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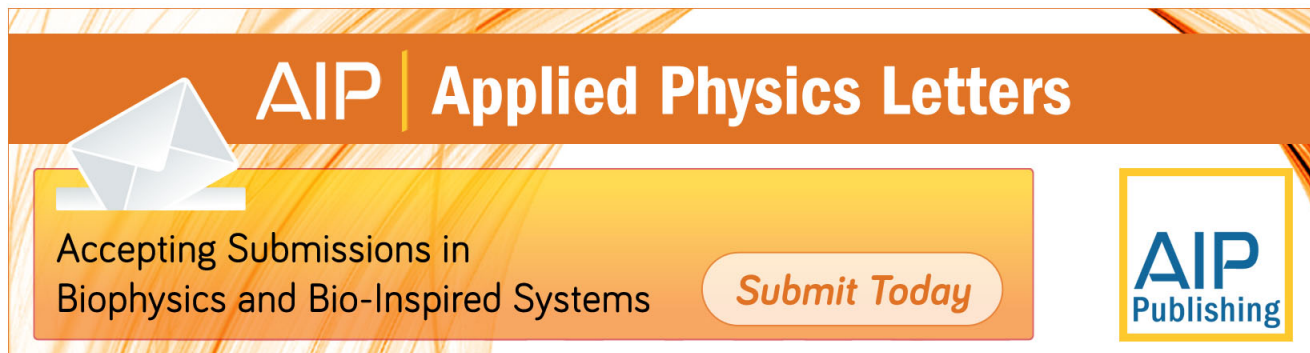
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Actuation and tracking of a single magnetic particle on a chip

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We present the defined actuation of a single magnetic particle on a crossbar array chip. Two orthogonal layers of parallel microwires are used to generate highly localized magnetic field gradients for particle trapping and movement. We introduce an analytical model to simulate the actuation of the particle, which is in precise agreement with the experimentally observed trajectory. The single-particle approach allows us to resolve subtle features of the induced magnetic field distribution. We demonstrate that the actuation strongly depends on the applied current sequence and introduce switching patterns for reliable control of an individual particle. © 2012 American Institute of Physics. [doi:10.1063/1.3673909]

Magnetic micro- and nanoparticles have been established as versatile tools in lab-on-a-chip applications.^{1,2} Due to their magnetic properties and small dimension, they offer possibilities to label, actuate, and separate on the micron and submicron scale.^{3–7} The force exerted on a particle with a magnetic dipole moment \mathbf{m} when exposed to a magnetic field \mathbf{B} is given by $\mathbf{F}_{\text{mag}} = (\mathbf{m} \cdot \nabla) \cdot \mathbf{B}$. For superparamagnetic particles, the magnetic moment is $\mathbf{m} = \mu_0^{-1} V \chi \mathbf{B}$, where μ_0 is the vacuum permeability, V is the volume of the particle, and χ is the magnetic susceptibility of the particle. Combining these two equations, the force on the particle can be expressed as $\mathbf{F}_{\text{mag}} = \mu_0^{-1} V \chi (\mathbf{B} \cdot \nabla) \cdot \mathbf{B}$. Hence, the particles are attracted by regions of high magnetic field strength. Magnetic tweezers with highly localized fields allow the precise control of even a single magnetic particle that can be used to study individual biomolecules.^{8,9} However, these techniques make use of external magnets that are difficult to integrate in lab-on-a-chip approaches. Alternatively, current carrying microwires^{10–17} or on-chip magnetic patterns in combination with switching external fields^{18–20} have been employed for localized particle actuation. A very flexible approach to control the position of magnetic particles on a chip without external magnets is given by microwire crossbar arrays as introduced by the group of Westervelt.¹¹ The microwires can be fabricated using standard lithography/lift-off technologies and are therefore easily integrated into chip-based devices. Particle actuation is achieved by driving appropriate current sequences through the orthogonally arranged microwire arrays, which generate magnetic field patterns on the chip. Lee *et al.* demonstrated that clouds of magnetic particles or biological cells can be actuated, separated, and combined with this approach.^{11–13} Here, we investigate on-chip actuation of an individual magnetic particle using a crossbar microwire array system. The single-particle approach allows defined trapping and movement without interference of particle-particle interactions. We introduce an analytical model for the actuation and demonstrate that the trajectory of the particle is in good agreement with our calcu-

lations. A current switching protocol with intermediate steps ensures that an individual particle is moved with 100% efficiency between source and target location.

Microwire arrays for particle actuation were fabricated in the clean room using standard microfabrication technology. Briefly, p-doped silicon wafers (Si-Mat Silicon Materials, Kaufering, Germany) were oxidized under wet conditions to grow 1 μm of silicon oxide for substrate insulation. The microwire arrays and contact pads were patterned via photolithography on the wafer using a double layer resist (LOR3B and NLOF2020, microresist technology, Berlin, Germany). After optical exposure and development (MIF326, microresist technology, Berlin, Germany), a stack of 10 nm Ti, 150 nm Au, and 7.5 nm Ti was deposited by electron beam evaporation followed by a lift-off in acetone. The structure was then insulated with a silicon oxide/silicon nitride/silicon oxide (ONO) layer (100 nm/50 nm/100 nm) using plasma enhanced chemical vapor deposition. Afterwards, a second microwire array was patterned orthogonal to the first array using the same fabrication steps as described above. A final top insulation layer of oxide and nitride (ONONONONONO; 150 nm/75 nm, respectively) was deposited to serve as a barrier for the liquid during magnetic actuation experiments. The individual microwires were processed at a width of 10 μm with an interwire spacing of 4 μm and the array consisted of two orthogonal layers of 17 wires each. A schematic of the chip's structure is shown in Fig. 1. The superparamagnetic particles used in this experiment were silanol terminated screenMAG particles with a hydrodynamic diameter of 1 μm (Chemicell GmbH, Berlin, Germany). These particles consisted of an iron oxide core (approx. 100 nm in diameter) suspended in a silica matrix.

The microwire arrays can be used to trap and actuate either single particles or clouds of several tens of particles. The latter were collected out of a homogeneous suspension of particles by passing a series of alternating horizontal and vertical currents (applied for 5 s each) through the wires surrounding the desired target cell. In order to deploy single particles into the magnetic trap, the particles were suspended in Milli-Q water and loaded into a glass micro capillary. This capillary was then brought into proximity to the active

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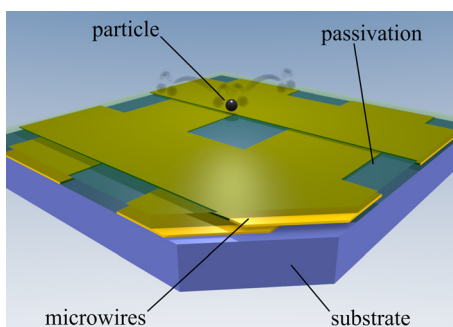


FIG. 1. (Color online) Schematic of the crossbar array chip. The microwires are processed on Si/SiO₂ substrates and are insulated by a silicon oxide/silicon nitride layer system (transparent). By controlling the current in the microwires, single particles (black) can be actuated on the chip's surface.

trap using x,y,z-micromanipulators. Subsequently, a gentle overpressure was applied to the capillary until a single particle was trapped. By changing the potential differences applied to each of the wires, the particle position was then manipulated as described below. To evaluate the experiments, the particle's motion was captured using a CCD camera (PL-B782U, PixeLINK, Ottawa, Canada) installed to the microscope setup. The video data obtained in this way was analyzed using digital image processing to determine the particle's position at different times during the experiment.

We investigated the influence of the applied current pattern on the actuation of a single particle from one cell of the array to another. To this end, switching between two magnetic traps on the chip was induced by different current protocols. Direct switching (switching the initial cell off and the target cell on in one step) yielded low transfer efficiencies and the particle was lost after several switching events. A linear switching protocol (ramping the currents from the initial to the target cell state) ensures a smoother transition of the magnetic field peak. Nevertheless, transition efficiencies of the particle are even lower than for the direct switching due to splitting of the peak during transition (see supplementary material²¹ for a more detailed description of direct and linear switching). In order to reliably move an individual particle, a current pattern with intermediate switching steps was introduced (see Figs. 2(a)–2(d)).

The simulation for this pattern shows that the peak of the magnetic field is gradually shifted from the initial to the target cell. In the experiments, we applied a repetitive sequence of the pattern for several tens of minutes with a minimum of 500 ms period between two states. Using this approach, we observed that a single particle reliably followed the magnetic field peak with 100% efficiency. To evaluate the stability and precision of the system, a single particle was moved repetitively in a small square on the array applying a current sequence with 1 s per state. The extracted positions were compared with an analytical simulation of the trajectory (see Figs. 3(a)–3(d)). For the simulation, we integrated over the cross-section of each current conductor and subsequently summed the contributions of all wires on the magnetic field. The particle trajectory was computed assuming that the magnetic and the viscous drag force are equal at all times (see supplementary material²¹ for a detailed description of the simulation). Figures 3(e) and 3(f) show plots of the simulated and experimentally determined x- and y-positions of the particle against time. As

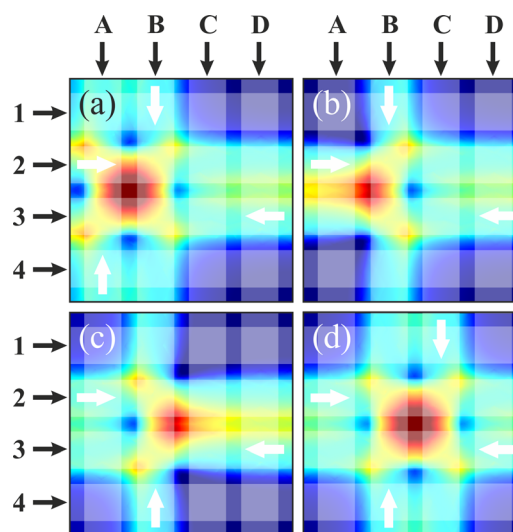


FIG. 2. (Color online) Simulated magnetic fields for the individual states in the switching protocol. The directions of the currents are indicated in white. The horizontal wires are labelled 1–4 and the vertical wires are labelled A–D. Additionally, the wires' positions are indicated by shaded regions. By introducing two intermediate steps with only three active wires, the peak in the magnetic field can be gradually moved from one cell to another (color scale: 1–10 mT; blue to red, respectively).

can be seen from the graphs, the experimental and simulated trajectories are in good agreement. Slight deviations are probably caused by discrepancies between the simulation and the experimental parameters. Comparing the graphs in Figs. 3(e) and 3(f), we observe a small difference in the lengths of the jumps in x- and y-directions for both experimental and simulated trajectories ($d_{x,\text{exp}} = 10.08 \pm 0.01 \mu\text{m}$, $d_{y,\text{exp}} = 10.53 \pm 0.02 \mu\text{m}$, and $d_{x,\text{sim}} = 10.68 \mu\text{m}$, $d_{y,\text{sim}} = 11.60 \mu\text{m}$). This effect is caused by the shape of the maximum in the magnetic field. Since the orthogonal microwire arrays are located in different layers, the y-oriented structures are $\sim 420 \text{ nm}$ closer to the chip's surface. Thus, the magnetic field exhibits a sharper peak in the y-direction and the particle has to move further to reach a stable condition. The single-particle approach allows us to reveal detailed features of the magnetic field such as the observed asymmetry and peak splitting (see supplementary information²¹). This information is lost with a cloud approach due to the repellent interactions of the individual polarized particles. The observed trajectory demonstrates the strong influence of small geometrical variations in the structure, which are taken into account in our analytical model.

In conclusion, we demonstrated reliable single-particle actuation using a chip-based microwire array system. Efficient current sequence patterns were developed and the corresponding time-dependent magnetic fields were calculated using an analytical model. We showed that the simulated trajectories of the particle matched the experimental traces, revealing even the subtle features of the magnetic field pattern due to the single-particle approach. By applying appropriate current sequences, individual particles were reliably moved over the chip's surface with a step size in the low micrometer range. While the maximal actuation distance is mainly limited by the geometrical layout of the device, efficiency, step-size, and precision can be tuned by the magnetic switching pattern. We believe that our approach opens up the possibility for various on-chip applications involving the

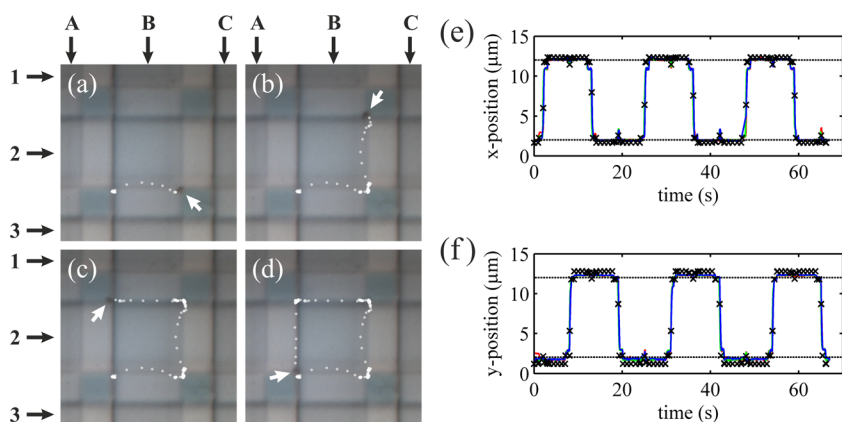


FIG. 3. (Color online) (a)-(d) Image series of a single particle moving in a square of four cells on the array. The particle's current position is marked by a white arrow, whereas previously detected positions are shown as white dots. The horizontal wires are labelled 1-3, while the vertical wires are labelled A-C. (e)-(f) Plots of the x- and y-positions against time of three experiments in which a single particle is lapping the square three times (lines) and the simulated data (symbols). The edges of the corresponding horizontal and vertical wires (wires 2 and B, respectively) are marked by a dashed line at 2 and 12 μm , respectively (enhanced online) [URL: <http://dx.doi.org/10.1063/1.3673909.1>].

manipulation of individual cells *in vitro*. For example, being able to control a single particle allows for precise stimulation of mechanosensitive cells with subcellular resolution.

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²¹See supplementary material at <http://dx.doi.org/10.1063/1.3673909> for simulation details and switching protocols for magnetic actuation.