JOURNAL OF APPLIED PHYSICS **97**, 10H503 (2005)

Magnetization reversal in patterned double-vortex structures

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(Presented on 10 November 2004; published online 11 May 2005)

The magnetization reversal process for micron and submicron disk-shaped dots is controlled by successive nucleation, displacement, and annihilation of a magnetic vortex. Here the reversal process for a system involving two ferromagnetic disks separated by a nonmagnetic spacer is investigated experimentally, analytically, and numerically. Permalloy ($Ni_{80}Fe_{20}$ or Py) dots with thicknesses of up to 40 nm and diameters of 0.5–2.5 μm separated by a copper spacer (1–45 nm thick) were considered. Micromagnetic simulations indicate that the disks will each support oppositely directed vortices at remanence and also show the hysteresis of the coupled structures. The calculations are compared to hysteresis loops and x-ray photoemission electron microscopy images of Py/Cu/Py dots produced by electron-beam lithography and magnetron sputtering. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1855207]

Understanding the influence of geometry on the properties of micron and submicron magnetic structures has been the focus of considerable research effort due to the potential technological applications such as field sensors, spintronic devices, or magnetic random access cells. Magnetically soft disk structures have received considerable attention from a fundamental physics viewpoint due to their tendency to support a stable vortex magnetization state. While the conditions necessary for a single-layer disk to support a vortex are well known, as is the hysteretic switching through vortex nucleation, displacement, and annihilation,[1,2] the properties of stacked magnetic disks separated by a thin, nonmagnetic spacer have received less attention (F/N/F). With this system, the disks will be coupled through both magnetostatic interactions as well as through bilinear exchange coupling. In this work, the magnetization reversal in patterned double-vortex structures is studied analytically, numerically, and experimentally.

Arrays of trilayer disks were fabricated on silicon wafers using electron-beam lithography and lift-off with high sensitivity, positive tone ZEP-520A resist.[3] Layers of Permalloy ($Ni_{80}Fe_{20}$ alloy or Py) of identical thickness separated by copper were sputter deposited and coated with a 1-nm-thick layer of Pd to protect against oxidation. Magnetic domain imaging was carried out using the photoemission electron microscope (PEEM-2) at the Advanced Light Source. The microscope is capable of probing the magnetization state at remanence with spatial resolution of <100 nm.[4] The sample is illuminated with monochromatic, circularly polarized x rays tuned to the L_2 (870.0 eV) and L_3 (852.7 eV) nickel absorption edges.[5] The difference in the absorption between x rays of each polarization is proportional to the magnetization of the sample that yields the magnetic circular dichroism (MCD) signal that is detected by monitoring the photoemission of electrons from the sample; the ratio of the intensities of the images taken at the L_2 and L_3 edges provides the final image. Hysteresis loops were measured using the longitudinal magneto-optical Kerr effect (MOKE).

Disks with diameters of 1.2, 2, and 2.5 μm of Py/Cu/Py layers with Py thicknesses of 20, 30, and 40 nm were examined via PEEM using a constant Cu spacer thickness of 1 nm. Figure 1 shows the images obtained for structures with 20-nm-thick Py. These images confirm that the top layers of many of these structures support the vortex magnetic state. Some of the largest disks were found in states other than that of a single vortex. (A number of the 40-nm-thick dots were found to be in a three-domain configuration, which will be

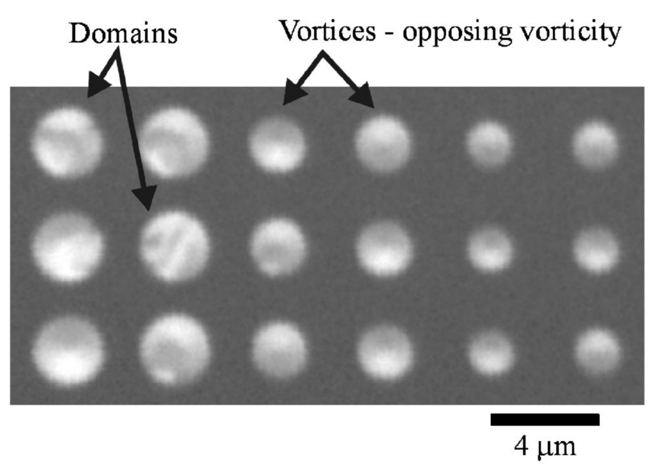

FIG. 1. PEEM images showing the in-plane magnetization state of the top disk for Py/Cu/Py layers (diameters of 1.2–2.5 μm), where the Py layers are 20 nm thick and the Cu is 1 nm. The grayscale map is proportional to the magnetization alignment with the in-plane direction of incidence of the x rays (long axis of the array) where white and black represent saturation in opposing directions.

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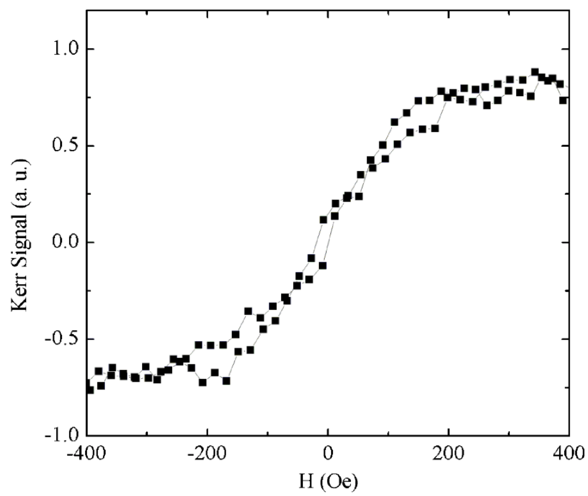

FIG. 2. In-plane MOKE hysteresis curves for 20 nm thick, 2 μm in diameter Py disks separated by 1 nm of Cu (midsized disks in Fig. 1).

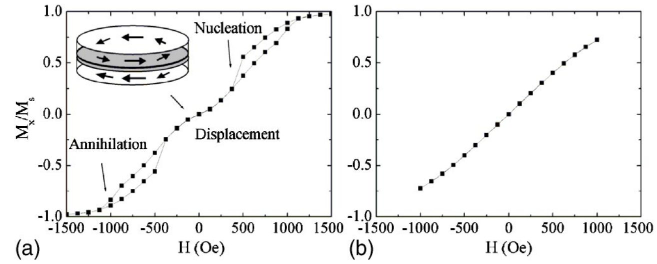

FIG. 3. Simulated hysteresis curve for (a) 500-nm-diameter, 20- nm-thick Py layers separated by a 1-nm-thick nonmagnetic spacer with bilinear exchange coupling of −250 Oe. (c) Simulated in-plane minor hysteresis loop for 500-nm-diameter, 40-nm-thick Py layers separated by a 1-nm-thick nonmagnetic spacer, neglecting bilinear exchange coupling. This hysteresis-free response corresponds to vortex displacement.

examined further in future investigations.) For single disks, the field stability of the vortex state increases as the disk radius decreases. In Fig. 2, the in-plane hysteresis curve for an array of 2-μm-diameter dots with 20-nm-thick Py is shown. There is indirect evidence for vortex behavior as there is zero remanence and the side lobes characteristic of the nucleation/annihilation processes are visible. Hysteresis loops for the thicker disks are similar in overall shape but show less clear evidence of side lobes.

Micromagnetic simulations were conducted using Landau–Lifshitz–Gilbert solvers[6] to gain insight into the remanent state and the reversal process for the F/N/F disks. For the calculations, Permalloy dots were defined with thicknesses t_m of 15–40 nm and diameters $2R$ of 0.5 and 1.0 μm separated by up to 45 nm of nonmagnetic metal (meant to represent Cu or Ag). Such systems are known to exhibit giant magnetoresistance (GMR) and thus are potential candidates for magnetic sensing applications. Py/Cu multilayers, for example, show oscillatory bilinear exchange coupling with a peak in the GMR signal for a spacer thickness of 0.9 nm corresponding to GMR ratios as high as 20%.[7] To favor the vortex magnetization state, the disks must be thicker than the exchange length and the aspect ratio $\beta = t_m/R$ must also be small.[1] The magnetic parameters used are the saturation magnetization M_s (800 emu/cm^3) and the exchange constant A (1.05×10^{-6} erg/cm). The magnetocrystalline anisotropy was neglected.

The simulations indicate that the disks will each support oppositely directed vortices in the remanent state for the proper choice of parameters. A number of simulations were carried out to gain insight into what conditions would favor this state. Parameters that were varied include the M_s value, t_m and R, the thickness of the nonmagnetic spacer t_s, and the interlayer bilinear exchange coupling J. For a disk that is close to the exchange length in thickness, the vortex state is stable for a single disk but may not be supported for a multilayer disk structure due to strong interlayer magnetostatic coupling. For a diameter of 500 nm, a single 15-nm-thick disk characterized by magnetic constants representative of Permalloy will support a vortex; however, two 15-nm-thick disks of the same diameter separated by a 1-nm-thick nonmagnetic spacer will settle into antiparallel, single-domain (SD) states when the sole source of coupling is magnetostatic. In-plane vortices normally form to reduce the magnetostatic energy in a single disk, but when there are two disks stacked vertically the energy of the single-domain state can be reduced through out-of-plane flux closure between the layers.

Increasing J (antiferromagnetic exchange coupling), t_m, t_s, or M_s sufficiently was found to increase the likelihood of observing the double-vortex state at remanence. Using 500-nm-diameter, 15-nm-thick Py disks with a 1-nm separation as a starting point (no bilinear exchange coupling), increasing the Py layer thicknesses to 40 nm, resulted in a stable double vortex. Keeping the disk thickness at 15 nm and increasing the separation similarly resulted in double vortices. For $t_s = 30$ nm the vortices formed but were off center, whereas for $t_s = 45$ nm centered vortices were observed. Increasing M_s resulted in greater curling of the magnetization, however, M_s of 1700 emu/cm^3 (iron) was not sufficient to induce centered vortices. Increasing J also has a stabilizing effect. 20-nm-thick disks separated by 1 nm, for example, did not support vortices for $J = 0$ but with a bilinear exchange field of −250 Oe, antiferromagnetically aligned vortices are stable. In general, the core polarizations were found to be oriented in the same direction and the windings are opposite for the two layers.

Examples of hysteresis curves for selected models that support the double-vortex state at remanence are shown in Fig. 3. Figure 3(a) shows a simulated hysteresis curve for 500-nm-diameter, 20-nm-thick Py disks separated by 1 nm with a bilinear exchange of −250 Oe. The shape of the in-plane hysteresis curve for this trilayer structure is similar to that of a single disk. When the magnetic field is reduced from saturation, vortices nucleate at opposing edges of the upper and lower disks and then move until they reach the disk edges and are annihilated. From saturation, the magnetization of the disks decreases more than for a single disk prior to vortex nucleation. If the field is kept below the annihilation field then reversible displacement of the vortices is observed [Fig. 3(b)], even when bilinear exchange coupling is neglected. Figure 4 illustrates the remanent state for stacked vortices and shows how the cores separate and move towards the disk edges when a magnetic field is applied,

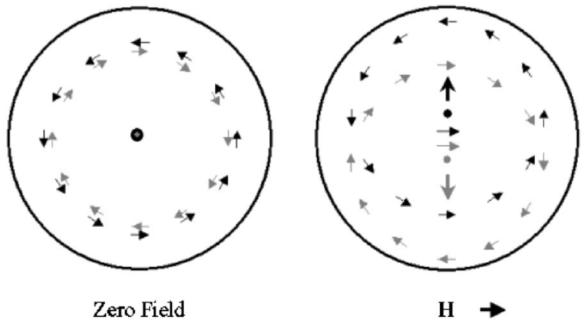

FIG. 4. The vortex core positions and directions of rotation are illustrated schematically for the top and bottom disks in black and gray, respectively, corresponding to those in Fig. 3.

resulting in a central region where the magnetization vectors for both disks are parallel to the applied field.

Analytical calculations of the magnetostatic energy and magnetic susceptibility were carried out for thin cylindrical dots where all quantities were averaged over the dot thickness. With the z axis directed parallel to the dot cylindrical axis, the magnetization components can be described by $m_z = \cos\Theta$ and $m_x + i m_y = \sin\Theta\exp(i\Phi)$ where the spherical angles Θ and Φ are functions of cylindrical coordinates (ρ,φ). For the vortexlike magnetization distribution, the equation $\Phi=\varphi+\nu\pi/2$ corresponds to the condition $m_\rho=0$, and it is assumed that the function $\Theta=\Theta(\rho)$ is axially symmetric. The "winding" index $\nu=\pm 1$ corresponds to magnetization rotation being counterclockwise or clockwise, respectively. The field dependence of the micromagnetic exchange energy is neglected assuming micron-size dot radii $R \gg R_0$ where $R_0=\sqrt{2A}/M_s$ is the micromagnetic exchange length. Numerical calculations of the coupling energy show that the core-core interaction energy is small and can be neglected for this case.

To calculate the response of the composite F/N/F system to an external in-plane magnetic field, a "rigid vortex" model is used. For this model the field-induced, side-surface magnetic charges play an important role. These charges and the corresponding magnetostatic energy for single-layer dots were calculated in Ref. 1. Using a similar approach, the magnetostatic coupling energy of the ferromagnetic layers in the F/N/F structure for a nonzero external field can be expressed (in units of $M_s^2 V$, V is the dot volume) as

$$w(\beta,d) = 2\pi F_{\text{int}}(\beta,d)s^2,$$
$$F_{\text{int}}(\beta,d) = \frac{1}{2\beta}\int_0^\infty dt e^{-td}(1-e^{-\beta t})^2 \frac{J_1(t)^2}{t^2}, \qquad (1)$$

where $s=l/R$ is the relative vortex core shift from the dot center $J_1(t)$ is the first-order Bessel function, and $d=t_s/R$ is the spacer thickness normalized by the dot radius.

The initial susceptibility χ and vortex annihilation (saturation) field H_{an} of the F/N/F structure were calculated assuming different signs of the layer vorticities corresponding to an initial (zero-field) "antiferromagnetic" state of the magnetization distributions in the disks. A symmetric separation of the vortex cores in response to an applied field is also assumed. Defining the auxiliary function $a(\beta,d)=2\pi[F_1(\beta)+F_{\text{int}}(\beta,d)]$, where the function $F_1(\beta)=\int_0^\infty dt[1-(1-\exp(-\beta t))/(\beta t)]J_1(t)^2/t$ (see Ref. 1), the initial susceptibility and vortex annihilation field H_{an} can be written as

$$\chi(\beta,d) = \frac{1}{2a(\beta,d)}, \text{ and}$$
$$H_{\text{an}}(\beta,d) = 2a(\beta,d)M_s. \qquad (2)$$

The magnetic susceptibility (2) decreases as a function of the aspect ratio β and increases as the spacer thickness is increased. The interlayer magnetostatic and exchange interactions also have a profound effect on the magnetic phase diagram of the system, the details of which will be reported elsewhere.[8]

In summary, the system of two magnetically soft disks separated by a nonmagnetic spacer shows complex, size-dependent magnetic properties. The simulations indicate that for the proper disk sizes, the disks will support oppositely directed vortices in the remanent state. However, single- and multidomain states may be stabilized more easily than for single disk structures due to the out-of-plane flux closure between the layers. Increasing the relative contributions of the interlayer exchange as compared to magnetostatic coupling or else improving vortex stability through increasing the magnetic layer thickness and/or decreasing the disk diameter favors the double-vortex state. Experimentally this prediction is supported by the observation of the vortex state at remanence for all dots with the smallest diameter (1.2 μm). Hysteresis measurements of these structures show evidence in support of the double-vortex switching predicted by the simulations.

ACKNOWLEDGMENTS

Work at Argonne was supported by the U.S. Department of Energy, BES Material Sciences under Contract No. W-31-109-ENG-38 and at Berkeley by the US Department for Energy under Contract No. DE-AC0376SF00098. One of the authors (K.S.B.) thanks the Natural Sciences and Engineering Research Council (NSERC) of Canada for a fellowship.

[1] K. Yu. Guslienko, V. Novosad, Y. Otani, H. Shima, and K. Fukamichi, Phys. Rev. B **65**, 024414 (2001).
[2] V. Novosad *et al.*, Phys. Rev. B **65**, 060402R (2002).
[3] ZEP-520A is a high sensitivity e-beam resist of positive tone produced by Nippon Zeon Co. (http://www.zeon.co.jp). ZEP consists of a copolymer of –-chloromethacrylate and- methalstyrene.
[4] S.-B. Choe, Y. Acremann, A. Scholl, A. Bauer, A. Doran, J. Stohr, and H. A. Padmore, Science **304**, 420 (2004).
[5] A. Thompson *et al.*, X-Ray Data Booklet, LBNL/PUB-490 Rev. 2 (2001).
[6] M. R. Scheinfein, LLG Micromagnetics Simulator™.
[7] G. Reiss, L. van Loyen, T. Lucinski, D. Elefant, H. Bruckl, N. Mattern, R. Rennekamp, and W. Ernst, J. Magn. Magn. Mater. **184**, 281 (1998).
[8] K. Buchanan *et al.* (unpublished).