

Manipulation of nonmagnetic nanobeads in dilute ferrofluid

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Patterns of submicron Co islands in conjunction with a uniform, static, or rotating magnetic field are used to demonstrate the possibility of assembling 100–300 nm nonmagnetic latex beads in designated locations and manipulating their movements on surfaces. © 2006 American Institute of Physics. [DOI: [10.1063/1.2167641](https://doi.org/10.1063/1.2167641)]

I. INTRODUCTION

Manipulation of magnetic beads by localized magnetic-field gradients has been demonstrated in a number of recent publications.^{1–4} In many applications, however, it is desirable to assemble and manipulate nonmagnetic materials without chemically binding them to magnetic beads. Such a manipulation method was recently proposed⁵ for micrometer-sized nonmagnetic beads. The objective of the present work is to demonstrate that similar methods can be extended to manipulate nonmagnetic colloidal particles whose characteristic size is on the order of 100 nm. The resulting manipulation method may be particularly useful for biological materials such as large biological molecules or viruses.

The proposed method employs submicron Co islands patterned on planar substrates in conjunction with an external static or rotating magnetic field to control movement of 100–300 nm latex beads in a massively parallel fashion. The basic idea behind this method can be described as follows. Nonmagnetic beads placed into magnetic fluid assemble at energy minima located in regions of minimum magnetic-field strength. An array of submicron magnetic islands creates a pattern of such energy minima separated by potential-energy barriers. The potential-energy landscape can be modified in various ways by superimposing a uniform magnetic field. Varying the direction of the superimposed uniform field, for example, rotates or shifts the pattern of potential-energy minima. Nonmagnetic particles positioned at these minima will follow such movement if it is not too fast. When the depths of the potential-energy wells substantially exceed the energy associated with thermal fluctuations, bead movements are nearly deterministic. Reducing the bead's size also reduces the depth of the potential-energy wells leading to significant Brownian motion.

The above assembly and manipulation method will be demonstrated experimentally using several different types of Co island patterns. Presentation of experimental results will be followed by a discussion of a very simple model of the

proposed manipulation system including analysis of potential barrier heights and resulting effects of Brownian motion.

II. EXPERIMENTAL SETUP AND RESULTS

Submicron cobalt islands were created using a liftoff process in which metals are evaporated over lithographically patterned layers of photoresist followed by subsequent photoresist removal. E-beam lithography on polymethylmethacrylate (PMMA) photoresist was followed by an e-beam evaporation of 10 nm of an adhesive layer of chrome and 50 nm of cobalt. The resulting Co islands ranged in size from $200 \times 200 \text{ nm}^2$ to $2200 \times 340 \text{ nm}^2$. Spacing of the islands was also varied from 200 nm to $1.1 \mu\text{m}$. An example of the island pattern is shown in Fig. 2(a). Previous studies by Johnson *et al.* indicate that cobalt islands of these dimensions can be single domain.⁶ However, since this work requires only that the islands have measurable remnant magnetization, the details of domain structure were not checked in this work. Coercivity distribution of the islands was obtained by observing changes in patterns of ferrofluid aggregation at the ends of the islands with changing applied in-plane field. Average coercivity of about 200 Oe was obtained with significant dispersion. Some islands were observed to switch around 100 Oe, while a few also switched at fields above 400 Oe. Such coercivity is consistent with that observed in other publications employing similar islands.⁶

Fluorescent latex beads of 100 and 200 nm diameters (Duke Scientific) were dispersed in separate experiments in an aqueous solution containing EMG 705 ferrofluid (Ferrotec) at 10% of stock concentration (corresponding to a volume concentration of iron oxide particles of about 1%). Although higher ferrofluid concentration could improve the manipulation method discussed below, such low dilution of the ferrofluid was used to make optical observation of the bead movements easier. The nonmagnetic fluorescent beads were sterically stabilized against aggregation, according to the manufacturer. They did not appear to aggregate together or stick to the substrate at the concentrations used. The resulting solutions of nonmagnetic fluorescent beads in dilute

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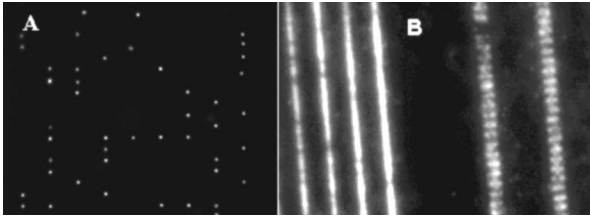


FIG. 1. Beads being held in place by static fields. In (a) 300 nm beads are held by a 400 Oe field over $1 \mu\text{m}$ by 340 nm islands in a rectangular array spaced $1 \mu\text{m}$ side to side and $3 \mu\text{m}$ end to end. In (b) 200 nm beads are held on arrays of $1 \mu\text{m}$ by 340 nm islands spaced 340 nm apart on the left and $2.2 \mu\text{m}$ by 340 nm islands also spaced 340 nm apart.

ferrofluid were placed between the patterned substrate and a glass slide clamped together around $5 \mu\text{m}$ glass spacers (glass microrods). A uniform magnetic field whose direction and magnitude could be varied dynamically was created using two Kepco bipolar operational power supplies/amplifiers attached to solenoids with iron cores. The rotating uniform magnetic fields were controlled by DASYLAB software. The behavior of the latex beads was observed using an upright Leica DMLFS (free standing) microscope with a high numerical aperture 100x oil-immersion lens placed close to the glass cover over the ferrofluid. Images of the moving beads were recorded by Photometrics CoolSNAP HQ fluorescent camera. Bead tracking was performed using Molecular Devices METAMORPH software.

First, static fields were used to demonstrate the ability of the islands to pull particles down out of the bulk of the solution and to trap them in the potential-energy wells at the field minima. Some sample results are shown in Fig. 1. In Fig. 1(a) particles are held over well-separated islands. Particles began to be trapped by the islands after a field of approximately 210 Oe was applied along the direction of the remanent magnetization. Brownian motion appeared to dominate at lower fields. At fields of 400–500 Oe no particle escape due to the Brownian motion was observed. In Fig. 1(b) particles are held over closely spaced islands arrayed into lines. In this case the energy barrier around the lines of islands is sufficient to prevent 200 nm particles from escaping into the bulk of the solution. However, particles did appear to hop between neighboring islands.

Next, rotating fields were used to move 100–300 nm beads along arrays of islands of various sizes and separations. In some experiments island's long axes were up to 45° with respect to the applied field. Figure 2 shows the results of one experiment using 300 nm particles on an array of $1 \mu\text{m} \times 340 \text{ nm}$ islands with a 5 Hz, 70 Oe field. Note that the field used to move the particles was a third of the field that was required to statically capture the particles. This resulted in erratic, but obviously directed motion of the beads as shown in Fig. 2(b).

III. DISCUSSION AND MODEL

Illustration of the potential-energy landscape created by the Co island pattern in the presence of the superimposed uniform field is shown in Fig. 3. When the uniform field is in the plane of the substrate and directed along the island's magnetization, minima of the total field magnitude occur

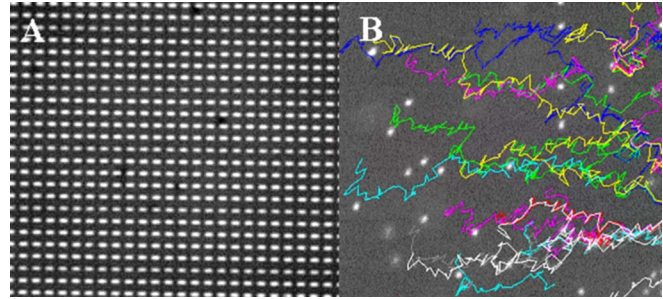


FIG. 2. (Color online) Results of moving beads. In (a) the underlying pattern of $1 \mu\text{m}$ by 340 nm islands is spaced 640 nm side to side and 500 nm end to end is shown. (b) shows the results of using METAMORPH software to track the motion of 300 nm beads along this pattern and off the edge of the frame under a 70 G, 5 Hz rotating field.

over the center of the islands. At these locations the field produced by the island and the uniform field are oppositely directed. Maxima of the total field, in this case, are located between the islands because the island's field and uniform field have the same direction there. As the uniform field is rotated clockwise and island's magnetization remains fixed, the potential-energy landscape shifts. When the uniform field opposes the direction of island magnetization (in this case field direction is shown by dotted line in Fig. 3), the potential-energy landscape (illustrated also by dotted line) shifts to have its minima between the islands. The nonmagnetic beads move by following this shift. Thus, movement of the beads can be viewed as occurring due to movement of the periodic potential.¹

The height of the potential-energy barriers with respect to the thermal fluctuation energy, kT , determines the probability that beads will exit their respective potential wells randomly. The potential barrier height can be estimated using the following expression for the energy of a spherical nonmagnetic bead of volume V_p placed inside homogeneous magnetic fluid of permeability μ_f in the presence of the magnetic field H whose spatial variations are small on the scale of the bead's size:⁷

$$U_{\text{mag}} = \frac{1}{2} \mu_f \frac{\mu_0 - \mu_f}{\mu_0 + 2\mu_f} V_p H^2. \quad (1)$$

Denoting the field due to the islands at the locations of the energy minima by \mathbf{H}_{is} and the superimposed uniform field by \mathbf{H}_0 , the potential-energy barrier is found from (1) to be

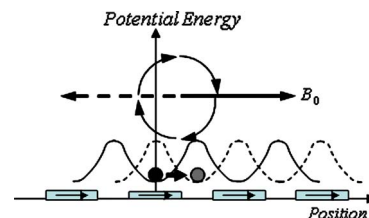


FIG. 3. (Color online) Shifting of the potential-energy landscape by rotating the uniform field perpendicularly to the substrate plane. The potential landscape illustrated by the solid line is shifted into one illustrated by the dotted line when the field rotates clockwise as indicated in the figure by solid and dotted arrows.

$$\Delta U_{\text{mag}} = \frac{1}{2} \mu_f \frac{\mu_0 - \mu_f}{\mu_0 + 2\mu_f} V_p [H_0^2 - (\mathbf{H}_0 + \mathbf{H}_{\text{is}})^2]. \quad (2)$$

Note that the height of the energy barrier is not the same in every direction. The minimal energy barrier height is obtained by comparing the total field at energy minima with the field in the bulk of the fluid. Expression (2) demonstrates that the barrier increases with the increase of the uniform field magnitude. However, for rotating magnetic fields, the field strength is limited by the coercivity of the islands.

For a given uniform field, the highest possible barrier is obtained when the field of the island cancels the uniform field exactly at the location of the energy minima, i.e., $\mathbf{H}_0 = -\mathbf{H}_{\text{is}} = \mathbf{H}_{\text{max}}$. This gives

$$\Delta U_{\text{mag}} = \frac{1}{2} \mu_f \frac{\mu_0 - \mu_f}{\mu_0 + 2\mu_f} V_p H_{\text{max}}^2. \quad (3)$$

In the experiments where the beads are assembled on top of the islands static uniform field of 500 Oe was employed. The value of the ferrofluid permeability can be estimated based on the manufacturers data to be $\mu_f \approx 1.06\mu_0$. Using (3), this leads to an upper bound on the energy barrier of about $60kT$ for 300 nm beads and about $20kT$ for 200 nm particles. The results obtained (examples are shown in Fig. 1) are consistent with large energy barriers since beads in those cases are not observed to leave the islands. Significant Brownian motion observed for 300 nm beads when the uniform field is reduced to 100 Oe suggests that the above upper bound may overestimate the actual barrier height by a factor of 2–4. This overestimate can be due to a number of factors including effects of the island field and significant reduction of fluid permeability at higher fields.

Large field magnitudes employed to demonstrate static bead assembly could not be used to obtain shifts of the potential-energy landscape. Since the coercivity of the islands is measured to be around 200 Oe, the uniform rotating field had to be below that value to observe reliable bead transport. In fact, many experiments kept the rotating field under 100 Oe to ensure that very few islands remagnetized. For 100 nm beads a uniform field of 100 Oe yields an upper bound on the energy barrier height of about $0.15kT$. For 200 and 300 nm beads the corresponding upper bound estimates on energy barriers are $1.2kT$ and $4.5kT$. Again, these upper

bounds may overestimate the actual barriers because they do not take into account effects of the island fields.

IV. CONCLUSIONS

Manipulation and assembly of 100–300 nm nonmagnetic beads in dilute ferrofluid was demonstrated using patterns of submicron Co islands in conjunction with uniform, static, or rotating, magnetic fields. When the uniform field was applied along the island magnetization, the nonmagnetic particles assembled over the islands. When the uniform field was rotated perpendicularly to the substrate, beads were transported along the substrate. The bead transport was clearly observable despite the significant Brownian motion present. A simplified model of bead assembly and transport was proposed based on introduction of shifting potential-energy landscape. The calculated heights of the energy barriers were roughly consistent with the observed Brownian motion magnitude. Although some care might be required to prevent aggregation of the nonmagnetic material or its adhesion to the substrate, the results indicate that the developed manipulation method may be viable for small particles of biological nature such as viruses or large proteins. The effect of Brownian motion can be further reduced if magnetic islands with larger coercivity are employed in conjunction with stronger uniform magnetic field and more concentrated ferrofluid. To be precise, the potential-energy landscape may be deforming while shifting. However, the first-order model can ignore such deformation.

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