Magnetization reversal and configurational anisotropy of dense permalloy dot arrays

Xiaobin Zhu and P. Grütter

Center for the Physics of Materials, Department of Physics, McGill University, 3600 University Street, Montreal Quebec H3A 2T8, Canada

V. Metlushko
Department of Electrical and Computer Engineering, University of Illinois at Chicago, Chicago, Illinois 60607-0024

B. Ilic
School of Applied and Engineering Physics, Cornell University, Ithaca, New York 14853

(Received 12 February 2002; accepted for publication 1 May 2002)

Electron beam patterned permalloy circular dots of 700 nm diameter with small separations were studied by magnetic force microscopy (MFM) in the presence of an in situ magnetic field. Images in the demagnetized state show that the dot is in a vortex state with a vortex core (singularity) in the center. Local hysteresis loops, measured by cantilever frequency shift in an external field, indicate that the magnetization reversal of individual disks is a vortex nucleation and annihilation process. By carefully doing MFM, nucleation and annihilation fields without MFM tip stray field distortions are obtained. Configurational anisotropy originated from magnetostatic coupling is found through hysteresis loops. © 2002 American Institute of Physics. [DOI: 10.1063/1.1489720]

The magnetic structure and magnetization reversal of small magnets have been widely studied due to fundamental research interest and application potential in high density storage media and magnetoresistive random access memory devices. As the particle size becomes smaller, it is energetically unfavorable to form domain structures. Elliptical particles or elongated particles with a high aspect ratio can form single domain structures, while particles with a circular shape will form a vortex state. Recently, the vortex structure, magnetization behavior, and interdot coupling have been studied by Lorentz microscopy, magnetic force microscopy (MFM), magneto optical Kerr effects, and alternating gradient magnetometry. In this letter, we will use MFM with in situ magnetic fields to study the vortex structures and its magnetization reversal. A local hysteresis loop technique is developed to study the reversal mechanism. The configurational anisotropy originating from interdot coupling is directly measured through hysteresis curves obtained by MFM as well as imaging.

Standard electron-beam lithography and lift-off techniques were used to pattern circular permalloy dots with a diameter of 700 nm and thickness of 25 nm on a square rectangular lattice with a lattice constant of 800 nm.

The magnetic structures and magnetization reversal were studied by a custom built vacuum MFM. The experiments were performed in constant height mode to reduce the destructive MFM tip-sample interactions. Silicon cantilevers with spring constants of 1 and 0.08 N/m, sputter coated with CoPtCr with thickness of 15 nm ($T_{15}$), 30 nm ($T_{30}$), and 50 nm ($T_{50}$) were used as magnetic probes. The experiments were performed in a vacuum of $1 \times 10^{-5}$ Torr.

![Image](image_url)

**FIG. 1.** (a) Vortex structure of permalloy disk; (b) zoom in of a vortex core with 140 nm scan size; (c) image at a field of 23 Oe; (d) image at a field of $-55$ Oe; (e) simulated moment distribution of a permalloy disk with the same size as the experiment; and (f) gray scale shows the moments of out of plane component in a 140 nm area of (e). Tip: $T_{50}$.

---

*Author to whom correspondence should be addressed; electronic mail: xzhu@physics.mcgill.ca*
done by Lorentz microscopy, micromagnetic simulation, and theoretical analysis. The simulated results, as shown in Figs. 1(e) and 1(f), indicate that the lowest energy state is a vortex state with most of the moments rotating along the disk radius. However, the center part (the vortex core), with a size of about 10 nm, points normal to the sample plane. Because it is small in size, the flux core is hardly observable at large tip-sample separation. The observed MFM contrasts with external field is also consistent with modeling. However, a detailed comparison will be discussed elsewhere.

A distinct characteristic of magnetic disks, which has been confirmed by measuring the hysteresis loop of arrays of dots or through the study of individual disks, is that the magnetization reversal has two transitions: the nucleation and annihilation of the magnetic vortex. Here, we develop a local hysteresis technique to characterize the two transitions of a single dot. The local hysteresis loop can be obtained by monitoring the cantilever frequency shift as a function of the external magnetic field, while the tip is located at a fixed position above the disk, as shown in the inset of Fig. 2. The cantilever frequency shift is then converted to the force gradient between magnetic probe and the disk, as shown in the inset. Cantilever: $k = 1 \text{ N/m}$.

![FIG. 2. Force gradient between the MFM tip and sample as a function of external field, while the tip is located at a fixed position 30 nm above the disk, as shown in the inset. Cantilever: $T_{15}$, $k = 1 \text{ N/m}$.](image)

Close examination of the hysteresis loop reveals that it is not symmetric. The absolute value of the force gradient is not symmetric, which is due to the $z$ component of the MFM tip stray field locally reversibly rotating the moments of the dots. The switching fields, however, are not symmetric either. The difference comes from the in-plane component of the tip stray field contributing to the magnetization reversal. Assume that the average in-plane component of tip stray field on the particle is $H_{\text{eff}}$, and the nucleation field without tip is $H_n$. We observe $H_n = (H_{p+} + H_{a-})/2 \approx 10 \text{ Oe}$ for the disk. The average contribution of the tip $H_{\text{eff}} = (H_{p+} - H_{a-})/2$ is less than $10 \text{ Oe}$ for $T_{15}$ and $25 \text{ Oe}$ for $T_{30}$ with a tip-sample separation of about 30 nm. Not only can the local hysteresis curve be used to characterize the magnetization behavior of small disks, but it is also possible to use this technique to characterize both in-plane and out-of-plane components of the tip stray field.

![FIG. 3. A series of images after applying different external fields. (a) Field ramped to 126 Oe, and imaging at 60 Oe; (b) field ramped to 23 Oe, and image at 60 Oe; (c) field ramped to $-20 \text{ Oe}$ after saturation at $-200 \text{ Oe}$, and imaged at $-60 \text{ Oe}$; and (d) field ramped to $-40 \text{ Oe}$ after saturation at $-200 \text{ Oe}$, and imaged at $-70 \text{ Oe}$. Tip: $T_{30}$.](image)
switching fields of the disks without tip stray field artifacts. The “hysteresis curve” (switching probability) can be obtained by characterizing ensembles of disks, as shown in Fig. 4. A two step transition can clearly be seen. Figure 4 shows that both the nucleation and annihilation fields depend on the direction of the external field. Table I lists the average switching field and its variation. We found that if the field is applied in the 100 direction of the array, a smaller annihilation and nucleation field is observed. The switching fields difference between 100 direction and 110 direction cannot be explained by dipole interaction for uniformly magnetized dots, which only yield a uniaxial anisotropy contribution. The observed anisotropy can be explained by nonuniform magnetization induced anisotropy, configurational anisotropy. Model calculation by Guslienko shows that the magnetostatic energy is anisotropic with a minima along the 100 or 010 direction with fourfold anisotropy. The anisotropy comes from high order multipole coupling, quadrupolar interaction being dominant. For magnetic disks without an external field, the stray field of each individual disk is very small, and the interdot dipolar and higher order multipolar coupling is negligible.

The hysteresis curve is obtained by averaging over 120 individual disks.

This work at McGill was supported by grants from NSERC of Canada and FCAR of Québec. This work at UIC was supported by the U.S. NSF Grant No. ECS-0202780 (V.M.).

<table>
<thead>
<tr>
<th>Field</th>
<th>( \langle H_s \rangle )</th>
<th>( \delta H_s )</th>
<th>( \langle H_n \rangle )</th>
<th>( \delta H_n )</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>14</td>
<td>5</td>
<td>104</td>
<td>9</td>
</tr>
<tr>
<td>110</td>
<td>32</td>
<td>9.3</td>
<td>115.5</td>
<td>11.5</td>
</tr>
</tbody>
</table>

9 The simulation uses the publicly available three-dimensional CODE from NIST, http://math.nist.gov/oommf. We used a unit cell of 4 nm \( \times 4 \) nm \( \times 5 \) nm, an exchange constant of \( 1.0 \times 10^{-11} \) J/m, and the damping constant of 0.5.
12 We assign \( \pm 1 \) to the single domain state, and 0 to the vortex state. The hysteresis curve is obtained by averaging over 120 individual disks.