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Letter to the Editor

Experimental determination of ultra-sharp stray field distribution from a magnetic vortex core structure

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ABSTRACT

The fine magnetic stray field from a vortex structure of micron-sized permalloy ($Ni_{80}Fe_{20}$) elements has been studied by high-resolution magnetic force microscopy. By systematically studying the width of the stray field gradient distribution at different tip-to-sample distances, we show that the half-width at half-maximum (HWHM) of the signal from vortex core can be as narrow as ~21 nm at a closest tip-to-sample distance of 23 nm, even including the convolution effect of the finite size of the magnetic tip. a weak circular reverse component is found around the center of the magnetic vortex in the measured magnetic force microscope (MFM) signals, which can be attributed to the reverse magnetization around the vortex core. Successive micromagnetic and MFM imaging simulations show good agreements with our experimental results on the width of the stray field distribution.

1. Introduction

The remnant magnetization state of micron- or submicron-sized soft magnetic thin-film elements, such as permalloy (Py) disks, consists of an in-plane curling spin configuration (vortex) and an out-of-plane magnetization in the center. A magnetic vortex is characterized by two Boolean parameters: the chirality (clockwise or anticlockwise) and the core polarity (pointing out of or into the plane of the vortex) [1]. That means four possible remnant vortex states may exist. This makes the vortex structure a promising candidate in the future industrial application as magnetoelectronic devices, such as magnetic random access memory (MRAM) cells.

Due to its potential importance for future application, the magnetic vortex structure has been widely studied by both theoretical calculations [2,3], and magnetic imaging techniques, such as spin-polarized scanning tunneling microscope (SP-STM) [4], Lorentz microscope (LM) [5], and magnetic force microscope (MFM) [2,6]. Study of spatial stray field distribution near the vortex core, which is mainly out-of-plane, is very important for the playback and switching of the core polarity. However, SP-STM is sensitive to the sample's surface local electron spin density and the LM is only sensitive to the in-plane field component. MFM is sensitive to the out-of-plane component of the stray field gradient, which makes it possible to determine the ultra-sharp stray field from a vortex core experimentally.

Until now, the vortex core has not been imaged by MFM with sufficient spatial resolution [2,6], although the measurement of the related internal spin structure of the magnetic vortex core suggests that it can have a dimension approaching 10 nm [4]. In this paper, we report a high-resolution magnetic force microscope (hr-MFM) measurement of the stray field gradient from the vortex core structure. By systematically studying the width of the stray field gradient distribution at different tip-to-sample distances, we show that the half-width at half-maximum (HWHM) of the signal from vortex core can be as narrow as ~21 nm at a closest tip-to-sample distance of 23 nm, even including the convolution effect of the finite size of the magnetic tip. The micromagnetic simulation is carried out to determine the magnetization arrangement within the Py-disk and its related stray magnetic field. The tip convolution effect is also taken into account by modeling an extended tip. The micromagnetic and MFM imaging simulations show good agreement with our experimental measurements for the width of the stray field distribution at different scan heights.

2. Experiment

The permalloy ($Ni_{80}Fe_{20}$) disk array was prepared by template-assisted e-beam lithography. The nominal diameter and thickness

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of these disks were 1.5 μm and 30 nm, respectively, capped by 1 nm carbon to avoid surface oxidation. The $Ni_{80}Fe_{20}$ array was firstly imaged by scanning electron microscope (SEM) and was found all the elements consisting of two stacked disks. The intersection of the two disks within every element showed mostly an olive-like shape. The disk array was then imaged by hr-MFM (Nanoscan Ltd., Switzerland) at different tip-to-sample distances. In the experiments presented in this work, we used a dynamical constant height MFM operation mode (the details of this operation mode and the hr-MFM used here have been described previously [7]). A high aspect ratio and low moment MFM tip was used. The resonant frequency f_0 and spring constant k of the cantilever (CL) is 40.853 kHz and 0.35 N/m, respectively. The amplitude A was set to 10 nm during the experiment. The atomic force microscope (AFM) measurement showed that the actual height of the elements was 25 nm. After acquiring the MFM images, the frequency shift versus distance (Δf–z') curve was repeatedly measured at non-magnetic regions above the surface of the olive shape to calibrate the exact tip-to-sample distances in experiment. In order to control the tip-to-sample distance in a large scale, we also applied an electrostatic potential V_p of 0.27 V (which is the difference of the contact potential difference V_{cpd} between the tip and the sample and the bias voltage applied on the tip V_{bias}) between the tip and the sample.

3. Micromagnetic model

The stable magnetization pattern in the sample was calculated by micromagnetic (μ-*mag*) simulations using Laudau–Lifshitz–Gilbert (LLG) equations. The typical material parameters for permalloy were chosen: saturation magnetization $M_S = 800\,\mathrm{kA\,m^{-1}}$, the exchange constant $A^* = 10^{-11}\,\mathrm{J\,m^{-1}}$ and damping constant $\alpha = 0.05$. The anisotropy coefficient for permalloy has a negligible effect on the magnetization process and was set to zero.

We carried out a three-dimensional micromagnetic simulation by dividing either the circular or olive-shaped element into cubic cells of $5 \times 5 \times 5\,\mathrm{nm}^3$, according to the exchange length $l_{ex} = (2A^*/\mu_0 M_S^2)^{1/2}$ (5 nm for permalloy) [8].

In the MFM simulation, we assume the frequency shift to be proportional to the force derivative $\Delta f \sim (f_0/2k)\cdot \partial F_z/\partial z$ [7], because the damping of the CL oscillation is constant throughout all the MFM images. For an extended tip, the magnetic force derivative $\partial F_z/\partial z$ is approximately proportional to the integral of the second-order derivative of the stray field $\partial^2 H_z/\partial z^2$ at the scan height z_0 (where CL is undeflected) by assuming the magnetization to be uniform within the modeled tip.

4. Results and discussion

Fig. 1a and b show the SEM and MFM images of a Py element which consists of two stacked disks. The intersection of two disks, which is caused by the lateral shift of the template during the evaporation of Py-film, forms an olive shape (short axis nearly equals to the radius of the disks). In Fig. 1b, the vortex core appears as a bright spot approximately in the center of the olive shape, which indicates a repulsive magnetic interaction between the out-of-plane magnetization in the vortex core and magnetic moment of the tip. The in-plane magnetization pattern calculated

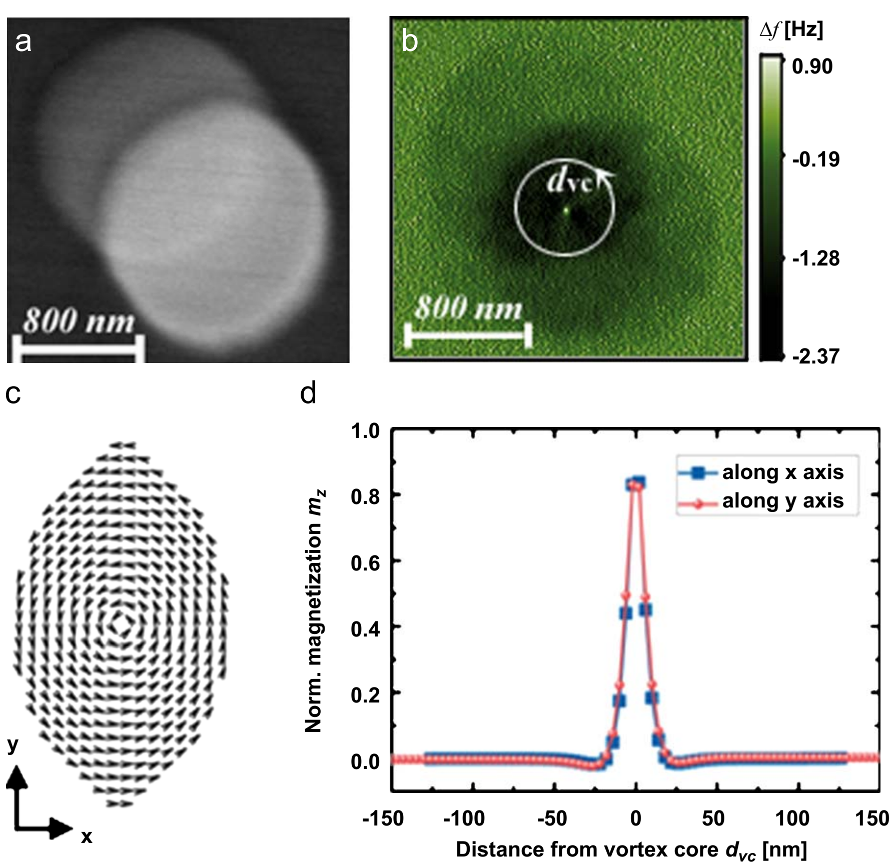

Fig. 1. SEM (a) and MFM (b) images of intersected Py-disks. The olive-like intersection also shows a vortex structure examined by μ-*mag* simulation. In (c), the in-plane magnetization pattern is shown where the size of the arrow reflects the magnitude of the in-plane component. The normalized out-of-plane component m_z as a function of the distance from vortex core d_{vc} is shown in (d). The line profiles of m_z across the vortex core along the short x-axis (line with squares) and the long y-axis (line with dots) are highly symmetrical.