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Chirality control of magnetic vortex in a square Py dot using current-induced Oersted field

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We have proposed a method for controlling the vortex chirality in a squared permalloy dot by using the circular Oersted field locally induced by flowing a DC current across a small Py/Cu junctions. The reliability of the chirality control has been evaluated by measuring the nonlocal spin valve signal. The desired vortex chirality has been obtained when the injecting DC current has a moderate magnitude. However, the large DC current is found to reduce the control reliability. Another possibility for controlling the vortex structure using the large DC current injection was also discussed. © 2011 American Institute of Physics. [doi:10.1063/1.3669410]

Efficient and reliable control of patterned magnetic nanostructures is key issues in recent years owing to their potential applications for ultra-high-density magnetic storage and spin-based electronic devices. Particularly, a magnetic vortex structure stabilized in a micron- or submicron-sized ferromagnetic structure has been gathering attention recently because of their high potentialities such as negligible magnetostatic interaction and high thermal stability.[1,2] Moreover, their static and dynamic magnetic properties can be tuned by adjusting the dot shape, its aspect ratio, and inter dot distance.[3–5] These flexibilities lead to a wide range of applications such as microwave filter and cancer cell destruction.[6]

A magnetic vortex structure can be characterized by an in-plane (chirality) and an out-of-plane (polarity) magnetizations. The vortex polarity (up and down) corresponds to the direction of the core magnetization and is simply manipulated by applying the external perpendicular magnetic field.[7] However, this method has limitations of the writing speed as well as the dot density. Recently, the core polarity was found to be reversed by injecting ac electric current in association with the resonant gyroscopic motion of the core induced by the spin-transfer torque[8,9] or locally generated Oersted field.[10,11] Such an electrical manipulation is very attractive means for the advances in ultra-high density spin devices with high speed operations. The vortex chirality (clockwise (CW) and counter clockwise (CCW)) is the whirling direction of the magnetization and can be controlled by an asymmetric nucleation energy of the magnetic vortex from the uniformly magnetized state in asymmetric shaped ferromagnetic dots such as D-shaped ferromagnetic disk[12] and odd-sided regular polygonal nanomagnet.[13] However, such methods cannot be applied for the symmetrical shaped ferromagnetic dots such as circular and square dot. Although a circular Oersted field created by a current perpendicular to the dot can reverse the vortex chirality in the symmetric dot, a large amount of the current with the magnitude of 50 mA is required even in a 300-nm-diameter circular dot.[14] Moreover, complicated nanofabrications are required for producing the vertically flowing current with a uniform current density. Here, we demonstrate that an efficient manipulation of the vortex chirality in a squared Py dot using a local current injection.

Figure 1(a) shows the conceptual image of our proposed method for controlling the vortex chirality in a square ferromagnetic metal (FM) dot. In the FM dot, the magnetization reversal proceeds through the nucleation, displacement, and annihilation of the vortex. When the magnetic field is applied along the horizontal direction, the vortex nucleates from the lower edge for the CW or the top edge for the CCW.[15] Thus, the nucleation side of the vortex depends on the chirality. Note that these two nucleation processes occur with the same probability because of no energy difference between two processes. To break the energy symmetry, we introduce the local magnetic field. The wide and narrow nonmagnetic metal (NM) electrodes are, respectively, connected to the upper and lower edges of the FM dot. When the dc current is injected into the FM dot from the upper electrode and extracted from the lower one, the circular Oersted fields, which facilitate the vortex nucleation, are induced in the vicinities of the FM/NM junctions. Although these two Oersted fields mutually assist the vortex nucleation with the opposite chirality, the influence of the Oersted field by the lower electrode is stronger than that by the upper electrode. Therefore, as shown in Fig. 1(a), when the magnetic field is swept from negative to positive (upward field sweep), the vortex with the CCW chirality is formed. On the other hand, when the magnetic field is swept from positive to negative (downward field sweep), the vortex formation with the CW chirality is prevented by the Oersted field. As a result, the vortex with CCW chirality is formed also in the downward

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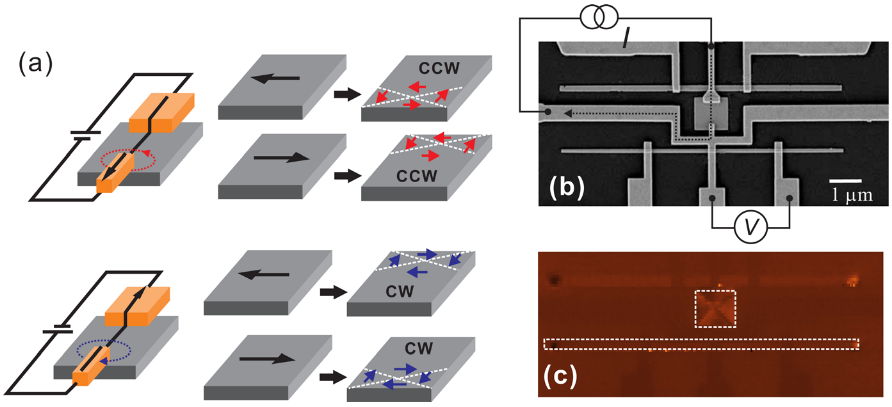

FIG. 1. (Color online) (a) Conceptual images for the chirality control in a square-shaped nanomagnet using a DC current injection. (b) SEM image of the fabricated device for controlling the vortex chirality together with the probe configuration for the nonlocal spin valve measurement. (c) MFM image of the fabricated lateral spin valve.

sweep. Vice versa, when the polarity of the dc current is changed, the vortex with opposite chirality is formed in each field sweep. In this way, we can control the vortex chirality by the local current injection combined with the in-plane field application.

To confirm the above idea, we prepared a lateral spin valve consisting of a permalloy (Py) square dot and a Py wire bridged by a cross-shaped Cu wire, as shown in Fig. 1(b). The dimension of the Py square dot is 1 μm in wide and 40 nm in thickness. The Py dot and wire were deposited by the e-gun evaporation with the base pressure of 5×10^{-9} Torr. The Cu wire was deposited by the Joule evaporation with the base pressure of 2×10^{-8} Torr. As in Fig. 1(c)), a Magnetic force microscope (MFM) image of the prepared device reveals that a single vortex is stabilized in the square Py dot. In the present device, the circular Oersted field for controlling the chirality can be generated by flowing the dc current across the Py/Cu junction. Here, we define the polarity of the dc current as follows. When the current flows from the upper (lower) to the lower (upper) electrodes, the polarity of the current is positive (negative). The formed chirality of the magnetic vortex can be detected by measuring the nonlocal spin valve signal with the probe configuration shown in Fig. 1(b),[16] where the nonlocal spin valve signals were measured by a standard current-bias ac lock-in technique. The nonlocal spin signal reflects the relative angle θ between the Py wire and the local magnetization in the Py dot beneath the injecting probe. When θ is 0 corresponding to the parallel configuration, the spin signal takes a maximum value. The signal becomes minimum at $\theta = \pi$ corresponding to the anti-parallel configuration. Therefore, when the vortex nucleates from the lower edge, the spin signal takes a minimum value before reversing the direction of the magnetic field. When the vortex nucleates from the opposite side, the spin signal takes a minimum value after reversing the direction of the magnetic field. Since the vortex chirality was determined from the nucleation position of the vortex, one can simply distinguish the chirality from the nonlocal spin valve measurement as schematically shown in Figs. 2(a) and 2(b). The vortex chirality in a micron- or submicron-sized individual ferromagnetic dot can be detected by other recently developed techniques such as Lorentz microscope,[12] micro magneto-optical Kerr effect,[1,17] anisotropic magnetoresistance measurements with NM,[18] and superconducting electrodes.[19] However, the nonlocal electrical detection utilized here is the most suitable technique for demonstrating the present chirality control because the device structure for the chirality control can be easily expanded to a lateral spin valve geometry.

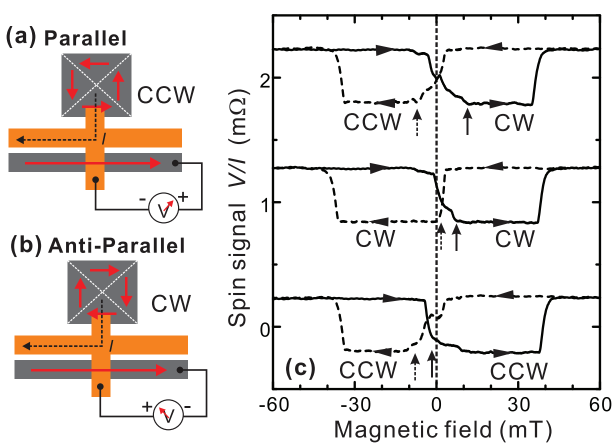

FIG. 2. (Color online) Schematic illustrations for nonlocal spin valve measurements together with the magnetization configurations at the remanent states for (a) CCW and (b) CW chiralities in the downward field sweep. (c) Three different kinds of nonlocal spin valve signals without the dc current injection. Each arrow indicates the field position where the spin signal becomes the minimum value. The solid and dotted lines correspond to the upward and downward field sweeps, respectively.

First, we measure the nonlocal spin valve signal loops without the dc current injection. Figure 2(c) shows the representatives of three different types of the signals. All signals exhibit clear spin valve effects, assuring that the spin current injected from the Py dot reaches to the Py wire. Here, the negative resistance changes in the low magnetic field ($|B| < 20$ mT) correspond to the magnetization reversal process of the Py dot under the Py/Cu junction. The positive resistance change at the field around 35 mT was due to the magnetization switching of the Py wire. These facts were confirmed by the anisotropic magnetoresistance measurements for the Py dot and wire. The spin signal change due to the magnetization reversal of the Py dot ($|B| < 20$ mT) shows the different field dependence for each measurement, meaning that the chirality of the vortex is not reproduced in each measurement. From the above considerations, we can easily determine the vortex chirality for each curve as in Fig. 2(c). Thus, when the dc current does not flow in the dot, the chirality of the Py dot randomly distributes. This is consistent with our previous study based on MFM analysis.[13]

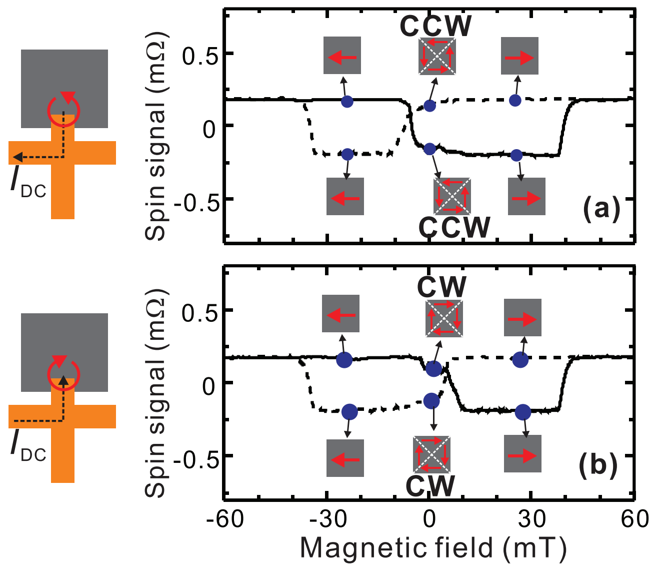

FIG. 3. (Color online) Nonlocal spin valve signals with (a) the positive DC current (+5 mA) and (b) the negative DC current (−5 mA) injections. The insets show the vortex chirality of the square dot at each field position expected from the spin signal. The solid and dotted lines correspond to the upward and downward field sweeps, respectively.

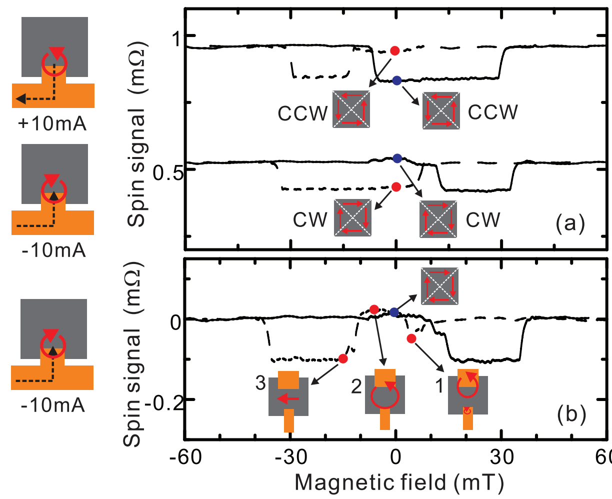

FIG. 4. (Color online) (a) Ordinary nonlocal spin valve signals for the DC currents ±10 mA together with the expected chiralities of the squared dot. (b) Unusual nonlocal spin valve signal for −10 mA together with the domain structures expected from the nonlocal spin signal. The solid and dotted lines correspond to the upward and downward field sweeps, respectively.

Then, we measured the nonlocal spin valve signal with the dc current injection. Figures 3(a) and 3(b) show nonlocal spin valve signal loops with the positive and negative dc current injections, respectively. Here, the magnitude of the injecting dc current is 5 mA. Since the overall resistance change is almost same as those in Fig. 2, we can neglect the influence of the Joule heating due to the DC current on the spin accumulation. According to our explanations described above, when the positive current is injected, the Py dot favors to form the vortex with CW chirality both in the upward and downward sweeps. On the other hand, when the negative current is injected, the CCW chirality is preferably formed both in the upward and downward sweeps. From the nonlocal signals shown in Figs. 3(a) and 3(b), it can be clearly confirmed that the vortex chirality in the square dot is desirably controlled by the dc current injection. We also confirmed the reproducibility of the nonlocal spin signal by repeating the measurement 10 times.

Finally, we note that the reliability of the present control method decreases under the large DC current injection. Figure 4 shows the nonlocal spin valve signals with the DC current injections of ±10 mA. In most of the measurements, we observed the nonlocal spin signal curves shown in Fig. 4(a), which are similar to those at ±5 mA, indicating that the desired chirality was formed in the Py square dot. However, an unusual curve shown in Fig. 4(b) was also observed in a few measurements. Although the desired chirality was obtained in the upward sweep, the signal in the downward sweep was quite different from Fig. 4(a). This unusual signal can be explained as follows. As mentioned above, in the downward sweep, the circular Oersted field induced by the DC current across the lower Py/Cu junction assists the nucleation of the CW vortex from the lower edge. At the same time, the nucleation of the CCW vortex from the upper edge is also assisted by the DC current across the upper Py/Cu junction. In the present control scheme described above, we neglected the influence of the Oersted field induced in the upper Py/Cu junction because the magnitude is smaller than that in the lower Py/Cu junction. However, this assumption probably becomes invalid under a large amount of the DC current. As a result, the two vortices from the upper and lower edges can be formed in the square dot, as shown in the inset 1 of Fig. 4(b). Since the core position of each vortex should be the center of each electrode, the size of the vortex in the upper junction is larger than that in the lower junction. When the negative magnetic field increases, the small vortex should be pushed out by moving the large vortex. After the annihilation of the small vortex, the square dot becomes a single vortex structure with the CCW chirality, and the spin signal simply varies with reflecting the motion of the CCW vortex, similar to the signal in the negative sweep of Fig. 3(b). Thus, the unusual change shown in Fig. 4(b) can be explained by assuming the formation of the double vortices. Although further experiments are required, these results imply another control method of the vortex structure.

In short, we demonstrated that the vortex chirality formed in a square Py dot can be controlled by the DC current passing through the Py/Cu junction. The vortex chirality was clearly detected by the nonlocal spin valve measurements. A large DC current injection was found to induce an unusual field dependence of the spin signal, implying the nucleation of double vortices.

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