Measurement of local magnetization in the buried layer of a pseudo-spin-valve submicron wire

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A pseudo-spin-valve (PSV) wire [Au(3 nm)/Py(10 nm)/Cu(5 nm)/Co(10 nm)/Si] was patterned by e-beam lithography into two sections with different widths, connected by a narrow part that acts as a domain wall trap. The two sections have different magnetic shape anisotropies and thus different coercive fields. Since the sample has two different magnetic layers (soft and hard) and two different anisotropies (thick and thin widths), this patterned system has more than two magnetic configuration states depending on the applied field strength. To probe local magnetization from the two different sections, x-ray magnetic circular dichroism (XMCD) measurements were done on the PSV wire with a microfocused x-ray beam. Measurements were done on the buried hard layer, from which magnetic information cannot be obtained by surface-sensitive techniques. The XMCD experimental results are compared with micromagnetic simulations. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1667798]

I. INTRODUCTION

One of the major driving forces in the magnetic storage industry is to increase the density of stored information per media volume. Recent advances in patterning techniques have made patterned magnetic films a viable alternative to the current continuous film technology. One promising material for such device application is a pseudo-spin-valve (PSV) structure, in which a conducting nonmagnetic layer is sandwiched between two magnetic layers with different coercivities. The electrical resistance in such layered materials can vary greatly depending on the relative magnetization orientation (parallel/antiparallel) between the two magnetic layers. This is commonly referred to as the giant magnetoresistance effect and has made these structures potential candidates for nonvolatile storage devices.[1–3]

In this study, we report on measurements performed on a PSV structure consisting of permalloy (NiFe) and Co magnetic layers. This material was patterned into a wire with two different widths connected by a narrow channel. Compared with a simple PSV wire pattern that has only two different magnetization orientations (parallel/antiparallel), the PSV wire pattern with two sections can have more than two magnetization orientations due to the different shape anisotropy in each section.

Many interesting magnetic systems are composed of alloyed or heterostructured multilayer films, and it becomes important to learn about individual constituents in a layer-specific or element-specific way. In this work, x-ray magnetic circular dichroism (XMCD) was used to study element-specific magnetism. XMCD measurements were performed in fluorescence geometry, and the penetrating capability of hard x rays enables magnetism studies from buried structures. The XMCD signal is the difference in absorption between left- and right-circularly polarized x-rays by a magnetic material. This difference is enhanced near absorption edges so that element specificity is obtained by tuning the x-ray energy to these characteristic atomic resonances. In addition to the element specificity, we measured spatially resolved magnetization with a circularly polarized beam focused to a micron size.

II. EXPERIMENTS

A PSV wire [Au(3 nm)/Py(10 nm)/Cu(3 nm)/Co(10 nm)] on a Si substrate was made by a combination of e-beam lithography, e-beam evaporation, and lift-off processes. The top Au layer was deposited to prevent oxidation. The wire was patterned into two sections with different widths (0.6, 0.3 μm), connected by a tapered narrow section (0.1 μm) that acts as a domain wall trap[4] (Fig. 1).

The same unpatterned film structure was grown on another Si substrate simultaneously for characterization of the film thickness and roughness, which are assumed to be similar to the patterned sample. From x-ray reflectivity measurements on this calibration sample, the layer thicknesses were found to be within 5% of the nominal values, and the roughnesses between layers at the interfaces were about 5–6 Å.

To probe local magnetization from two different sections having different widths, XMCD measurements were done on

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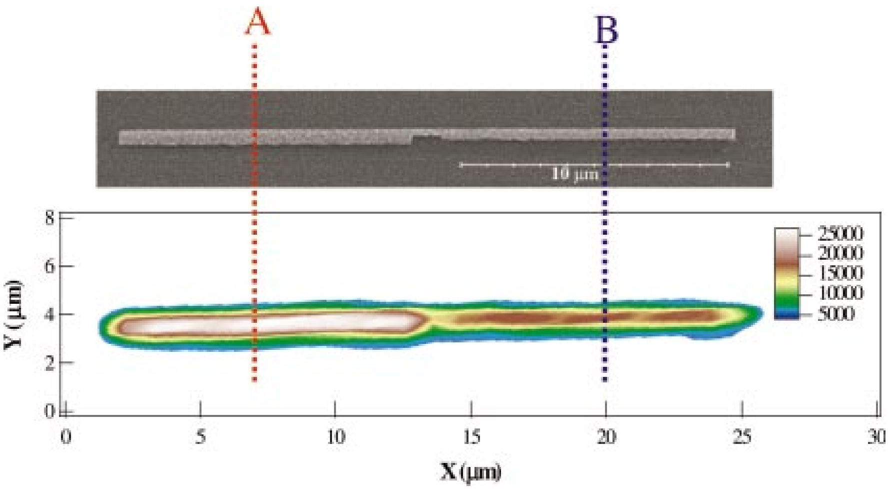

FIG. 1. (Color) Scanning electron microscope image of a PSV wire (top) and Co K_α fluorescence signal mapping (bottom). Hysteresis loops were measured at A and B.

the PSV wire with a microfocused x-ray beam at the 4ID-D beamline of the Advanced Photon Source at Argonne National Laboratory. Circularly polarized x rays were produced by passing monochromated undulator radiation through a diamond (111) quarter-wave plate in Bragg transmission geometry.[5] The circularly polarized beam was focused down to $1.5\,\mu\text{m}\times 1.5\,\mu\text{m}$ at the sample using mirrors in Kirkpatrick–Baez geometry.[6] Fluorescence from the sample was collected by energy-dispersive Ge solid-state detectors, and a magnetic field was applied along the wire using an electromagnet. By tuning the incoming photon energy to near absorption edges of each constituent element, the magnetization reversal processes of the soft (NiFe) and hard layer (Co) can be investigated separately.

The incoming x-ray energy was first tuned to near the Co K edge, and the dichroic x-ray absorption spectra were taken to find the energy with maximum XMCD signal (7.713 keV). The XMCD signal is defined here as the absorption difference normalized to the total absorption $[\text{XMCD}\sim(I^+ - I^-)/(I^+ + I^-)]$. I^+ and I^- are fluorescence intensities when the magnetic field is applied parallel or antiparallel, respectively, to the incoming x-ray beam direction. The homogeneity of the buried Co layer was mapped by moving the sample on a micro-stage and monitoring the Co K_α fluorescence. The sample was found to be homogeneous, as shown in Fig. 1 (bottom). The hysteresis loops from the Co layer was obtained by measuring the XMCD signal as a function of an applied field while flipping the helicity of the circularly polarized incoming x rays. The magnetization of the bottom Co layer, which is below Au/permalloy/Cu layers, can be deduced from the Co XMCD signal. Two separate hysteresis loop measurements were done at points A and B, as indicated in Fig. 1.

Subsequently, similar XMCD measurements at the Ni and Fe K edges (7.112 and 8.333 keV respectively) were performed on the permalloy ($Ni_{80}Fe_{20}$) layer. However, the lower Fe content in this layer on one hand, and the reduced XMCD signal (as defined earlier) at the Ni K edge of NiFe relative to other Ni concentrations on the other,[7] resulted in noisier data at these edges. This problem, however, is overcome at Fe and Ni L edges, as shown by Castaño *et al.*[8]

III. RESULTS AND DISCUSSION

Cobalt layer hysteresis loops from the XMCD measurements are shown in Fig. 2(a). The XMCD signal is proportional to the magnetization of the Co layer since variations in XMCD are correlated to variations in the local magnetization. The switching field is larger for the thin section than for the thick section, as expected. The results of the XMCD

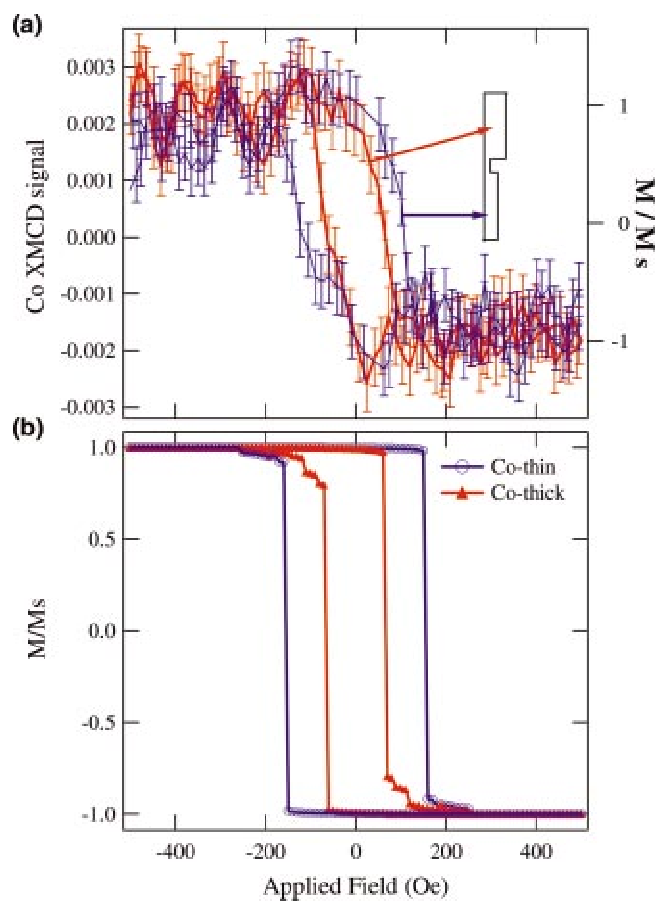

FIG. 2. (Color) Cobalt layer magnetization hysteresis from XMCD signal (a) and micromagnetic calculation results (b). The inside loops are from the thick section and the outside loops are from the thin section.

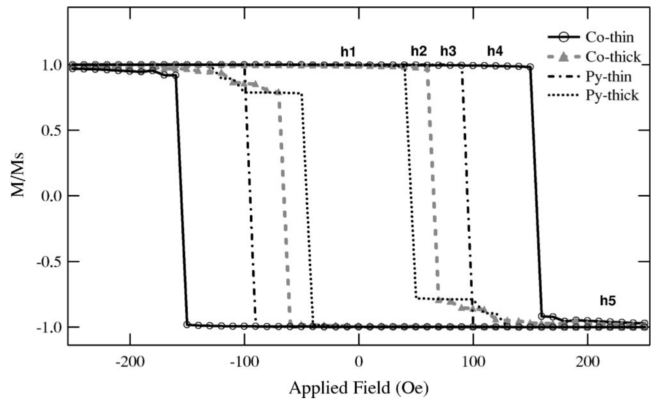

FIG. 3. Micromagnetic simulations results on Co and permalloy layers. For each layer, two hysteresis loops, corresponding to the thin and wide sections, are shown.

measurement from the Co layer were compared with micromagnetic simulations.

Micromagnetic calculations were done on the PSV-wire system using OOMMF program.[9] It was assumed that the Cu layer between the permalloy and Co layers is thick enough that the two magnetic layer are not coupled. It was also assumed that in each layer, the magnetization is uniform in the out-of-plane direction, allowing for two-dimensional simulations. The simulation cell size was 20 nm×20 nm, and the equilibrium configuration was assumed when $|M\times H|/M_s^2 \leqslant 10^{-5}$ was reached. From OOMMF calculation results [Fig. 2(b)], the hysteresis loop for the thin (thick) section was obtained by averaging magnetization of the cells that are in the thin (thick) section. The simulated and measured hysteresis loops are in good agreement except for small discrepancies due to a slight misalignment between the sample and the applied field direction.

Figure 3 shows four calculated hysteresis loops of thin and thick sections from each layer by OOMMF program. The field values of the upper loops at which domain schematics were drawn in Fig. 4 are designated $h1-h5$. These schematics represent magnetic domain configuration from the micromagnetic simulation results. Initially the whole sample is magnetized to the left $(h1)$. As the field direction is reversed, the permalloy magnetization of the thick section is reversed first $(h2)$. This is expected since permalloy is soft compared with Co, and the shape anisotropy of the thick section is lower than that of the thin section. The connecting narrow section in the middle acts as a barrier preventing domain propagation; that is, as a domain wall trap. As the field is increased in the reverse direction, the Co magnetization of the thick section $(h3)$ is reversed. The domain wall in this Co layer is also in the connecting narrow section. As the applied field is increased further, the field is strong enough to overcome the domain wall trap barrier, and the permalloy magnetization of the thin section $(h4)$ is reversed next. The magnetization of both layers is reversed at higher field eventually $(h5)$.

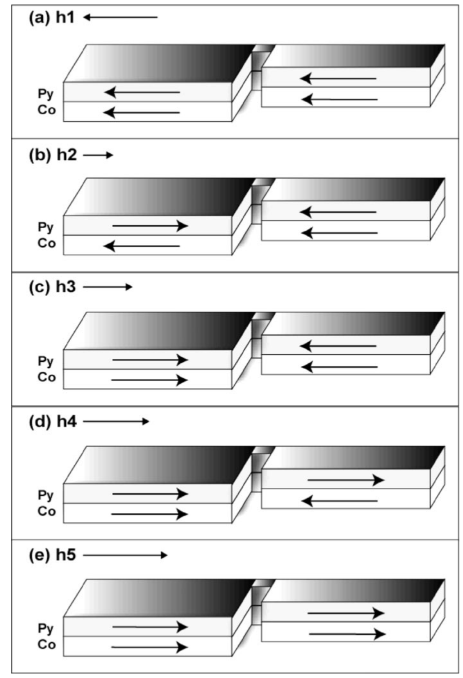

FIG. 4. Magnetization orientation schematics from micromagnetic simulation. The Au and Cu layers are not shown. The arrows inside the films indicate layer magnetization directions. $h1-h5$ refer to their respective fields on the hysteresis loops from micromagnetic simulation in Fig. 3.

IV. SUMMARY AND CONCLUSIONS

An element-specific technique with scanning capability was used to measure element-specific hysteresis loops from the buried Co layer in a patterned PSV system. We showed that the two sections of different widths can be isolated by having a domain wall trap in between. As a reversing field is applied, the thick section reverses its magnetization while the thin section retains its magnetization. The domain wall trap in the middle prevents domain propagation from the thick section to the thin section. This result was simulated using a micromagnetic simulation program. The simulation result also shows that a single pattern can have more than two magnetization orientations depending on the applied field strength.

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