Vortex chirality in an array of ferromagnetic dots

M. Grimsditch,[1] P. Vavassori,[2] V. Novosad,[1] V. Metlushko,[3] H. Shima,[4,5] Y. Otani,[4,5] and K. Fukamichi[4]
[1]*Materials Science Division, Argonne National Laboratory, Argonne, Illinois 60439*
[2]*INFM, Dipartimento di Fisica, Universitá di Ferrara, I-44100, Italy*
[3]*Department of Electrical Engineering and Computer Science, University of Illinois at Chicago, Chicago, Illinois 60607*
[4]*Department of Materials Science, Graduate School of Engineering, Tohoku University, Sendai 980-8579, Japan*
[5]*Japan Science & Technology Corporation, CREST, Kawaguchi 3320012, Japan*
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Magnetization of an array of submicron permalloy dots was investigated using the diffracted magneto-optical Kerr effect. The shapes of the higher-order hysteresis loops are explained by the magnetic form factors associated with a vortex spin structure in each disk. The imaginary part of the form factor also explains the unexpected measured differences between hysteresis loops obtained on positive and negative diffraction orders. Shape effects account for the coherent chirality of the vortices over the array.

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The ever-increasing demand for miniaturization, and the development of microfabrication techniques has led to a dramatic increase in the number of scientific investigations and in funding for nanoscience related research. The increased attention being devoted to this field is leading to novel fabrication techniques, the development of new techniques suitable for characterizing nanostructures as well novel material properties. A particularly active subfield is the investigation of magnetism in small nanometer-sized particles. Much of the drive for these investigations is the hope that understanding magnetism at these length scales will enable realization of advanced spintronic devices. Here we present a theory to interpret the results obtained using the magneto-optic diffraction technique. We show that the technique combined with the theory provides information on the chirality of the magnetic vortex state that develops in small circular magnetic disks. This information cannot be extracted from conventional magneto-optic experiments.

It is generally accepted that a magnetically soft circular particle with diameter and thickness above the exchange length undergoes magnetization reversal via nucleation, displacement, and annihilation of a magnetic vortex.[1–7] Although the vortex state clearly exists in micromagnetic simulations, experimental confirmation is a more subtle issue. Thus, Lorenz microscopy was successfully used to identify the vortex state in circular permalloy dots[1,2] magnetic force microscopy (MFM) images that show the contrast in the center of the particle can be interpreted as a magnetic vortex state in which the core has an out-of-plane magnetization component.[3–5] The experimental hysteresis loops, which mimic those calculated by micromagnetics with sharp magnetization jumps at the so-called nucleation and annihilation fields, and zero remnant magnetization, also provide support for a vortex magnetic state in submicron-size circular dots.[4–7] However, since hysteresis loops for systems, which have bidomain or two-vortices remnant states, are not very different from those for a single-vortex state, these loops must be interpreted with caution.

Due to high sensitivity, magneto-optical methods are widely applied for studying magnetic dot arrays. When the period of an array is larger than the wavelength of light, the array produces diffraction and the measurements can be performed in reflected and diffracted beams.[8–13] These investigations demonstrated that such measurements provide a new tool to address the possible mechanisms of magnetization reversal, but analysis of the results was only qualitative. In the present work, we have used diffracted magneto-optical Kerr effect measurements (DMOKE) to investigate arrays of circular permalloy ($Fe_{81}Ni_{19}$) dots. We now show that form factors can be extracted from micromagnetics simulations and that the imaginary part of the form factor (ignored in previous reports) is defined by the chirality of the vortex state. The agreement between the experimental and calculated diffraction hysteresis loops suggests that the vortex chirality is coherent across the array and is determined by deviations from a perfectly circular shape.

The array of 60-nm thick disks, with nominal diameter of 800 nm arranged on a square lattice with a period of 1.6 μm, was prepared using *e*-beam lithography and lift-off techniques. The details of the sample fabrication and its characterization using conventional MOKE have been given in Ref. 14. The incident beam is polarized in the plane of incidence (*p* polarization) and the magnetic field is applied perpendicular to the plane of incidence, as described in Ref. 11. This arrangement corresponds to the transverse MOKE geometry where the changes in the sample magnetization lead to changes in the intensity (I) of the reflected and diffracted beams, leaving their polarization state unchanged.

Figure 1 shows the hysteresis loops measured in the zeroth-through third-diffraction orders. The intensity variation $\Delta I/I$ in the zeroth-diffraction order is simply proportional to the average magnetization of the sample. The transition from the saturated single domain to the vortex magnetic state is indicated by the magnetization jump at the nucleation field $H_n = 350$ Oe. The linear part around $H \approx 0$ corresponds to reversible displacements of the vortex core along a direction perpendicular to the applied field. When the magnetic field reaches the vortex annihilation field, $H_{an} = 600$ Oe, the vortex is swept out of the dot. As seen in Fig. 1, the hysteresis loops measured in higher diffraction orders are quite different from the zeroth-order loop. Of particular interest are the nonvanishing magneto-optical signal at remanence, the changes in the shape of the loops with increasing

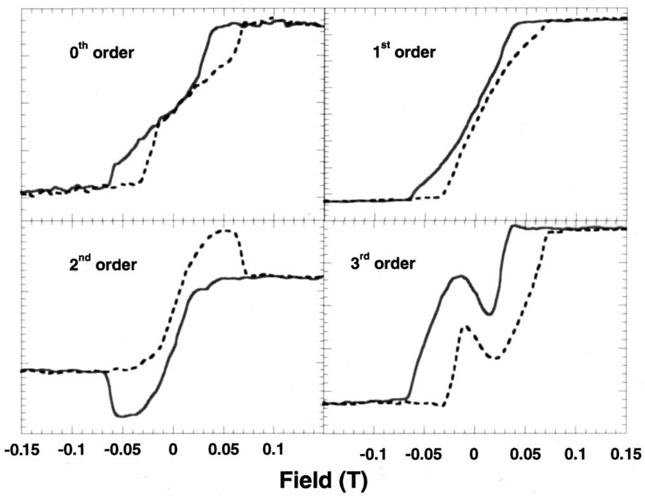

FIG. 1. DMOKE loops of various orders from an array of dots 60-nm-thick permalloy circular dots with diameter 0.8 μm. The angle of incidence is 45°.

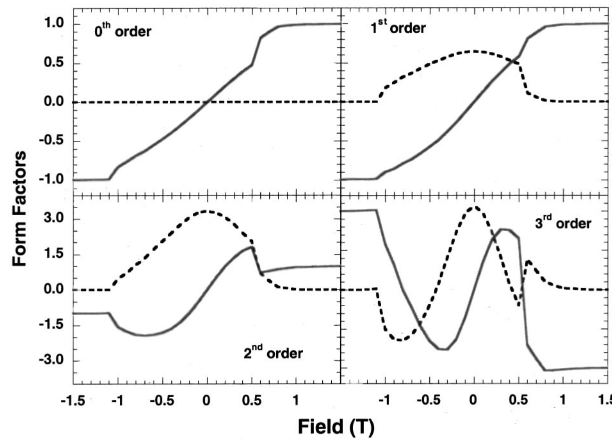

FIG. 2. Field dependence of the real (full lines) and imaginary (dashed lines) form factors obtained from micromagnetic calculations.

diffraction order n, and the fact that the decreasing field portion (full line) can lie below the increasing field portion (dashed line).

The magnetization reversal process explained above determines the well-known magneto-optical response of the individual circular dots that leads to Fig. 1(a). In the case of optical diffraction, the magneto-optical signal is also superimposed on the diffracted beams. As has been discussed in Refs. 11 and 13, the magneto-optical contribution to the nth-order diffracted beam is proportional to the magnetic form factor (f_n^m) defined by

$$f_n^m = \int m_y \exp[in\mathbf{G}\cdot\mathbf{r}]dS, \tag{1}$$

where $\mathbf{G}$ is the reciprocal lattice vector of the array, m_y is the component of the magnetization perpendicular to the plane of incidence, and the integral is carried out over a unit cell of the array; in this case a single dot.

The electric field E_d^n in the nth-order diffracted beam can be written as follows:

$$E_d^n = E_0(r_{pp}f_n + r_{pp}^m f_n^m), \tag{2}$$

where E_o is the incident electric field, and f_n is "the nonmagnetic form factor" (viz. the form factor determined by the shape of the particle) defined by the integral over a unit cell,

$$f_n = \int \exp[in\mathbf{G}\cdot\mathbf{r}]dS, \tag{3}$$

r_{pp} and r_{pp}^m are nonmagnetic and magnetic coefficients that depend on the complex refractive indices of the dots and substrate, the incidence and diffraction angles, and, only for r_{pp}^m, the complex magneto-optical constants.

The intensity of the nth-order diffracted spot is given by

$$I_a^n = E_d^n(E_d^n)^*. \tag{4}$$

Expanding expression (4) and considering only particles that are centrosymmetric and consequently have only a real part of the nonmagnetic form factor fn, we obtain for the magnetic part of the intensity (ΔI_m^n) of the nth diffracted order,

$$\Delta I_m^n \alpha 2 f_n \,\mathrm{Re}[(r_{pp}^m/r_{pp})f_n^m]. \tag{5}$$

For a given diffraction order the ratio $(r_{pp}^m/r_{pp}) = K = K' + iK''$ is a complex number so we can rewrite Eq. (5) as

$$\Delta I_m^n \alpha \{\mathrm{Re}[f_n^m] - (K''/K')\mathrm{Im}[f_n^m]\}. \tag{6}$$

Since to date there is no theory that describes the functional form of K for the diffracted beams, we are forced, at this stage, to treat (K''/K') as an adjustable parameter. Using the expressions for r_{pp}^m and r_{pp} for specular MOKE Ref. 15, and the refractive index and magneto-optical constants of permalloy we obtain $|K''/K'|$ in the range 0–0.3. Since the value of $|K''/K'|$ increases with incidence angle we have also assumed $|K''/K'|$ to be proportional to the diffraction order n.

To obtain the field-dependent magnetic form factors we have used the object oriented micromagnetic framework (OOMMF), a public domain micromagnetics program developed at the National Institute of Standards and Technology by Donahue and Porter.[16] The simulation was made for a circular particle of 800 nm in diameter and 60 nm thick. The material parameters used for the calculation are those contained in the OOMMF program for permalloy. At each field the magnetization distribution is extracted, and the form factors calculated using Eq. (1). In Fig. 2 we show the real and imaginary parts of the form factors for zeroth to third order.

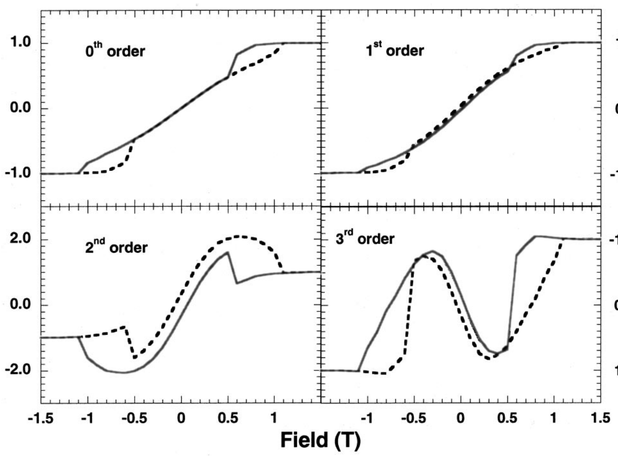

FIG. 3. Hysteresis loops calculated from the form factors in Fig. 2 assuming $K''/K'=0.05$ n. Full and dashed lines indicate increasing and decreasing field, respectively.

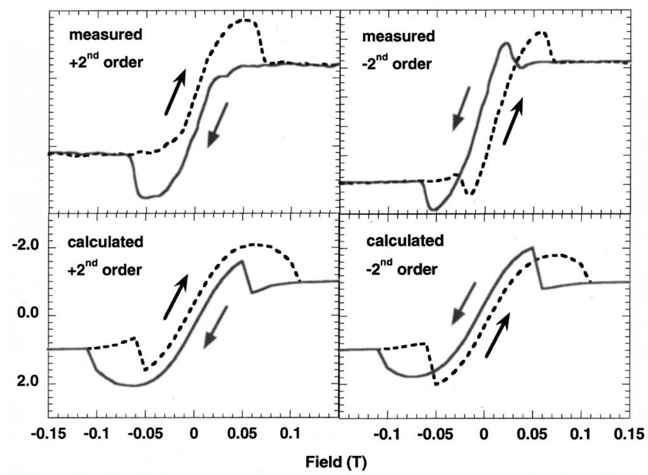

FIG. 4. $\pm$2nd-order hysteresis loops. The upper loops are experimental, the lower ones are calculated with the form factors of Fig. 2 with $K''/K'=0.05$ n. Full and dashed lines indicate increasing and decreasing field, respectively.

It is important to note that the loss of center of inversion symmetry when the vortex is nucleated leads to a large imaginary part of the form factor.

Using Eq. (6) and choosing $K''/K'=-0.05n$, the form factors in Fig. 2 predict the loops shown in Fig. 3. For the zeroth-through second-order loops there is good agreement between the measured and calculated loops. Note, however, that the calculations do not reproduce the observed nucleation and annihilation fields. Given the complexity of magnetization reversal,[17] this is not too surprising. Agreement between the calculated and measured third-order loop is less satisfactory but the calculated loops still reproduce the basic features: in particular, if the downward (full) and upward (dashed) branches lie above or below each other. The diminished agreement for the third-order loop is clearly an indication of the shortcomings of our present understanding. Attempts to improve agreement by adjusting K''/K' and the ratio of particle size/(reciprocal lattice vector) were not successful. Other possible reasons for the discrepancy could be, variations from the perfect cylindrical geometry used in the micromagnetic simulations or simplifications in deriving Eq. (6). Further work is clearly required to resolve this issue.

The above formalism predicts that the relative sign of the real and imaginary form factors should change sign on going to negative diffraction orders [i.e., diffraction on the opposite side of the reflected beam corresponds to a change in the sign of n in Eq. (1)]. Experimentally we have found that the loops obtained on positive- and negative-diffraction orders are indeed different. The second-order loops, for which the imaginary form factor is large (Fig. 2), provide a particularly clear example. In Fig. 4 we show the measured and calculated loops for the ± 2 diffraction orders. The only change in the calculated loops is changing K''/K' from -0.1 to $+0.1$. Agreement between experiment and calculation is quite astounding. Satisfactory agreement is also obtained for the ± 1, ± 3, and ± 4th order diffraction loops. In each case the calculations reproduce the basic features of the loops and the switch in the sign of the magneto-optical signal at remanence.

The relative sign of the real and imaginary form factors [Eq. (1)] is determined by the chirality of the vortex in the particle. Since the relative sign must be fixed in order to reproduce the measured loops, the experimental results imply that the chirality is coherent in the majority of the dots of the array. Furthermore, the asymmetry of the loops measured on the positive-and negative-diffraction orders was found to be unaffected by, changes in the location where the laser spot is focused, changes in the incident angle, or the number of loops that are added in a given run. We conclude from this that the number of vortices with positive and negative chirality is an intrinsic property of the sample and is reproduced in time sequences and spatially over the array. Although we cannot conclude that *all* the particles have the same chirality, the above results provide strong evidence that a great majority of particles nucleate vortices with identical chirality. Experimentally we have also ascertained that the relative sign of the contribution of the imaginary and real parts of the form factor can be reversed by rotating the sample by 180° about its normal. From the above considerations this can be understood as being equivalent to reversing (for a given history of the applied field) the chirality of the vortex in each particle. This, besides being a further confirmation of the coherency of the chirality, indicates that, for a given field history, the chirality is an intrinsic property of each dot.

We believe that shape effects are responsible for the coherent chirality. A recent Lorentz microscopy study[18] of circular dots with a clearly visible flat edge on one side, showed that the chirality is indeed controlled by the shape. Furthermore, using micromagnetic modeling, we have ascertained that even a 0.2% asymmetry in the sample shape (barely discernible by eye) is sufficient to produce preferential chirality. Since microfabrication techniques, which include patterning uncertainties (induced by possible proximity overdose effects), and directional effects during electron-beam evaporation, could easily produce systematic shape changes at the 0.2% level, this seems like the most likely explanation for our observation of a coherent vortex state.

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[1] M. Schneider, H. Hoffmann, and J. Zweck, Appl. Phys. Lett. **77**, 2909 (2000).
[2] J. Raabe, R. Pulwey, R. Sattler, T. Schweinböck, J. Zweck and D. Weiss, J. Appl. Phys. **88**, 4437 (2000).
[3] T. Shinjo, T. Okuno, R. Hassdorf, K. Shigeto, and T. Ohno, Science **289**, 5481 (2000).
[4] V. Novosad, K. Yu. Guslienko, H. Shima, Y. Otani, K. Fukamichi, N. Kikuchi, O. Kitakami, and Y. Shimada, IEEE Trans. Magn. **37**, 2088 (2001).
[5] T. Pohil, D. Song, and J. Nowak, J. Appl. Phys. **87**, 1395 (2000).
[6] A. Fernandez and C. Cerjan, J. Appl. Phys. **87**, 1395 (2000).
[7] R. P. Cowburn, D. K. Koltsov, and A. O. Adeyeye, Phys. Rev. Lett. **83**, 1042 (1999).
[8] O. Geoffroy, D. Givord, Y. Otani, B. Pannetier, A. D. Dos Santos, M. Schlenker, and Y. Souche, J. Magn. Magn. Mater. **121**, 516 (1993).
[9] Y. Souche, M. Schlenker and A. D. Dos Santos, J. Magn. Magn. Mater. **140–144**, 2179 (1995).
[10] Y. Souche, V. Novosad, B. Pannetier and O. Geoffroy, J. Magn. Magn. Mater. **177–181**, 1277 (1998).
[11] P. Vavassori, V. Metlushko, R. Osgood III, M. Grimsditch, U. Welp, G. Crabtree, Wenjun Fan, S. Brueck, B. Ilic, and P. Hesketh, Phys. Rev. B **59**, 6337 (1999).
[12] P. Vavassori, V. Metlushko, M. Grimsditch, B. Ilic, P. Neuzil, and R. Kumar, Phys. Rev. B **61**, 5895 (2000).
[13] I. Guedes, V. Metlushko, N. Zaluzec, M. Grimsditch, P. Vavassori, B. Ilic, P. Neuzil, and R. Kumar, Phys. Rev. B **62**, 11 719 (2000).
[14] V. Novosad, K. Yu. Guslienko, Y. Otani, H. Shima, S. G. Kim, and K. Fukamichi, Phys. Rev. B **65**, 060402 (2002).
[15] Z. Q. Qiu, S. D. Bader, Rev. Sci. Instrum. **71**, 1243 (2000).
[16] M. J. Donahue and D. G. Porter, OOMMF User's Guide, Version 1.0. (National Institute of Standards and Technology, Gaithersburg, MD, 1999).
[17] K. Yu. Guslienko, V. Novosad, Y. Otani, H. Shima, and K. Fukamichi, Phys. Rev. B **65**, 024414 (2002).
[18] M. Schneider, H. Hoffmann, and J. Zweck, Appl. Phys. Lett. **79**, 3113 (2001).