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Investigation of domain-wall formation and motion in magnetic multilayers

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Abstract

The magnetization-reversal processes in two electrodeposited $[Co_{64}Ni_{31}Cu_5$ 2 nm/Cu$]_{200}$ multilayers are investigated using an advanced magneto-optical indicator film (MOIF) technique together with SQUID and vector vibrating sample magnetometry. The non-magnetic Cu spacers are $\cong$ 1 nm thick in one specimen leading to predominantly antiferromagnetic exchange coupling between the ferromagnetic $Co_{64}Ni_{31}Cu_5$ layers, and $\cong$ 3 nm in the other, with ferromagnetic coupling. The hysteresis loop of the ferromagnetic multilayer is conventional, indicating the stages of domain-wall formation, motion and saturation. Nucleation and movement of domain walls in different layers proceed in a partially uncorrelated manner, and are determined by defects near the surface edge and inside of the multilayer. As a result, the front of the magnetization reversal has a staggered configuration. The antiferromagnetic multilayer has an atypical loop, first with one susceptibility, then a step to a new value, then another susceptibility, and with non-symmetrical behavior about the field axis. Narrow and non-staggered domain-wall images in antiferromagnetically coupled layers are observed. The MOIF technique is used to provide a portrait of the vertical component of the magnetostatic field intensity, helping to elucidate the spin-flip and/or spin-flop processes which are apparently responsible for the hysteresis behavior.

Keywords: Magnetic multilayers; Magnetization reversal process; Antiferromagnetism; Magnetic-optical detection; Magnetic domains; Spin-flop process; Domain-wall motion

1. Introduction

The discovery of the giant magnetoresistance (GMR) effect has attracted increased interest in magnetic multilayers [1]. Determining the domain structure and its dynamics in magnetic multilayers is difficult, in part, because most techniques are surface sensitive and reveal only static domain structure. Recently, we have shown that the magneto-optical indicator film (MOIF) technique is able to reveal not only static domain structure in these materials, but also its dynamics, during the magnetization reversal in two magnetic multilayer thin-film systems [2, 3]

The MOIF technique uses a garnet film placed on the specimen to be studied. A domain structure of the specimen is directly imaged in real time through the magneto-optical Faraday effect in the

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indicator film. The resulting Faraday portrait of the sample's stray magnetic fields presents detailed information about the static and dynamical domain structure, as well as the defects of crystal structure that affect the spin distribution in the sample.

2. Experimental

Two electrodeposited thin-film samples were investigated: a ferromagnetic [$Co_{64}Ni_{31}Cu_5$ (2 nm)/ Cu (3 nm)]$_{200}$ multilayer, and an antiferromagnetic [$Co_{64}Ni_{31}Cu_5$ (2 nm)/Cu (1 nm)]$_{200}$ multilayer. The details of the preparation [4] and GMR behavior [5] of the magnetic multilayers have been reported elsewhere. All measurements reported in this paper were performed at room temperature.

The MOIF technique [6] is based on the Faraday rotation of linearly polarized light in an indicator film, a Bi-substituted iron garnet film with in-plane anisotropy, placed on the sample. The polarized light passes through the indicator film and is reflected by an Al underlayer covering the bottom surface of the film, adjacent to the sample surface. While the light is passing through the indicator film its polarization experiences a Faraday rotation through an angle proportional to the component of the local magnetic field parallel to the light propagation direction. The transmitted intensity of the reflected beam through an analyzing polarizer varies with the local field in the light path. The bright or dark variations of the image formed by an optical system represent the variations of the stray fields associated with the magnetization components parallel to the optical beam, not only near the sample surface but also inside it.

The ferromagnetic sample evidenced a very strong uniaxial anisotropy in nucleation and movement of the domain boundaries (DB). The MOIF pictures shown in this paper were obtained with the magnetic field direction near the easy axis. It was impossible to generate and shift the DB in the available range of fields (~ 10 mT) oriented 90° to the easy axis of the sample. The antiferromagnetic sample also has easy and hard directions for formation and movement of domain boundaries. However, the characteristic differences for these two directions are much less pronounced than in the ferromagnetic sample.

DC magnetization measurements were carried out in a commercial vector vibrating sample magnetometer (VVSM) and in a commercial SQUID magnetometer.

3. Results

The hysteresis loop of the ferromagnetic multilayer measured with a SQUID magnetometer is shown in Fig. 1. It is a conventional loop, indicating

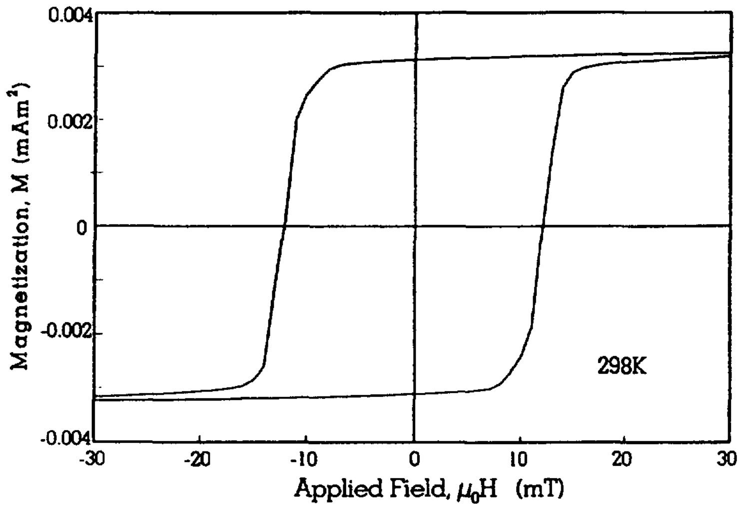

Fig. 1. Hysteresis loop measured with a commercial SQUID magnetometer for a ferromagnetic [$Co_{64}Ni_{31}Cu_5$ (2 nm)/Cu (3 nm)]$_{200}$ multilayer.

the stages of domain-wall formation, motion and saturation.

A series of MOIF images, presented in Figs. 2 and 4, demonstrates some particularities in the formation and transformation of domain structure in the process of remagnetization of the ferromagnetic sample, as the external magnetic field is changed. In both figures, the sample was first magnetized to saturation by opposite polarity strong (−80 mT) field. After that the field was gradually reduced to zero, inverted and increased until domains with opposite magnetization started to appear. Fig. 2 shows images obtained after changing the field from −80 to +13.0 to +14.0 mT. The left top figure of this set demonstrates the local character in domain nucleation. Islands of magnetic domains, magnetized in the opposite direction to the initial direction of magnetic moment vector, appear virtually simultaneously in many places in the multilayer sample. In particular, one can distinctly see two such islands in the left top part of the picture. At the field 13.2 mT (the left middle picture), the boundaries of these domains begin to move. At the same time, it easy to note the increase

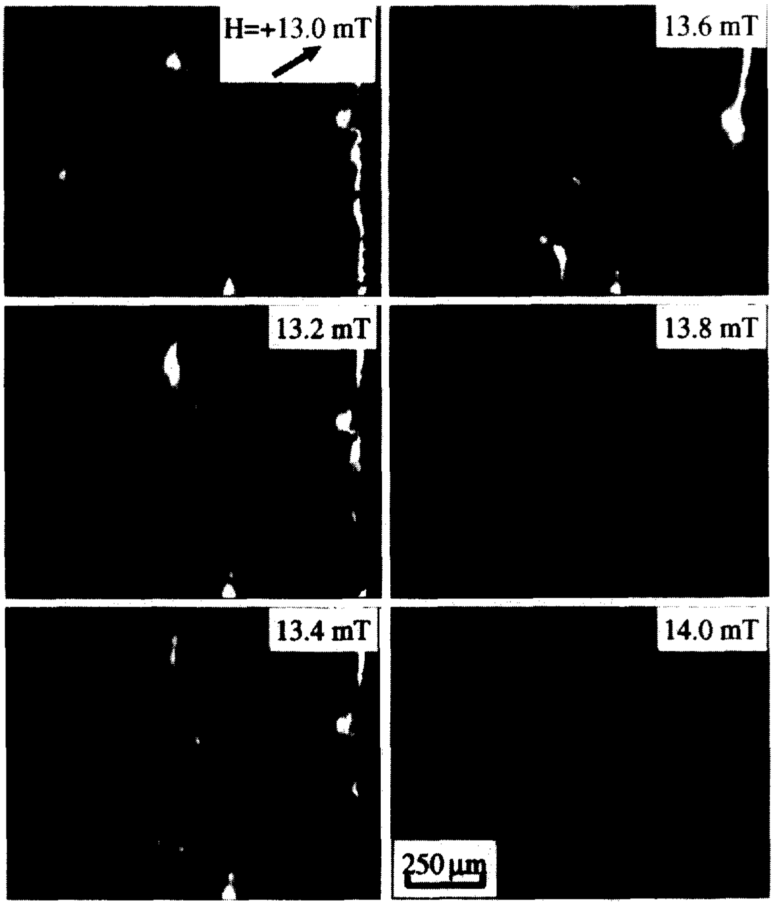

Fig. 2. MOIF images of domain motion and rotation in the ferromagnetically coupled multilayer. First the sample was magnetized near saturation (−80 mT) in the negative direction. Then the field was gradually reduced to zero, increased in the + direction until a new phase is nucleated. The first image (+13.0 mT) shows the nonuniform domains ("islands") formed for magnetic fields near the coercivity. Intense black and white borders indicating domain walls are evident. As the field is further increased (13.0–13.4 mT), domain growth is seen. Domain rotation begins to dominate above 13.4 mT, evidenced by the weakening of the contrast within the sample. The sample is near saturation at 14.0 mT, where the dominant feature is the intense black-band at the edge of the sample.

in the thickness of the domain-wall images. Upon further increase of the field (left bottom picture), the dark and light boundary regions start spreading into each other. However, complete annihilation as a result of this movement has not taken place (right top picture). The intensity of the light boundary region of the upper right domain is substantially decreasing, while the dark boundary region of the left bottom domain practically disappears. This effect can be explained by staggered domain walls, as shown schematically in Fig. 3. Here we see a DB that runs through several layers of the material. If the walls from separate layers are aligned, one over the other, then the magnetic charges associated with the walls will reinforce each other and produce a strong stray field (and a narrow, strong contrast region in the MOIF image). A staggered configuration, as illustrated, will produce a weaker, more diffuse DB magneto-optical contrast. Moreover, we can expect the walls in different layers to have different pinning characteristics. So it is reasonable to expect that as the external field is increased, some domain walls will sweep through some layers while domain walls in adjoining layers remain pinned. This would obviously further weaken the wall contrast as seen in the MOIF, and can account for the observed blurring and gradual decrease in intensity of DBs (middle and bottom right panels in

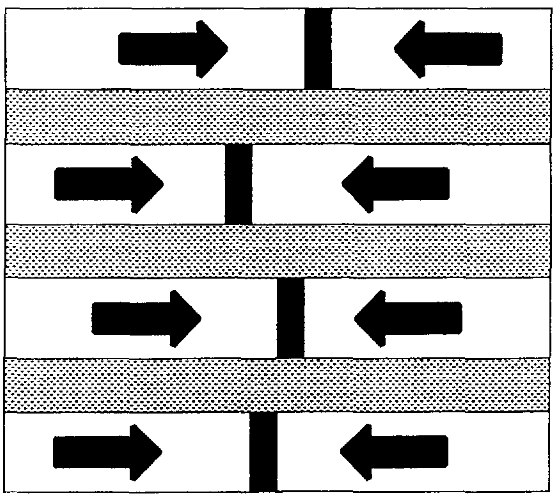

Fig. 3. Schematic illustrating staggered domain walls in a ferromagnetic multilayer.

Fig. 2). Further increase of the field (middle and bottom pictures on the right) brings about a gradual decrease in the intensity of the remaining boundary regions, which is evidence of the movement, extension, and annihilation of DB in the rest of the layers, until they completely disappear through the full thickness of the sample.

The MOIF images presented in Fig. 4 display broadened domain walls due to staggered domain formation in a ferromagnetically coupled multilayer during remagnetization. The values of the nucleation field and DB movements on this picture differ some from the analogous fields in Fig. 2, due to small differences in the applied field directions relative to the sample. The change from Fig. 4(d)–(e) (-18 to $+15$ mT) shows a broadening of the domain wall. Nucleation and movement of domain walls in different layers proceed in a partially uncorrelated manner, and are determined by defects near the surface edge and inside of the multilayer. As a result, the front of the magnetization reversal has a staggered configuration. Although less visible in the image, similar staggering is responsible for the decrease in contrast of the domain wall in going from Fig. 4(a)–(b) (16.0–17.5 mT).

The hysteresis loop and domain behavior of the antiferromagnetic multilayer is quite different from the ferromagnetic multilayer. The longitudinal (x) and the perpendicular (y) hysteresis loops of this multilayer, as measured with the VVSM, are shown in Fig. 5. The increased perpendicular values in the $\pm$(20–70) mT range arise from domain rotation processes. The arrows from + saturation to the notation DW (point where domain wall formation is observed in MOIF) refer to some portion of spins in each layer that have rotated, from the saturation direction, until up to 180° immediately preceding DW. This interpretation is consistent with a spin-flip process.

Features of the domain structure transformation of the antiferromagnetic sample are seen in Fig. 6. As in the ferromagnetic case, the sample was magnetized to near saturation in a magnetic field of -80 mT. The field was then gradually reduced to zero, and increased to 5.1 mT. The left top picture in the set displays the magnetic structure of the sample prior to the nucleation of many domains. The increase of the magnetic field to some critical

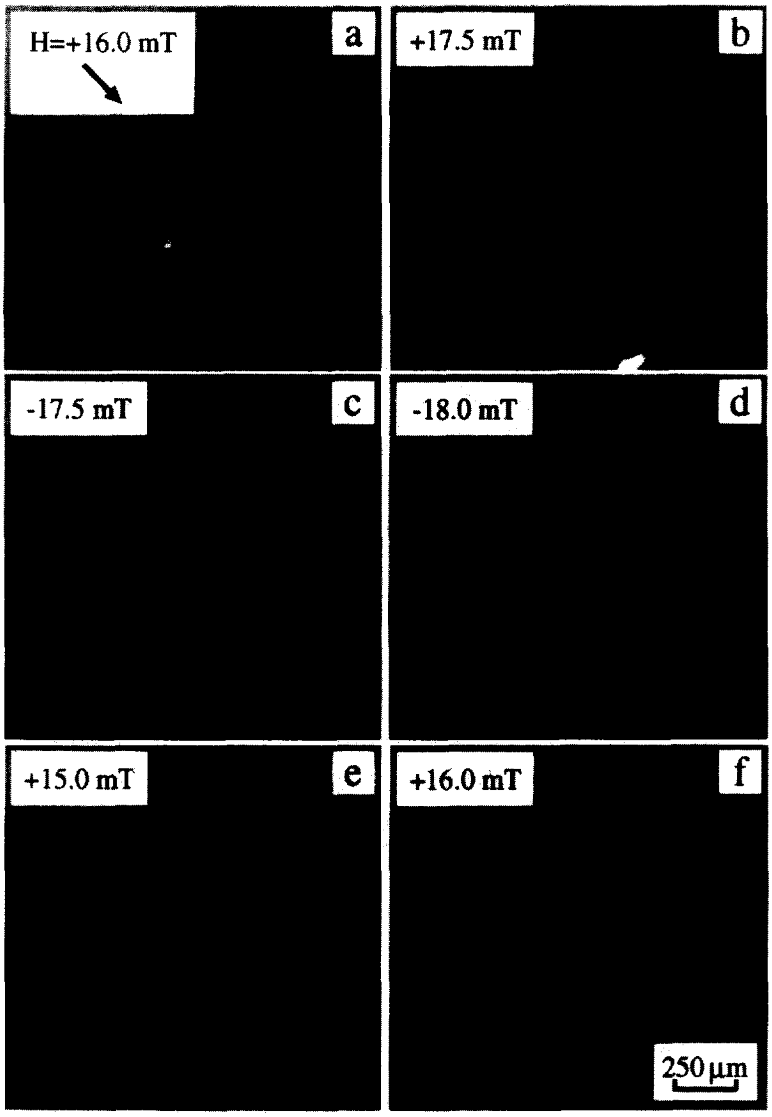

Fig. 4. MOIF images showing broadened domain walls due to staggered domain formation in the ferromagnetically coupled multilayer during remagnetization. (a) (at +16.0 mT) shows a jagged black domain wall, which weakens in intensity as it moves under increased fields. (b) (+17.5 mT). In (a), an inhomogeneous distribution of magnetization, M, can be seen behind the sharply defined remagnetization front, which appears during the process of domain wall movement. (c) and (d) (−17.5 and −18 mT) are the results of changing the field to the opposite direction to (a) and (b) which shows a different pattern. (e) and (f) (+15 and 16.0 mT), which are in similar fields as shown in (a) and (b), but is the result of a minor loop reversal, displays similar features to the first set, with more evident wall broadening.

value (left middle picture) in the sample led to nucleation of a new magnetic phase. However, unlike the ferromagnetic samples, in this multilayer the domain walls are always narrow, and their imaged intensity was much lower even than the non-broadened walls in the ferromagnetic sample. After annihilation of such boundaries, no other walls in such regions were observed. The other

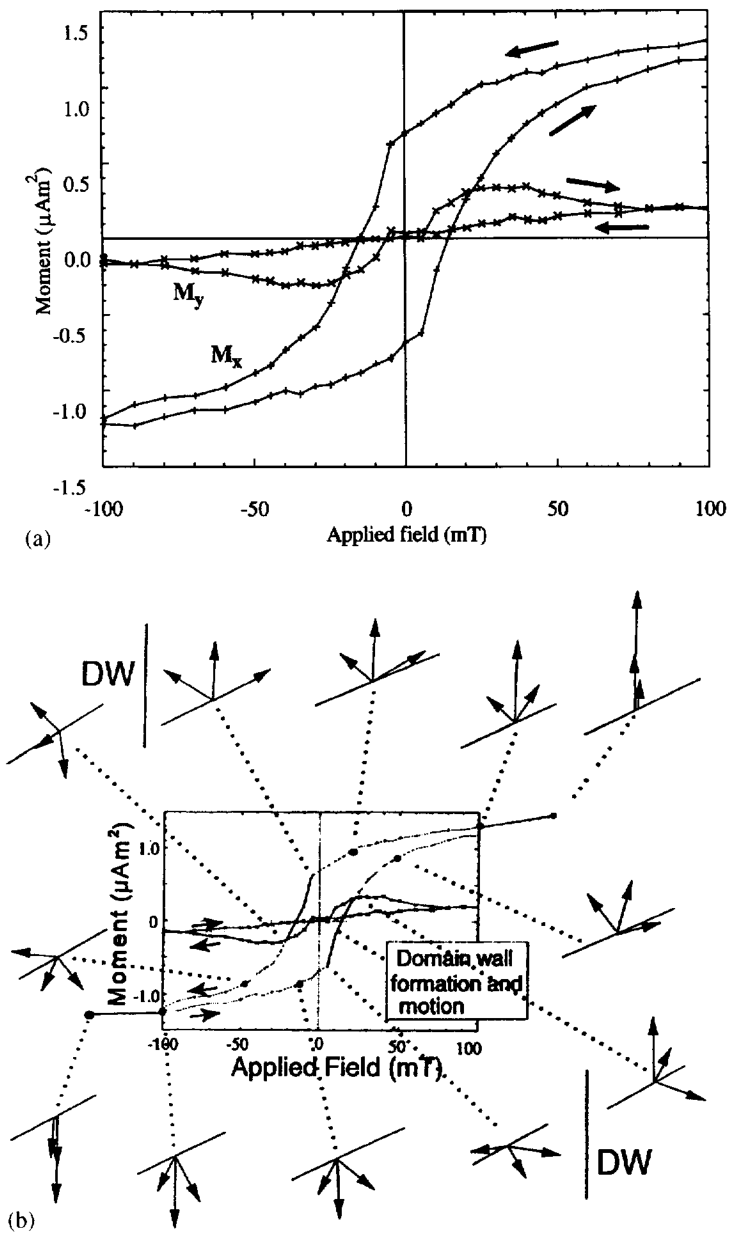

Fig. 5(a). Hysteresis loops measured with a commercial VVSM for the longitudinal (x) and the perpendicular (y) magnetizations of a $[Co_{64}Ni_{31}Cu_5$ (2 nm)/Cu (1 nm)$]_{200}$ multilayer. Both the x and y axes are in the plane of the sample; there is no appreciable out-of-plane component. Fig. 5(b). The four arrows within the plot indicate the traversal directions. The arrows external to the plot illustrate possible magnetizations (consistent with a spin-flip mechanism) at different positions of the hysteresis loops. Two of the arrows at each position represent possible interpretations of the magnetization from alternate layers, the third arrow is the vector sum of these two. The vector sum arrow has x and y components derived from the M_x and M_y hysteresis loops of Fig. 5(a). The easy axis of the sample is shown by the slanted baseline. Domain wall formation and motion occurs in the region indicated on the ascending loop (and also on the corresponding region of the descending loop). Outside these regions, domain rotation predominates. The formation of the domains is reflected in the loops by the sudden change in slopes. When the domain walls appear (noted by DW), the system displays antiferromagnetism (evident in the external arrows).

distinctive feature of the antiferromagnetic multilayer, with its thin non-magnetic layer, is its non-equal shift of the observed DB in positive and negative external magnetic fields. In the left bottom picture (in its central lower part), one can see remains of non-remagnetized region of the sample. Reversed polarity magnetic field applied to the sample causes essentially no domain boundary movement, even in the case when its amplitude is higher than the magnetic field needed for DB formation. One can see in the top right picture (in the right-hand part) that there are new DB on the sample edge which by $H = -5.3$ mT almost completely remagnetize the sample. These edge-nucleated domains annihilate with the "old" low-mobility or completely stationary walls (picture at $H = -5.3$ mT) in the final stage. The left-hand part of the pictures contains many defects with characteristics different from the rest of the sample.

The strength of the MOIF technique in examining the dynamics of the domain motion during magnetization reversal is revealed in Fig. 7. Note that some features change in seconds whereas

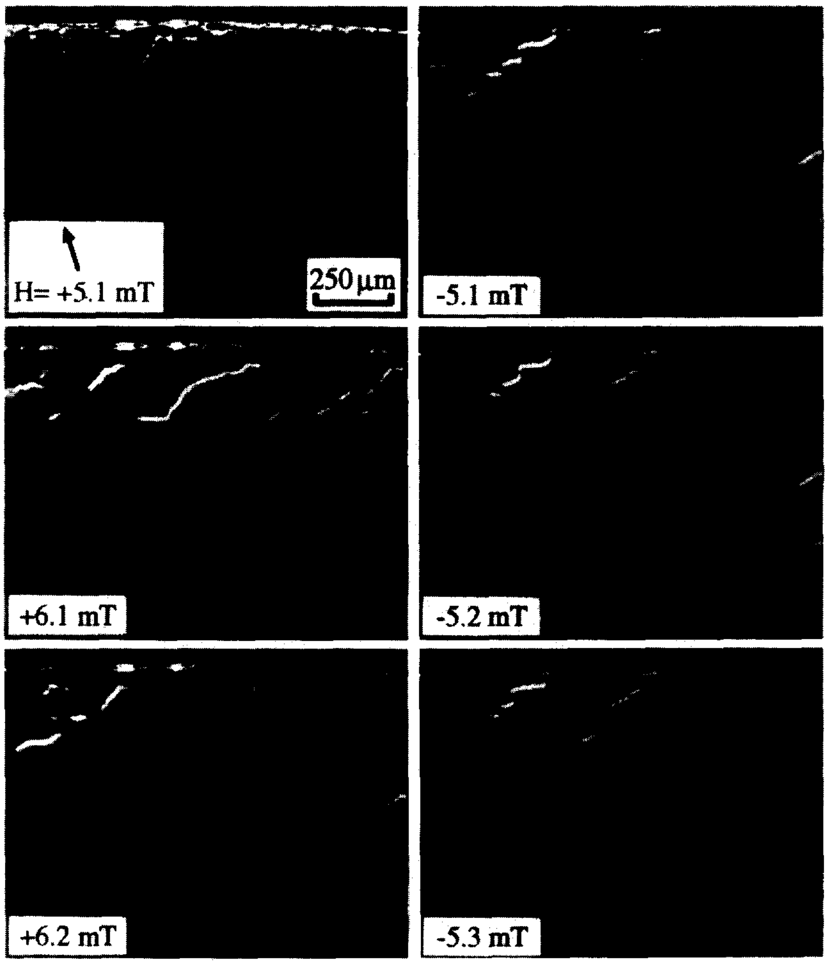

Fig. 6. MOIF images of antiferromagnetically coupled multilayer during transversal of minor loop, showing nucleation and motion of domain walls. The three images on the left are made after magnetizing at −80 mT; those on the right after magnetizing at +80 mT. Isolated domains ("islands") can be seen in the center and rightside regions of the images.

others take minutes. At some moments of time, individual DB are found to jump a substantial distance (in comparison with the thickness of this particular DB). These individual Barkhausen jumps are related to the pinning strength of some appropriate defect. Detailed examination of these effects is beyond the scope of this paper.

4. Discussion and conclusion

We see in Fig. 6 domains with a strong black or white contrast along domain walls perpendicular to the applied field, but with very little contrast along edges parallel to the applied field. This effect can be explained by either spin-flip or spin-flop magnetization reversal processes indicated schematically in Fig. 8.

If spin-flip is the dominant reversal mechanism, then the magnetizations across domain walls are anti-parallel. The edges running perpendicular to the magnetization show strong contrast in the MOIF image because they represent domain walls between head-to-head (or tail-to-tail) domains, which produce a strong stray field. The low contrast at edges running parallel to the magnetization indicates the presence of 180° Néel walls, which produce only a minimal stray field.

Whereas the first explanation involves only a single film layer, an explanation that assumes a spin-flop magnetization mechanism requires at least two film layers that are antiferromagnetically coupled. Consider a domain in which, as a result of the spin-flop magnetization mechanism, the magnetization is directed 90° from the magnetization in the surrounding domains. The magnetization inside the spin-flop affected domain has anti-parallel alignment between successive film layers. (The magnetization in the surrounding domains is parallel through all layers.) Magnetic charge will

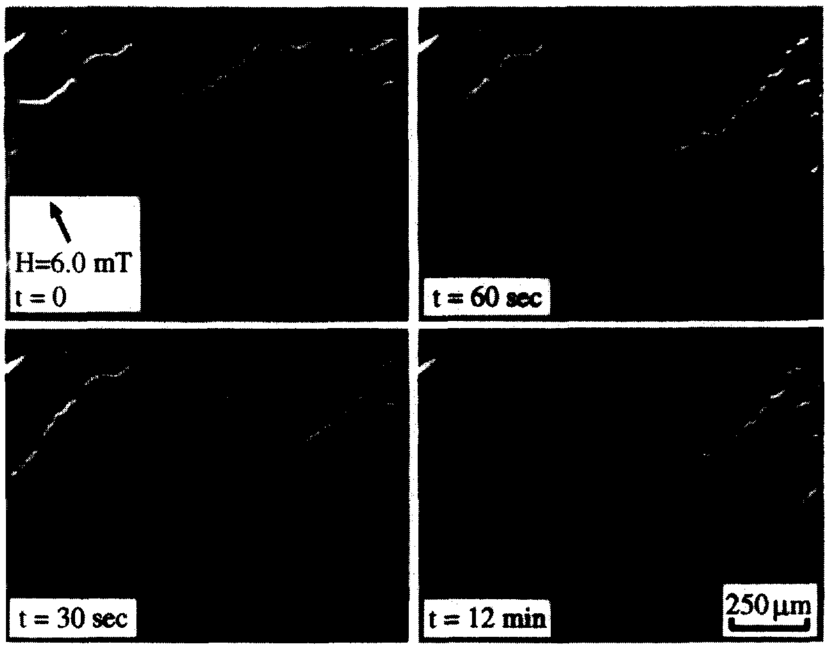

Fig. 7. MOIF images of antiferromagnetically coupled multilayer in a constant applied field, showing magnetic after-effect of domain walls. The left top picture illustrates the magnetic structure of the sample at the first moment after domains have been formed. During the following 30–60 s, spontaneous movement of the domain walls occurs, traveling fairly long distances, as seen on the left bottom and right top pictures. After this, the movement becomes less visible, while at some moments in time, individual Barkhausen jumps have been observed. As a result of DB drift over a period of time, some of the DB annihilate and, as a consequence, remagnetization of a substantial portion of the sample (right bottom picture) occurs.

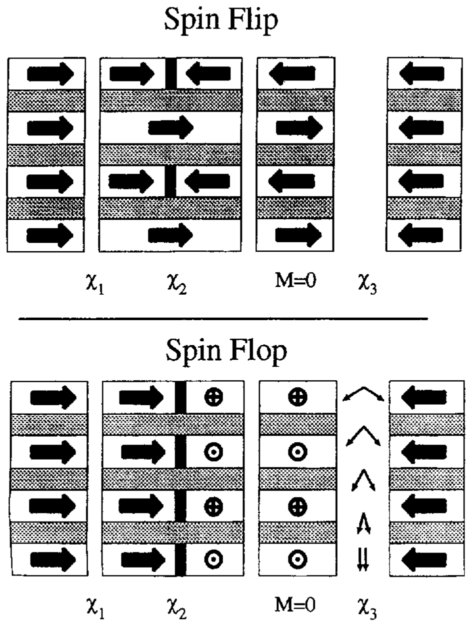

Fig. 8. Schematic illustrating spin-flip and spin-flop processes in an antiferromagnetic multilayer. For the spin-flip process, all the magnetizations are in the plane of the magnetic layers. The magnetization at $M = 0$ is antiferromagnetic alignment from layer to layer. For the spin-flop process, domains form in each layer, rotated 90° to the field direction. These domains are antiparallel between adjacent magnetic layers.

accumulate along those edges of the spin-flopped domain that are perpendicular to the direction of the surrounding magnetization, and the associated domain walls will show strong contrast in the MOIF image. Conversely, there will be little charge accumulation along domain edges parallel to the surrounding magnetization, because the stray fields from adjacent layers inside the spin-flopped domain will cancel, and so the MOIF images of such walls will have low contrast.

The results presented illustrate the potential of the MOIF technique for the direct experimental examination of the static and dynamic magnetization reversal processes in multilayer structures and for its utilization as a non-destructive characterization technique for quality control. Moreover, the magnetization reversal processes can be observed in real time.

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