March 2009

Static and Dynamic Properties of Magnetic Vortices in Micron-size Ferromagnetic Disks

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Keywords: Permalloy, magnetic vortex, magnetic disk storage, chirality, magnetoresistance, micromagnetics, magnetization

Introduction

Ferromagnetic circular disks of sub-micron to nanoscale order has drawn much interest for various applications such as high density magnetic data storage, magnetic field sensors, logic operation devices.

It has been revealed both theoretically and experimentally that for particular ranges of dimensions of cylindrical and other magnetic elements a curling in-plane spin configuration (vortex) is energetically favored, with a small spot of the out-of-plane magnetization appearing at the core of the vortex[1]. Vortex structure is characterized by two binary properties, a chirality (counter-clockwise or clockwise direction of the in-plane rotating magnetization) and a polarity (the up or down direction of the vortex core's magnetization)[2].

In this study, the behavior of magnetic vortex structure inside a sub-micron scale magnetic dot with regard to the chirality of the vortex was investigated. Asymmetric dot was used to control the chirality of the vortex structure. Two independent approaches were taken to reveal the unique behaviors of the vortex.

Experimental Procedure

A magnetic disk consisting of Permalloy (Py) is prepared by means of conventional electron-beam lithography and lift-off technique. Py disks 40 nm in thickness were grown using an electron beam evaporator with a base pressure of 2×10^{-9}Torr. The procedure was repeated to attach copper electrodes 80nm in thickness to Py pattern for magneto-resistance measurement. Figure 1 shows a scanning-electron-microscope (SEM) image of a magnetically coupled pair of asymmetric disks. The diameter of the disks are 1 μm and the separating distance is 200 nm, thickness 40nm. 5% of its diameter at the right and left sides are cut in disk A and disk B, respectively, to induce a mutually opposite chirality. When the initial magnetic field over 100 mT was applied in positive direction of vertical axis (Fig.2 (a)), the CW and CCW chiralities are respectively formed in disks A and B.

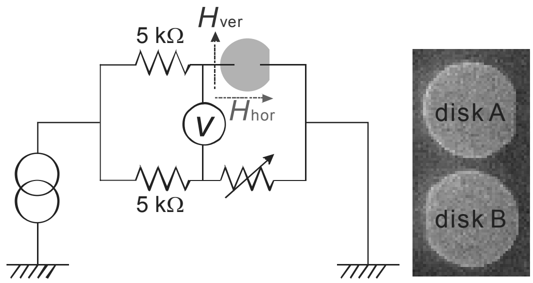

Fig. 1: Schematic diagram of the bridge circuit for the magnetoresistance measurement together with a SEM image of the fabricated paired asymmetric disks

For further understanding of vortex behavior in asymmetric disks, the magnetization process of a vortex structure under various magnitudes of applied external magnetic field has been investigated. High resolution micro magneto-optic Kerr effect (micro-MOKE) magnetometer was used for the measurement at three respective local regions of a prepared permalloy magnetic disk 4 μ m in diameter.

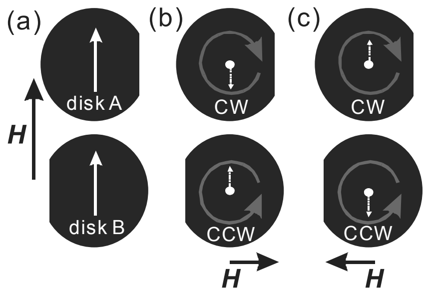

Fig. 2: (a) Formation of the magnetic vorticies with mutually opposite chirality by positive vertical magnetic field H_{ver}. (b) Inward vortex motion (c)Outward vortex motion.

Results and Discussion

The annihilation field with different chirality configuration as shown in Fig. 2 (b) and (c) has been studied. Figure 3(a) shows the resistance change of the disk A as a function of the horizontal positive magnetic fields inducing inward vortex motions. The vortex annihilation is observed as a step in the resistance change at 50 mT. Figure 3(b) shows the resistance change as a function of the horizontal negative magnetic fields inducing outward vortex motions. The annihilation field is 55 mT, larger compared to the inward vortex motion. The difference of annihilation field in two cases could be ascribed to the magnetostatic interaction derived from surface charges that appear when the vortex core is shifted from the center of the disk. In the case of outward vortices motion, magnetic charges develop strong magnetostatic interaction and prevent the vortex motion to outside when compared to the case of inward vortex motion, where surface charge appears at the outer side of the coupled disks.

Figure 4 shows the result of local magnetization measurement of magnetic disk under external magnetic field varying between 48 mT to 62 mT. The transition of the hysteresis shape indicates that under low maximum magnetic field, the vortex nucleation is affected by the magnetic state prior to annihilation. When the maximum magnetic field is increased to 62 mT , the vortex nucleation always takes place at the chipped end , hence the chirality of the vortex is determined by the applied external field. From these measurements, we have found that there is a threshold magnetic field to control the vortex chirality using the chipped disk.

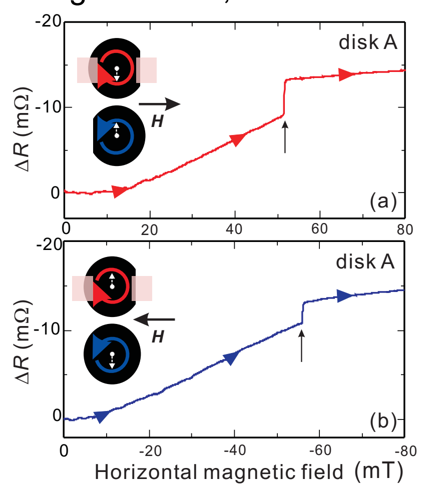

Fig. 3: Magnetoresistance of disk A for (a)inward and (b)outward annihilation. The arrows indicate the vortex annihilation fields.

Summary

The magneto-static character of vortex structure confined in a Py disk was investigated. The effect of chirality to the magnetization process of a coupled disks and the stability of chirality control has been observed experimentally and numerically. The annihilation field is found to depend on the vortex chirality when the two vortices have mutually opposite chiralities. The experimental results are well reproduced by the micromagnetic simulation. This result indicates that the vortex chirality is an additional parameter for controlling the magnetic property in the coupled vortex systems.

The local region measurement by micro-MOKE revealed the existence of threshold field for a saturated state and a metastable state prior to magnetization saturation (**C-state**).

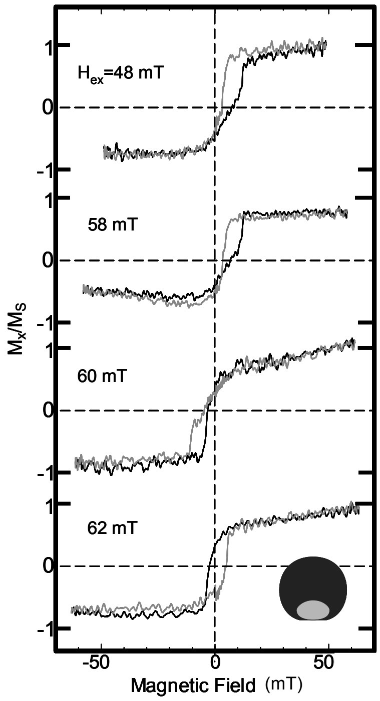

Fig.4: micro-MOKE measurement of magnetization process at the local region of magnetic disk as shown in the inset.

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