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SINGLE DOMAIN MAGNETS IN BIO-MEDICAL APPLICATIONS

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INTRODUCTION: Miniaturizing mechanical, optical, magnetic, and electronic components is part of a MEMS research effort, with the goal of reducing the size of operating laboratory systems into sub-millimeter or even sub-micron dimensions. There are several factors that make magnetic components attractive for use in MEMS and bio-medical applications. Magnetic components can generally create larger forces at a larger distance than their electrostatic counterparts. Since magnetic devices are responsive to magnetic fields and field gradients generated by the current carrying wires, they also tend to be of low input impedance. In the sub-micron size range, magnetic objects are often in the single domain state where the magnetization can only be in two possible stable states. This fact can be exploited in a variety of applications if the challenges in fabrication can be overcome. Single domain magnets are by default permanent magnets, and require no energy to be magnetized by outside sources. Their small size also translates into large gradient magnetic fields that can be generated, and therefore large magnetic forces that can be applied. Additionally, the fact that the single domain magnets are permanently magnetized allows for both attractive and repulsive forces to be utilized. Based on these principles, several applications of single domain magnets to various technologies will be presented, including magnetic micro-manipulation of individual magnetic beads with micron resolution, micro-manipulation of single domain magnets and development of micro-fluidic micro-motors, utilization of magnetostatic interaction for micro-magnetic tweezers, and ultra-high gradient magnetic separation systems.

MAGNETIC MICROMANIPULATION OF INDIVIDUAL MAGNETIC BEADS: We recently introduced a new micromanipulation technique that utilizes integrated micro-coils and magnetic micro-tips for localized positioning of micron-sized magnetic objects [1]. The magnetic manipulator is shown in Fig. 1, and is fabricated by winding a 25 μm diameter copper magnet wire around a 50 μm diameter soft-ferromagnetic wire. The usual winding design consists of two coil layers with 6-8 turns each. In order to create high field gradients, soft ferromagnetic wire is electrochemically etched into a sharp probe in aqueous 40% sulfuric acid solution at 3 V. The tip is then positioned in the vicinity of the coil, as seen in Fig. 1, in order to be maximally magnetized by the coil fields. The micro-tweezer's tip was placed on a mechanical stage for positioning the tip above the viewing lens of the microscope. The coil component of the manipulator was connected to a programmable constant current source for tunable operation of the device. The samples to be manipulated were placed inside a rectangular cross section quartz capillary tube with 40 μm capillary wall thickness. White light illumination was coupled to the capillary tube from a 1 mm diameter optical fiber connected to a white light source. The capillary tube containing the magnetic particles was placed between the tip and the lens, and the micro-tip was positioned within several microns of the outside capillary tube surface.

Figure 1

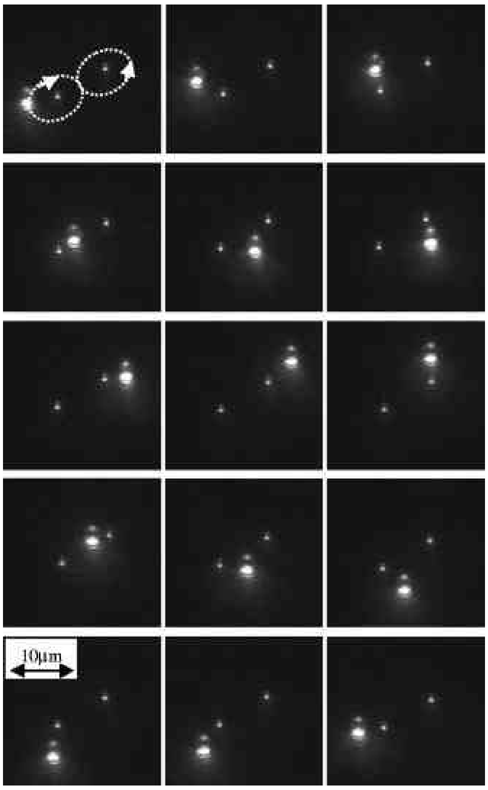

Figure 2

Figure 2 shows a composite of successive images of the magnetic bead manipulated so as to trace a "figure eight" around the non-magnetic beads. The non-magnetic polystyrene beads in the figure are 10 µm apart, and we are able to achieve sub-micron positioning resolution. One should also note the high dark background contrast in Figure 2 due to the illumination method used in the micromanipulation technique. Although the tip of the micromanipulator is very close to the particle, there is no observable scattered light from the manipulator tip, due to the total internal reflection at the outside capillary surface. Forces of 10 pN and sub-micron positioning control were demonstrated on the 2.8 µm diameter superparamagnetic beads.

ELECTRO-MAGNETIC MICRO-FLUIDIC MICROMOTOR


Figure 3

Manipulation of magnetic objects by the micro-manipulator described in the previous section was extended to applying torques and forces on a magnetic single domain particle inside a fluid, acting as a micro-fluidic micro-motor. Magnetic micro-motors with sub-millimeter dimensions have previously been fabricated by semiconductor processing techniques. We miniaturized and simplified the micro-motor design by arranging three micro-manipulator coils and tips into an equilateral triangle arrangement, as shown in Figure 3. This device acted as the three-phase stator of the micro-motor positioned outside of the fluid, while an individual single domain particle placed in a fluid acted as the rotor. The rotor was a cylindrical nickel particle, 40 µm long and 1 µm in diameter, and is fabricated by electro-deposition of nickel into a porous nano-channel glass membrane.

The electric currents through the three micro-coils were sinusoidally driven at a 120 degree phase difference in respect to each other (three-phase motor). This arrangement of the currents provided the sinusoidal attractive and repulsive forces to be applied to the magnetic rotor, resulting in the rotational motion of the single domain particle.

Figure 4 shows the composite sequence of images demonstrating one full rotation of the rotor.

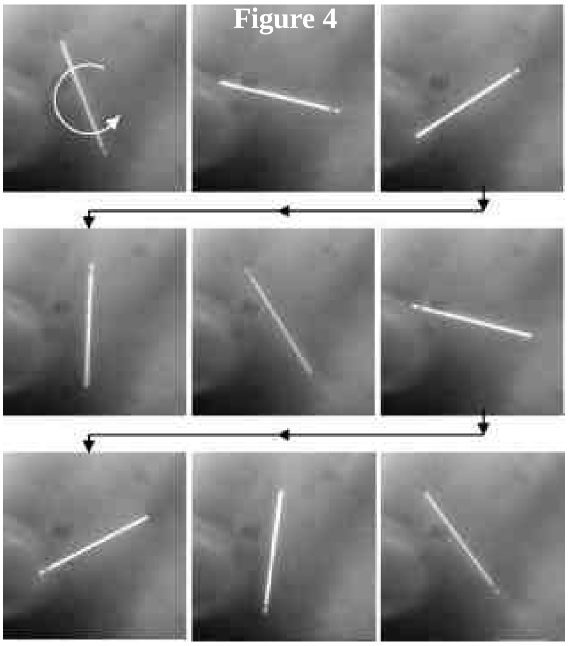
Figure 4

MAGNETIC MICRO-WIRE MAGNETO-STATIC TWEEZERS

Manipulation of magnetic micro-wires in fluid environments described in the previous section was extended into a regime where magneto-static interaction between two micro-wires is utilized for the construction of a magneto-mechanical tweezers system. The opposite poles of the micro-wires are attracted to each other, and form a natural clamping system. Figure 5 shows a sequence of images where the two magnetic nickel wires, 9 micro-meters long and 250 nm in diameter, are closed by the magnetic micro-manipulator.

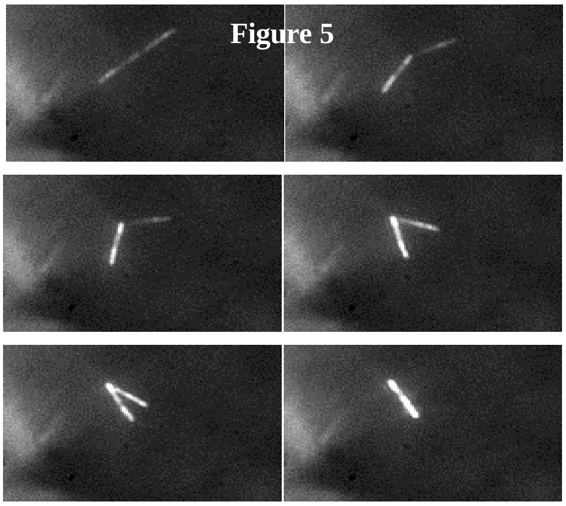
Figure 5

We developed several methods of opening and closing magnetostatic nanowire tweezers using hysteresis properties of this coupled magnetic system as well as using the localized manipulator of Figure 1.

ULTRA-HIGH GRADIENT MAGNETIC SEPARATION

In the described uses of magnetic wires in microfluidic applications, the magnetization of the wires has always been along the wire long axis. However, the wire can be a source of strong gradient fields along the entire length of the wire if the external field is used to orient the magnetization perpendicular to the wire long axis. This principle is often used in ultra-high gradient magnetic separation applications where a fluid of interest is passed through a magnetized wire mesh. A nanoporous membrane partially filled with magnetic wires can provide a potentially superior template for magnetic separation in bio-medical applications.

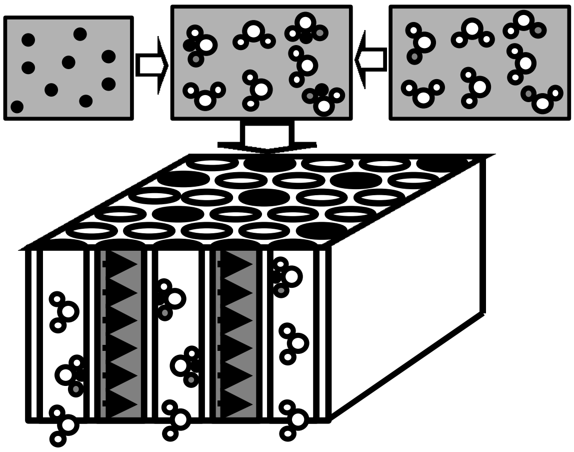

Figure 6

Figure 6 shows a simple example of applying a magnetic separation filter. The magnetic beads on the left are engineered to bind to the specific biological system (molecules, proteins, viruses, bacteria) and are mixed with the biological solution of interest on the right. After the binding process, the solution is passed through the partially filled ultra-high gradient magnetic separation filter. An external magnetic field is applied parallel to the filter surface in order to magnetize the ferromagnetic cylinders perpendicular to the wires' long axis. Inside the filter, the biological system bound to the magnetic bead is trapped on the walls of the capillaries while the unbound units are passed though. The trapped particles can later be released by removing the external magnetic field.

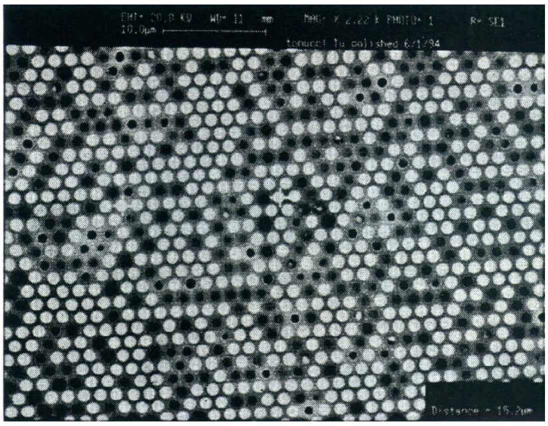

Figure 7

Figure 7 shows an example of a partially filled porous membrane that could be used for the described purpose.

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