Control of vortex state in cobalt nanorings with domain wall pinning centers
Manohar Lal, S. Sakshath, Vineeth Mohanan Parakkat, and P. S. Anil Kumar

Citation: AIP Advances 8, 056023 (2018); doi: 10.1063/1.5007239
View online: https://doi.org/10.1063/1.5007239
View Table of Contents: http://aip.scitation.org/toc/adv/8/5
Published by the American Institute of Physics

Articles you may be interested in
Enhanced spin wave propagation in magnonic rings by bias field modulation
AIP Advances 8, 056006 (2018); 10.1063/1.5006576

Strain-mediated magnetic response in La_{0.67}Sr_{0.33}MnO_3/SrTiO_3/La_{0.67}Sr_{0.33}MnO_3/BaTiO_3 structure
AIP Advances 8, 055808 (2018); 10.1063/1.5006597

Enhanced magnetoelastic coupling in a composite multiferroic system via interposing a thin film polymer
AIP Advances 8, 055907 (2018); 10.1063/1.5007655

Ultrahigh density vertical magnetoresistive random access memory (invited)
Journal of Applied Physics 87, 6668 (2000); 10.1063/1.372805

Realization of zero-field skyrmions with high-density via electromagnetic manipulation in Pt/Co/Ta multilayers
Applied Physics Letters 111, 202403 (2017); 10.1063/1.5001322

Barrier breakdown mechanism in nano-scale perpendicular magnetic tunnel junctions with ultrathin MgO barrier
AIP Advances 8, 055908 (2018); 10.1063/1.5007656
Control of vortex state in cobalt nanorings with domain wall pinning centers

Manohar Lal,1 S. Sakshath,2,ª Vineeth Mohanan Parakkat,1 and P. S. Anil Kumar1

1Department of Physics, Indian Institute of Science, 560012 Bangalore, India
2Department of Physics, Technical University of Kaiserslautern, D-67663 Kaiserslautern, Germany

(Presented 8 November 2017; received 1 October 2017; accepted 27 October 2017; published online 2 January 2018)

Magnetic rings at the mesoscopic scale exhibit new spin configuration states and switching behavior, which can be controlled via geometrical structure, material composition and applied field. Vortex states in magnetic nanorings ensure flux closure, which is necessary for low stray fields in high packing density in memory devices. We performed magnetoresistance measurements on cobalt nanoring devices and show that by attaching nanowires to the ring, the vortex state can be stabilized. When a square pad is attached to the free end of the wire, the domain wall nucleation field in the nanowire is reduced. In addition, the vortex state persists over a larger range of magnetic fields, and exists at all in-plane orientations of the magnetic field. These experimental findings are well supported by our micromagnetic simulations. © 2017 Author(s).

I. INTRODUCTION

The study of the formation of the equilibrium magnetic states and magnetization reversal in thin films and miniaturized magnetic devices are of tremendous interest due to the potential applications in diverse areas such as magnetoelectronic devices and drug delivery systems etc.1–4 In mesoscopic sized devices, geometry plays an important role to control the magnetic properties such as dipolar interactions and anisotropy.4–6 Among various closed loop geometries viz. square, triangle and rings,7–11 mesoscopic rings are of particular interest due to its flux closure (vortex) state because it has minimal stray field. These states are predicted to be highly stable in nonvolatile high density storage devices that require controlled and reproducible transitions.12,13 The two chiralities (clockwise and counter-clockwise) of the states represent the memory bit. A direct transition between the two states requires a circular rotating magnetic field, which is complicated to generate.14 It would be simpler for device applications to switch through an intermediate “onion” state, which can be generated by a unidirectional magnetic field.15,16 However, suitable modifications are required to control the dynamics of domain walls (DWs) in mesoscopic ring devices to reproducibly induce the flux closure state and to stabilize it over a wide range of magnetic fields.5,9,17,18

In this article, we present our efforts to improve the stability of the vortex state. We fabricated two types of cobalt nanoring (NR) devices and study their switching behavior through magnetoresistance (MR) measurements. In type-1 devices the NR is attached with two nanowires (NWs) at diametrically opposite positions. In type-2 devices the NR is attached with one NW, whose other end is attached to a 5 µm x 5 µm square pad. This shows the effects of reduction of the magnetic field needed to nucleate a DW in the NW. In addition, the effect of changing the position of the DW in the ring on the stability of the vortex state in the devices is studied by varying the in-plane angle at which the

ªElectronic email: sakshaths@gmail.com
magnetic field is applied during the MR measurements. We explain the magnetic switching process in our experiments using micromagnetic simulations in the object oriented micromagnetic framework (OOMMF).

II. EXPERIMENTAL DETAILS

Cobalt NR devices were fabricated by e-beam lithography on commercial 500 nm SiO$_2$/Si(100) wafers using established procedures. Two types of devices were fabricated, whose SEM (scanning electron microscope) images are shown in Fig. 1: NR in contact with two NWs at diametrically opposite points (Type-1) and the NR attached with a NW, whose free end is attached with a 5 µm square pad (Type-2). The NRs and NWs consist of 20 nm thick Co films with a capping layer of 4 nm Pd. The NW and NR have same width of 80 nm. The inner diameter of the NR is 2 µm. Electrical contacts leads consisting of Au/Cr layers were made after a second level of lithography, followed by deposition and a lift-off process. The contact leads are labeled from 1 to 10 (Fig. 1).

In order to investigate the magnetic switching behavior of the devices, MR measurements were performed by synchronously monitoring the resistances between the various Au/Cr electrical contacts 1 and 10, while varying the strength (H) and in-plane orientation ($\phi$) of an external magnetic field. Each MR data set was averaged for 20 iterations to improve the signal to noise ratio. The resistance between contacts i and j is referred to henceforth as $R_{ij}$.

III. RESULTS AND DISCUSSIONS

A. Magnetoresistance of devices and analysis

The changes in the resistance (normalized) $R_{27}$ due to the corresponding changes in the magnetic domain configuration in the device type-2 during the process of magnetization reversal at $\phi$=0° are shown in the top panel of Fig. 2(a). It provides information about the changes of domain structure in the whole device. It can be seen that as the field is varied from +2.672 kOe to -2.672 kOe, the device goes through 5 distinct metastable states: $B_1 \rightarrow B_2 \rightarrow B_3 \rightarrow B_4 \rightarrow B_5$. State $B_1$ refers to the saturation of the moments in the direction of the magnetic field. As the field is decreased, at remanence, nearly all the magnetic moments align along arc of the ring and parallel to NW in the NW due to shape anisotropy. The current density $J$ and the magnetization $M$ vectors are nearly parallel to each-other at every site, except in the pad because complex domain patterns can appear in such big pads. Hence the resistance should be the highest close to remanence, as explained by the equation.

$$\rho_H (M, J, \varphi) = \rho_{\perp} + (\rho_{\parallel} - \rho_{\perp}) \cos^2 \varphi$$

(1)

where $\varphi$ is the angle between $M$ and $J$, $\rho_{\parallel}$ and $\rho_{\perp}$ are the resistivities at $\varphi$=0° and 90°, respectively.

The state $B_2$ corresponds to reversal of the square pad at the field -0.220 kOe, while the NW and NR are not reversed yet. Therefore, a DW is created at the junction of the pad and the NW. The presence of a DW between the electrical contacts is associated with a low resistance state, causing a reduction of resistance. As the field is reduced further, the DW depins and propagates until being pinned at the junction of NW and NR (state $B_3$ at -0.874 kOe). The NW is reversed during this process. At lower fields, one half of the ring reverses, leading to a vortex state and an increase
FIG. 2. Normalized MR and micromagnetic simulations data for the devices at $\phi=0^\circ$. (a) Upper panel: MR ($R_{27}$) for the type-2 device with the 5 states labelled as $B_1$, $B_2$, $B_3$, $B_4$, and $B_5$. Lower panel: MR ($R_{47}$) for the type-1 device showing 4 states labelled as $A_1$, $A_2$, $A_3$, and $A_4$. (b) Simulated hysteresis curve for the device type-2 showing the 5 states. (c) The simulated magnetic domain pattern for the type-2 device. The color and arrows indicate the direction of the local magnetic moments.

In resistance at state $B_4$ at -0.973 kOe. The vortex state persists until -1.364 kOe, when the reverse onion state $B_5$ is formed. In sweep-down/sweep-up field curves, the switching corresponding to the field 1.181/-1.181 kOe is not understood yet.

In comparison, the lower panel of Fig. 2(a) shows the MR measured through the resistance ($R_{47}$) for the device type-1 at $\phi=0^\circ$. In the process of reversal, it goes through four states $A_1 \rightarrow A_2 \rightarrow A_3 \rightarrow A_4$, which are the forward onion, DW pinned, vortex and reverse onion states respectively. The reversal of the type-1 devices and the formation of a vortex state in them is investigated in our earlier report. The presence of the square pad in type-2 devices allows for easy nucleation of DWs, causing a reduction in the magnitude of the fields needed to switch the device between the various states. The vortex state persists over a range of larger field 0.391 kOe in type-2 devices than in type-1 devices (0.315 kOe) because of 2 reasons that enable a transition into the vortex state at lower magnetic fields: (1) The DW nucleated in the pad gets injected into the NW at lower field, and (2) there is no DW pinning center at the ring opposite to junction of NW and NR, as compared to type-1 device.

B. Micromagnetic simulations

Micromagnetic simulations were performed to understand the microscopic domain configurations in the magnetization reversal process for the type-2 devices using the OOMMF software, which finds the minimal energy configuration by solving the Landau-Lifshitz-Gilbert equation. The saturation magnetization ($M_s=1.168x10^6$ A/m) and saturation field along hard axis ($H_s=48$ Oe) of the cobalt continuous film were obtained by SQUID (superconducting quantum interference device) magnetometry and MOKE (magnetic optical Kerr effect) measurement. The anisotropy parameter $K_{eff}=2.8x10^3$ J/m$^3$ was calculated using the formula $K_{eff}=(M_s x H_s)/2$. The exchange energy $A$ was assumed to be $3.3x10^{-11}$ J/m. In the simulation, the device geometry was the same as in the experiment, the devices were discretized into cell-size of 5x5x5 nm$^3$ and the $H$ was applied in-plane.

The simulated hysteresis curve for the type-2 device at $\phi=0^\circ$ is shown in Fig. 2(b). There are five metastable states $SB_1$, $SB_2$, $SB_3$, $SB_4$, and $SB_5$, as in the MR measurements. The magnetic domain configurations of these states are depicted in Fig. 2(c). Here, the arrows and color in the image indicate
the direction of the magnetic moments. SB\textsubscript{1} corresponds to the forward saturated onion state. As the strength of the field is reduced, the reversal process in the device begins at the pad with the nucleation of DWs (SB\textsubscript{2}), which get injected into the NW and propagates towards the NR until it is pinned at the junction of the NW and NR (SB\textsubscript{3}). Then, the DW at the opposite end of the NR is depinned easily because it has no pinning center, leading to the reversal of the first half of the ring and a vortex state (SB\textsubscript{4}). Subsequently, a definite energy is needed to move the DW/DWs out of the pinning site due to the presence of the NW. Therefore, the vortex state is stabilized and persists over a field rage of 0.800 kOe until the formation of reverse onion state (SB\textsubscript{5}) at -1.455 kOe. The magnetization states in device structures that are of mesoscopic size have a very strong dependence on the exchange energy and the dipolar fields, but a weak dependence on the crystalline anisotropy.\textsuperscript{22} Consequently, the deviations from ideal shapes can cause DW pinning at the junction of the wire and the ring, and to produce differences between the experiment and the simulations.

C. Angular dependence of magnetization reversal

In order to study the effect of nucleation of the DWs at different positions of the ring, the MR (R\textsubscript{47}) of the devices was measured along $\phi=0^\circ$, 45$^\circ$ and 90$^\circ$ (Fig. 3). The dataset corresponding to each angle is shifted for clarity. R\textsubscript{47} is affected by the domain changes of the NR and NW. At $\phi=45^\circ$, pad reverses at smaller field due to easy nucleation of DWs. Also, the switching fields corresponding to reversal of the NW and formation of vortex state, are increased as compared to $\phi=0^\circ$ because it is the component of the field along NW which injects the DW in the NW. At $\phi=90^\circ$, the reversal of NW occurs by coherent rotation of magnetic moments (i.e. without injection of DW) that results an increase in the switching field of the vortex state. As $\textbf{J} \perp \textbf{M}$ at every site in the NW, as predicted by equation (1), the change in resistance is larger at high fields when $\phi=90^\circ$ than at other angles. However, as the number of states remains the same at each $\phi$, we speculate that the rings always go through a vortex state.

To assist our interpretation of the data in Fig. 3(a) we performed micromagnetic simulations of the magnetization reversal at each $\phi$ for the devices. The hysteresis of the type-2 device corresponding to $\phi=0^\circ$, 45$^\circ$ and 90$^\circ$ are compared in Fig. 3(b). A total of 5 metastable states exist at $\phi=0^\circ$ and 45$^\circ$. The simulations indicate that the vortex state is stabilized irrespective of the orientation of the in-plane magnetic field. But the state persists over smaller range of fields as we move away from $\phi=0^\circ$, reaching a minimum at $\phi=90^\circ$. At $\phi=90^\circ$, the magnetic moments in NW align along its axis before the reversal of pad due to the high demagnetizing field.

IV. CONCLUSIONS

We fabricated two types of cobalt nanoring devices with width 80 nm: (i) symmetric devices, where the nanoring is attached to two nanowires at diametrically opposite positions, and (ii) asymmetric devices, where the nanoring is attached to a nanowire that is attached with a square pad. We studied their magnetization reversal encompassing metastable states experimentally using magnetoresistance measurements and numerically using micromagnetic simulations. In case of the nanoring attached
to a nanowire that is connected to a square pad, a vortex state was found to exist as a metastable state. The easy nucleation of multiple domain walls in the square pad reduces the switching field corresponding to reversal of the nanowire. The asymmetry of the device causes the vortex state to be induced at lower fields than in the symmetric device. By varying the in-plane orientation of the magnetic field, we studied the effect of variation of the position of the domain wall on the switching behavior of the devices and found that the vortex state could always be stabilized in the asymmetric devices.

SUPPLEMENTARY MATERIAL

See supplementary material for the complete angular dependent study of the magnetization reversal.

ACKNOWLEDGMENTS

We acknowledge the Nano Mission Council, Department of Science and Technology for funding and the National Nanofabrication Center, IISc for access to the clean room facility.

1. X. L. Liu, Y. Yang, C. T. Ng, L. Y. Zhao, Y. Zhang, B. H. Bay, H. M. Fan, and J. Ding, Adv. Matter. 27, 1939 (2015).
2. J. Vcelak, P. Ripka, and A. Zikmund, J. Supercond. Novel Magn. 28, 1077 (2015).
3. C. B. Muratov and V. V. Osipov, IEEE Trans. Magn. 45, 3207 (2009).
4. E. Tadmor, Y. J. Rosen, I. K. Schuller, and S. Bar-Ad, Journal of Applied Physics 112, 103903 (2012).
5. M. Lal, S. Sakshath, and P. S. Anil Kumar, IEEE Magn. Lett. 7, 2507505 (2016).
6. C. C. Wang, S. Jain, and A. O. Adeyeye, Journal of Applied Physics 102, 113902 (2007).
7. C. A. F. Vaz, J. J. Torres-Heredia, and E. Munoz-Sandoval, J. Magn. Magn. Mater. 294, e7–e12 (2005).
8. H. Y. Yian and X. R. Wang, Phy. Rev. B 92, 054419 (2015).
9. M. Kläui, C. A. F. Vaz, L. J. Heyderman, U. Rudiger, and J. A. C. Bland, J. Magn. Magn Mater. 290, 61 (2005).
10. A. Imre, E. Varga, B. Ilic, V. Metlushko, G. Csaba, and A. Orlov, IEEE Trans. Magn. 42, 3641 (2006).
11. J.-G. Zhu, Y. Zheng, and G. A. Prinz, J. Appl. Phys. 87, 6668 (2000).
12. A. Imre, L. Zhou, A. Orlov, G. Csaba, G. H. Bernstein, W. Porod, and V. Metlushko, “Application of mesoscopic magnetic rings for logic devices,” Fourth IEEE Conference on Nanotechnology, Munich, Germany (IEEE, Piscataway, NJ, 2004), pp. 137–139.
13. M. Kläui, J. Phys.:Condens.Matter 20, 313001 (2008).
14. M. A. Mawass, K. Richter, A. Bissig, R. M. Reeve, B. Krüger, M. Weigand, H. Stoll, A. Krone, F. Kronast, G. Schütz, and M. Kläui, Phys. Rev. Applied 7, 044009 (2017).
15. K. Richter, A. Krone, M.-A. Mawass, B. Krüger, M. Weigand, H. Stoll, G. Schütz, and M. Kläui, Phys. Rev. B 94, 024435 (2016).
16. T. Manohar, S. Sakshath, D. Venkateswarlu, and P. S. Anil Kumar, https://doi.org/10.1016/j.jmmm.2017.06.097, “Control of stable magnetization states in permalloy nanorings using magnetic nanowires,” J. Magn. Magn. Matr. (2017) (in press).
17. M. Kläui, C. A. F. Vaz, J. A. C. Bland, W. Wernsdorfer, G. Faini, E. Cambril, L. J. Heyderman, F. Nolting, and U. Rudiger, Phys. Rev. Lett. 94, 106601 (2005).
18. M. J. Donahue and D. G. Porter (1999), OOMMF User’s Guide, Version 1.1, Interagency Report NISTIR 6376, National Institute of Standards and Technology, Gaithersburg, MD.
19. M. F. Lai, Z. H. Wei, C. R. Chang, and J. C. Wu, Phy. Rev. B 67, 104419-1 (2003).
20. M. Kläui, C. A. F. Vaz, L. Lopez-Diaz, and J. A. C. Bland, J. Phys. Condens. Matter 15, R985 (2003).
21. T. J. Hayward, Sci. Rep. 5, 13729-1 (2015).