# Magneto-optical indicator film study of the magnetization of a symmetric spin valve

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*Abstract* - **A magneto-optical indicator film (MOIF) technique is used for direct experimental study of the magnetization reversal process in a symmetric NiO/Co/Cu/NiFe/Cu/Co/NiO spin valve. It is shown for the first time that the reversal of the free center layer proceeds by nonuniform magnetization rotation. The observed switching mechanism is presumed to be associated with the influence of the nonuniform magnetostatic field that follows from surface roughness and the polycrystalline structure of the magnetic layers.**

## I. INTRODUCTION

Since the discovery of the giant magnetoresistance (GMR) effect in magnetic multilayers [1], materials with GMR have attracted interest due to their importance both for a fundamental understanding of spin-dependent electron transport and for device applications. Among these materials, symmetric spin valve structures are one of the prime candidates for such applications [2]. They consist of three magnetic layers with different coercivities separated by two non-magnetic spacers. Ideally, the outer two magnetic layers are magnetically pinned while the center magnetic layer is free to switch. Many characteristics that are important for application of symmetric spin valves, such as the switching field, coercivity, and Barkhausen noise, are governed by the magnetization reversal process in the center magnetic layer. Therefore, improvement of these characteristics requires that the magnetic microstructure of the center magnetic layer and its behavior during magnetization reversal be determined and understood. This situation emphasizes the necessity of the development of methods whereby such information can be obtained. In this paper we show that the magneto-optical indicator film (MOIF) technique [3] can be successfully used for a study of the magnetization reversal of the symmetric NiO/Co/Cu/NiFe/Cu/Co/NiO spin valve and, in particular, of its center layer.

## II. EXPERIMENTAL

The NiO substrates used in this work were 50 nm thick polycrystalline films, deposited 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 x $10^{-8}$ Torr. The top NiO layer was deposited by sputtering a Ni target with an 85/15 mixture of $Ar/O_2$.

Magnetic properties of the spin valve were studied with a SQUID magnetometer, magnetoresistance measurements, and the MOIF technique. The MOIF technique places an indicator film (Bi-substituted iron garnet with in-plane anisotropy) on the sample to reveal the domain structure of the sample. The magnetization vectors in the garnet film, which are in the plane in the absence of external fields, develop out-of-plane components if normal components of the stray magnetic field from the sample are present. Stray field components are revealed by the magneto-optical Faraday effect as polarized light is passed through the garnet film and reflected back by an Al underlayer. Viewed in a polarizing microscope, the resulting Faraday picture of the sample gives information about its domain structure. A background subtraction has been carried out for image enhancement [3].

The magnetoresistance measurements were made using a four-point probe with the applied magnetic field parallel to both the direction of current flow and the plane of the foil. All results presented here were obtained at room temperature.

## III. RESULTS AND DISCUSSION

Fig. 1 presents a schematic cross section of the symmetric spin valve under study. In this structure the center permalloy layer is free to switch while the outer two cobalt layers are magnetically pinned by antiferromagnetic NiO. Fig. 2 shows

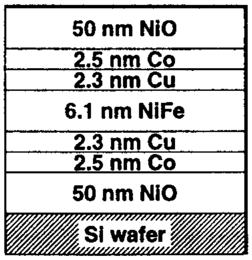

Fig. 1. A schematic cross section of the symmetric spin valve studied in the present investigation.

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the hysteresis loop of the symmetric spin valve. From this loop, two critical fields are seen that characterize the switching of the center permalloy layer (about 1-2 mT), and the outer cobalt layers (about 90 mT). The magnetoresistance data shown in Fig. 3a correspond closely to the magnetic measurements. In the low-resistance state the magnetizations in adjacent magnetic layers are parallel, and in the high-resistance state the magnetizations are antiparallel. Changes in magnetoresistance occur at the same magnetic fields in which the switching of the permalloy or cobalt layers takes place. The low-field magnetoresistance loop presented in Fig. 3b corresponds to switching only the permalloy layer. The spin valve had been magnetized to saturation along the positive magnetic field axis prior to the low-field measurements. The center of the low-field loop is shifted about 0.5 mT from zero field by the coupling field that exists between the permalloy and cobalt layers across the Cu. From this we conclude that there is a weak ferromagnetic coupling between magnetic layers in the spin valve.

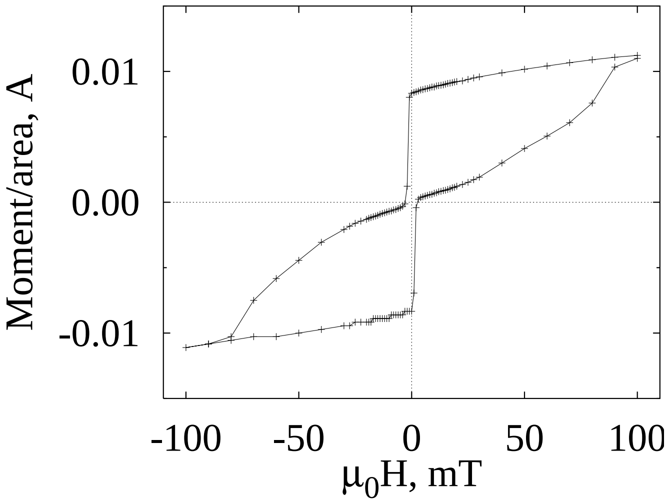

Fig. 2. The hysteresis loop of the spin valve.

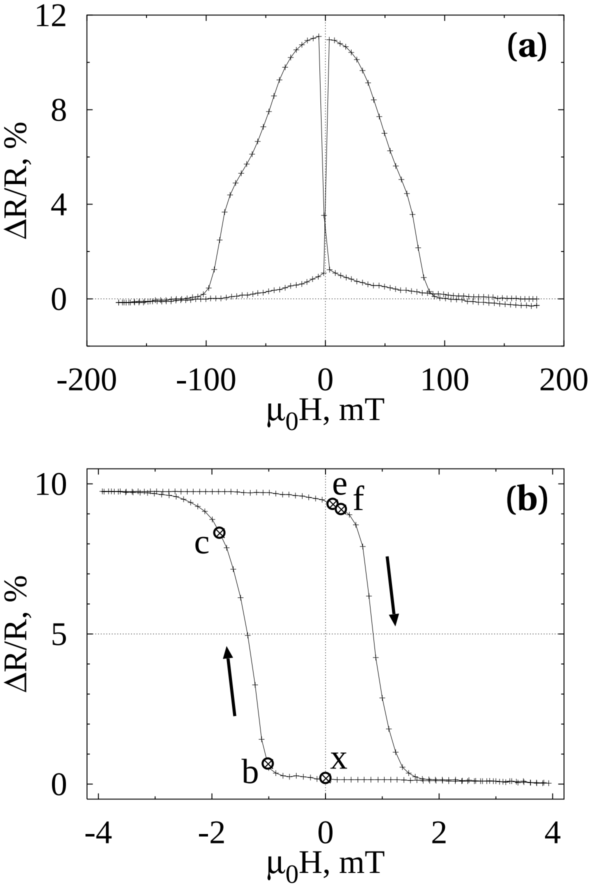

Fig. 3. The magnetoresistance loops for the spin valve in the high-field(a) and the low-field(b)cases. The letters shown at the low-field loop indicate the ΔR/R values which correspond to the magnetization states labeled by the same letters in Fig. 4. Before measuring the low-field curve, the specimen had been magnetized to saturation along the positive field direction.

Fig. 4 shows MOIF images of a typical reversal process for a portion of the symmetric spin valve. In Fig. 4(a), the spin valve has been magnetized to saturation in the direction shown as +H. In this state the spins in all three magnetic layers are parallel. The almost vertical white band indicates that the magnetostatic stray field at the edge of the specimen is directed out of the image, perpendicular to the sample surface. As the field was turned off the magnetization state was almost preserved [this state corresponds to the letter "x" in the magnetoresistance loop in Fig. 3(b)]. Upon application of a very small reverse field the magnetization reversal of the permalloy layer starts. Figs. 4(b) and 4(c) illustrate this process and correspond to the letters "b" and "c" in Fig. 3(b). Under such conditions, the nonuniform image in the MOIF film reflects the nonuniform magnetization reversal of the permalloy layer. As the magnetic field increases farther, the almost complete loss of image contrast corresponds to the completion of the switching of the permalloy layer [Fig. 4(d)]. The magnetostatic field contrast at the edge of the sample under such conditions is very weak because the permalloy's magnetization has become antiparallel to the spin directions in the cobalt layers.

Upon reducing the magnitude of the applied field through zero to small positive values (i.e., tracing out the upper part of the minor loop in Fig. 3(b)), similar processes in the opposite direction were observed in the permalloy layer [Figs 4(e) and 4(f)], which correspond closely to the asymmetric magnetoresistance loop in Fig. 3(b) (letters "e" and "f"). Fig. 4(g) shows the MOIF image of the spin valve magnetized to saturation along the direction of the action of a negative magnetic field. Switching the cobalt layers to the field direction, which proceeded in large field, changed the image contrast at the film edge to black. (Magnetization reversal in the cobalt layers can be distinguished from that of the center permalloy layer by the relative strength of the applied field, cf. Fig. 2.) The character of the successive change in the film edge contrast indicates that the magnetization of the cobalt layers occurs in a non-uniform manner and with different

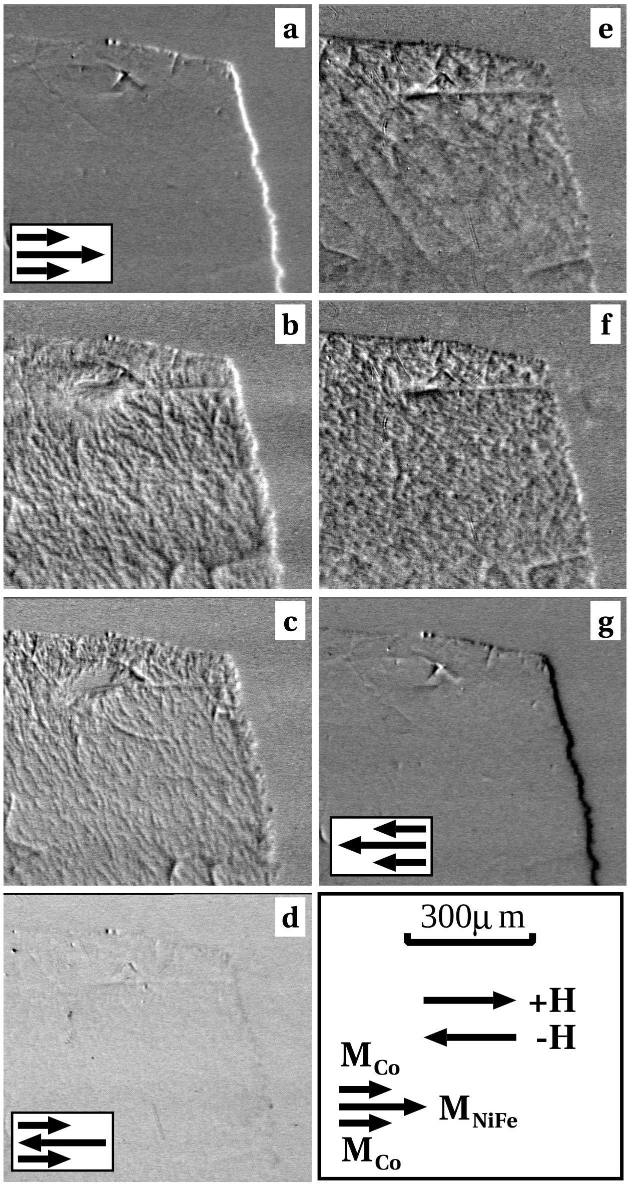

Fig. 4. MOIF images showing a succession of the magnetization reversal of the spin valve. The applied field (a) H=+80 mT, (b) -1, (c) -1.8, (d) -5.5, (e) +0.1, (f) +0.3, and (g) -80. The short arrows on the pictures indicate the magnetization directions of the Co layers while the long arrows indicate that of the NiFe layer.

values of magnetic field for the top and bottom layers. However, the magnetization reversal process itself in the interior of cobalt films was not observed. It is also worthwhile to note that if the reversal starts from the state shown in Fig. 4(g), then the asymmetry of the magnetoresistance loop and low-field magnetization reversal is reversed.

Thus, the magnetization reversal of the permalloy layer in the symmetric spin valve studied here is essentially a nonuniform process. It proceeds by incoherent magnetization rotation, which is in contrast to the magnetization reversal of electrochemically produced CoNiCu/Cu multilayers [3,4], where nucleation of domain walls and their motion over large distances occurs. In general, it is clear that the low-field switching of the symmetric spin valve is governed by the coercivity of the center layer and coupling between pinned and unpinned layers. The ferromagnetic coupling is due to both the exchange and the magnetostatic interaction across the Cu spacers. The origin of the magnetostatic coupling may be understood in terms of "orange-peel" [5] or "pinhole" [6] models. In the former, the coupling follows from film surface roughness while the latter ascribes the coupling to thin continuous columns of magnetic materials which join magnetic layers. In both cases local ferromagnetic coupling will vary from point to point in the film plane. It is also clear that, for a thin magnetic film with thickness comparable to the surface roughness, the magnetostatic interaction between the top and bottom surfaces will tend to form a nonuniform intrinsic magnetic field. These concepts can provide an explanation for the nonuniform magnetization observed in our experiment. An additional contribution to such behavior could come from the polycrystalline structure of the permalloy layer.

The results presented illustrate the possibilities of the MOIF technique for direct experimental observation of the magnetization reversal processes in spin valve structures and nondestructive characterization of their quality. Moreover, the magnetization reversal processes can be observed in real time.

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