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Effects of Interlayer Coupling in Elongated Ni$_{80}$Fe$_{20}$/Au/Co Nanorings

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We describe the magnetization reversal processes in multilayer elongated Ni$_{80}$Fe$_{20}$ (10 nm)/Au(t = 0 to 20 nm)/Co(20 nm)/Si(001) nanorings. For a field applied in-plane along the long axis, the hysteresis loops display a two-step switching for both t = 0 nm and 2 nm, and a three-step switching for t = 10 nm and 20 nm. Onion-to-vortex and vortex-to-reverse onion state transitions occur for a thin Au spacer due to strong exchange coupling between the layers. For a thick Au spacer layer, the Ni$_{80}$Fe$_{20}$ layer switches first, then a two-step reversal of the Co, correlated with domain motion in the Ni$_{80}$Fe$_{20}$, occurs without the formation of vortex states as a result of magnetostatic interactions. There is a good agreement between the experimental results and micromagnetic simulations.

Index Terms—Co/Au/Ni$_{80}$Fe$_{20}$, elongated nanorings, exchange coupling, MOKE.

I. INTRODUCTION

PATTERNED trilayer ferromagnetic/nonmagnetic/ferromagnetic (F/N/F) systems are of fundamental interest due to the strong interactions between the magnetic layers, and have application in magnetic random access memory, magneto-electronic devices, and especially GMR multilayers [1], [2]. Interlayer magnetostatic coupling plays a significant role when the lateral size of the device is reduced [3], and both magnetostatic and exchange coupling affect the switching process and coercive field of the patterned F/N/F system, depending on the thickness and material of the spacer layer [4].

Recently, interlayer exchange coupling has been widely researched in nanostructures with various dimensions and materials of both the ferromagnetic layers and spacer layer [4]–[10]. Buchanan et al. [4] investigated the magnetization reversal in patterned Py/Cu/Py nanodots and observed a state where two magnetic disks separated by a nonmagnetic spacer each support single vortices. Smith et al. [5] studied the interlayer coupling in patterned submicron Co/Au/ Ni nanostructures with different shapes such as diamonds, ellipses, and rectangles using off-axis electron holography.

However, there are limited reports on the competing effects of interlayer exchange and magnetostatic coupling in magnetic nanorings. Magnetic nanorings have been studied due to their potential applications in the high density magnetic-random access memory (MRAM) [11] or logic devices [12]. A thin film ring shows two characteristic magnetic configurations. One is the vortex state with a low remanence and stray field where the magnetization has a closed flux configuration, and another is called the onion state with two opposite head-on ($180^\circ$) domain walls [13]. In this work we systematically investigate the magnetization reversal processes in multilayer elongated Co(20 nm)/Au(t)/Ni$_{80}$Fe$_{20}$(10 nm) nanorings as a function of the thickness t of Au by means of MOKE measurements. Minor loops were also measured to separate the magnetic switching behavior of the Ni$_{80}$Fe$_{20}$ and Co layers. We show that the switching process differs qualitatively depending on how effectively the Au layer exchange-decouples the layers. The combined effects of interlayer coupling and ring spacing on the switching behavior are correlated with 3-D micromagnetic simulations together with magnetic force microscopy.

II. EXPERIMENTAL DETAILS

Periodic arrays of elongated rings with varied interring spacing were fabricated by deep ultra violet lithography at 248 nm exposure wavelength followed by lift-off on a silicon substrate [14]. Si/SiO$_2$/Co(20 nm)/Au(0–20 nm)/Ni$_{80}$Fe$_{20}$(10 nm)/Au(3 nm) multilayers shown in Fig. 1(a) were deposited using electron beam evaporation at a rate of 0.2 Å/s. The pressure was maintained at 5 × 10$^{-6}$ Torr during the deposition process. To prevent oxidation, all samples had a 3 nm-thick Au capping layer on the top. Successful lift-off was determined by the color change of the patterned film and confirmed by examination under a scanning electron microscope (SEM). Fig. 1(b) is a SEM micrograph of arrays of ring width w = 150 nm, length l = 1150 nm, aspect ratio R = 1.7 along the long axis, and inter-ring spacing s = 530 nm. The collective magnetic switching behavior of ring arrays was characterized by focused magneto-optical Kerr effect (MOKE) magnetometry at room temperature with a spot size of about 5 µm. The magnetic states of the elongated rings were imaged by magnetic force microscopy (MFM). A magnetized Si low-moment tip coated with CoCr at a scan height of 100 nm was used. Three dimensional micromagnetic simulations were performed for the patterned F/N/F system with varied Au thickness by using the 3D object oriented micromagnetic framework (OOMMF) code from the National Institute of Standards and Technology [15]. The material parameters used are as follows: saturation magnetization $M_s$(NiFe) = 860 emu/cm$^3$ and...
Au/Co NANORINGS for the hysteresis loops as to /40/49/48 /110 /109/41 and 2 nm, the only other 0.5. The anisotropy constant was set to 600 Oe) transitions. For the case of 120 Oe) and vortex-to-re-

which is insensitive to the Au in the x, y, and z directions respectively, and 20 nm, the

cubic cells for the cubic cells. All the loops show a common third peak (high and

atomic force microscopy. The inset shows the surface topography of Au (2 nm) grown on Co (20 nm) using

axis of the rings, and (c) The field-derivative of the ascending branch of the

Fig. 2. Hysteresis loops for (a) the continuous films Ni₈₀Fe₂₀(10 nm)/

An(t)/Co(20 nm) with various thickness t from 0 nm to 20 nm, (b) the corresponding elongated nanoring arrays for a field applied along the long axis of the rings, and (c) The field-derivative of the ascending branch of the hysteresis loops. The peaks correspond to the steps in the hysteresis loops. The inset shows the surface topography of Au (2 nm) grown on Co (20 nm) using atomic force microscopy.

\[
\text{M}_{\text{eff}}(\text{Co}) = 1.4 \times 10^3 \text{ emu/cm}^3, \text{ exchange stiffness constant } A(\text{NiFe}) = 1.3 \times 10^{-6} \text{ erg/cm}, \text{ and } A(\text{Co}) = 3 \times 10^{-6} \text{ erg/cm}. \text{ damping parameter } \alpha \sim 0.5. \text{ The anisotropy constant was set to zero to model polycrystalline Co. The size of the unit cell used is } 10 \times 10 \times 2 \text{ nm}^3 \text{ in the x, y, and z directions respectively, and the simulation used } 5 \times 5 \times 20 \text{ nm}^3 \text{ cubic cells for the single Co layer.}
\]

III. RESULTS AND DISCUSSION

Fig. 2(a) shows the MOKE M-H loops of the continuous films as a function of Au spacer layer thickness. The MOKE signal is sensitive to the top Ni₈₀Fe₂₀ layer, and shows a decrease in coercivity as the Au layer thickness increases and the Ni₈₀Fe₂₀ and Co layers become exchange-decoupled. However, for the elongated nanorings, the light scatters from the edges of the rings, so the MOKE signal is sensitive to both top and bottom layers. The corresponding MOKE M-H loops as a function of Au spacer layer thickness for field applied along the long axis of the rings are shown in Fig. 2(b). The magnetostatic interaction between adjacent rings is neglected due to the relatively large inter-ring spacing [16].

For \( t = 0 \) and 2 nm, two significant steps are observed corresponding to the onion-to-vortex (\( \sim -120 \text{ Oe} \)) and vortex-to-reverse onion (\( \sim -600 \text{ Oe} \)) transitions. For the case of \( t = 0 \) nm, the correlated reversal in the two FM layers is caused by the strong ferromagnetic exchange coupling between them. For Au (2 nm) grown on the Co layer, the spacer layer is discontinuous and an island structure is formed, shown in the inset of Fig. 2(c), where the heights of the island are around 2–3 nm. As a result, the two FM layers are still ferromagnetically coupled through pinholes in the Au, resulting in a correlated reversal of the bottom layer and top layer. However, at \( t = 10 \) and 20 nm, a three-step switching is observed. Compared to \( t = 10 \) nm, the \( t = 20 \) nm sample shows a lower field for the second step and the plateau between the second and the third switching events is greater.

Fig. 2(c) displays the derivative with respect to field for the loops with varied spacer layer thickness. Peaks 1 to 6 indicate the average switching fields \( H_1 \) to \( H_6 \) for the hysteresis loops as a function of \( t \). All the loops show a common third peak (high field peak) at \( H_{\text{SW}} = -600 \text{ Oe} \) which is insensitive to the Au thickness. This is attributed to the Co (hard) layer switching to a reverse onion state. For \( t = 0 \) and 2 nm, the only other
peak present occurs at $H_3 = -115$ Oe for $t = 0$ nm and at $H_2 = -125$ Oe for $t = 2$ nm. This is attributed to the onion-to-vortex transition for the coupled Ni$_{80}$Fe$_{20}$ and Co layers. For $t = 10$ and 20 nm, the first step occurs at $H_3 \approx H_4 = -35$ Oe, corresponding to the Ni$_{80}$Fe$_{20}$ layer reversal, and the middle step occurs at $H_5 = -230$ Oe for $t = 10$ nm, and $H_6 = -190$ Oe for $t = 20$ nm, corresponding to the start of reversal in the Co layer.

To understand the details of the switching behavior, minor loops were measured from positive saturation to a negative field of $-400$ or $-500$ Oe, then back to positive saturation, and the switching fields were found by differentiation of the loops. We also show the MOKE minor loops in the field range of $-350$ to $+350$ Oe in the insets of Fig. 3(a). For $t = 0$ nm and 2 nm, each minor loop descending from saturation shows one-step switching at a field $H_{34} = -115$ Oe and $H_{23} = -125$ Oe, corresponding to the onion-to-vortex transitions for the coupled top and bottom layers, the same process as in the major loops. The ascending loops show that the onion state is recreated at $+600$ Oe, again, the same as in the major loops. The field range of $+/-350$ Oe shows no hysteresis indicating reversible behavior: the rings stay in a reverse onion state. This data is consistent with strong coupling between the layers, such that the rings undergo an onion-vortex transition at $\sim 120$ Oe and a vortex-onion transition at $\sim 600$ Oe.

At $t = 10$ nm, an asymmetric two-step switching is observed in the minor loop. The switching fields $H_{34}$ and $H_{43}$ in the descending branch correspond to those of the major loop, and in the field range of $+/-350$ Oe, clear two-step switching is seen. We assume that the low-field step corresponds to the switching of the Ni$_{80}$Fe$_{20}$ layer, which is exchange-decoupled from the Co but magnetostatically coupled to it, promoting parallel alignment of the Co and Ni$_{80}$Fe$_{20}$ onion states. The second step represents partial reversal of the Co. It is possible that pinholes still enable some exchange coupling between the layers, which competes with the magnetostatic interactions that favor antiparallel alignment. At $t = 20$ nm, the steps are sharper and the switching processes occur more abruptly. We expect exchange coupling to be absent (suggested also by the lower coercivity of the Ni$_{80}$Fe$_{20}$ in the continuous film) and reversal is governed by magnetostatic effects. From its state at $-400$ Oe, the ring returns to positive saturation via a three step process, the first of which probably represents the Ni$_{80}$Fe$_{20}$ layer realigning antiparallel to the Co layer.

The effects of interlayer thickness on the switching behavior were also investigated by MFM which is primarily sensitive to the stray field from the top layer due to its proximity to the tip. The experiments were performed at remanence after saturating the samples along the long axis. Fig. 3(b)–(e) shows remanent MFM images of the elongated nanorings. For $t = 0$ nm, shown in Fig. 3(b), the rings appear as onion states in which the two walls (showing as black or white) may be on the same or opposite sides of the ring. Additionally, about 35% of the rings are in a vortex state at remanence, with little MFM contrast. The rings have a spread in switching field, and because the onion-vortex switching field is small, some of the rings have already switched into vortex states at zero field. Fig. 3(c) shows the remanent states for $t = 2$ nm. Most rings form onion states with misalignment of the walls away from the field axis, but vortex states were also observed in less than 20% of the rings. The results are in a very good agreement with the hysteresis loops for $t = 0$ nm and 2 nm, respectively. For $t = 10$ nm and 20 nm, the remanent states present onion states, shown in Fig. 3(d) and (e), without any vortex states. In all the samples, the domain walls are preferentially located at corners of the rings, as seen in single-layer rings studied earlier [17].

3-D micromagnetic simulations were performed for the elongated nanorings with varied spacer layer thickness.
Figs. 4(a)–(d) show the simulated M-H loops and magnetic configurations for a Co(20 nm)/Au(0.5 nm)/Ni80Fe20(10 nm) ring with $t = 0$ to 20 nm for a field applied along the long axis. Compared with Fig. 2(b), the simulated M-H loops have a good agreement with the corresponding experimental hysteresis loops. For the coupled ring at $t = 0$ nm, a two-step switching is observed in both experimental and simulated M-H loops, while in the other simulated cases, where exchange coupling is broken, three-step switching is seen. In the right column of Figs. 4(a)–(d), the simulated micromagnetic configurations are shown at various points on the simulated hysteresis loops.

For $t = 0$ nm, as the applied field is reduced from positive saturation to the field $H_A$, both Ni80Fe20 and Co layers form an onion state, shown in Fig. 4(a), just before the step. At higher field $H_B$, the layers form a vortex state, and after the second step, a reverse onion state. This is in excellent agreement with the experimental data, including the magnitudes of the switching fields. For $t = 10$–20 nm, a qualitatively different behavior is seen. The first, low-field step shows complete reversal of the Ni80Fe20 layer from onion to reverse onion state, without forming a vortex; the Co layer is unchanged. The second step corresponds to a partial reversal of the Co layer by domain wall motion (HC and H2). It is interesting to note that the Ni80Fe20 layer does not remain invariant, but instead the ring arrays," it is interesting to note that the figure also shows the reversal process of an isolated 20 nm Co layer.

The behavior for thick Co/Cu(6 nm)/NiFe (6 nm) elliptical rings reported previously [7]. These rings, which had thinner layers and a narrower ring width compared to the rings of the present study, also showed three-step switching over a range of geometries. In this case the first step corresponded to the onion-reverse onion switch of the NiFe layer (the transition occurs by propagation of reverse domains from the ends of the ring, without forming a vortex, due to the influence of magnetostatic interaction from the Co), and the second and third steps to the Co layer onion-vortex and vortex-reverse onion transitions. In the present study, the thicker magnetic layers increase the importance of interlayer magnetostatic coupling, and the wider ring makes nonuniform states easier to form, facilitating the anti-alignment of the Co and NiFe layers during the Co reversal, which did not happen in the previous work.

IV. SUMMARY

We describe the magnetization reversal processes in multi-layer elongated Ni80Fe20(10 nm)/Au(0.5)/Co(20 nm)/Si(001) nanorings as a function of the Au thickness $t$. For $t = 0$ and 2 nm, strong ferromagnetic coupling dominates the magnetic switching process and the two FM layers reverse together in a two-step switching corresponding to onion-to-vortex and vortex-to-reverse onion transition. For $t = 10$ nm and 20 nm, magnetostatic coupling between the two FM layers is significant. The hysteresis loops show a three-step switching in which the Ni80Fe20 layer reverses first, followed by two-step reversal of the Co. The Co reversal is accompanied by displacements of domain walls in the already-reversed Ni80Fe20, which tends to adopt a magnetization state that is antiparallel to that of the Co as a result of magnetostatic coupling.

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