Vortex motion in chilarity-controlled pair of magnetic disks

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(Received 20 November 2006; accepted 21 February 2007; published online 26 March 2007)

The authors investigate the influence of the vortex chirality on the magnetization processes of a magnetostatically coupled pair of magnetic disks. The magnetic vortices with opposite chiralities are realized by introducing asymmetry into the disks. The motion of the paired vortices are studied by measuring the magnetoresistance with a lock-in resistance bridge technique. The vortex annihilation process is found to depend on the moving directions of the magnetic vortices. The experimental results are well reproduced by the micromagnetic simulation. © 2007 American Institute of Physics. [DOI: 10.1063/1.2716861]

Patterned domain structures are useful for application in future spintronic devices as well as for the further understanding of the fundamental spin-related physics. In particular, the magnetic vortex structure, stabilized in a ferromagnetic disk with a diameter less than a micron, has a potential as a unit cell for high density magnetic storage because of negligible magnetostatic interaction.1,2 Therefore, understanding the magnetization process of the magnetic vortex is an important issue for further development. In a single magnetic disk, the magnetic properties such as the susceptibility and the field stability can be determined by geometrical parameters, such as the aspect ratio of the diameter to the thickness.3,4 In two or more magnetic disks, another geometrical parameter, i.e., the separation distance between disks, becomes important because of the magnetostatic interaction.5 Although the magnetic vortex at the remanent state does not induce the magnetostatic interaction because of the flux-closure domain, application of the in-plane magnetic field breaks the symmetry in the flux-closure structure, leading to the magnetic charge at the edge of the disk. When the separation distance is much smaller than the diameter, the magnetic properties are strongly modified. This means that the magnetic properties of the vortex can be tuned by adjusting the separation distance.

The magnetic vortex is described by two topological quantities: polarity and chirality. The vortex polarity, which is the magnetization direction of the vortex core, strongly correlates to the dynamical trajectory of the vortex core6,7 and the spin-current induced vortex motion.7,8 The chirality, which is the rotational direction of magnetic moments whirling either clockwise (CW) or counterclockwise (CCW), determines the direction of the vortex shift induced by the in-plane magnetic field. In a single magnetic disk, these two quantities do not contribute to the magnetization process because of the well defined symmetry. However, in coupled vortex systems, these quantities are expected to affect the vortex behaviors because of the magnetostatically induced asymmetric interaction. Here, we study the influence of the vortex chirality in a system of two coupled vortices. We found that the vortex chirality strongly affects the vortex annihilation fields.

In a perfect circular disk, CW and CCW states are degenerate because the in-plane shape anisotropic energy is isotropic. However, the chirality of the magnetic vortex is known to be controlled by introducing the asymmetry. For example, in the disk with a flat edge on one side, the vortex easily nucleates from the flat edge, assisted by the larger demagnetizing field, than that at the round edge when the magnetic field is applied parallel to the flat edge.9,10 Thus, the chirality can be tuned by the magnetic field. We consider paired magnetic disks in which each disk has a flat edge at left-or right-hand side, as shown in Fig. 1(a). When the positive vertical magnetic field is applied, the vortex states with opposite chiralities (disk A: CW, disk B: CCW) are stabilized in the remanent state. In such a vortex system, the horizontal magnetic field induces a mutually opposite vortex movement. When the positive horizontal field is applied in the remanent state, the vortices approach each other with increasing magnetic field (i.e., inward motion). On the other hand, when the negative horizontal magnetic field is applied, the vortices move away from each other (i.e., outward motion).

![FIG. 1.](image)

(a) Formation of the magnetic vortices with mutually opposite chiralities by introducing the positive vertical magnetic field $H_{ver}$. After the application of the magnetic field, the chiralities of disk A and disk B are CW and CCW, respectively. (b) Inward vortex motion by applying a positive horizontal magnetic field $H_{hor}$. (c) Outward vortex motion by applying a negative horizontal magnetic field.
As mentioned above, the paired magnetic vortices have mutually different chiralities in the remanent state after applying the positive vertical magnetic field of 2000 Oe. Here we study the difference between the inward and outward motions of paired vortices. Figure 3(a) shows the resistance change of disk A as a function of the horizontal positive magnetic fields inducing the approach of the vortex cores. The vortex annihilation is clearly observed as a step in the resistance change at 500 Oe. Figure 3(b) shows the resistance change as a function of the horizontal negative magnetic fields inducing the separation of vortex cores. The arrows indicate the vortex annihilations, responding to the vortex nucleation and annihilation, respectively, at −100 and 360 Oe.

In order to confirm that the magnetic vortex has a desired chirality, the positional dependence of the vortex annihilation field is measured. When the vertical magnetic field is swept from the negative to the positive direction as in the inset of Fig. 2(b), the magnetic vortex nucleates from the flat edge and annihilates from the round edge. However, when the field sweep direction is reversed after the vortex nucleation, the magnetic vortex goes back to the flat edge and then annihilates from the flat edge. Figure 2(c) shows the MR when the magnetic field is swept from 0 to −1000 Oe after the vortex nucleation. The vortex annihilation is observed at −420 Oe, which is larger than that from the previous measurement. The similar tendency is observed in disk B. According to the micromagnetic simulation using the object-oriented micromagnetic framework (OOMMF) software, the annihilation field from the flat edge is 450 Oe, which is larger than the corresponding annihilation field for the round edge of 400 Oe. Here, the cell size, the saturation magnetization $M_S$, the exchange constant, and the damping parameter $\alpha$ are 10 nm, 716 emu/cm$^3$, 1.3 × 10$^{-6}$ erg/cm, and 0.5, respectively. The position dependence of the annihilation field is qualitatively reproduced by the numerical simulations. These facts clearly indicate that the vortex chirality has a desired direction. The numerically obtained annihilation fields are slightly larger than the values in the experiment. This discrepancy is due to the zero-temperature approximation in the numerical simulation.12,13

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To understand more quantitatively, we also studied the vortices’ motions with the mutually opposite chiralities under similar magnetic field conditions by micromagnetic simulations using the same parameters as the previous calculations. We found that the annihilation field for the inward motion is 540 Oe, which is smaller than −630 Oe for the outward motion. Thus, the experimental results are well reproduced by the micromagnetic simulations.

In conclusion, we study the influence of the vortex chirality in the coupled pair of vortices. The annihilation field is found to depend on the vortex chirality when the two vortices have mutually opposite chiralities. This result indicates that the vortex chirality is an additional parameter for controlling the magnetic property in the coupled vortex systems.

8We have systematically studied the stability of a single vortex by changing the diameter and percentage of chipped area and found that the 5% chipped disk is the most reliable for chirality control.
9http://math.nist.gov/oommf/