) because of the effect of imperfections or other non-uniformities inherent in the electrodeposition process.

Summary

The MOIF technique has been used to observe the dynamics of the domain wall behavior during remagnetization of an electrodeposited magnetic multilayer. The remagnetization of the layer system proceeds by the nucleation and motion of head-to-head and tail-to-tail domain walls in alternating magnetized layers.

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References

[1] B. Heinrich and J.F. Cochran, "Ultrathin metallic magnetic films: magnetic anisotropies and exchange interactions" Adv. in Phys.Vol. 42, pp. 523-639, 1993.

[2] *Magnetic Multilayers*, edited by L.H. Bennett and R.E. Watson (World Scientific,River Edge, NJ, 1994).

[3] S. Zhang and P.M. Levy, "Effects of domains on giant magnetoresistance" *Phys. Rev.* Vol B50, pp. 6089-6093, 1994.

[4] L.A. Dorosinskii, M.V. Indenbom, V.I. Nikitenko, Yu.A. Ossip'yan, A.A. Polyanskii, and V.K. Vlasko-Vlasov, "Studies of HTSC crystal magnetization features using indicator magnetooptic films with in-plane anisotropy: Physica C Vol. 203, pp. 149-156, 1992.

[5] L.H. Bennett, R.D. McMichael, L.J. Swartzendruber, S.Z. Hua, D.S. Lashmore, A.J. Shapiro, V.S. Gornakov, L.M. Dedukh, and V.I. Nikitenko, "Magneto-optical indicator film observation of domain structure in magnetic multilayers", Appl. Phys. Lett. Vol. 66, pp. 888-890, 1995.

[6] S.Z. Hua, D.S. Lashmore, L. Salamanca-Riba, W. Schwarzacher, L.J. Swartzendruber, R.D. McMichael, L.H. Bennett, and R. Hart, *"Giant magnetoresistance peaks in CoNiCu/Cu multilayers grown by electrodeposition" J. Appl. Phys.* Vol. 76, pp. 6519-6521, 1994.

[7] B. Dieny, J.P. Gavigan, T.P. Reboullat, "Magnetisation processes, hysteresis and finite-size effects in model multilayer systems of cubic or uniaxial anisotropy with antiferromagnetic coupling between adjacent ferromagnetic layers" J. Phys. Conden. Matter,Vol. 2, 159-185 (1990).

[8] B. Dieny and J.P. Gavigan, "Minimum energy versus metastable magnetsation processes in antiferromagnetically coupled ferromagnetic multilayers" J. Phys. Conds. Matter Vol. 2 pp. 187-194, 1994.