Experimental study of magnetization reversal processes in nonsymmetric spin valve

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We have investigated a nonsymmetric bottom giant magnetoresistance spin valve with the structure Si/NiO/Co/Cu/Co/Ta, as well as single ferromagnetic Co layers on antiferromagnetic NiO, with or without a nonmagnetic Cu spacer. Magnetic hysteresis loops have been measured by SQUID magnetometry, and magnetic domain structures have been imaged using an advanced magneto-optical indicator film (MOIF) technique. The MOIF technique demonstrated that the first stage of magnetization reversal is characterized by nucleation of many microdomains. With increasing reversed field, the domain walls move over small distances (5–20 μm) until annihilation. The domain size was observed to increase with the thickness of the Co layer. When an alternating magnetic field was applied, the domain structure was dramatically changed. © *1997 American Institute of Physics.* [S0021-8979(97)73908-2]

I. INTRODUCTION

The discovery of the giant magnetoresistance (GMR) effect has evoked increased interest in magnetic multilayers, and especially in spin valves. Determining the domain structure and its dynamics in magnetic multilayers is important, and there are a number of techniques[1] which will reveal the domain structure: transmission electron microscopy,[2] scanning electron microscopy with polarization analysis (SEMPA),[3] Bitter pattern,[4] Kerr, magnetic birefringence, and magneto-optical gradient effects,[5] and magnetic force microscopy.[6,7] Recently, we have used the magneto-optical indicator film (MOIF) technique to demonstrate that the reversal of the free center layer proceeds by nonuniform magnetization rotation.[8] In this article we apply the MOIF technique to a nonsymmetric spin valve, and demonstrate the ability to reveal not only the static domain structure, but also its dynamics upon application of an ac magnetic field.

The MOIF technique[9,10] 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 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.

II. EXPERIMENTAL DETAILS AND DISCUSSION

The hysteresis loop of the spin valve was measured with a superconducting quantum interference device (SQUID) magnetometer (Fig. 1). It is evident that there are two critical fields, the first corresponding to the switching of the top, nonpinned cobalt layer, occurring over the range of ≈6–9 mT, and the second the switching of the bottom, pinned cobalt layer, occurring over the range ≈50–80 mT. These transition fields correspond to the results of the MOIF images.

The MOIF technique 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 and dark variations of the image formed by an optical system represent the variations of the stray fields in the indicator film, which are associated with the magnetizations not only near the sample surface but also inside it.

Three types of specimens were investigated in this study. Their structures are schematically profiled in Figs. 2–4. The NiO substrates were 50 nm thick polycrystalline films, de-

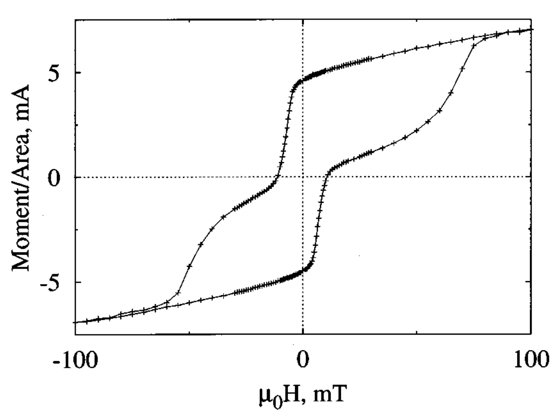

FIG. 1. The room-temperature hysteresis loop of a nonsymmetric bottom Si/NiO/Co/Cu/Co/Ta GMR spin valve, measured with a SQUID magnetometer.

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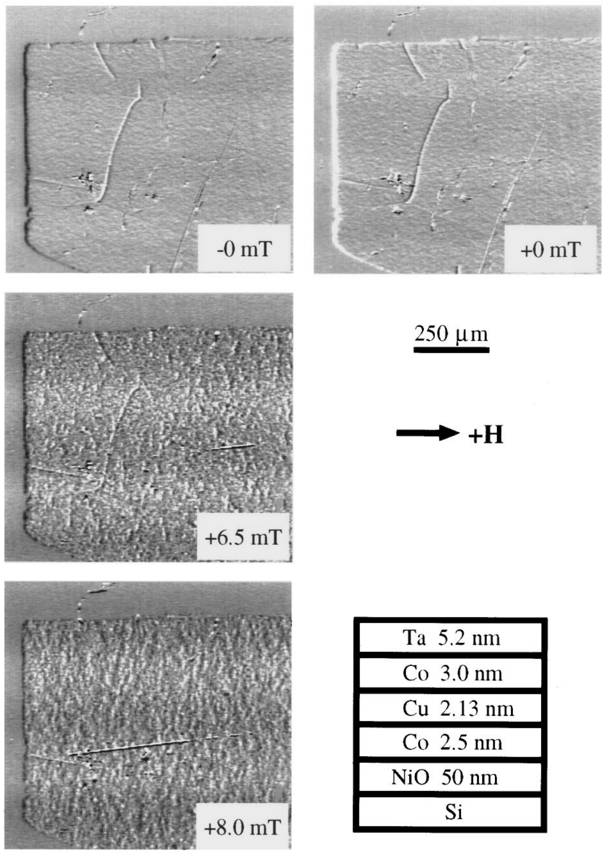

FIG. 2. Schematic profile of the structure of a nonsymmetric spin-valve sample. The MOIF images represent the process of remagnetization.

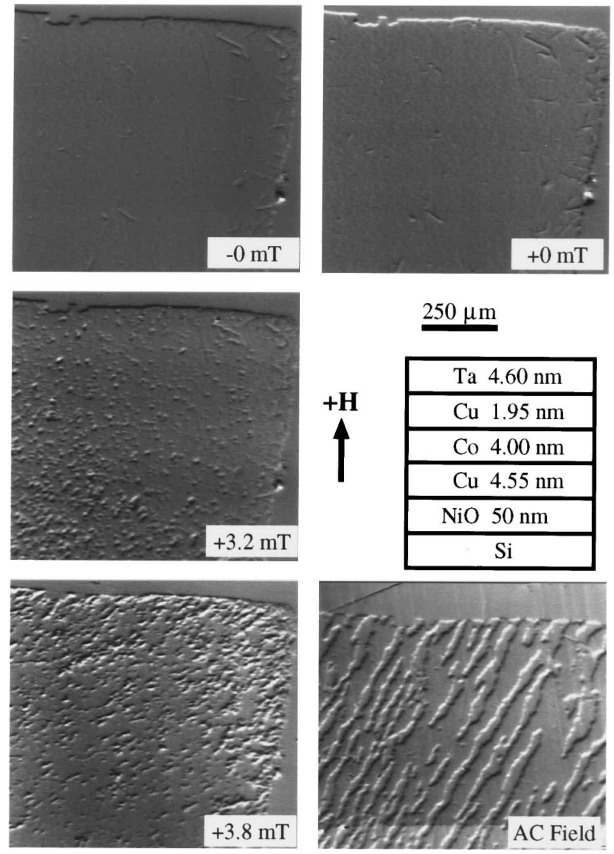

FIG. 3. Schematic profile of the structure of a single cobalt layer sample, otherwise similar to the nonsymmetric spin-valve sample. The three MOIF images on the left and the top right image represent the process of remagnetization. The image on the bottom right is the result of a 30 Hz ac field.

posited on a Si wafer. The metal films were deposited at room temperature by dc-magnetron sputtering in an Ar pressure of 2 mTorr in a system with a background pressure of 1×10^{-8} Torr. The first specimen investigated, shown in Fig. 2, is a nonsymmetric bottom GMR spin valve with the structure Si/NiO/Co/Cu/Co/Ta. The analysis of the sample magnetization was evident from the magneto-optical image of the leakage field on the sample edges. The details of the domain structure were studied using computer subtraction of the background image, which reduces the contrast from nonmagnetic defects. The background image was obtained by averaging two image fields saturated at large magnetic fields of opposite polarities and then reduced to zero field. Using this technique, the leakage fields compensated each other (the same saturated regions of the sample was light in one of the images and dark in the other).

The set of images in Fig. 2 represents the process of demagnetization in the nonsymmetric spin valve. The sample was first magnetized to saturation in a -80 mT field. After reducing the field to zero, the sample had the magneto-optical portrait displayed in the top left picture. As is evident from the picture, the sample is magnetized in its own plane, along the plane parallel to the top edge. Magnetic charges concentrated along the vertical edge of the sample produce leakage fields which form the dark band in the left region of the image. Light regions correspond to the leakage field from magnetic charges of opposite sign. Black and white images of scratches are visible in the picture, as are incipient ripples of magnetization. When the field direction and value are changed to approximately 6.5 mT (middle picture in left row), this ripple acquires more contrast, and intensive microdomain nucleation starts throughout the sample. At further increase of field ($H=8$ mT, bottom picture in left row), the microdomains become larger in size, adjacent microdomains merge, and the domain structure seen appears. Simultaneously with the development of the magnetic structure, reduction in the black contrast is observed at the sample edge. Its contrast is practically extinguished after the microdomains disappear at the field near 10 mT. The appearance of a new white contrast at the sample edge occurs gradually.

The set of images in Fig. 3 represents the process of remagnetization of one Co layer, which was prepared at the same conditions as the upper (low-coercive) layer in the two Co-layer spin-valve structure of Fig. 2. This structure was prepared to be similar to the spin valve without the pinned Co layer. As in the previous figure, the sample was first magnetized to saturation in a -80 mT field, then the field is reduced to zero, (left top picture). There is no magnetic structure visible in the magneto-optical portrait except from scratches (mainly in the right part of the picture). Positive field increase produces a large amount of nucleation of a new magnetic phase, as can be seen in the middle left picture at $H=3.2$ mT. The density is not even across the sample. With the given orientation of the field and sample, the most in-

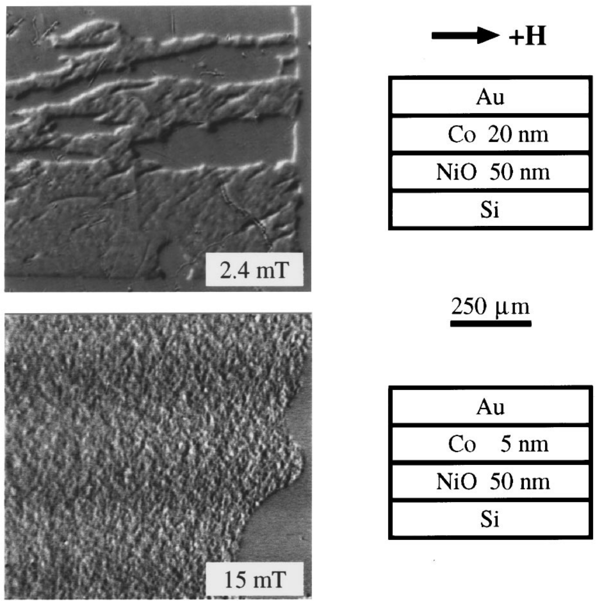

FIG. 4. Schematic profile of the structure of two different thickness single cobalt layer adjoining NIO, as in the bottom layer of a nonsymmetric spin-valve sample. The image contrasts the domain structure in Co of different thickness during remagnetization. The field is oriented horizontally in these images. The structures shown were capped with a protective Au layer.

tense domain nucleation appears at the lower left region of the sample. With further field increase (3.8 mT, left bottom picture), this nucleation process moves to the top right and generates new domain nucleations in the top right of the sample as well as the expansion due to boundary movement and merging of already existing domains in the left bottom region. With subsequent field increases (not shown), the remagnetization process is practically completed at the field of $\approx$4.5–5.0 mT. The sample edge (at the top) becomes white and the magnetic structure is limited to a few defects in the film. This situation continues as the field is further increased to +80 mT (not shown), and then reduced to zero (the top right picture). On the whole, the magnetization parameters of the Co layer (coercive field, characteristic dimensions of domain structure, etc.) are similar to the characteristics of the spin valve structure. Some observed differences and behavior peculiarities can be explained by differences in the cobalt thickness, and particularly by the absence of the exchange interaction with the other Co layer, as distinct from the spin-valve where such exchange is present.

In the same sample with an alternating magnetic field, an effect of specific domain structure formation was discovered, similar to dissipative structures observed in diverse nonlinear systems.[1] The magneto-optical portrait of such a structure for an ac frequency of 30 Hz is presented in the bottom right picture. When an $\approx$1 Hz, 6 mT ac field was applied, microdomains formed similar to those shown in the dc presented pictures in the middle and bottom left. The sample was remagnetized in each cycle. As the frequency increased, some of the microdomains merged and formed domains whose dimensions were comparable with the sample dimension. The number of new domains nucleating declined, and the macrodomain boundaries begin to be oriented along some direction. (Since the coil that produces this field has a large inductance, its amplitude decreases with increased frequency.) Upon achieving the critical frequency (30 Hz, 4.4 mT), the stabilized domain structure abruptly stopped changing and settled upon a pattern similar to that presented in the bottom right picture. This dissipative structure appears only in a small range of orientations of the external magnetic field.

The set of images in Fig. 4 demonstrates the behavior of the domain structure in Co layers of different thickness during remagnetization. The field is oriented horizontally in these images. The Co layers were deposited onto NiO substrates, under the same conditions as in the two Co-layer spin-valve structure in Fig. 2. The Co was 20 nm thick in the top picture, 5 nm in the middle picture. The sample remagnetization was obtained from the (negative) saturated state. During remagnetization of the thicker sample (20 nm, top picture) large-scale domain structure was formed at low valve field. In thinner films the domain structure appeared at larger fields. For the 5 nm film (bottom picture), the structure appeared at 15 mT. The characteristic dimensions of the domain structure in such films are substantially smaller, and the field range where remagnetization occurs expands. For a 2.5 nm film, we were unable to detect domain structure by the MOIF technique, although the domains were resolved in the spin-valve structure of Fig. 2, with layers of similar thickness. After magnetization of the film in large fields, the magnetostatic field is visible on the sample edge. The magnetic image intensity from the charges on the sample edge practically disappeared after the field was decreased, inverted and then increased to 49 mT. This indicates that there was a remagnetization process on a smaller scale.

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