Spin Reorientation Transitions and Domain Structure in Magnetic Multilayers

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***Abstract* - Spin reorientation phase transitions and the evolution of the magnetic phases states arising during magnetization reversal of antiferromagnetic CoNiCu/Cu superlattice are studied using magneto-optical indicator film technique, accompanied by vector hysteresis loop measurements. The spin-flop and nonsymmetric angle phases have been found and analyzed. It is shown that they arise due to the nucleation and growth of domains.**

I. Introduction

Since the discovery of antiferromagnetic coupling between ferromagnetic layers through intervening nonmagnetic layers in magnetic multilayers [1], there have been numerous investigations into these systems. As a result, we now know that they exhibit rich and varied magnetic properties [2] not found in bulk materials. Despite the large efforts which have gone toward understanding the mechanisms for these properties, the picture is still not entirely clear. At the same time, these properties are known to depend on spin configuration, which are expected to be rich in these systems due to their rich magnetic phase diagrams [3, 4], but up to now very little has been done on the true spin configuration of both the initial ground states and magnetic phases arising during spin reorientation transitions. In this paper, we present direct experimental results of the states of magnetic phases arising in an antiferromagnetic CoNiCu/Cu superlattice remagnetized under the action of an applied magnetic field.

II. Experimental

The CoNiCu/Cu multilayer composed of 200 bilayers was electrodeposited on a (100) oriented copper single crystal substrate [5]. The magnetic layer composition is estimated to be $Co_{64}Ni_{31}Cu_5$, its thickness is 2 nm. The Cu layer is 1 nm thick. As previously reported [5], these superlattices with such layer thicknesses exhibit the maximum giant magnetoresistance, indicating the antiferromagnetic interlayer exchange coupling.

The magnetic state was studied using a magneto-optical indicator film (MOIF) technique [6,7]. The MOIF technique is based on the Faraday effect in Bi-substituted yttrium-iron-garnet film (with in-plan magnetization) placed on top of the specimen. We have used the leakage fields around a 400 μm hole in the CoNiCu/Cu multilayer to enable the MOIF technique to provide information on the spin configuration over all stages of the spin reorientation transitions. The hole is easily distinguished in the MOIF image (Fig.1). The dark and light magneto-optical contrast seen on the opposite sides of the hole indicates stray flux emanating from the sample and entering into it, respectively, while the sections of the hole side parallel to the magnetization in the sample have, in fact, not been revealed. In this way, the total magnetization value can be estimated by analyzing the magneto-optical signal intensity.

An axis of symmetry of the hole image (dashed line inside the hole in Fig. 1) coincides with the total local magnetization direction. When the magnetization of the sample is uniform around the hole, the local distortions of the magneto-optical image of the hole are associated with imperfections of the edge of the hole.

A commercially manufactured vector vibrating sample magnetometer (VSM) was used to provide hysteresis loops. As a function of the angle in the plane of the sample, the maximum coercivity direction is called the preferred direction in this paper. It arises from the radial anisotropy in the electrodeposition process.

III. Results and discussion

Fig. 1a-e demonstrates the transformation of stray field near the hole in the course of magnetization reversal of the multilayer, as the applied magnetic field, H, acts along an arbitrary direction in the sample plane. At the state shown in Fig. 1a, the sample has been magnetized to near saturation in the direction coinciding with the symmetry axis of the hole image. As the H was reduced to zero, inverted, and gradually increased, the contrast of the hole image became weaker and, at the certain H value, domains of a new phase started to appear (Fig. 1b). Domains grew over the whole volume of the sample in a very small range of H. Fig. 1c is taken just after domain-wall displacement processes have been completed. The symmetry axis of the new image of the hole is turned with respect to the initial direction. It is seen that the hole image contrast in Fig. 1c is weaker than that in Fig. 1a. This means that the new magnetic phase is of the canted (or nonsymmetric-angle) type. Magnetic moments of alternate layers, M_1 and M_2, are indicated by arrows in Fig. 1. The angle between M_1 and M_2 is determined by the contrast and the orientation by the symmetry axis. With further increase of H, simultaneously intensification of the hole image contrast and the turning of the symmetry axis of the

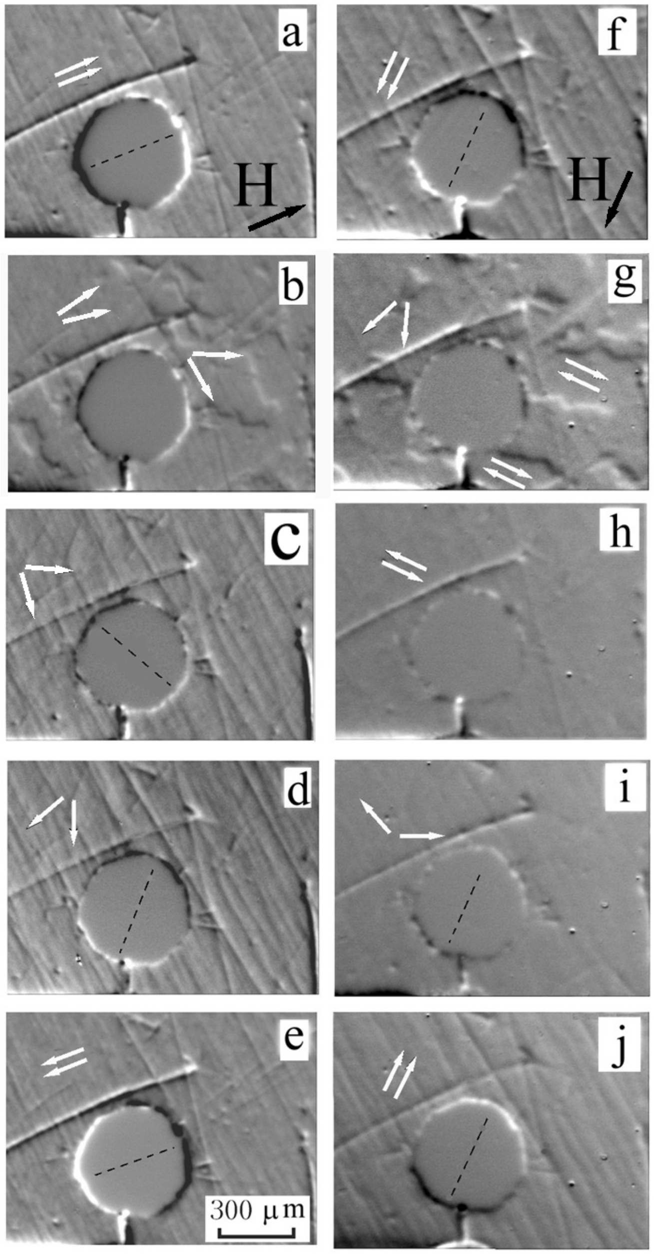

Fig. 1 Stray fields near the hole during the remagnetization of the sample along an arbitrary (a - e) and preferred (f - j) in-plane axis. (a) H = +21 mT, (b) -7.2, (c) -13.4, (d) -14.7, (e) -21, (f) +21 mT, (g) -5.5, (h) -6.3, (i) -10.5, (j) -21. The arrows indicate magnetic moments in alternate ferromagnetic layers. The dashed line inside the hole indicates the symmetry axis of its image. Image intensities are also determined by scratches, ferromagnet inclusions, slip bands, and other structure defects.

hole image towards the H direction is observed (Fig. 1d). At the saturation state, the symmetry axis of the hole image coincides with the initial one (Fig. 1e).

Thus, upon remagnetization of the antiferromagnetic CoNiCu/Cu superlattice along an in-plane arbitrary axis, the nonsymmetric-angle phase, whose state depends on the direction and magnitude of H, is realized. The largest change in the state of this phase takes place due to the nonuniform spin reorientation transition resulting from the nucleation and growth of the new magnetic phase. These phases, as a rule, were nucleated near crystal defects, and in particular, near hole edges. Similar pictures were observed during remagnetization of the multilayer along any in-plane direction, except when the direction coincides with the preferred axis, or is 90° from it.

Figs. 1f-j illustrate remagnetization of the sample previously magnetized to near saturation (Fig. 1f) along the in-plane preferred axis. At the first stage of remagnetization, there was observed as before weakening magneto-optical contrast (not shown), and then nucleation and growth of new phase domains (Fig. 1g). However, after domain-wall displacements have been completed, stray fields near the hole edges, in fact, are not revealed (Fig. 1h). The stray fields can be seen only near local defects disturbing the conditions for antiferromagnetic interlayer coupling. This also proves that the CoNiCu/Cu superlattice is an antiferromagnetic system, because in the case of a ferromagnetic system, a monodomain state (but not a demagnetized one) is realized after completing displacement processes.

With further increase of H, the magneto-optical contrast reappears and then grows, as seen in Fig. 1i. Now the dark and light hole edges in the initial image are replaced by light and dark ones, respectively, and the symmetry axis coincides with the initial direction. It is obviously due to simultaneous rotation of M_1 and M_2 to the H direction (Figs. 1i, 1j). Moreover, it indicates that, due to the nucleation and growth of new-phase domains, the nonuniform spin-flop [3] transition takes place (see directions of M_1 and M_2 in Figs. 1g and 1h).

Investigations at different stages of magnetization of the hole images taken when the field was perpendicular to the preferred direction show that there is a gradual change from a dark and light contrast into a light and dark one, i.e., a gradual rotation of spins from 0^o to 360^o has taken place. Small-scale low-amplitude magnetic inhomogeneities appear. No large-scale domains were revealed.

The above spin reorientation phase transitions are confirmed by vector hysteresis loops, measured for both longitudinal (M_x) and perpendicular magnetizations (M_y). Some of the loops are shown in Fig. 2. The field direction for Fig. 2a corresponds to the direction for for Figs. 1f-1j. The spin reorientations in this direction result in very small M_y values. The field direction for Fig. 2b corresponds approximately (+45° from the preferred direction) to the field direction for Fig. 1a-1e. The large hump in the M_y in Fig.2b would not be present for a ferromagnetic material. In Fig. 2c the field was rotated approximately -60° from the preferred direction to give an M_y in the opposite direction.

The relative arrangements of the spins in both sublattices, M_1 and M_2, presented schematically by arrows in Fig.3, is determined by analyzing M_x and M_y hysteresis loops under the assumption that $|M_1| = |M_2|$ = constant. The external magnetic field interval of the domain walls formation and propagation were determined by MOIF technique. It is seen

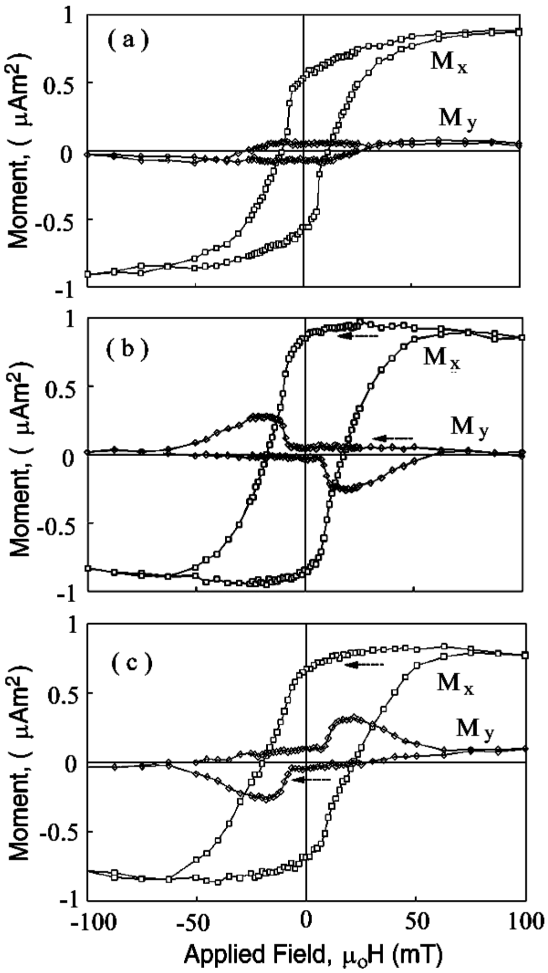

Fig. 2 Hysteresis loops measured for the longitudinal (x) and perpendicular (y) components of the magnetization of the multilayer. (a) is for the preferred direction, (b) is for the preferred direction plus 45^o, and (c) is for the preferred direction minus 60^o. Arrows in (b) and (c) indicate the loop sections for decreasing applied field. The general upward slope in M_y is a measurement artifact.

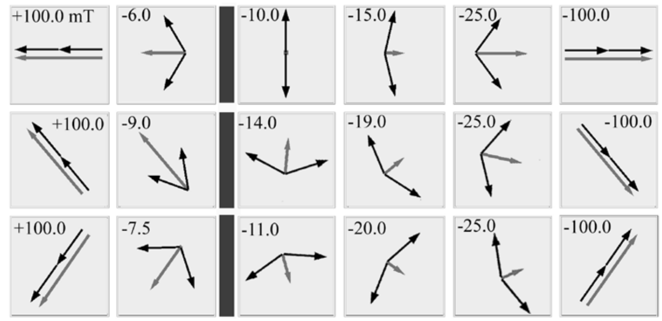

Fig. 3 Orientations of M_1 and M_2 at adjusting layers (black arrows) and total magnetization M_t (gray arrow) are calculated from hysteresis loops measured for the longitudinal (x) and perpendicular (y) components of the magnetization of the multilayer at different H values. The top row corresponds to Fig. 2a, the middle to Fig. 2b, and the bottom to Fig. 2c. The vertical black bands indicate the regions of nucleation and motion domain walls

the character of the changes of relative magnetization orientations between layers received by both vector VSM and MOIF methods is the same.

In summary, the present study has provided direct experimental observation by the MOIF technique and vector VSM analyses of spin-reorientation transitions and of subsequent evolution of these states with changing magnetic field in CoNiCu/Cu magnetic superlattice with antiferromagnetic exchange coupling between ferromagnetic layers. It is shown that, depending on the magnitude and direction of the field, different (similar to that described theoretically [3]) collinear, canted symmetrical and nonsymmetrical phases can be realized by nonuniform spin-flop processes due to interphase boundaries nucleation and motion. It should be noted that the structure of such boundaries [8] differs essentially from the classic ferromagnetic domain walls.

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