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TI Magnetophoretic Capacitors for Storing Particles and Cells in a Tri-Axial Magnetic Field

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ABSTRACT: One of the main goals in the field of lab-on-a-chip is the manipulation of microparticles and cells on microfluidic chips. Methods based on magnetic forces, with remote controllability over particle movement, are considered one of the most appealing techniques toward this goal. Recently, inspired by electronic circuits and to transport particles in a controlled fashion in a tri-axial magnetic field, magnetophoretic circuits based on TI-shaped magnetic thin films are introduced. However, to date, capacitors are not used in order to store transported particles in these circuits. Here, TI magnetophoretic capacitors are introduced and characterized. The capability of the capacitor for storing particles of different sizes at various rotating magnetic field frequencies is studied. Towards this goal, finite element methods are used to simulate the magnetic potential energy distribution created by the magnetic thin films. Also, the trajectory of the magnetic particles, considering the drag forces, based on semi-analytical analysis and statistical methods, is investigated. The simulation results are validated experimentally. At the operating frequency of 0.1 Hz loading efficiency of 98% was achieved. Adding this circuit element to the magnetophoretic circuits results in a complete chip, with important applications in lab-on-a-chip systems, single-cell biology, and drug screening.

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1- Introduction

Manipulation of microparticles is of interest in many fields, such as biomedical engineering and colloid science. Towards this goal, many methods have been proposed, among which the magnetophoretic circuits are considered a novel promising approach [1, 2]. In these circuits, a magnetic thin film is patterned on a chip, which then gets magnetized in an external magnetic field and precisely transports magnetic particles on it. These circuits are composed of different circuit elements, including conductors, capacitors, and transistors, and offer various particle manipulations such as particle transport, storage, and retrieval.

A recent version of magnetophoretic circuits is based on the TI design [3]. These chips operate in a triaxial magnetic field, with a vertical bias field, in which a repulsive force between the particles prevents them from forming clusters and clogging the chip. Although TI conductors, which transport the particles are already proposed, TI capacitors, where the particles can be stored, are not presented yet. In this work, for the first time, these capacitors are introduced and characterized. We use experimentally validated simulations to find the proper operating frequencies, the performance of the proposed capacitors, and the particle average velocities. With the proposed capacitors, fully operational magnetophoretic circuits can be designed to manipulate particles.

2- Theory and Simulations

A semi-analytical model is used to simulate the magnetic forces. In this method, each magnetic bar (i.e., the I bar and the head and body segments of the T pattern) is modeled as an oblate spheroid [4]. Then, the obtained magnetic potential is used to calculate magnetic potential energy using Equation (1).

$$U = \frac{1}{2}\mu_0 V_p \left(\chi_p - \chi_f\right) H^2 \quad (1)$$

where μ0, V_p, χ_p, χ_f, and H stand for the magnetic permeability of the particle, the volume of the particle, the magnetic susceptibility of the particle, the magnetic susceptibility of the surrounding fluid, and magnetic field intensity, respectively. Then, the magnetic force acting on this particle is calculated based on Equation (2).

$$\vec{F} = -\nabla U \quad (2)$$

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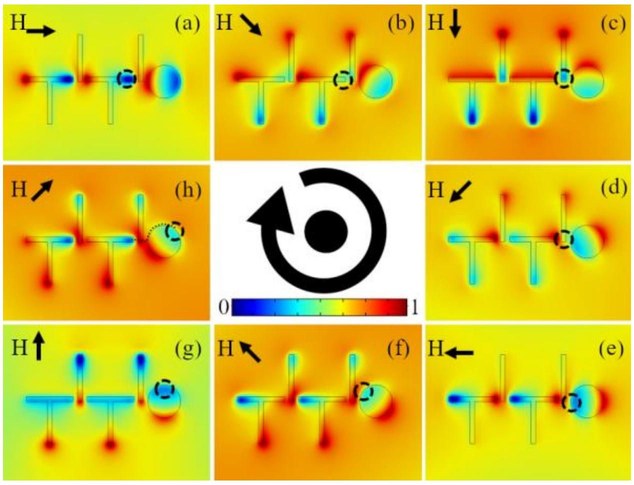

Fig. 1. Energy distribution simulation results for the proposed capacitor based on a magnetic disk. In each panel, the direction of the magnetic field is shown with a black arrow.

The particle velocity is then calculated based on Stokes's law for small particles in a fluidic environment, based on Equation (3).

$$\vec{v} = \frac{\vec{F}}{6\pi\eta_f r_p} \quad (3)$$

where η_f and r_p stand for the viscosity of the fluid and the particle radius, respectively. Calculating the velocity at each time point gives us the particle position at the next time point.

In our simulations with COMSOL software, stationary analysis, and magnetic field physics were chosen. After defining the materials (permalloy with magnetic permeability of 100,000 for the magnetic thin films), a proper mesh to achieve a converged solution was chosen. Then, the boundary conditions (external magnetic field) were defined, before running the calculations.

To fabricate the chips, NFR16D2 photoresist was deposited on silicon wafers and then exposed to UV light. After development, a 5nm thin film of titanium and a 100nm thin film of permalloy were deposited on the chips, using the metal evaporation technique. After a lift-off process, the chips became ready to be used in experiments.

3- Results and Discussion

A TI pattern was fabricated and used for manipulating the particles. The trajectories of particles were recorded experimentally and compared with the ones obtained in simulations. After validating the simulation results, the operation of the capacitor design shown in Figure 1 was evaluated. Our simulation results show that by applying a magnetic field along a magnetic bar or a disk, two magnetic poles with low energies form on both sides, one of which disappears by superimposing a vertical bias field. In a periodic TI magnetic pattern, a rotating in-plane magnetic field, at any angle creates a magnetic pole at the tip of the bars aligned toward the field direction (See Figure 1, where the blue and red regions represent the area with low and high energies, respectively). The successive poles form closely and hand over their follower magnetic particles along the magnetic track towards the magnetic disk (circular pattern in Figure 1). When the particle approaches the disk, it moves to the pole formed by the disk and then circulates it. By further rotating the magnetic field, the particle remains close to the disk. Hence, this geometry behaves as a capacitor, which stores the particles. In Figure 1, the position of the particle at each time point is depicted with dashed circles. The dotted line in Figure 1h represents the particle trajectory. It shows that the particle has moved from the right tip of the T bar in Figure 1a to the upper right side of the circle in Figure 1h.

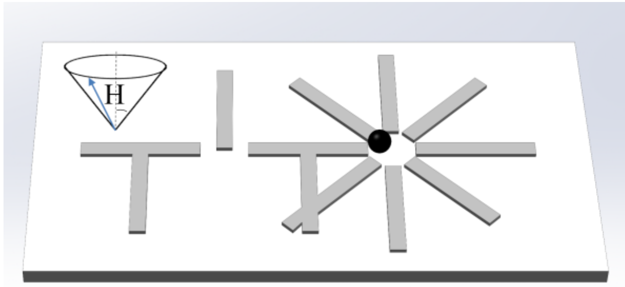

Fig. 2. Schematic of the proposed capacitor based on I bars. H shows the applied magnetic field. The sphere represents a stored particle.

The ratio of the diameter of the particle to the gap between the TI pattern and the disk is an important parameter for device operation. Based on our achieved results, for proper particle transport along the magnetic track and storage in the capacitor, this ratio cannot be smaller than 1.6.

Another important parameter to be studied is the applied magnetic field frequency. At high frequencies, particles need to move faster to follow the poles, which results in higher drag forces. Based on our studies, at frequencies of 0.1Hz, the particles could move smoothly, and a capacitor loading efficiency of 98% is achieved. At this frequency, the capacitor loading rate is 5.88 particles per minute.

Since the conducting path is composed of the I bars, it may be more interesting to form the capacitors based on them. A three-dimensional (3D) **schematic** of this design is presented in Figure 2. In this design, as opposed to a magnetic disk, the I bars are placed in a circular arrangement. Our simulation results show that the particle moves on the internal perimeter of the capacitor pattern. The ratio of the particle diameter to the gap size for this design to operate properly needs to be greater than 2.6.

In the proposed chips, the position of the particles is synched with the external magnetic field. Hence, the particle velocity is a function of the magnetic field frequency. The movement of the particles is analogous to the movement of electrons in electrical circuits, where electrical current is proportional to the externally applied electric voltage difference (Ohm's law). Assuming the magnetic pattern periodicity and the magnetic field frequency to be 26 µm and 0.1 Hz, respectively, the average particle velocity on this chip is 2.6 µm/s.

4- Conclusion

Magnetophoretic circuits with the ability to precisely transport microparticles offer many important capabilities to lab-on-a-chip systems. In this work, two magnetophoretic capacitors for the circuits based on the TI pattern were introduced for the first time. In the first design, a magnetic disk plays the capacitance role. By choosing a small disk, compact circuits can be designed. But since the particles move in the perimeter of the disk, a small perturbation may distract it from its position. In the second design, magnetic I bars in a circular arrangement form the capacitor. This capacitor stores the particles internally and can better protect them against possible perturbations. But this design occupies a larger area on the chip. At low frequencies, the particle transport is less affected by the drag forces and higher efficiencies can be achieved. Based on our simulations, at the operating frequency of 0.1 Hz, a particle loading efficiency of 98% resulted. The proposed capacitor can be used in designing fully operational magnetophoretic circuits, with crucial applications in single-cell biology and medicine.

References

[1] B. Lim, V. Reddy, X. Hu, K. Kim, M. Jadhav, R. Abedini-Nassab, Y.W. Noh, Y.T. Lim, B.B. Yellen, C. Kim, Magnetophoretic circuits for digital control of single particles and cells, Nat Commun, 5 (2014) 3846.

[2] R. Abedini-Nassab, D.Y. Joh, M.A. Van Heest, J.S. Yi, C. Baker, Z. Taherifard, D.M. Margolis, J.V. Garcia, A. Chilkoti, D.M. Murdoch, B.B. Yellen, Characterizing the Switching Thresholds of Magnetophoretic Transistors, Adv Mater, 27(40) (2015) 6176-6180.

[3] R. Abedini-Nassab, S. Bahrami, Synchronous control of magnetic particles and magnetized cells in a tri-axial magnetic field, Lab Chip, 21(10) (2021) 1998-2007.

[4] J.A. Stratton, Electromagnetic Theory, McGraw-Hill Book Company, Inc, 1941.

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