

Microelectromagnets for the control of magnetic nanoparticles

C. S. Lee, H. Lee, and R. M. Westervelt^{a)}

Division of Engineering and Applied Sciences and Department of Physics, Harvard University, Cambridge, Massachusetts 02138

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A microelectromagnet matrix and a ring trap that position and control magnetic nanoparticles are demonstrated. They consist of multiple layers of lithographically defined Au wires separated by transparent, insulating polyimide layers on sapphire substrates. Magnetic field patterns produced by these devices allow microscopically precise control and manipulation of magnetic nanoparticles. A microelectromagnet matrix produces single or multiple peaks in the magnetic field magnitude, which trap, move, and rotate magnetic nanoparticles, as well as electromagnetic fields to probe and detect particles. Microelectromagnets are new tools with which to study and manipulate nanoparticles and biological entities. © 2001 American Institute of Physics.
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Magnetic nanoparticles and nanocrystal quantum dots have been grown in solution with excellent control, and their quantum characteristics have been studied.^{1,2} Nanoscale Co bars and wires grown with high uniformity orient in an applied magnetic field. The quantized charge of a single semiconductor nanocrystal has been measured³ and the feasibility of nanocrystal quantum dot lasers has been demonstrated.⁴ In most experiments optical methods have been used to test nanocrystals suspended in fluids. Methods to move, control, and probe nanoparticles are needed to study and explore the advantages of their quantum characteristics. The ability to move magnetic particles can be also important in biological and biomedical applications, for example, to separate and manipulate cells and DNA marked with magnetic particles in submicron scale. Microelectromagnets consisting of multiple layers of lithographically patterned wires may open up those possibilities. Microelectromagnets⁵ have been used to control and manipulate cold atoms on the micron scale as one seeks ways to build integrated atom circuits on a chip in the field of atom optics. Microelectromagnet mirrors,⁶ traps,⁷ and guides⁸ have been successfully demonstrated, and many microelectromagnet devices for cold atoms have been proposed and developed.⁹

In this letter, we report the microscopic control and manipulation of magnetic nanoparticles using a microelectromagnetic matrix and a microelectromagnet ring trap. Specifically, we report the two-dimensional manipulation of superparamagnetic particles using a matrix and the trapping of superparamagnetic particles using a single circular trap. The matrix is a multilayer structure with the capability to trap and move nanoparticles suspended in fluid above the chip with microscopic spatial resolution. High magnetic fields ($B \sim 0.1$ T) and high field gradients ($\nabla B \sim 10^4$ T/m) produced by microelectromagnets allow precise control and manipulation of magnetic particles at room temperature, enabling the study of their motion and characteristics in microscopically confined regions. Any type of particle with a magnetic moment can be manipulated, including ferromagnetic

nanoparticles, paramagnetic particles, superparamagnetic nanoparticles, and even biological entities such as magnetotactic bacteria.¹⁰

Two types of microelectromagnet were fabricated, simulated, and tested: a matrix and a ring trap. Figures 1(a) and 1(b) show a schematic diagram and a micrograph of a ring trap; Figs. 1(c) and 1(d) show a schematic diagram and a micrograph for a matrix. These structures are constructed on sapphire substrates by layers of lithographically patterned conductors separated by insulating layers. The ring trap is a single circular current-carrying wire with an insulating layer spun on top. The matrix consists of two arrays of straight wires aligned perpendicular to each other, separated by an insulating layer, with an additional insulating layer spun on top. Patterned conductor layers can be produced by optical

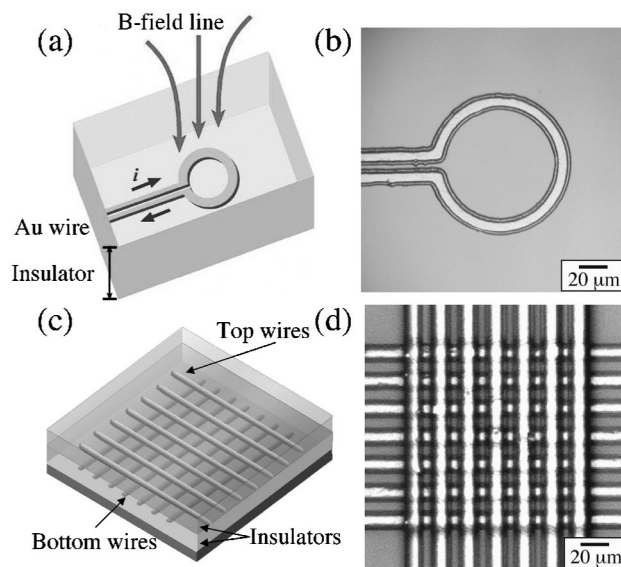


FIG. 1. (a) Schematic diagram of a microelectromagnet ring trap, where I indicates the direction of current flow. (b) Micrograph of a fabricated ring trap. (c) Schematic diagram of a microelectromagnet matrix. The matrix consists of two layers of current-carrying conductors with two layers of insulators. (d) Micrograph of a fabricated matrix (7×7 wires). Each wire has a width of $10 \mu\text{m}$, height of $3 \mu\text{m}$, and center to center spacing between wires of $20 \mu\text{m}$.

^{a)}Electronic mail: westervelt@deas.harvard.edu

lithography or by electron-beam lithography, covering a wide range of length scales. Electroplating patterned conductor layers increases their cross-sectional area and permits large currents, which produce large magnetic fields. Insulating layers are used in multilayer structures to prevent electrical shorting between wires and between wires and magnetic particles.

The operating principle of nanoparticle manipulation by microelectromagnets is illustrated in Fig. 1(a). The magnetic field produced by a current-carrying microelectromagnet attracts magnetic particles to maxima in the field magnitude. The potential energy is $U = -mB$, where m is the particle's magnetic moment and B is the magnitude of the field. The potential energy U remains constant for constant field magnitude if the direction of the field changes slowly enough so that the direction of the particle's moment m can follow closely. For a particle suspended in fluid, the viscosity and fluid dynamics determine this rate. The field magnitude B scales with the characteristic size d of the wire as $B \propto I/d$, gradients of the field magnitude as $\nabla B \propto I/d^2$, and curvatures as $\nabla^2 B \propto I/d^3$, where I is the wire current.⁵ For small devices, large gradients and curvatures can be produced. The wire size for the devices shown in Fig. 1 is $10 \times 3 \mu\text{m}^2$. For the matrix reported here, current densities as high as 10^7 A/cm^2 were achieved at room temperature with cooling provided by heat conduction through the sapphire substrate, yielding $B \approx 0.1 \text{ T}$ and $\nabla B \approx 5 \text{ mT}/\mu\text{m}$. Improvements in ∇B and $\nabla^2 B$ are possible if the devices are made on the submicron scale by electron-beam lithography.

Localized electromagnetic fields can be generated by microelectromagnets to perturb and sense the response of nanoparticles; two examples are nuclear magnetic resonance (NMR) and electron spin resonance (ESR). Due to their small size and their geometry, microelectromagnets are able to generate ac magnetic fields at rf and microwave frequencies in a small volume containing a single nanoparticle or group of nanoparticles, and the response of the magnetization inside the nanoparticle can be tested.

The strength of the trap can be estimated for ferromagnetic and paramagnetic particles. For a ferromagnetic particle with magnetic moment $m = N\mu_B$, where N is the number of Bohr magnetons, the potential energy is $U = -mB = -N\mu_B B$. The average kinetic energy of a particle due to thermal motion is $K = (3/2)k_B T$, where k_B is the Boltzmann constant. The particles will be attracted to field maxima, provided $|U| \geq K$. The condition $N \geq (3/2)k_B T / \mu_B B$ determines the minimum magnetization of a ferromagnetic nanoparticle that can be trapped. For $B = 0.1 \text{ T}$, this gives $N \geq 6700$ at $T = 300 \text{ K}$, a magnetization corresponding to nanoscale particles. Nanoscale particles may become superparamagnetic. For a paramagnetic particle with magnetic moment $m = (\chi B / \mu_0) V$, where χ is the magnetic susceptibility, V is the particle volume, and μ_0 is the permeability of free space, the potential energy is $U = -mB = -(\chi B^2 / \mu_0) V$. The minimum size of a paramagnetic particle that can be trapped is $V \geq (3/2)k_B T \mu_0 / \chi B^2$.

Figure 2 shows computed magnetic field profiles for a microelectromagnet matrix for two different sets of wire currents. Figure 2(a) shows how a single peak in the field magnitude can trap and move high field seeking magnetic par-

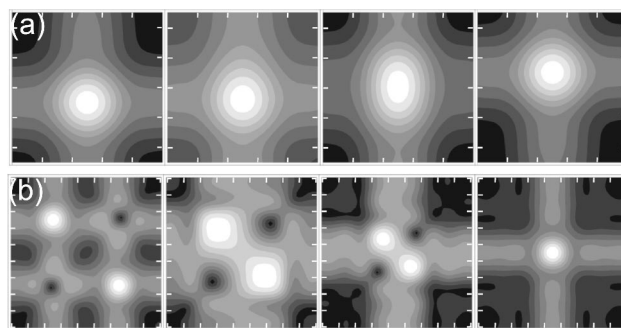


FIG. 2. (a) Simulation of a moving peak in the magnetic field magnitude produced by a matrix; the white ticks show wire positions. Currents were adjusted to approximate a Gaussian magnetic field peak. The peak moves continuously between two adjacent wires, in steps that are less than the wire spacing. (b) Simulation of two separate peaks in the magnetic field magnitude which move diagonally and converge at one position.

ticles continuously over the matrix with spatial resolution less than the wire spacing. The currents in the conductors were adjusted to approximate a Gaussian peak in the magnetic field magnitude at each peak position. Figure 2(b) shows how two separate magnetic field peaks can be produced and moved diagonally to converge at one position. This profile could be used to bring two nanoparticles together. A single peak can also be split into multiple peaks that move apart. By making a matrix with submicron wire spacing, it may be possible to trap and move a single nanoparticle suspended in a fluid to a desired position equipped with electrical leads or sensors and study its characteristics. Because each wire in a matrix can carry a different current, many magnetic field profiles can be created.

Experiments to trap and move magnetic nanoparticles using microelectromagnets were done using superparamagnetic magnetite particles.¹¹ A drop of fluid with magnetic nanoparticles in suspension was placed on the microelectromagnet, either a ring trap [Fig. 1(b)] or a matrix [Fig. 1(d)]. Current was supplied to the microelectromagnets from either a power supply (ring trap) or a group of 14 current sources controlled by a computer (a 7×7 wire matrix). For the matrix, currents $< 0.1 \text{ A}$ were applied to wires in the top layer and currents $< 0.3 \text{ A}$ in the bottom layer. The peak magnetic field above the matrix for these conditions was $< 4 \text{ mT}$. Motion of the nanoparticles was observed using an optical microscope equipped with a digital camera.

Figure 3 shows the operation of a ring trap containing superparamagnetic particles with the magnetic field off [Fig. 3(a)] and with the magnetic field on [Fig. 3(b)]. The density of particles is clearly smaller without the field. Single superparamagnetic particles are trapped several seconds after the field is applied. Because each polymer-coated particle contains a magnetic nanoparticle, Fig. 3 demonstrates the trapping of single superparamagnetic nanoparticles. The magnetic trapping energy and the thermal kinetic energy do not change substantially with the added polymer coating; the polymer makes the location of each nanoparticle visible.

Figure 4 shows the operation of a microelectromagnet matrix to move a group of superparamagnetic particles continuously over short distances that are comparable to the wire spacing, longer distances, and to move two groups of particles together and join them into a single larger group. Fig-

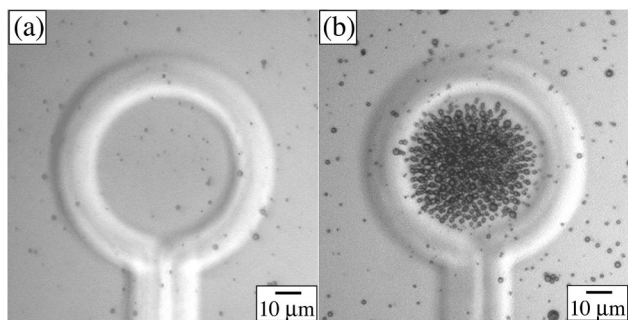


FIG. 3. Micrograph of superparamagnetic particles in fluid above (a) a ring trap with no current and (b) $I=0.35$ A. The particles are 1–20 nm magnetite nanoparticles coated with a polymer composed of polystyrene and carboxylic acid, suspended in a water based solution; the coated particle diameters are 1–2 μm . A spherical magnetite nanoparticle with 10 nm diameter has a magnetic moment of $\sim 10^5 \mu_B$. The current $I=0.35$ A in (b) produces a magnetic field peak of $B=2.7$ mT at the center of a ring trap above the insulating layer.

ure 4 demonstrates that a matrix can build larger objects in two dimensions from nanoparticles, a capability that can be used to assemble custom designed structures. An important capability of a matrix is to move nanoparticles continuously over distances much smaller than the wire spacing. With this capability the position of nanoscale particles can be controlled using a matrix with submicron wire spacing. The continuous motion of magnetic particles in Fig. 4(a) by incre-

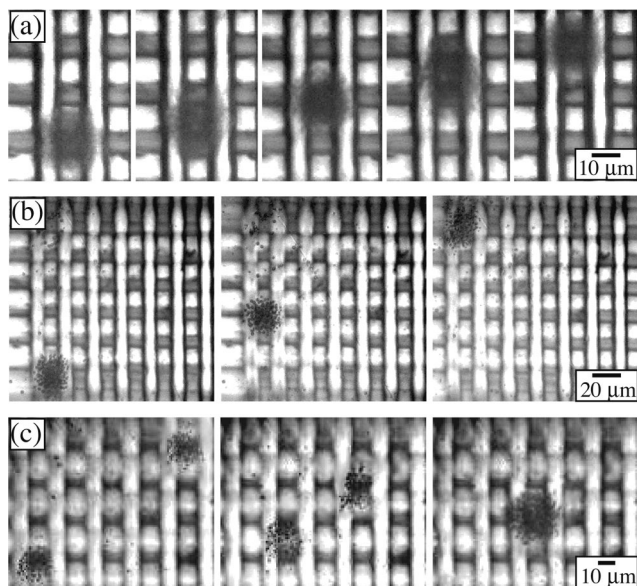


FIG. 4. (a) Demonstration of moving a group of superparamagnetic particles over two wires of a microelectromagnet matrix. The wire currents were adjusted so they continuously move particles by increments that are less than the wire spacing. The size of the particle group is broader above the wire, in agreement with the simulation in Fig. 2(b). (b) A group of particles is moved vertically by the matrix over a longer range of five wire spacings. (c) Two groups of particles are moved diagonally to join them together at a single location. Particles can be moved diagonally at any angle. These experimental results agree well with the motion of peaks of the magnetic field magnitude shown in Fig. 2. Current was passed through all 14 wires for the demonstrations shown.

ments that are less than the wire spacing is in agreement with the continuous motion of the magnetic field peak shown in Fig. 2(a). Note that the size of the particle group is broadened above a wire in both experiment and theory. Figure 4(b) shows that a matrix can move a group of particles over a longer distance, five wire spacings for this case. Together, Figs. 4(a) and 4(b) demonstrate that the matrix can move and precisely locate magnetic nanoparticles anywhere on its surface. In Fig. 4(c) the matrix simultaneously moves two groups of particles diagonally and joins them into a single large group of particles, in agreement with the motion and joining of two peaks in the magnetic field shown in Fig. 2(b). Moving magnetic beads along a line has been recently demonstrated using a single layer micromagnetic system;¹² the device requires an external magnetic field and the particles move in steps of several hundred microns.

The microelectromagnet matrix is a versatile device, which can create complex static or dynamic magnetic field profiles for many experimental purposes. Using a matrix, we have demonstrated the trapping of particles at a desired location, the continuous motion of particles in two dimensions, and the simultaneous motion and joining of two separate groups of particles into one group. A matrix can also rotate magnetic particles above a fixed position utilizing time dependent current control.¹³ To control and manipulate semiconductor nanocrystals, microelectromagnets or microelectrode arrays could produce electric field peaks that interact with the particle's induced electric dipole moment.

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