COMPLEMENTARY IMAGING OF GRANULAR Co-Ag FILMS WITH MAGNETO-OPTICAL INDICATOR FILM TECHNIQUE AND MAGNETIC FORCE MICROSCOPY

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A Magneto-optical indicator film (MOIF) technique and magnetic force microscopy were used for visualization and direct real-time experimental study of the magnetization processes of magnetic $Co_{90}Ag_{10}$ granular films. It is shown that the magnetization reversal of the as-deposited films follows a specific two-step course. The first stage is characterized by gradual spin rotation to large angles up to 90° without domain formation. Further magnetization reversal proceeds by the nucleation and motion of zigzag-shaped domain walls. The dendritic structure of the domain walls was observed using both techniques. Also tracks of magnetic inhomogeneities remaining behind moving zigzag-shaped domain walls was revealed by MOIF.

75.60.Ch, 61.16.Ch, 75.60.Lr

In the last few years nanostructured materials consisting of magnetic and nonmagnetic components have attracted a great deal of attention [1,2]. It has been discovered that such materials exhibit peculiar properties, in particular giant magneto resistance. These materials are very attractive for use in the next generation of magnetic field sensors and computer disk drive reading elements. As a result, the development of experimental techniques for the investigation of real-time magnetization dynamics and nondestructive characterization of magnetic multilayered and clustered systems is of great interest [3–6].

In this paper we demonstrate the use of a novel magneto-optical indicator film (MOIF) technique for the study of ferromagnetic granular films. The MOIF technique was initially developed for investigation of magnetization processes and quality characterization of high-temperature superconductors [7], and has more recently been used to study magnetic multilayers [8]. We also illustrate the use of magnetic force microscopy (MFM) as a complementary method to MOIF. With MFM one can study magnetic structures smaller than can be resolved via MOIF. Magnetic features as small as 10 nm have been reported using MFM [9], but such resolution is sample dependent, and the sample studied here revealed no significant features smaller than about 250 nm.

The Co-Ag granular films were prepared at room temperature by laser sputtering on glass substrates in a vacuum chamber at a pressure of approximately 10^{-4} Pa. A 1.06 μm wavelength pulse laser was used with 10 ns pulses at a rate of 25 s^{-1}. The target was pressed from Co and Ag powders and annealed in a vacuum at 800 °C for 4 hours. The nominal composition of the 1000 Å thick films was 90% Co and 10% Ag (atomic fractions). The grain size was shown by scanning electron microscopy to be ≈ 0.2 μm.

The MOIF technique [7,8] places on top of the sample a transparent Bi-substituted iron garnet indicator film with in-plane anisotropy. Polarized light is passed through the indicator film and is reflected by an Al underlayer. The normal component of the magnetic stray field (B_z) is detected in a polarized microscope by the magneto-optic Faraday effect.

The magnetic force microscopy (MFM) investigations employed a standard commercial microscope utilizing a dual scan technique. In the first pass a cantilever with an integral magnetized tip is tapped along the surface to determine the sample's topography. A second scan is then performed that tracks at a constant height (typically ≈ 75 nm) above the surface while vibrating the cantilever. In contrast to the MOIF technique which responds to B_z, the MFM is sensitive to $\partial B_z/\partial z$ or $\partial^2 B_z/\partial z^2$ [10,11].

A typical granular film magnetization reversal is illustrated in Fig. 1(a-f). Fig. 1(a) shows the MOIF image resulting from a saturating in-plane magnetic field of 150 mT directed parallel to the lower left edge of the film. The dark thin stripe indicates magnetic flux leaving the sample through the edge perpendicular to the external field. The gray tone of the edge parallel to the field indicates that the magnetization is directed along this edge. This image changes only slightly as the applied field is reduced to zero, but when a field in the opposite direction is applied and is slowly increased, the MOIF pattern changes. Fig. 1(b) was obtained after the field was brought to -2.4 mT. The edge parallel to the applied field becomes dark, whereas the perpendicular edge is seen to be gray, indicating that the magnetization has rotated to the direction approximately perpendicular to the magnetic field. The magnetization rotation proceeds gradually and somewhat non-uniformly as the magnetic field is increased. A further increase in the applied field causes the nucleation and growth of domains with magnetization parallel to the external field (Figs. 1(c-f)). The direction of the magnetization in the domains is established by analysis of the stray fields at the sample edges (compare, for example, the tone of the sample edges in Figs. 1(e) and 1(f)), and has been independently verified via vector VSM (vibrating sample magnetometer) measurements.

An important feature of the motion of the nucleated 90^0 domain walls is their creep. This phenomenon is apparent from a comparison of Figs. 1(d) and 1(e) which are at the same field value, but Fig. 1(e) was obtained within 30 s of Fig. 1(d). Although the applied field is not changed a considerable displacement of the domain walls is observed. Time dependence of magnetization is often found to follow the form $M = M_0 - S\ln(t/\tau)$. The magnetic viscosity coefficient, S, has been shown to be related to the irreversible susceptibility, χ_{irr} by $S = kT\chi_{\mathrm{irr}}/vM$, where v is the activation volume, roughly the inverse of the pinning site density [12]. Because χ_{irr} is large and we expect a high density of pinning sites at Ag inclusions in the predominantly Co film, significant time dependent effects are not surprising.

The two-step magnetization process (gradual rotation of the magnetization up to a large angle followed by nucleation and growth of domains)is observed when the the external magnetic is applied in any direction in the film plane, although the details may differ. In particular, the critical magnetization angle and the form and size of the domain walls will vary with the field direction, though they are always arranged along the magnetic field direction. VSM measurements have confirmed a uniaxial anisotropy much smaller than the magnetocrystalline anisotropy of pure Co granules, so it is reasonable to suspect that these films are comprised of randomly oriented uniaxial Co clusters coupled by strong exchange interactions.

The large scale domain walls shown in Fig. 2 have a zigzag form typical for charged walls, but a more fine tree-like structure can also be discerned. A similar structure is studied in Fig. 3, where one section of the film is imaged using both MOIF and MFM, in zero applied field. Fig. 3(a) is the MOIF image, with two rectangles indicating the regions where higher resolution MFM scans were performed (Fig. 3(b) and 3(c)). It is clear from the first MFM image that the black line has a complicated structure with multiple sections. This can just be discerned in the MOIF image, but the fine cross-tie pattern revealed by the MFM scans is not evident in Fig. 3(a). Fig. 3(c) shows that the tip of the sawtooth has a more complicated dendritic structure than is apparent from the MOIF image. Just outside and below this image is a micron-scale pit in the film surface that was detected by the topographical portion of the MFM scan. This imperfection is most likely responsible for the pinning of the domain wall and some of the features observed in Fig. 3(c).

The tree-like domain wall dynamics are found to be irreversible in the following sense: if the magnetic field sweep is stopped and reversed, existing domain walls remain at rest, and new domain walls nucleate at the edge of the sample and move toward and eventually annihilate the old domain walls. Fig. 4 illustrates light “ghost” tracks that occur immediately following the passage of zigzag-shaped domain walls. These tracks require from 5 to 30 minutes to disappear, even without an applied field.

To summarize, we have shown the Co-Ag granular film magnetization sequence to be comprised of a large angle magnetization rotation followed by domain wall nucleation and motion. Although a uniaxial in-plane anisotropy was detected by vector VSM measurements, a simple model including the uniaxial anisotropy would not explain the high remanence and the near 90° magnetization rotation observed for most directions of the applied field.

The domain wall pattern was observed through a complementary combination of MOIF and MFM techniques to have a fractal-like structure. The domain walls exhibited time dependent creep in constant field, and moving domain walls were observed to leave magnetic “tracks” in the magnetization.

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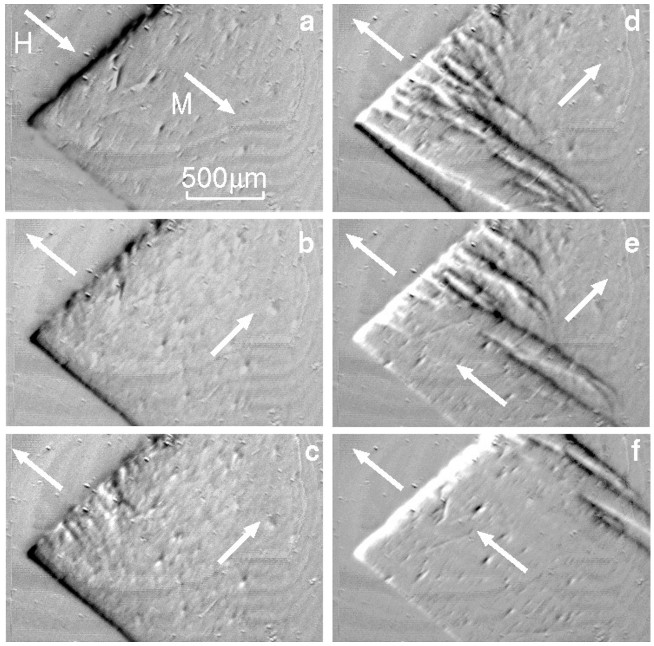

Fig. 1: MOIF patterns demonstrating a two-step magnetization of a ferromagnetic granular $Co_{90}Ag_{10}$ film. Direction of magnetic field, H, and approximate magnetization vectors are indicated. (a) H = 150 mT, (b) -2.4 mT, (c) -2.65 mT, (d,e) -3.05 mT, (f) -3.4 mT. Fig. 1(e) is obtained within 30 s of Fig. 1(d).

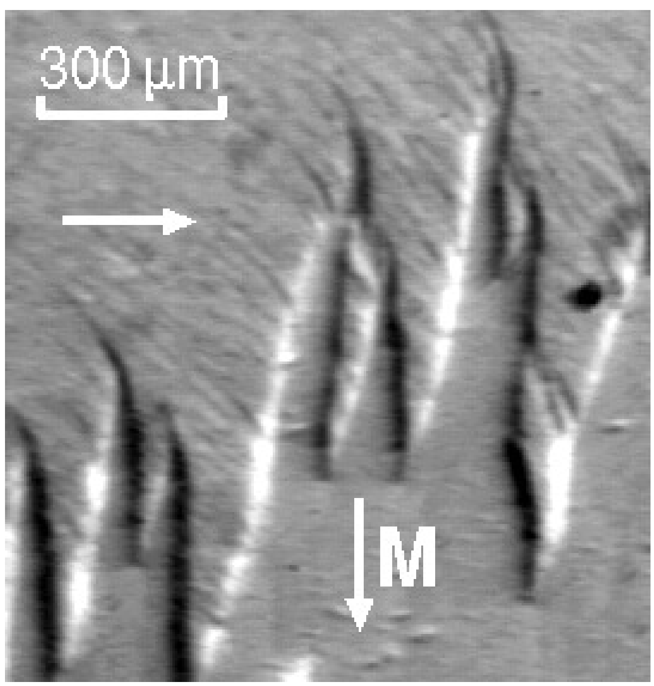

Fig. 2: MOIF image of tree-like domain walls.

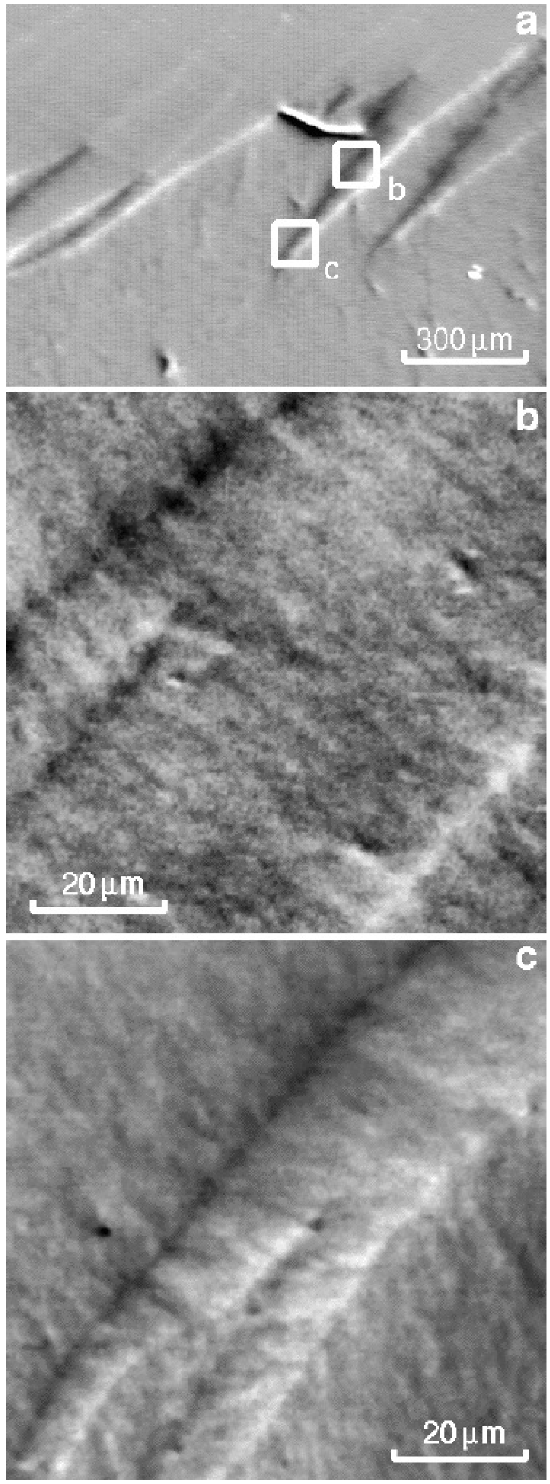

Fig. 3: Domain structures in a Co-Ag granular film, imaged by (a) MOIF, and (b,c) higher resolution MFM as indicated.

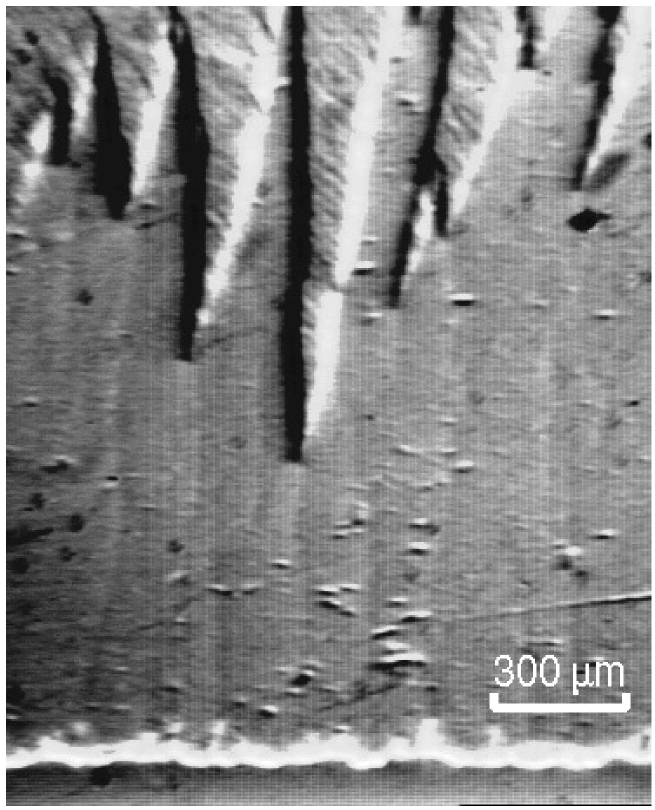

Fig. 4: MOIF image of magnetic tracks (light stripes) remaining after passage of zigzag-shaped domain walls.