MIT Open Access Articles

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

The MIT Faculty has made this article openly available. **Please share** how this access benefits you. Your story matters.

Citation: Adeyeye, A.O., C. Nam, and C.A. Ross, with Yang Ren. "Effects of Interlayer Coupling in Elongated $\text{Ni}_{80}\text{Fe}_{20}/\text{Au}/\text{Co}$ Nanorings." *Magnetics, IEEE Transactions On* 46.6 (2010) : 1906-1909. Copyright © 2010, IEEE

As Published: <http://dx.doi.org/10.1109/tmag.2009.2038799>

Publisher: Institute of Electrical and Electronics Engineers

Persistent URL: <http://hdl.handle.net/1721.1/62015>

Version: Final published version: final published article, as it appeared in a journal, conference proceedings, or other formally published context

Terms of Use: Article is made available in accordance with the publisher's policy and may be subject to US copyright law. Please refer to the publisher's site for terms of use.

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

Yang Ren^{1,2}, Adekunle Olusola Adeyeye¹, C. Nam³, and Caroline A. Ross³

¹Information Storage Materials Laboratory, Department of Electrical and Computer Engineering,
National University of Singapore, Singapore 117576, Singapore

²Singapore-MIT Alliance, Singapore 117576, Singapore

³Department of Materials Science & Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139

We describe the magnetization reversal processes in multilayer elongated $\text{Ni}_{80}\text{Fe}_{20}(10\text{ nm})/\text{Au}(t = 0\text{ to }20\text{ nm})/\text{Co}(20\text{ nm})/\text{Si}(001)$ nanorings. For a field applied in-plane along the long axis, the hysteresis loops display a two-step switching for both $t = 0\text{ nm}$ and 2 nm , and a three-step switching for $t = 10\text{ nm}$ 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 $\text{Ni}_{80}\text{Fe}_{20}$ layer switches first, then a two-step reversal of the Co, correlated with domain motion in the $\text{Ni}_{80}\text{Fe}_{20}$, 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/ $\text{Ni}_{80}\text{Fe}_{20}$, 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°)

domain walls [13]. In this work we systematically investigate the magnetization reversal processes in multilayer elongated $\text{Co}(20\text{ nm})/\text{Au}(t)/\text{Ni}_{80}\text{Fe}_{20}(10\text{ nm})$ 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 $\text{Ni}_{80}\text{Fe}_{20}$ 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]. $\text{Si}/\text{SiO}_2/\text{Co}(20\text{ nm})/\text{Au}(0 - 20\text{ nm})/\text{Ni}_{80}\text{Fe}_{20}(10\text{ nm})/\text{Au}(3\text{ nm})$ multilayers shown in Fig. 1(a) were deposited using electron beam evaporation at a rate of $0.2\text{ \AA/s}$. The pressure was maintained at $5 \times 10^{-8}\text{ Torr}$ 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 $w = 150\text{ nm}$, length $l = 1150\text{ nm}$, aspect ratio $R = 1.7$ along the long axis, and inter-ring spacing $s = 530\text{ nm}$. 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 $5\text{ }\mu\text{m}$. 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 $M_s(\text{NiFe}) = 860\text{ emu/cm}^3$ and

Manuscript received October 30, 2009; accepted December 09, 2009. Current version published May 19, 2010. Corresponding author: A. O. Adeyeye (e-mail: eleaao@nus.edu.sg).

Color versions of one or more of the figures in this paper are available online at <http://ieeexplore.ieee.org>.

Digital Object Identifier 10.1109/TMAG.2009.2038799

Fig. 1. (a) The trilayer structure of the elongated nanorings with varying spacer thickness (t), and (b) a SEM image of the elongated nanorings.

Fig. 2. Hysteresis loops for (a) the continuous films $\text{Ni}_{80}\text{Fe}_{20}(10 \text{ nm})/\text{Au}(t)/\text{Co}(20 \text{ nm})$ 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.

$M_s(\text{Co}) = 1.4 \times 10^3 \text{ emu/cm}^3$, exchange stiffness constant $A(\text{NiFe}) = 1.3 \times 10^{-6} \text{ erg/cm}$ and $A(\text{Co}) = 3 \times 10^{-6} \text{ erg/cm}$, damping parameter $\alpha \sim 0.5$. The anisotropy constant was set to zero to model polycrystalline Co. The size of the unit cell used is $10 \times 10 \times 2 \text{ nm}^3$ in the x, y, and z directions respectively, and the simulation used $5 \times 5 \times 20 \text{ nm}^3$ 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 $\text{Ni}_{80}\text{Fe}_{20}$ layer, and shows a decrease in coercivity as the Au layer thickness increases and the $\text{Ni}_{80}\text{Fe}_{20}$ and

Fig. 3. (a) Minor loops of the elongated $\text{Ni}_{80}\text{Fe}_{20}(10 \text{ nm})/\text{Au}(t)/\text{Co}(20 \text{ nm})$ nanorings with $t = 0 \text{ nm}$ to 20 nm for a field applied along the long axis of the rings, starting from positive saturation. The insets show the corresponding minor hysteresis loops for the field range of -350 Oe to $+350 \text{ Oe}$. (b)–(e) Remanent MFM images after saturation for the $\text{Ni}_{80}\text{Fe}_{20}(10 \text{ nm})/\text{Au}(t)/\text{Co}(20 \text{ nm})$ nanorings with (b) $t = 0 \text{ nm}$, (c) $t = 2 \text{ nm}$, (d) $t = 10 \text{ nm}$, (e) $t = 20 \text{ nm}$. Dashed lines indicate vortex-state rings.

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 $t = 0 \text{ nm}$, 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 $t = 10 \text{ nm}$, the $t = 20 \text{ nm}$ 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 $H_{sw} = -600 \text{ Oe}$ 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

Fig. 4. Simulated major hysteresis loops with magnetic configurations of the elongated $Ni_{80}Fe_{20}$ (10 nm)/Au(t)/Co(20 nm) nanorings for (a) $t = 0$ nm, (b) $t = 2$ nm, (c) $t = 10$ nm, (d) $t = 20$ nm, and (e) isolated Co nanoring (20 nm) shown at various fields. For each field, the Co (left) and $Ni_{80}Fe_{20}$ (right) layers are shown separately. The bottom row shows the reversal of an isolated Co ring.

peak present occurs at $H_1 = -115$ Oe for $t = 0$ 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 $H_5 = -295$ 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 $H_{s1} = -115$ Oe and $H_{s2} = -125$ 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 ~ 120 Oe and a vortex-onion transition at ~ 600 Oe.

At $t = 10$ nm, an asymmetric two-step switching is observed in the minor loop. The switching fields H_{s3} and H_{s4} 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 $\text{Co}(20\text{ nm})/\text{Au}(t)/\text{Ni}_{80}\text{Fe}_{20}(10\text{ nm})$ 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 $t = 0\text{ nm}$, 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 $t = 0\text{ nm}$, as the applied field is reduced from positive saturation to the field H_A , both $\text{Ni}_{80}\text{Fe}_{20}$ 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 $t = 10\text{--}20\text{ nm}$, a qualitatively different behavior is seen. The first, low-field step shows complete reversal of the $\text{Ni}_{80}\text{Fe}_{20}$ 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 (H_G and H_J). It is interesting to note that the $\text{Ni}_{80}\text{Fe}_{20}$ layer does not remain invariant, but instead the walls in its reverse-onion state are displaced. This has the result of making the $\text{Ni}_{80}\text{Fe}_{20}$ and Co layers aligned antiparallel, which is a result of the magnetostatic interaction between them. The third step corresponds to the formation of a reverse onion state in the Co, and the realignment of the reverse onion state in the $\text{Ni}_{80}\text{Fe}_{20}$, so that the ring is saturated. For comparison, the figure also shows the reversal process of an isolated 20 nm Co ring, which reverses conventionally via a vortex state [Fig. 4(e)].

The behavior for thick t may be compared to that of $\text{Co}(8\text{ nm})/\text{Cu}(6\text{ nm})/\text{NiFe}(6\text{ nm})$ 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 $\text{Ni}_{80}\text{Fe}_{20}(10\text{ nm})/\text{Au}(t)/\text{Co}(20\text{ nm})/\text{Si}(001)$ 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 $t = 10\text{ nm}$ and 20 nm , magnetostatic coupling between the two FM layers is significant. The hysteresis loops show a three-step switching in which the $\text{Ni}_{80}\text{Fe}_{20}$ 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 $\text{Ni}_{80}\text{Fe}_{20}$, which tends to adopt a magnetization state that is antiparallel to that of the Co as a result of magnetostatic coupling.

ACKNOWLEDGMENT

This work was supported by the Singapore-MIT Alliance.

REFERENCES

- [1] J. G. Zhu and Y. Zheng, "The micromagnetics of magnetoresistive random access memory," in *Spin Dynamics in Confined Magnetic Structures: I. Topics in Applied Physics*, B. Hillebrands and K. Ounadjela, Eds. Berlin: Springer, 2002, vol. 83, pp. 289–325.
- [2] M. M. Miller, G. A. Prinz, S. F. Cheng, and S. Bounnak, "Detection of a micron-sized magnetic sphere using a ring-shaped anisotropic magnetoresistance-based sensor: A model for a magnetoresistance-based biosensor," *Appl. Phys. Lett.*, vol. 81, pp. 2211–2213, 2002.
- [3] C. C. Chen, C. Y. Kuo, Y. C. Chang, C. C. Chang, L. Horng, T. Wu, G. Chern, C. Y. Huang, M. Tsuno, M. Takahashi, and J. C. Wu, "Size dependence of magnetization reversal of ring shaped magnetic tunnel junction," *J. Magn. Magn. Mater.*, vol. 310, pp. 1900–1902, 2007.
- [4] D. J. Smith, R. E. Dunin-Borkowski, M. R. McCartney, B. Kardynal, and M. R. Scheinfein, "Interlayer coupling within individual submicron magnetic elements," *J. Appl. Phys.*, vol. 87, pp. 7400–7404, 2000.
- [5] K. S. Buchanan, K. Y. Guslienko, A. Doran, A. Scholl, S. D. Bader, and V. Novosad, "Magnetic remanent states and magnetization reversal in patterned trilayer nanodots," *Phys. Rev. B*, vol. 72, p. 134415, 2005.
- [6] C. C. Chen, C. C. Chang, C. Y. Kuo, L. Horng, J. C. Wu, T. Wu, G. Chern, C. Y. Huang, M. Tsunoda, and M. Takahashi, "Fabrication and characterization of microstructured magnetic tunnel junction rings," *IEEE Trans. Magn.*, vol. 42, pp. 2766–2768, 2006.
- [7] F. J. Castaño, D. Morecroft, W. Jung, and C. A. Ross, "Spin-dependent scattering in multilayered magnetic rings," *Phys. Rev. Lett.*, vol. 95, p. 137201, 2005.
- [8] T. J. Hayward, T. A. Moore, D. H. Y. Tse, J. A. C. Bland, F. J. Castaño, and C. A. Ross, "Switching behavior of individual pseudo-spin-valve ring structures," *Phys. Rev. B*, vol. 72, p. 184430, 2005.
- [9] R. K. Dumas, K. Liu, C. P. Li, I. V. Roshchin, and I. K. Schuller, "The breakdown of the fingerprinting of vortices by hysteresis loops in circular multilayer ring arrays," *Appl. Phys. Lett.*, vol. 91, p. 202501, 2007.
- [10] T. Miyawaki, M. Kohda, A. Fujita, and J. Nitta, "Local Hall measurement of magnetization reversal and magnetic interaction in Fe/Au/Fe trilayer rings," *Phys. Stat. Sol. (C)*, vol. 5, no. 1, pp. 294–297, 2008.
- [11] J. G. Zhu, Y. F. Zheng, and G. A. Prinz, "Ultrahigh density vertical magnetoresistive random access memory," *J. Appl. Phys.*, vol. 87, pp. 6668–6673, 2000.
- [12] C. A. Ross, F. J. Castaño, W. Jung, B. G. Ng, I. A. Colin, and D. Morecroft, "Magnetism in multilayer thin film rings," *J. Phys. D: Appl. Phys.*, vol. 41, p. 113002, 2008.
- [13] C. A. F. Vaz, T. J. Hayward, J. Llandro, F. Schackert, D. Morecroft, J. A. C. Bland, M. Kläui, M. Laufenberg, D. Backes, U. Rudiger, F. J. Castaño, C. A. Ross, L. J. Heyderman, F. Nolting, A. Locatelli, G. Faini, S. Cherifi, and W. Wernsdorfer, "Ferromagnetic nanorings," *J. Phys. Condens. Mater.*, vol. 19, p. 255207, 2007.
- [14] N. Singh, S. Goolaup, and A. O. Adeyeye, "Fabrication of large area nanomagnets," *Nanotechnology*, vol. 15, pp. 1539–1544, 2004.
- [15] R. McMichael and M. Donahue [Online]. Available: <http://math.nist.gov/oommf>
- [16] A. O. Adeyeye, S. Goolaup, N. Singh, C. C. Wang, X. S. Gao, C. A. Ross, W. Jung, and F. J. Castaño, "Magnetostatic coupling in arrays of elongated $\text{Ni}_{80}\text{Fe}_{20}$ rings," *J. Phys. D: Appl. Phys.*, vol. 40, p. 6479, 2007.
- [17] J. Wang, A. O. Adeyeye, and N. Singh, "Magnetostatic interactions in mesoscopic $\text{Ni}_{80}\text{Fe}_{20}$ ring arrays," *Appl. Phys. Lett.*, vol. 87, p. 262508, 2005.