Domain Wall Tip for Manipulation of Magnetic Particles

L. E. Helseth and T. M. Fischer
Department of Chemistry and Biochemistry, Florida State University, Tallahassee, Florida 32306-4390, USA

T. H. Johansen
Department of Physics, University of Oslo, P.O. Box 1048 Blindern, Norway
(Received 28 March 2003; published 12 November 2003)

We demonstrate a method for manipulation of single magnetic microparticles based on a domain wall tip displaced in a controlled manner. By applying an external magnetic field, the tip can either drag or push magnetic particles. This kind of tweezers has potential applications in probing and manipulating colloidal systems.

DOI: 10.1103/PhysRevLett.91.208302 PACS numbers: 85.85.+j

In 1950 Crick and Hughes reported the first demonstration of magnetic tweezers in biology [1]. They used small magnetic particles in combination with large permanent magnets to probe the physical properties of cells. Since then, both macroscopic and microscopic magnetic tweezers have found widespread use due to their low cost and high versatility. They have been used to stretch and manipulate DNA, transport ferrofluids, and for probing the cell environment [2–6]. It has also been proposed that movable nanomagnets can be used to manipulate vortices in superconductors [7,8]. In a recent paper we demonstrated that Bloch walls can be used to trap or repulse paramagnetic colloidal particles, sensitively depending on the external magnetic field [9]. A drawback of the one dimensional domain wall is that it cannot manipulate individual particles. Here we report manipulation of single paramagnetic beads using a domain wall tip. We demonstrate that the tip can be used to attract or repel beads, depending sensitively on the external field, and suggest that this method can be used to probe and manipulate magnetic particles in colloidal systems.

As the starting point, we use bismuth-substituted ferrite garnet films grown by liquid phase epitaxy on 0.5 mm thick (100) gadolinium gallium garnet substrates to generate the domain walls; see also Ref. [10]. In the current Letter we report studies applying a garnet film of thickness 4 μm. Because of the low uniaxial anisotropy, it is possible to excite in-plane magnetized domain wall tips using two different methods. First, by creating stress points near the edge one can obtain single domain wall tips as the one shown in Fig. 1(a). Second, by introducing small defects within the magnetic film (e.g., scratches or inclusions) one may create Néel spikes; see Fig. 1(b) [11]. In the current work we choose to use the first method to generate single domain wall tips for manipulation of the magnetic particles. The typical wall coercivity is about 100 A/m, and it moves in response to a perpendicular field at a rate 0.1–1 μm per A/m, depending on, e.g., the local stress distribution. For weak field modulations (<500 A/m) the domain wall displacement varied linearly with the applied magnetic field. However, in the case of larger modulation one observes that the domain wall tip cannot return to its initial position, i.e., we have irreversible motion. In practice, this means that the tip traverses a well-defined, reversible trajectory if we tune the magnetic field within a certain range. The domains can be visualized with a polarization microscope (Olympus A70, used in reflection mode) via their magneto-optic effect and their displacement controlled with a resolution of 1 μm.

A spherical paramagnetic bead with radius a ($a = 1.4$ μm in our experiments) is located a distance x from the magnetic tip, and its center is a height z above it. The paramagnetic beads, supplied by Dynal (Dynabeads M270), were coated with a carboxylic acid (COOH-) group. Adhesion of the beads to the garnet film could be prevented by coating the garnet film with a negatively charged polyelectrolyte using the layer by layer adsorption technique [12,13]. The coating results in electrostatic

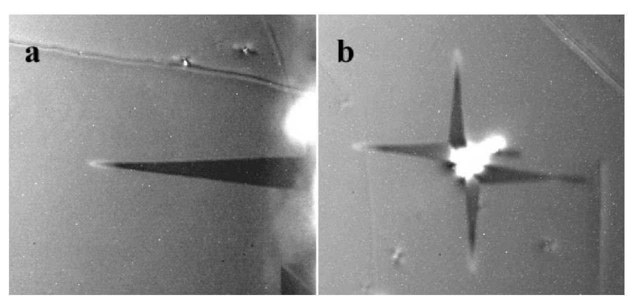

FIG. 1. Two different ways to obtain a domain wall tip. In (a) roughnesses at the edge generate the characteristic domain. We found that it is most efficient to simply make a small scratch (typically 0.1 mm or less) at the edge. In (b) a small inclusion in the film generates typical Néel spikes, which result in four characteristic domains.

 © 2003 The American Physical Society

double layer repulsion between the beads and the film, and the center of the bead is stabilized a distance z above the surface of the garnet film. In this work we assume $z \approx a$, which is a good choice since the electrostatic repulsion is expected to result in a lift of less than the particle radius. To this end, it is important to point out that although the material properties of the garnet film are fixed, we may alter the surface properties by coating the film. In this way one may simulate a wide range of different charge and adhesion properties.

Figure 2 shows the basic geometry for pushing or dragging the particles. Here we apply a strong external magnetic field ($H_{\rm ex} \approx 12$ kA/m) perpendicular to the magnetic film, thus aligning the magnetic moment of the beads. In 2(a) both particles are located inside the domain wall tip, and we observe that when the tip is moving they follow its displacement. The white arrows in the figure indicate the magnetization directions of the domain walls and the domain wall tip, which were determined by observing the particle behavior. For example, one observes that in external fields the particles never stay on the line midway between the walls, but instead distinctly closer to one of them, a feature that is not possible for a Bloch wall [14]. In 2(b) it is seen that one of the particles has jumped outside the tip. This happens when the tip motion is too fast, and the colloidal particle is not able to follow the tip. In this way we are able to separate and thereafter drag or push individual particles. Figure 2(c) demonstrates how the tip can be used to drag and position the particles with high precision. Here two consecutive pictures are superimposed in order to show the particle movement. Particle 1 is sitting close to the tip and is therefore dragged both horizontally and vertically in the same direction as the tip. On the other hand, particle 2 is located close to the domain wall (not near the tip), and its motion reflects the domain wall motion only. This picture therefore clarifies the roles of the domain wall and the domain wall tip in transporting particles. Note also that all the other particles in the picture do not move. Experimentally we were able to position the particles with a resolution of 1 μm, and we were able to drag them up to about 100 μm following the trajectory of the domain wall tip. Figure 2(d) shows another experiment with a different domain wall tip. Two consecutive pictures are also here superimposed in order to show the particle movement. Note that we drag a single particle along the domain wall tip in the direction of the black arrow, without moving the surrounding particles.

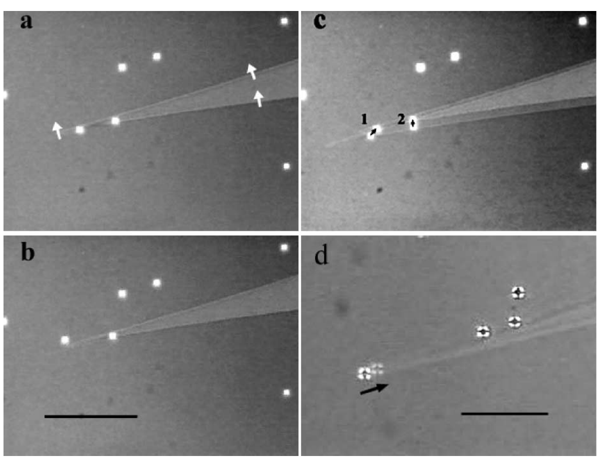

FIG. 2. Two of the possible modes of operation are shown in (a) and (b). Here the tip can be used to drag or push colloidal particles in the presence of a strong magnetic field. The black scale bar is 30 μm. In (c) two pictures are superimposed on each other to show how the tip can be used to drag the particles. The black arrows indicate the particle displacement. (d) shows another experiment with another domain wall tip. Here we drag a single particle along the domain wall tip without moving the surrounding particles. To show that only one particle has been dragged, we have made the second layer more transparent so that the particle appears weaker after being dragged. Note that only one particle appears weaker (i.e., has been moved). The black scale bar in (d) is 20 μm.

To understand the behavior described above, we assume that the magnetic field of the tip couples to the magnetic moment of the bead through its dipole field. If we assume that the tip is pointing in the y direction, and its magnetic moment is directed along the x axis, the stray field can be approximated by

$$\boldsymbol{H}_d = \frac{m_d}{4\pi r^3}\left[\frac{3x}{r^2}\boldsymbol{r} - \hat{\mathbf{x}}\right], \qquad r = \sqrt{x^2 + y^2 + z^2}, \quad (1)$$

where m_d is the magnetic moment of the tip, $\boldsymbol{r}$ is a vector pointing from the magnetic tip to the bead, and $\hat{\mathbf{x}}$ is the unit vector along the x axis. We assume that the magnetic moment of the tip is related to the magnetization M_s ($M_s \sim 10^5$ A/m) of the garnet film by $m_d \approx (4\pi/3)w^3 M_s$. Here w is the domain wall width at the tip, which we estimate to be $w \approx 300$ nm [15,16]. The tip is here taken as a spherical particle of radius w, which is expected to be reasonable approximation, except at very small distances where the actual geometry of the tip should be accounted for in more detail. The force from the magnetic tip on the magnetic bead is given by $\boldsymbol{F} = \mu \boldsymbol{\nabla}(\boldsymbol{m} \cdot \boldsymbol{H})$, where μ is the permeability of water, $\boldsymbol{m}$ is the magnetic moment of the bead, and $\boldsymbol{H}$ is the sum of $\boldsymbol{H}_d$ and the homogenous external applied field in the z direction, $\boldsymbol{H}_{\rm ex}$. The paramagnetic bead can be modeled as a point particle with magnetic moment $\boldsymbol{m} = (4\pi/3)a^3\chi_{\rm eff}\boldsymbol{H}$, where $\chi_{\rm eff}$ is the effective susceptibility. The field aligns the magnetic moment of the bead, and the x and y components of the force are found to be

$$F_x = -\frac{2K}{r^5}\left\{\frac{x^3}{r^5} - \frac{\pi z H_{\rm ex}}{m_d}\left[1 - 5\left(\frac{x}{r}\right)^2\right]\right\}, \quad (2)$$

$$F_y = -\frac{yK}{2r^5}\left\{\left[1 + 4\left(\frac{x}{r}\right)^2\right]\frac{1}{r^3} + \frac{20\pi H_{\rm ex}}{m_d}\frac{xz}{r^2}\right\}, \qquad (3)$$

where $K = \mu\chi_{\rm eff} m_d^2 a^3/\pi$. Because of negligible inertia, the viscous drag $F_v = f\eta a v$ is equal to the magnetic dipole force. Here f is the effective viscous drag coefficient, η the viscosity of water, and v the velocity of the bead.

There are two conditions that must be fulfilled if we want to move the particles in a controlled manner. First, the particles must not adhere to the interface, and we found that in the presence of the polyelectrolyte coating more than 90% of the particles could be moved by the domain wall tip. Second, the maximum velocity the particles can be moved with occurs when the hydrodynamic drag balances the magnetic force. To this end, we observed in all our experiments that if the domain wall tip is moved with a sufficiently large velocity, the particle cannot follow the motion of the tip (maximum observed velocity is $\sim$30 μm/s).

Experimentally we also found that in the absence of an external field the beads are always attracted to the tip, whereas in an external field $H_{\rm ex} > 300$ A/m they may become repelling. We observed that we could push the particles in front of the tip in a finite external field. To this end, we moved the tip gently towards a particle in a field of $H_{\rm ex} \approx 10$ kA/m, and the bead was repelled and maintained a distance $x \sim a$. If we stopped moving the tip, the bead came to rest at approximately the same distance. Naively one may expect that a particle located at the tip ($x = y = 0$) should be repelled in the direction of the dipole moment given a finite external field along the positive z direction, and it may therefore seem puzzling that a finite field is required. However, a closer look at the competition between repulsive and attractive forces allows an explanation of this behavior. Figure 3 shows F_x for different values of $H_{\rm ex}$. Equation (2) predicts that for $H_{\rm ex} > 10$ A/m, a zone of repulsion is introduced near the tip. This field is below our resolution limit, and the crossover could not be detected experimentally. Moreover, this suggests that for very small applied fields also the earth field is of importance, and that for precise manipulation under such conditions it may be required to screen the earth field. From Fig. 3 we see that when $H_{\rm ex} =$ 250 A/m, the maximum value of the repulsion is larger than the attraction, and one may expect the repulsion to be dominant close to the tip. From Eq. (2) it is found that for a sufficiently strong magnetic field, i.e., when terms containing $H_{\rm ex}$ dominate, a particle positioned at ($x > 0$, $y = 0$) will feel a repulsive force when $x < z/2$ and an attractive force when $x > z/2$. Thus, our observations find a qualitative explanation based on the simple theory presented here.

As an additional example, the supplemental video file [17] shows how two particles are pushed by a domain wall tip in an external field $H_{\rm ex}$ varying between 8.0 and 8.4 kA/m. The magnetic field is tuned manually, and the tip follows the movements of the tuning hand. As long as the field modulation is small, we find that the domain wall tip follows the same trajectory every time we turn up or down the magnetic field. If the modulation is too large (typically above 500 A/m), the domain configuration changes, or the tip may perform an irreversible jump to a completely different location. It should also be mentioned that it is more difficult to control the motion of the particles by pushing them (i.e., as opposed to dragging them), since they always try to move to one side, as can be seen in the video. One may expect that to some extent a more controlled pushing procedure could be obtained by using a tip with a y-directed dipole moment in order to avoid the asymmetric situation considered here. On the other hand, for small movements, one may expect pushing and dragging to be equally efficient.

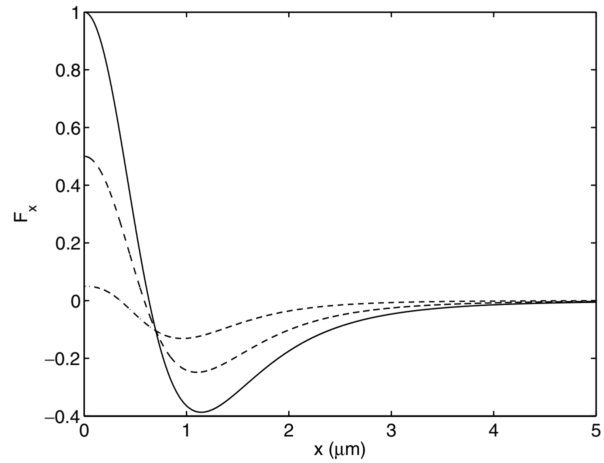

FIG. 3. The normalized x component of the force [Eq. (2)] as a function of distance from the tip under the assumption that $z = a$. Here the solid line corresponds to $H_{\rm ex} = 500$ A/m, the dashed line to $H_{\rm ex} = 250$ A/m, and the dash-dotted line to $H_{\rm ex} = 25$ A/m.

It should be noted that the technique is not limited to particles resting on the magnetic film. The particles could also be deposited on a different interface, with the magnetic film facing the particles from above. Since garnet films are transparent at visible wavelengths, one may use a microscope to look at the particles through the garnet film.

In conclusion, we have investigated the manipulation of magnetic particles using domain wall tips. The domain walls were generated by inducing a stress pattern near the edge of a magnetic film and controlled with a homogenous magnetic field. We showed that the particles are attracted or repelled from the tip, depending on the external magnetic field. We also demonstrated that the tip can be used to move particles with micrometer precision, a feature which could find use in probing magnetic structures.

We thank H. Riegler for lending us the video microscope and Professor H. Möhwald for generous support and stimulating discussions. This study was supported by DFG within the priority program ''Wetting and structure formation at interfaces.''

[1] F. H. C. Crick and A. F.W. Hughes, Exp. Cell Res. **1**, 37 (1950).
[2] C. Gosse and V. Croquette, Biophys. J. **82**, 3314 (2002).
[3] S. B. Smith, L. Finzi, and C. Bustamante, Science **258**, 1122 (1992).
[4] C. Haber and D. Wirtz, Rev. Sci. Instrum. **71**, 4561 (2000).
[5] J. Moreland, J. Phys. D: Appl. Phys. **36**, R39 (2003).
[6] M. A. Hayes, N. A. Polson, and A. A. Garcia, Langmuir **17**, 2866 (2001).
[7] L. E. Helseth, Phys. Rev. B **66**, 104508 (2002).
[8] P. E. Goa, H. Hauglin, A. A. Olsen, D. Shantsev, and T. H. Johansen, Appl. Phys. Lett. **82**, 79 (2003).
[9] L. E. Helseth, T. M. Fischer, and T. H. Johansen, Phys. Rev. E **67**, 042401 (2003).
[10] L. E. Helseth, A. G. Solovyev, R.W. Hansen, E. I. Il'yashenko, M. Baziljevich, and T. H. Johansen, Phys. Rev. B **66**, 064405 (2002).
[11] B. D. Cullity, *Introduction to Magnetic Materials* (Addison-Wesley, Reading, MA, 1972).
[12] The garnet film was inserted in a test tube and then covered by 5 mg/mL PSS (poly sodium 4-styrene sulfonate) mixed with 0.5 M NaCl, inserted in an ultrasonic bath for 10 min, and finally washed with water. We could also produce a multilayered film (up to six layers) by adding polyallylamine hydrochloride using the method of Ref. [13]. However, we did not find any significant improvements in the mobility of the beads.
[13] G. Decher, Science **277**, 1232 (1997).
[14] The direction of the wall can also be checked independently by magneto-optic detection using the method of Ref. [15]. In principle it is possible that the domain wall has some inclination with the magnetic film (i.e., some z component). However, this should give rise to an additional orientation dependent Faraday rotation, which was not observed here.
[15] B. E. Argyle and E. Terrenzio, J. Appl. Phys. **55**, 2569 (1984).
[16] M. H. Kryder, T. J. Gallagher, and R. A. Scranton, J. Appl. Phys. **53**, 5810 (1982).
[17] See EPAPS Document No. E-PRLTAO-91-080343 for a video file of a domain wall tip example. A direct link to this document may be found in the online article's HTML reference section. The document may also be reached via the EPAPS homepage (http://www.aip.org/pubservs/epaps.html) or from ftp.aip.org in the directory /epaps/. See the EPAPS homepage for more information.