Anomalous switching behavior of antiparallel-coupled Co layers separated by a super thin Ru spacer

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The details of the magnetization reversal in coupled ferromagnetic Co/Ru/Co trilayers deposited on obliquely sputtered Ta underlayers were studied using the magneto-optical indicator film technique. The ground states of the sandwich are characterized by noncollinear magnetization orientations in the two Co layers, which can be remagnetized by the motion of 180° and non-180° domain walls. In the latter case, the angle between the magnetization vectors in the adjacent domains was revealed to be about ±100°, and an anomalous magnetization reversal was observed. The canted magnetization states and their mutual transformations are discussed in terms of the competition between ferromagnetic coupling through pinholes and antiferromagnetic coupling across the Ru layer. [DOI: 10.1063/1.1452706]

Modern methods of epitaxial heterophase structure growth allow synthesis of quasi-two-dimensional magnetic materials with unique physical properties and exciting potential practical applications.[1] For trilayers composed of two ferromagnets separated by a nonferromagnet, the bilinear exchange interaction between ferromagnetic layers oscillates from ferromagnetic to antiferromagnetic[2] as the nonmagnetic spacer thickness is varied.

If the exchange interaction is antiferromagnetic, antiparallel spin orientation in the adjacent ferromagnetic layers will occur. However, that orientation relationship may be changed if pinholes exist in the nonmagnetic layer,[3–5] because direct local contact between the ferromagnetic layers have been created. Such pinholes are inevitably present in ultrathin (in the order of 1 ML) nonmagnetic spacers. Real time magnetic domain studies of the remagnetization characteristics of such materials have not yet been performed. In this work an investigation of the remagnetization processes in the Co/Ru/Co system is presented. The Co layers (having thicknesses of 2.6 and 2.1 nm, respectively) and Ru (0.5 nm thick) were deposited onto a Si substrate covered with Ta (10.6 nm thick) that was sputtered at an oblique angle of 60° with respect to the Si substrate. The oblique sputtering provided an unusually high value for the uniaxial anisotropy of the Co layer deposited directly on top of the Ta underlayer.[6]

The domain structure was studied by means of the magneto-optical indicator film (MOIF) technique.[7] The leakage field from the sample causes local deflection of the magnetization of the indicator film from the in-plane direction. These deflections are revealed by the Faraday effect in the garnet of the light that is reflected from the bottom aluminum layer. When the polarizer and analyzer are slightly uncrossed, these deviations are responsible for the black and white contrast formation in the magneto-optical (MO) images, corresponding to the opposite directions of the leakage magnetic field component perpendicular to the indicator film. The intensity at each image point is determined by the total magnetostatic charge at that point, due to the divergence of **M** either at domain walls or at the sample edges. Figure 1 shows the MO image of the corner of a uniformly magnetized sample in zero field. The magnetization angle was calculated from the maximal MO intensities I_{I} and I_{II} measured along vertical and horizontal lines, respectively [indicated by the long axes of the small rectangles shown in Fig. 1(a)] at the corner of the sample. In Fig. 1(a) the intensities indicate that the magnetic moment of the free Co layer is rotated clockwise almost 100° from the direction of the pinned Co layer as described below.

The topological relief formed during oblique sputtering of the Ta underlayer induces a very high anisotropy in the adjacent Co layer.[6] From that earlier study, it is known that the easy axis of the bottom (pinned) Co layer will beperpendicular to the direction of oblique sputtering, and therefore lies nearly perpendicular to the horizontal edge of the sample. In this article the magnetization directions of the pinned and free Co layers are indicated in the figures by white and black arrows, respectively. Since we know the direction of M in the pinned Co layer, we can use Fig. 1(a) to determine the direction of the free Co layer as follows. If the magnetization in both Co layers were collinear the magnetic charges on the vertical sample edge would be nearly absent because no charge is produced when **M** lies parallel to an edge. Magneto-optical contrast would reveal only the horizontal sample edge.

The existence of contrast on the mutually perpendicular sample edges points unambiguously to noncollinearity between the magnetization directions in the Co layers due to direct coupling through the ultrathin Ru layer.[3–5] So, the sample under investigation is not, in the strict sense, a synthetic antiferromagnet, but may be thought of as a ‘‘synthetic weak ferromagnet.’’ The remagnetization mechanism of the synthetic ‘‘weak ferromagnet’’ was shown to be analogous to

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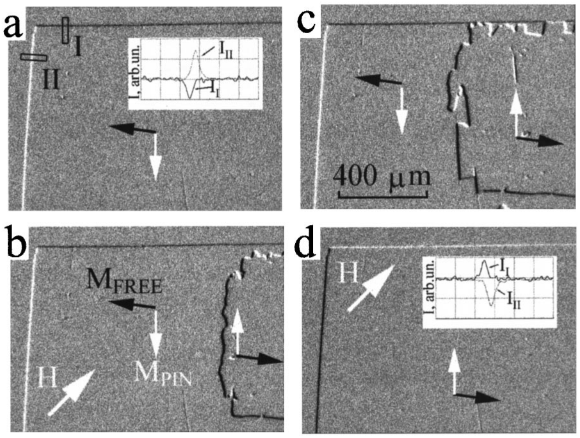

FIG. 1. MOIF image of the remagnetization process of a Co/Ru/Co homogeneous structure in a field oriented along the total magnetization vector: (a) $\mu_o H = 0$ mT after magnetization in a field of +60 mT; (b) $\mu_o H = -9.4$ mT; (c) $\mu_o H = -9.4$ mT after a 5 s wait; (d) $\mu_o H = -13.0$ mT. (a) and (d) show the intensity change of the MO signal.

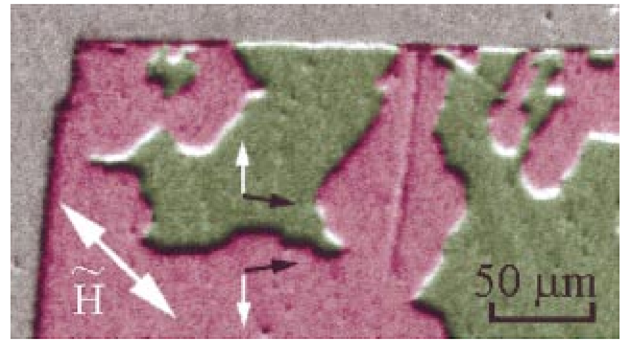

FIG. 2. (Color) MOIF images of the domain structure of the sample after it was remagnetized in an alternating field applied at an angle of 90° clockwise relative to the field orientation of Fig. 1.

the remagnetization mechanism of the synthetic antiferromagnet when the external magnetic field is oriented either along the total magnetization axis or along the underlayer-induced easy axis. In each of the Co layers, at some value of the external magnetic field, heterogeneous spin-flip processes begin in a correlated fashion that leads to the nucleation and motion of 180° domain walls [Figs. 1(b) and 1(c)]. Comparison of the images of Figs. 1(a) and 1(d) reveals inversion of the contrast on the sample edges, indicating that the magnetization has reversed in both Co layers.

The remagnetization process for fields applied perpendicular to the net magnetization direction takes place in a different manner that includes switching of the magnetization one layer at a time. Under field cycling, the sample exhibits domains that correspond to the original ground state and to a second state that is not an inversion of the original ground state. Figure 2 contains a MO image of the sample remagnetized from the original ground state [Fig. 1(d)] after approximately 80 cycles of field reversal at an amplitude of ~60 mT perpendicular to the original magnetization direction. The newly formed domains (which increase in size with each cycle) are emphasized by means of computer processing by being colored pink, while the original domain areas are indicated in green. One can clearly see in Fig. 2 that both vertical and horizontal sample edges incorporated in the new domain areas are colored in black, indicating that the total magnetization has changed its orientation from Fig. 1(d) by ~90°. The magnetization directions of the Co layers in the new domains were determined in the same manner as shown in Fig. 1 from the MO signal intensity analysis at the mutually perpendicular sample edges after the sample was completely remagnetized into the new ground state. In that new ground state, the magnetic moment of the free Co layer is turned 100° counterclockwise relative to the magnetization of the pinned layer.

Figure 3 shows the details of the anomalous remagnetization process of the sample having the two different ground states (as described in the above paragraph) separated by non-180° walls. In such a two-ground state (e.g., two-phase) system, the remagnetization takes place in three stages. In the first stage (at a small, ~8.8 mT field), remagnetization of the newly created (pink) domains occurs first via the nucleation and growth of 180° domains (marked with dark-pink color). The nucleation of such ordinary 180° domains, however, takes place as a rule on the non-180° domain walls [Fig. 3(b)]. The newly formed domain walls subsequently move through the previously created new domain area only, and during a short period of time that depends on the field value [Figs. 3(b)–3(e)], sweep up nearly the complete pink

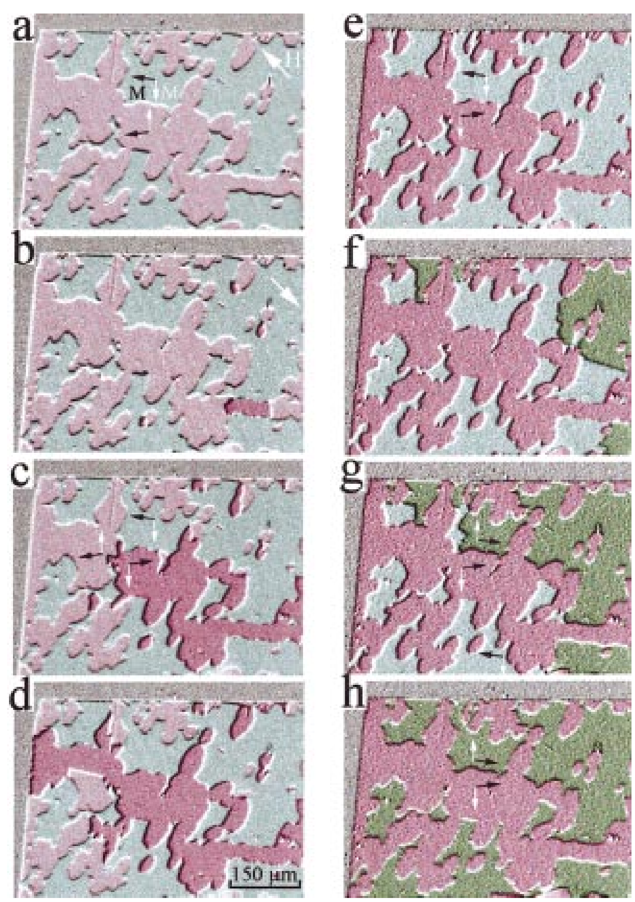

FIG. 3. (Color) MOIF images of the remagnetization processes of the Co/Ru/Co two-phase structure: (a) $\mu_o H = 0$ mT after magnetization in field +60 mT; (b) $\mu_o H = -8.4$ mT; (c) −8.4 mT after 45 s; (d) −8.4 mT and 90 s; (e) −12 mT; (f) −29.4 mT; (g) −30 mT; (h) −34.8 mT.

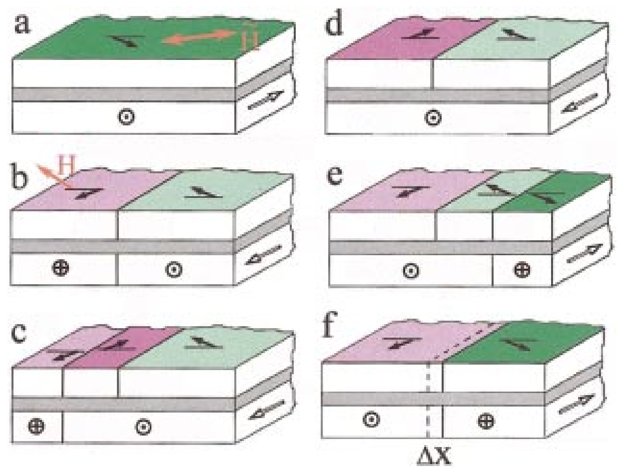

FIG. 4. (Color) Schematics of the magnetic moment distribution in Co/Ru/Co at different stages of its remagnetization process.

area. During this process the non-180° walls do not move. In the second remagnetization stage (from ~9 to ~29 mT), there was no directly visible change in the domain structure. The third stage [Figs. 3(f)–3(h)] starts at higher fields (~29.4 mT) with the nucleation of new 180° domains (marked with dark-green color) in the regions comprised of the initial ground state phase.

By computer substraction of each MO image from the preceding image, it is possible to track changes in position of the non-180° walls. Analysis of such changes showed that the non-180° walls did not move during stage 1. In the second stage, the non-180° walls moved only a very small distance on the order of the MO image wall width. The largest shift took place during stage 3. It should be noted, however, that non-180° domain wall movements occurred only during the passage of an adjacent 180° domain wall.

Figure 3 illustrates the magnetization changes in both Co layers during a single field reversal. During field reversal back to its original direction, the magnetization changes occur in a similar three stage process and similarly concluded with further growth of the new-phase region (pink colored). Thus, during each half-cycle of a hysteresis loop, there occurs a one-directional movement of the slow-moving (i.e., non-180°) boundaries, which separate the regions of the sample with different ground states. After creating the domain structure shown in Figs. 2 and 3 using a perpendicular field, external magnetic fields with an orientation different from that shown in Figs. 2 and 3 did not visibly shift the non-180° domain walls, even when applying our maximum achievable 250 mT magnetic field.

Spin reorientations in the Co/Ru/Co trilayer that occur under application of an alternating external magnetic field are schematically summarized in Fig. 4. Figure 4(a) corresponds to the ground state of the sample as shown in Fig. 1(d). In this state, the free layer spins are turned 100° clockwise relative to the spin direction in the bottom, high anisotropy layer. Figure 4(b) illustrates the spin distribution corresponding to the MO image in Fig. 3(a). As mentioned above, from the analysis of the MO signal intensity from Figs. 2 and 3 one can derive that the magnetic moment in one of the domains of the "free" Co layer lies in a mirror position compared to its orientation in the domain of the other ground state. The free layer magnetization is turned counterclockwise from the magnetization direction of the pinned layer. This domain wall in Fig. 4(a) between adjacent domains in the free layer is a 20°-domain wall and it is bound to a 180°-domain wall in the high coercivity (pinned) layer.

Figure 4(c) correlates with Figs. 3(b)–3(d) and shows the inversion of the spin directions in a new magnetic phase generated by the simultaneous motion of 180° walls in the top and bottom layers. If the sense of rotation within the walls is the same for the two layers, the top and bottom films can maintain the same relative orientation as the coupled walls move. Figure 4(d) demonstrates the spin distributions that are formed at the end of the first stage [Fig. 3(e)]. The pinned layer became a monodomain and in the free layer, a 160° domain is left. Figure 4(e) shows the inversion of spin directions in the initial magnetic phase [Figs. 3(f) and 3(g)] during the third stage of remagnetization accompanying a field reversal. Figure 4(f) illustrates the spin structure after completion of the third stage that ultimately leads to a shift in the original domain boundary by a small value Δx. Note, also, that on opposite sides of the 160° domain wall in the free Co layer shown in Fig. 4(d) the magnetization twists in opposite directions. Because of the competing forces acting on the magnetic moments on either side of the wall, including the antiparallel coupling through the Ru, the inhomogeneous pinhole coupling, and the demagnetizing field of the film, such a domain wall would be expected to require a large field to move. Field cycling allows this domain wall to move by the easier process of adding and subtracting 180° walls from alternate sides.

The observations in this study show that pinholes in the nonmagnetic Ru layer lead to noncollinearity of the spins in the exchange biased ferromagnetic layers, leading to a nonzero magnetization at $H=0$ and to magnetization reversal processes which involve the cooperative behavior of both Co layers simultaneously. If H is applied perpendicular to the total magnetization vector in the case of the present study, M reverses via a multiple-stage process which involves the nucleation and motion of non-180° domain walls.

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