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Vector analysis of the magnetic polarity from individual magnetic nanoparticles

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ABSTRACT

Vector analysis from individual Fe_3O_4 nanoparticles was achieved by magnetic force microscopy (MFM) technique with a micromagnetic modeling, which visualises the vector signals of the magnetic field from Fe_3O_4 nanoparticles. It is demonstrated that the MFM method combined with micromagnetics can effectively analyze the magnetic charge distribution with varying time. With this technique, the vector distribution of the magnetic field of the individual Fe_3O_4 magnetic nanoparticles was clearly presented, which will be of great importance for applications in nanobiological systems.

1. Introduction

Magnetic nanoparticles are attracting much attention because they offer the opportunity to study magnetism in between the atomic and bulk limits and because they are of potential interest for applications such as ultra-high-density magnetic recording devices [1–5], biotechnology and biomedical sciences [6–12]. Over the past few decades, the magnetic properties of iron oxide nanoparticles have been widely explored mainly due to their potential applications in various fields, including storage media, environmental remediation, and biomedicine [6,7,9,12,13]. This makes them an excellent candidate for a variety of diagnostics and therapeutics, such as magnetic resonance imaging (MRI) [14–17], targeted drug delivery, hyperthermia and magnetic particle imaging (MPI) [18,19]. In the last decade, the introduction of new experimental techniques, such as electron holography, superconducting quantum interference device (SQUID), vibrating sample magnetometer (VSM), and alternating gradient force magnetometer (AGM), has provided direct ways to probe the magnetic properties. However, these conventional magnetometer instruments give only macroscopic information about magnetic characteristics. In comparison, Magnetic force microscopy (MFM) is an ideal tool to investigate the magnetic behaviors of nanosize magnets due to its high lateral resolution, which can provide microscopic information about the magnetic behavior of an individual nanomagnet [4,5,13]. In addition, extensive experiments and theoretical studies on magnetic nanoparticles show that the magnetization reversal process of this kind of media is very complicated, and sometimes the results of these studies are not consistent with each other [20–22]. For instance, in some cases, the accurate value of reversal fields of magnetic nanoparticles was different with the measuring value by conventional magnetometer instruments or showed a different dependence on diameter. Furthermore, when the nanoparticles become more and more densely, the magnetization reversal processes become affected by interparticle interactions. Therefore, the physical nature of the magnetic properties of magnetic nanomaterials is very worthy of study. The related research on the mechanisms of magnetic properties and moments of $BiFeO_3$ (BFO) with both magnetic and strong ferroelectric orders have been previously investigated by Ahadi et al. [23–25]. On the basis of the above, it is clearly of prime importance to study the reversal properties and moments of individual nanoparticles as well as their mutual interactions.

In this work, to better understand the magnetization reversal properties of magnetic nanoparticles, we have adopted a magnetic force microscopy with a micromagnetic modeling to investigate the vector signals of Fe_3O_4 nanoparticles applied in nanobiological systems.

The MFM measured signal can be considered as the convolution of the magnetized surface and the tip's sensitivity field, this can also be written as Eq. (1)

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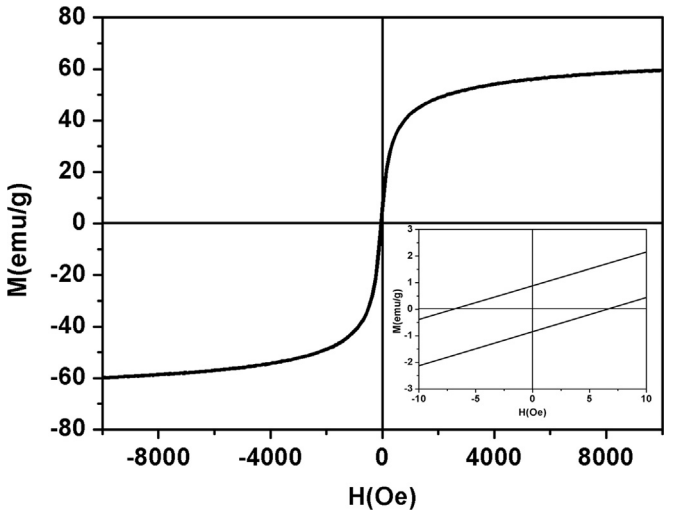

Fig. 1. Magnetic hysteresis loop of the Fe_3O_4 nanoparticles (inset: magnification of the low-field region).

$$F_z'(x, y, z_0) = \iint G_\rho(x - x', y - y', z_0)\rho(x', y')dx'dy' \quad (1)$$

Taking the Fourier transform of both sides of Eq. (1), the following expression for the magnetic pole density distribution can be derived

$$\rho(x', y') = F^{-1}\left\{\frac{F_z'(k_x, k_y)}{G_\rho(k_x, k_y)}\right\} = \rho_{\max}\cdot\rho_i(x, y) \quad (2)$$

In Eq. (2), k_x, k_y are the components of the wave vector in Fourier space, $\phi(k_x, k_y)$ the magnetic force gradient, $G_\rho(k_x,k_y)$ the MFM tip Green's function, $\rho_{\max}$ the maximum magnetic charge density at the pole area, and ρ_i the normalized magnetic charge in the ith cuboid mesh.

By using the "magnetic dipole approximation" and assuming that the magnetization is perpendicular to the sample surface, based on Eq. (3), the three-dimensional Green's function of magnetic force microscopy for a point magnetic dipole tip with respect to a point magnetic charge can be analytically obtained in the frequency domain, as shown in Eq. (3)

$$G_\rho(k_x, k_y, z) = \frac{m_z}{2\mu_0}(k_x^2 + k_y^2)e^{-\sqrt{k_x^2+k_y^2}z} \quad (3)$$

The two-dimensional Fast Fourier Transforms (FFTs) are used to implement this algorithm numerically. The raw image is transformed into Fourier space and then multiplied by a window function before performing the deconvolution procedure. In the micromagnetic modeling, the magnetic pole density is treated as the input driven force for the magnetic domain evolution, and the simulations of the magnetization reversals are accomplished based on the LLG equations. Thus, the evolution of magnetic reversal process can be analyzed and demonstrated.

2. Experimental

The Fe_3O_4 powders were obtained by emulsion method of nitrates dissolved in distilled water, PEG-20000 as a surfactant. 2 M NH_4OH was dropped into the solution until pH=9.0 to form the suspension. The suspension was aged at 90 °C for 3 h, then centrifuged, washed with distilled water and ethanol to reduce

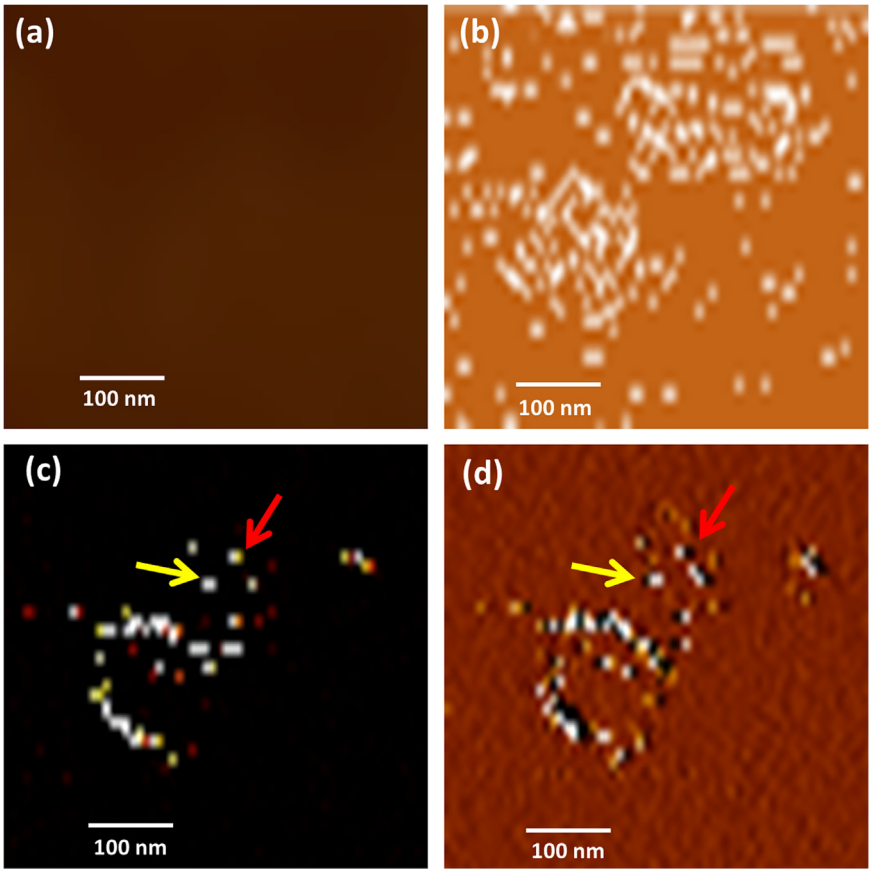

Fig. 2. MFM images [(a) topography image of SiO_2 substrate (b) topography image of the Fe_3O_4 sample (c) amplitude image of the Fe_3O_4 sample (d) phase image of the Fe_3O_4 sample]. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)