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Systematic study of magnetic tip induced magnetization reversal of e-beam patterned permalloy particles

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Patterned nanoscale permalloy particles, with different aspect ratios and widths, were studied by magnetic force microscopy in different operating modes with various magnetic tips. The stray field from the magnetic tip itself could reverse the particle moment orientation while acquiring topography data or when the tip is very close to the sample. Model calculations show that in most cases the stray field from the tip is big enough to reverse the particle's moment. To reduce the tip's influence, one should be very careful in choosing the magnetic tip coating and the operating mode of the microscope. Control of the magnetic state of an individual particle is demonstrated. [DOI: 10.1063/1.1452683]

I. INTRODUCTION

Patterned magnetic particles are currently widely studied due to fundamental issues and their potential for use in ultrahigh density storage media. Magnetic force microscopy (MFM) is a very powerful tool by which to study these particles due to its high spatial resolution and high sensitivity.[1] It is well known that the MFM tip can distort magnetic structures.[2] When the particle size is of submicron scale, distortions due to the tip's stray field can be very severe, especially for magnetically soft nanoparticles[3,4] or while imaging in the presence of an external magnetic field.[5] In this article we will show that the magnetic tip can directly flip nanoparticle moments. We will discuss how to reduce tip-induced magnetization reversal by choosing an appropriate operating mode. Finally, we demonstrate control of the particles' moment states by using the local tip stray field to induce switching.

II. EXPERIMENTAL TECHNIQUES

Elliptical permalloy nanoparticles with different aspect ratios from 1:1 to 1:10, widths of 100, 150, and 200 nm, and nominal thickness of 30 nm were prepared by e-beam lithography and lift-off techniques.

MFM images were taken in tapping/lift mode,[6] constant frequency shift mode,[2] and constant height mode with different magnetic probes. In tapping/lift mode, the topography and magnetic contrast can be separated. The sample's topography is obtained in the tapping mode part of the scan, where the cantilever's oscillation amplitude is maintained constant by a feedback loop. Magnetic contrast is subsequently obtained in lift mode by monitoring the cantilever's frequency or phase shift upon rescanning the previously measured topography with a user controlled height offset. In constant frequency shift mode a feedback circuit adjusts the sample height in order to keep the cantilever resonant frequency constant. It is challenging to study magnetic nanoparticles in this mode, because dc voltage is usually applied to the sample in order to stabilize the feedback.[2] Electrostatic differences between the substrate and particles can lead to strong convolution of the magnetism with the topography. In constant height mode, instead of tracking the sample's surface, the tip scans across the surface at a predetermined height while the cantilever frequency shift is monitored. Unavoidable sample tilt is compensated for by tilt correction hardware.

The magnetic tips used for the MFM images presented in this article are thin film coated silicon cantilevers from Nanosensors GmbH. The silicon cantilevers have a typical spring constant of 2 N/m, resonance frequency of 70 kHz, and quality factor of 150 in air and 40 000 at 1.0×10^{-5} Torr. The tips were sputtered coated with 15, 30, and 50 nm of NiCo, 30 and 60 nm of NiFe, and 10, 15, 30, and 50 nm of CoPtCr, respectively, and magnetized along their axes prior to imaging.

III. RESULTS AND DISCUSSION

Due to shape anisotropy, the elliptical nanoparticles with aspect ratios larger than 1:2 are usually single domain. The MFM image of individual particles shows dark and bright contrast, which represents attractive and repulsive interaction between the tip and sample. Switching fields of typically less than 100 Oe were determined from MFM studies in external magnetic fields. The exact value depends on the particle aspect ratio and that will be discussed elsewhere.[7]

Both simple model calculations[8] and sophisticated techniques, such as Lorentz electron tomography[9] and electron

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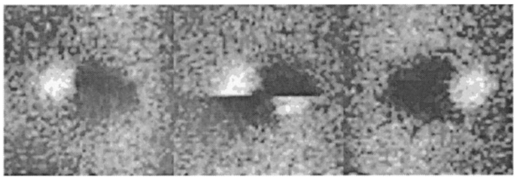

FIG. 1. Three consecutive scans of the same 200 nm×500 nm particle. The tip is a 60 nm permalloy coated probe. The images were acquired in air using tapping/lift mode with a lift height of 80 nm on a Digital Instruments multimode nanoscope.

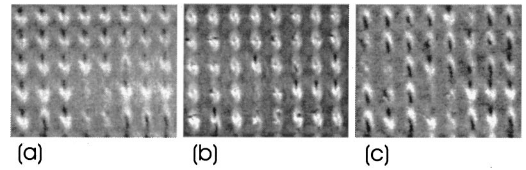

FIG. 3. Influence of the tip–sample separation on the magnetic particle structure. All images were acquired in constant height mode at 120, 60, and 120 nm, images (a)–(c), respectively, with a 30 nm CoPtCr coated tip, constant height mode in vacuum, and particle size of 150 nm×750 nm.

holography,[10] demonstrate that the stray field close to the end of low moment tips (such as 30 nm CoPtCr) is substantial (a few 100 Oe at distances of a few 10 nm). Less appreciated is the fact that the radial component decays much slower than the z component. At lateral distances of a few hundred nm, the radial component can thus be larger than the z component.[11] For particles of a few hundred nm in dimension, the associated magnetic torque thus extends over the entire particle volume. The magnetic state of a small particle, as observed by MFM, is thus expected to be potentially strongly influenced by the magnetic tip's stray field. In some cases this is easily detected as a discontinuity in the raw MFM data. A typical example is shown in Fig. 1. The first image indicates that the nanoparticle forms single domains. The second scan shows that the particle has a double domain like structure. Inspection of the raw data shows that the contrast changed in a single scan line, indicating that the tip's stray field reversed the particle's moment. The third image shows the same particle forming a single domain state, but with reversed orientation compared to that in the first image. This kind of reversal is very common in large area scans, and multiple reversals of the same particle can be observed. In passing, we would like to point out that data such as those presented in Fig. 1 can be (mis)interpreted as being a multidomain state, so MFM data of nanoparticles, even if published, need to be carefully scrutinized.

The occurrence of tip induced magnetic reversal depends on the tip's stray field and the local switching field of the individual particles. Figure 2 shows tapping/lift MFM images of the same location on a array of 0.2 μm×1 μm particles. The images were acquired in different scan directions, 0° and 180°, respectively. The lift height was chosen to be 120 nm, which we found empirically to give minimal tip induced switching of the sample's magnetization. However, what is not negligible is the magnetic influence of the tip during tapping. For the 0° scan, Fig. 2(a) shows that all the particles are oriented the same way, with the left side being attractive (dark). If we now change the scan direction 180°, Fig. 2(b) shows the magnetic orientation switches too, with the left side now being repulsive (bright). In order to make an easier particle by particle comparison between the two scan directions, the data of Fig. 2(b) were software rotated 180°.

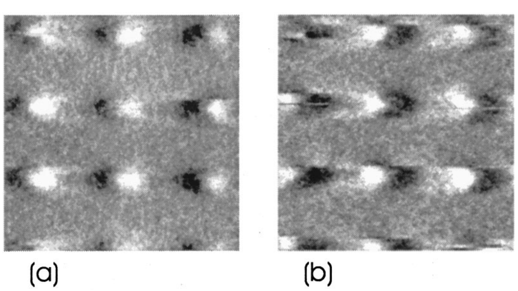

FIG. 2. Two magnetic scans of the identical area, but with the scan directions differing by 180°. Image (b) was off line rotated to have the same orientation as (a). Tip: 50 nm NiCo, tapping/lift mode in air; lift height: 120 nm; particle size: 0.2 μm×1.0 μm.

Since we observe negligible influence as we acquired the magnetic contrast images (a result of the large lift height used), the reversal must happen as we acquire an image of the topography during tapping. This is not that surprising, given that the tip is very close to, if not in contact with, the sample during tapping. In fact, the reversal occurs twice—once during the forward scan and once during the backward scan of the tapping part, prior to lifting the tip and rescanning the same line at a large separation. The final magnetic state of the particles thus does not depend on their initial state, but only on the initial position of the tip for each double-scan line. This type of tip influence is not detectable by just comparing the contrast from backward and forward scan lines during lift mode, since there is negligible influence when we acquire magnetic contrast for sufficiently large tip–sample separations. Instead, comparing the images from different scan directions is necessary.

The occurrence of magnetization reversal is also tip–sample separation dependent. Images in constant height mode with different tip–sample separations clearly demonstrate this. We found that not only large moment tips can reverse the orientation of the sample's magnetic moment, but also small moment tips such as a 50 or 30 nm CoPtCr tip can. Figure 3 shows three continuous images of the same array with different tip–sample separations, 120, 60, and 120 nm, respectively. In Fig. 3(a) a predominant single domain structure is observed at the initial large tip sample separation of 120 nm. No sign of tip induced sample magnetization reversal can be detected. Tip induced moment reversal can, however, be found for smaller tip–sample separations, as shown in Fig. 3(b). One can observe the absence of bipolar contrast. Note how difficult it is to detect the tip's influence at this image magnification. The reversed domain structures can be clearly seen by increasing the tip and sample separation back to the 120 nm distance, shown in Fig. 3(c). Some particles form a metastable low moment state (weak MFM contrast) after tip induced reversal.

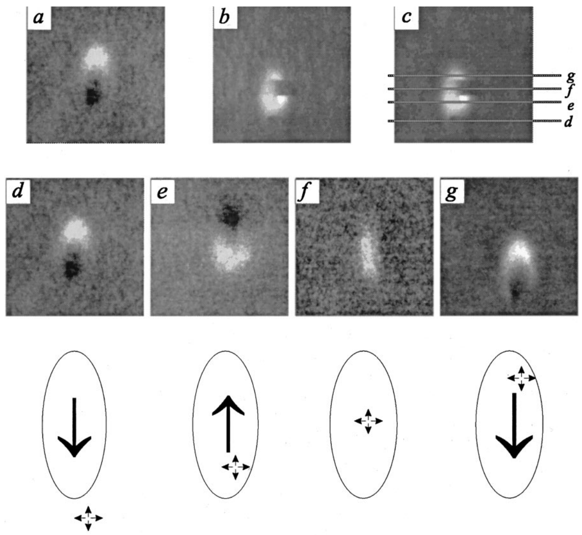

FIG. 4. Control of an individual particle magnetic state by accurate 3D tip positioning. Tip: 50 nm CoPtCr, constant height mode in vacuum, particle 150 nm$\times$600 nm.

By carefully controlling the height of the tip above a particle, reproducible switching into distinct magnetic states is possible. This is demonstrated in Fig. 4. By imaging at constant height with a large tip–sample separation of 120 nm, we find that 150 nm$\times$600 nm particles form single domain states [Fig. 4(a)]. When the tip–sample separation is reduced to 60 nm, close inspection of Fig. 4(b) shows that particle magnetization reverses back and forth several times during imaging from bottom to top. One can achieve control of the final particle magnetization state by adjusting the tip–sample separation from 60 to 120 nm at specific locations, indicated by the lines in Fig. 4(c). The different domain structures that result are shown in Figs. 4(d)–4(g), which were imaged repeatedly and are distortion free at constant height of 120 nm. Schematic representations of the influence of the in-plane component of the tip's stray field on the sample's moment are shown below Figs. 4(d)–4(g). When the tip is scanning along line (d), the stray field at the sample's location is too small to induce switching of the sample's moment. However, when the tip reaches line (e), the tip's stray field can induce switching. In (f), the symmetry of the tip's stray field does not favor any particular orientation of the sample's moment, and a low moment configuration is obtained. Finally, when the tip is in (g) its stray field tends to favor a moment pointing downwards, and consequently reversal occurs. Similar control of the final particle's magnetic state was achievable in particles up to a maximum of 1 μm in length.

In summary, it is challenging to image the undistorted magnetic structure of soft, small particles by MFM. This is due to unavoidable substantial perpendicular and in-plane tip stray fields. Minimizing the tip's magnetic moment reduces the influence of the tip on the sample, but also reduces the signal that can be measured. The latter can partially be compensated for by operating the MFM in vacuum or at low temperatures.[12] Operating parameters in both tapping/lift and constant height operation modes can strongly influence the magnetic structure being observed. Often, the effect is obvious as a discontinuity in the magnetic data. However, in tapping/lift mode, subtle effects, especially on small, soft particles, can only be detected by changing the scan direction. Comparing reverse scan data is not sufficient, since the major effect is due to the close tip–sample proximity during the forward and reverse tapping scan prior to magnetic lift mode imaging. Finally, the tip's influence on the magnetic state of an individual particle can be used to locally change its magnetic structure in a controlled way. We demonstrated this by carefully controlling the three-dimensional tip position. At a small tip–particle separation, the tip can change the particle moment (write information), while at a large tip–sample separation the tip can be used to read information from the particle. We envision using this technique as being used to control the inputs and outputs of submicron implementations of magnetic cellular automata.[13]

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