Vertical stack of Co nanorings with current-perpendicular-to-plane giant magnetoresistance: Experiment and micromagnetic simulation

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Vertical stacks of two Co rings with deep submicron lateral sizes and different thicknesses are fabricated and studied. The experimental results suggest the existence of a metastable domain wall structure revealed by the micromagnetics simulation. The technologically important vortex-vortex switching is found dominated by the annular Oersted field of perpendicularly injected dc, but also significantly affected by the spin-transfer torque. The efficiency of the spin-transfer torque and the switching process are discussed.

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Because of both the interesting physics at reduced dimensions and the possible industrial applications, nanomagnets have attracted considerable attention in recent years.[1–3] Extensive studies have been carried out on nanomagnets such as magnetic disks, wires, bars, and rings. Among them, the magnetic nanoring is particularly interesting with the very simple and well-defined magnetic states due to their high symmetry, i.e., the flux-closure "vortex" state and the bidomain "onion" state.[4–7] It is not only well suited for the investigation of fundamental magnetic properties, such as nucleation, movement, and annihilation of domain walls, but also superior in the application because the flux-closure vortex state could prevent the interaction between very close elements.

The magnetic states and switching in rings from submicron to micron scales have been intensively investigated in recent years.[5–9] However, there are only few reports on the vertical stack of rings,[10,11] especially in the current-perpendicular-to-plane (CPP) configuration.[11] The unique advantages of the CPP configuration are as follows. The technologically important vortex state as well as the vortex-to-vortex switching can be effectively realized with the annular Oersted field produced by the dc passing through the structure perpendicularly and detected with the giant magnetoresistance (GMR) effect. In addition, the CPP-GMR measurement is suitable for a magnetic ring as small as deep submicron size, which is required by applications such as data storage and may present magnetic configurations different from those appearing in larger rings. A vertical stack of many CoFe rings in the CPP configuration has recently been experimentally demonstrated with the lateral size of about 600 nm,[11] where the current-induced magnetization switching is observed and attributed to the Oersted field.

We have also fabricated similar vertical stacks, but comprising only a thick Co ring and a thin Co ring,[12] in much smaller sizes. In such a structure, the spin-transfer torque is also expected to play a role in the switching, as evidenced in the elliptical magnetic nanopillar.[13–19] The stacks are fabricated from a magnetic multilayer (bottom) Cu(40 nm)/Co2(3 nm)/Cu(10 nm)/Co1(10 nm)/Au(10 nm) (top), in which the Co2(3 nm)/Cu(10 nm)/Co1(10 nm)/Au(10 nm) layers are patterned into rings with outer (inner) diameters of 290 nm (90 nm) and 350 nm (120 nm). The schematic structure as well as the scanning electron microscopy (SEM) image of one stack are shown in Fig. 1. The fabrication process is similar to that for an elliptical nanopillar.[20] A ring-shaped metal mask is first fabricated with electron beam lithography and lift-off process. Then the pattern is transferred into the multilayer with Ar ion milling. The resistance is measured with a small ac and the lock-in technique at room temperature. The electrical current flowing from the bottom to the top is defined as positive, as depicted in Fig. 1.

In previous studies on magnetic rings, the uniform external field has been utilized to switch the magnetic states. However, the uniform field is not very effective to induce the annular magnetic vortex state as well as the transition between the vortex states, which in contrast should be easily realized in the CPP configuration with the annular Oersted field produced by a perpendicularly injected dc. The procedure to create the vortex state in our stacks is as follows. A large external field of 2 kOe is first applied to induce the onion state and hence the domain walls in the rings. Then a dc of 50 (−50) mA is injected to produce the annular Oersted field, followed by the removal of the external field. The annular Oersted field is estimated to be 320 Oe in the middle of the ring. The vortex states are thus supposed to be induced by the annular Oersted field in the rings through domain wall motion. Finally, the dc is also removed. The final state after such a procedure is hereafter called the A (A') state, expected to be two parallel (P) magnetic vortices with the same chirality in Co1 and Co2 rings, respectively (hereafter denoted as parallel vortex-vortex configuration). The chirality of the magnetic vortex is decided by the annular Oersted field; therefore A and A' states should have opposite chiralities.

The parallel vortex-vortex configuration is experimentally confirmed in both A and A' states for all the samples by

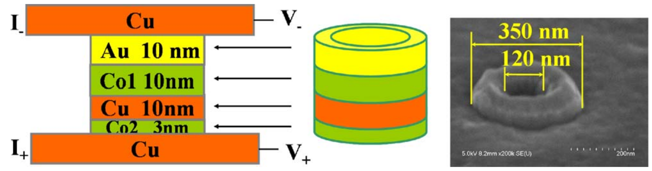

FIG. 1. (Color online) Schematic structure and SEM image for the vertical stack of Co rings.

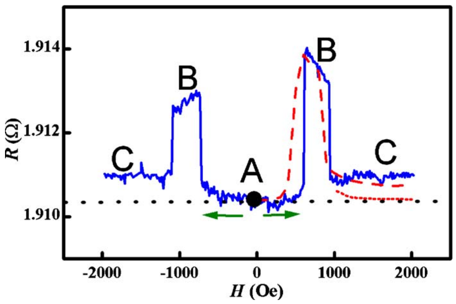

FIG. 2. (Color online) Resistance evolution with external field for the parallel vortex-vortex state of a sample with outer (inner) diameter of 350 nm (120 nm). The blue solid line is the experimental result while the red dashed line is the simulation result. The dotted black line indicates the resistance level of the *A* state. The red short dotted line is the simulation result obtained by intentionally presetting both rings in the "normal" onion states.

measuring their resistance evolutions with the external field. Plotted in Fig. 2 is the result for the *A* state of a stack with the outer (inner) diameter of 350 nm (120 nm). As the external field is increased in both directions, the resistance rises first at about 600 Oe and then falls again at about 1000 Oe. Such a resistance dependence on the external field is also observed for other samples with both sizes. This result can only be explained with the parallel vortex-vortex state. As illustrated in Fig. 3, increasing the external field in either direction first transforms the magnetic vortex into the bidomain magnetic onion in one of the two rings, leading to the *B* state with increased resistance because of the deviation from the parallel magnetic configuration. With further increasing the field, the rest of the magnetic vortex is also broken into the magnetic onion, resulting in the *C* state. Because the two magnetic onions are parallel to each other in the *C* state, the resistance is reduced again.

A and *C* states are expected to have the same resistance because of the parallel magnetic configurations. However, it is noticed that in Fig. 2 the resistance of the *C* state is slightly higher than that of the *A* state. Such a resistance difference is also observed for other samples.

To explain this anomalous resistance difference, a three-dimensional micromagnetic simulation was performed with OOMMF software[21] using $3\times3\times3$ nm^3 cells. Based on the simulation results, the resistance is estimated and also shown in Fig. 2. The simulated resistance curve agrees roughly with the measured resistance curve. The higher resistance of *C* state is also reproduced in the simulated curve.

To find what causes the higher resistance of the *C* state, the magnetic configurations in Co1 and Co2 rings are drawn

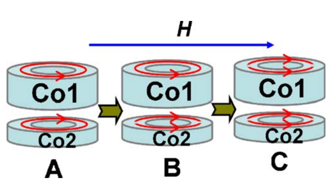

FIG. 3. (Color online) The schematic evolution of magnetic configuration with external field for the parallel vortex-vortex state.

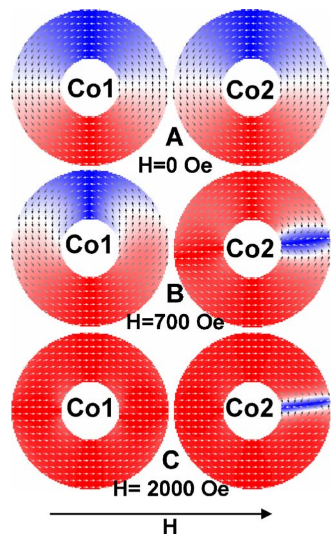

FIG. 4. (Color online) The simulated magnetic configurations for the *A*, *B*, and *C* states shown in Fig. 2.

in Fig. 4 for *A*, *B*, and *C* states. In the *A* state, both rings are in the vortex configuration. The transition from *A* to *B* is finished by the vortex-to-onion switching in the Co2 ring. Remarkably, the spins in the head-to-head domain wall in the Co2 ring in the *B* state are opposite to the external field. Usually, the spins in the domain walls in a normal onion state are aligned with the external field. This abnormal onion configuration remains in the *C* state. The magnetic vortex in Co1 ring is broken into a normal onion state with further increasing external field, leading to the switching from *B* to *C* states. Thus, the different domain wall structures in the two Co rings lead to the increased resistance in the *C* state.

As a comparison, the simulated resistance dependence on the external field obtained by intentionally presetting both Co rings in the normal onion states is also plotted in Fig. 2, showing that the difference between the two normal onion states is not large enough to result in an observable resistance difference between *A* and *C* states.

The abnormal domain wall structure in Fig. 4 is energetically unfavorable because of not only the increased external field energy but also the increased exchange energy due to the increased angle between neighboring spins in the domain wall. Thus, it is a metastable state. It should be pointed out that the formation of this abnormal domain wall structure is not affected by the Co1 ring, though magnetic interaction is reported between the two rings in the vertical stack.[10] When this metastable state is formed, the Co1 ring is still in the vortex configuration with very small stray field and thus unlikely to affect the Co2 ring. In fact, with only the Co2 ring, this metastable state still appears in the simulation.

The simulation results explain the experimentally observed resistance difference between *C* and *A* states, suggesting the existence of a metastable domain wall structure. Such a structure is not observed in rings with larger size, presenting only vortex and normal onion configurations. Another metastable domain wall structure, a 360° domain wall, has also been reported in deep submicron sized rings.[22] It seems that small rings have more complicated magnetic structures,

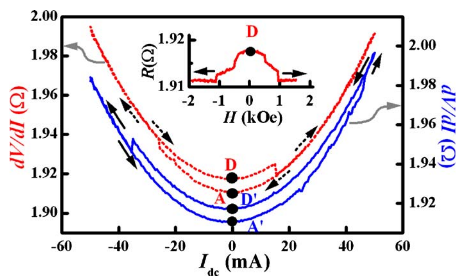

FIG. 5. (Color online) Current-induced magnetization switching for the same sample in Fig. 2. The inset is the resistance dependence on the external field for the D state.

in addition to the normal vortex and onion states.

The annular Oersted field produced by the dc passing through the structure perpendicularly is employed to switch the vortex states in the rings. The differential resistance dV/dI dependences on the dc I_{dc} are shown in Fig. 5, where A is switched to D and A' is switched to D' by the dc in the absence of an external field. The inset in Fig. 5 is the resistance dependence on the external field for the D state. Similar to the discussions on Figs. 2 and 3, D can be deduced to be an antiparallel (AP) vortex-vortex state. The same conclusion is also obtained for the D' state. According to a previous theoretical calculation,[23] the thinner Co ring is easier to be switched by the annular Oersted field. Thus, the two resistance transitions appearing in each loop indicate the reversal of the magnetic vortex in the Co2 ring. On the other hand, the vortex state in the Co1 ring is not reversed by the 50 mA current; otherwise symmetric loops should be observed. The $A\Delta R$ value is about 500 nm^2 Ω, the same level as our previous elliptical nanopillars.[20] Notable is that the two dV/dI loops present opposite switching directions and much different switching currents. The opposite switching directions are caused by the opposite chiralities in A and A', requiring the opposite annular field to switch to the AP states by reversing the magnetic vortex in the Co2 ring. The difference in the switching currents should be explained with the spin-transfer torque. As indicated in Fig. 6, in the A-D switching, both the

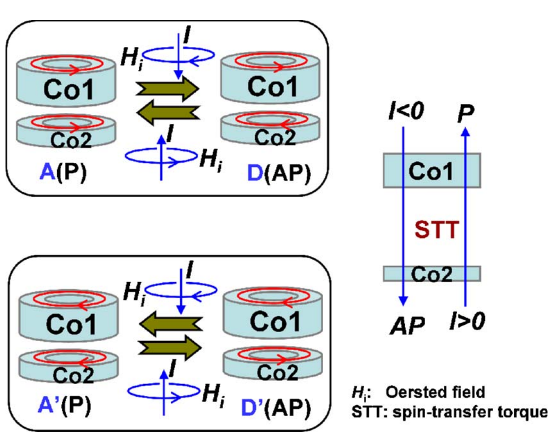

FIG. 6. (Color online) The roles of Oersted field and spin-transfer torque in the current-induced magnetization switching.

spin-transfer torque and the Oersted field reverse the magnetization of the Co2 ring. On the contrary, the spin-transfer torque and the Oersted field always conflict with each other in the A'-D' switching. Therefore, the switching currents for the A-D switching are much smaller than those for the A'-D' switching. The switching directions indicate that the Oersted field is dominant over the spin-transfer torque. The averaged switching current is $I_S^{A\text{-}D}=20.5$ mA for the A-D switching and $I_S^{A'\text{-}D'}=40.8$ mA for the A'-D' switching. If we denote the contributions of the Oersted field and the spin-transfer torque produced by unit dc as α and β, respectively, we have $(\alpha+\beta)I_S^{A\text{-}D}=(\alpha-\beta)I_S^{A'\text{-}D'}$, and hence $\alpha\approx 3\beta$, implying that the effect of the Oersted field is about three times as large as that of the spin-transfer torque. This is in contrast to the spin-transfer torque-dominated switching in an elliptical magnetic nanopillar as small as 100–200 nm.[13] The reason may be that in the magnetic vortex, the Oersted field is collinear with the magnetization and thus very effective in the switching. If we denote the switching currents caused by purely the Oersted field and purely the spin-transfer torque as I_S^O and I_S^S, respectively, we have $\alpha I_S^O=\beta I_S^S=(\alpha+\beta)I_S^{A\text{-}D}$. Therefore, $I_S^S=4I_S^{A\text{-}D}=82$ mA and $I_S^O=I_S^S/3=27.3$ mA. This roughly estimated I_S^S corresponds to a switching current density of 1.0×10^8 A/cm^2, not much different from that to switch the elliptical nanopillars.[20] This is interesting because the switching modes are totally different. The nanopillar is usually regarded as a macrospin and switched by the spin-transfer torque through uniform precession.[13] On the contrary, the magnetization of the magnetic vortex is not uniform and hence cannot be regarded as a macrospin. Therefore, the uniform precession in the elliptical nanopillar is not expected in the ring. The switching of the magnetic vortex should proceed through nucleation followed by the domain wall motion. It seems that different switching mode does not lead to different switching current density.

The current-induced magnetization switching in the vertical stack of rings is a complicated process. Besides the nonuniform annular magnetization, the Oersted field also varies along the radial direction, written as $H_i=(I/2\pi r)(r^2-r_{in}^2)/(r_{out}^2-r_{in}^2)$, where r is the distance to the center of the ring, and r_{in} and r_{out} are the inner and outer radii, respectively. In addition, the spin-transfer torque also plays a role in the switching. The spin-transfer torque possibly helps the nucleation and the domain wall motion by twisting the magnetization.

A previous theoretical report[24] claims that the effect of the Oersted field is about 10^4 times as large as that of the spin-transfer torque in a vertical stack of two magnetic rings and thus the spin-transfer torque is negligible. However, our experimental results show that the spin-transfer torque is significant. The effect of the spin torque is not observed in a previous experimental report[11] on a much larger stack including many CoFe rings. The reason may be the large size as well as that too many interfaces may cancel the spin-transfer torque.[25]

In conclusion, in the deep submicron-sized CPP-GMR nanopillar with ring shape, a special domain wall structure may exist with spins opposite to the external field. The vortex state can be created and switched by both the Oersted field and the spin-transfer torque. The effect of the spin-transfer torque is estimated to be about one-third of the effect of the Oersted field. It is also estimated that the efficiency of the spin-transfer torque does not vary much between the switching of a ring and the switching of a nanopillar.

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[1] C. Stamm, F. Marty, A. Vaterlaus, V. Weich, S. Egger, U. Maier, U. Ramsperger, H. Fuhrmann, and D. Pescia, Science **282**, 449 (1998).
[2] S. A. Wolf, D. D. Awschalom, R. A. Buhrman, J. M. Daughton, S. von Molnár, M. L. Roukes, A. Y. Chtchelkanova, and D. M. Treger, Science **294**, 1488 (2001).
[3] R. P. Cowburn and M. E. Welland, Science **287**, 1466 (2000).
[4] J. G. Zhu, Y. Zheng, and G. A. Prinz, J. Appl. Phys. **87**, 6668 (2000).
[5] J. Rothman, M. Klaui, L. Lopez-Diaz, C. A. F. Vaz, A. Bleloch, J. A. C. Bland, Z. Cui, and R. Speaks, Phys. Rev. Lett. **86**, 1098 (2001).
[6] S. P. Li, D. Peyrade, M. Natali, A. Lebib, Y. Chen, U. Ebels, L. D. Buda, and K. Ounadjela, Phys. Rev. Lett. **86**, 1102 (2001).
[7] M. Kläui, C. A. F. Vaz, J. A. C. Bland, W. Wernsdorfer, G. Faini, and E. Cambril, Appl. Phys. Lett. **81**, 108 (2002).
[8] M. Kläui, C. A. F. Vaz, L. Lopez-Diaz, and J. A. C. Bland, J. Phys.: Condens. Matter **15**, 985(R) (2003).
[9] M. Kläui, C. A. F. Vaz, J. A. C. Bland, T. L. Monchesky, J. Unguris, E. Bauer, S. Cherifi, S. Heun, A. Locatelli, L. J. Heyderman, and Z. Cui, Phys. Rev. B **68**, 134426 (2003).
[10] F. J. Castaño, D. Morecroft, W. Jung, and C. A. Ross, Phys. Rev. Lett. **95**, 137201 (2005).
[11] M. T. Moneck and J. G. Zhu, J. Appl. Phys. **99**, 08H709 (2006).
[12] T. Yang, A. Hirohata, M. Hara, T. Kimura, and Y. Otani, Appl. Phys. Lett. **90**, 092505 (2007).
[13] J. C. Slonczewski, J. Magn. Magn. Mater. **159**, L1 (1996).
[14] L. Berger, Phys. Rev. B **54**, 9353 (1996).
[15] M. Tsoi, A. G. M. Jansen, J. Bass, W.-C. Chiang, M. Seck, V. Tsoi, and P. Wyder, Phys. Rev. Lett. **80**, 4281 (1998).
[16] J. A. Katine, F. J. Albert, R. A. Buhrman, E. B. Myers, and D. C. Ralph, Phys. Rev. Lett. **84**, 3149 (2000).
[17] Y. Jiang, S. Abe, T. Ochiai, T. Nozaki, A. Hirohata, N. Tezuka, and K. Inomata, Phys. Rev. Lett. **92**, 167204 (2004).
[18] Z. Q. Lu, Y. Zhou, Y. Q. Du, R. Moate, D. Wilton, G. H. Pan, Y. F. Chen, and Z. Cui, Appl. Phys. Lett. **88**, 142507 (2006).
[19] M. Laufenberg, W. Bührer, D. Bedau, P.-E. Melchy, M. Kläui, L. Vila, G. Faini, C. A. F. Vaz, J. A. C. Bland, and U. Rüdiger, Phys. Rev. Lett. **97**, 046602 (2006).
[20] T. Yang, A. Hirohata, T. Kimura, and Y. Otani, J. Appl. Phys. **99**, 073708 (2006).
[21] http://math.nist.gov/oommf/
[22] F. J. Castaño, C. A. Ross, C. Frandsen, A. Eilez, D. Gil, H. I. Smith, M. Redjdal, and F. B. Humphrey, Phys. Rev. B **67**, 184425 (2003).
[23] M. Maicas, Physica B **343**, 247 (2004).
[24] J. Guo and M. B. Jalil, IEEE Trans. Magn. **40**, 2122 (2004).
[25] L. Berger, IEEE Trans. Magn. **34**, 3837 (1997).