1-1-2006

A 3-D microelectrode system for dielectrophoretic manipulation of microparticles

Dafeng Chen
Nanyang Technological University, Singapore

Hejun Du
Nanyang Technological University, Singapore

Haiqing Gong
Nanyang Technological University, Singapore

Weihua Li
University of Wollongong, weihuali@uow.edu.au

Institute of Physics Publishing Journal of Physics: Conference Series **34** (2006) 1008–1013
doi:10.1088/1742-6596/34/1/167 International MEMS Conference 2006

A 3-D Microelectrode System for Dielectrophoretic Manipulation of Microparticles

D.F. Chen[1], H. Du[1,*], H.Q. Gong[1], and W.H. Li[2]

[1]School of Mechanical & Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798

[2]School of Mechanical, Materials & Mechatronic Engineering, University of Wollongong, NSW 2522, Australia

[*]Corresponding author: mhdu@ntu.edu.sg

Abstract. This paper presents a microfluidic system for manipulation and separation of micron-sized particles based on the combined use of negative dielectrophoresis (DEP) and hydrodynamic forces. A 3-D microelectrode structure (so called paired electrode array) are constructed face to face on the top and bottom sides of the microchannel and driven with high-frequency AC voltage to generate dielectrophoretic gates. Depending on the relative strengths of the two forces, particles such as polystyrene beads or cells carrying by a laminar flow can either penetrate the gate or settle there. This gives rise to certain applications including selectively concentrating particles from the flow, separating particles depending on their sizes or dielectric properties, and automatically positioning particles to selective locations. For this purpose, a microfluidic device consisting of the paired electrode array sitting on the channel has been fabricated using microfabrication techniques. Polystyrene beads were used to study the performance of the device. Experimental results including the concentration and separation of particles are presented.

1. Introduction

There is great interest in the development of microdevices for effective microparticle manipulation and separation in very small volumes. It has been shown that dielectrophoresis (DEP), which arises from the interaction of non-uniform AC electric field with the induced dipole in the particle [1], can be used for the analysis and separation of a variety of microscopic particles. Depending on the dielectric properties of the particles and medium, particles are either attracted to regions of high field strength (positive DEP) or repelled from them (negative DEP) [2]. According to the dipole theory, the DEP force is proportional to the gradient of the electric field square. To generate the required nonuniform electric field, a variety of electrode designs have been proposed, including planar designs such as interdigitated electrode arrays (IDA) [3, 4], polynomial design [5], and castellated design [6].

This paper presents a microfluidic device comprising a three-dimensional electrode structure for separation and accumulation of micron-sized particles based on negative DEP and hydrodynamic force. Compared to the planar electrodes, the 3-D electrode arrangement provides a more confined electric field distribution, which overcomes the particle escape problem in the planar electrodes. The electrode structure is constructed by aligning two layers of microelectrodes face to face on the top and bottom sides of the microchannel. Dielectrophoretic gates are generated with a high-frequency AC

voltage applied on the electrode pairs. Particles carrying by the fluid can be deflected by the gate, or run through the gate, giving rise to particle accumulation and separation. Polystyrene beads of different sizes are used to study the performance of the device. Experimental results including the concentration and separation of the particles are presented. In combination with a flow, the present microsystem shows the advantage that particles are manipulated in a continuous flow and in a rapid processing time.

2. Theoretical background

The DEP force arises from the interaction of non-uniform electric field with the induced dipole in the particle. For a spherical dielectric particle, the time-averaged force on the particle in AC electric field is given by [1]

$$F_{\mathrm{DEP}} = 2\pi\varepsilon_m a^3 \mathbf{Re}\left(f_{cm}\right)\nabla E^2 \tag{1}$$

where ε_m is the permittivity of the surrounding medium, a is the particle radius, E is the root-mean-square (rms) value of the electric field, and f_{cm} is the Clausius-Mossotti factor.

Negative DEP ($\mathbf{Re}(f_{\mathrm{cm}}) < 0$) takes place when the particle is less polarizable than the suspending medium [1]. In the case of planar electrode sitting on the bottom of the channel, particles are repelled away from the electrode and carried away in the presence of a flow. In this paper, a second layer of electrodes on the top is used and aligned face to face with the bottom electrode, forming the paired microelectrode system [7], as shown in Figure 1. With ac voltage applied on the electrode pairs, dielectrophoretic gates are formed between them. In the present of a flow, particles can either be collected at the end of the electrode or penetrate the gate. This depends on the relative strength of the DEP force (Eqn 1) and the drag force on the particle

$$F_{\mathrm{HD}} = 6\pi\eta a v \tag{3}$$

where η is the viscosity of the fluid, v is the flow velocity.

The two force components are acting on the particle simultaneously and compete against each other. The particles will be deflected from the direction of flow as long as $F_{\mathrm{DEP}} > F_{\mathrm{HD}\perp} = 6\pi\eta a v \sin\theta$. The velocity of flow is

$$v < v_{th} \tag{4}$$

with $v_{th} = \dfrac{F_{\mathrm{DEP}}}{6\pi\eta a \sin\theta}$, the maximum allowed velocity or threshold velocity.

It implies that the threshold velocity depends on a number of parameters, including the DEP force, fluid viscosity η, particles size a, and the aligning angle θ of the electrode. At the velocity higher than v_{th}, particles will penetrate the gates and move along with the flow. Different particles have different threshold velocities, meaning that adjusting the flowrate can separate them.

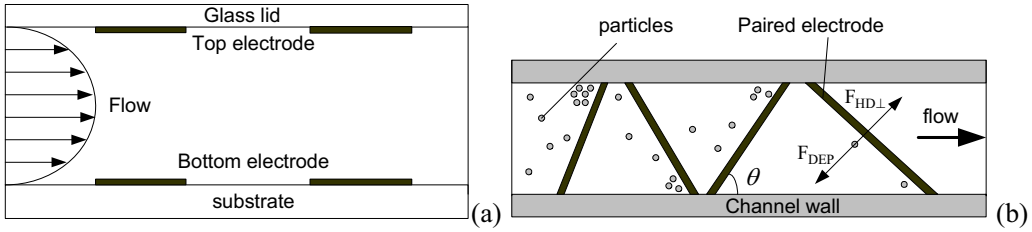

Figure 1. (a) Schematic diagram of paired microelectrode system (cross section). (b) The paired electrode system (top view) used for particle accumulation and separation in this paper.

3. Materials and microfabrication

3.1. Microparticles and media.

Polystyrene particles (cross-linked with 4 to 8% divinylbenzene DVB) of radius 4.8 μm and 8.0 μm from Duke Scientific Co. (CA, USA) were used in the investigation. Before use, the particles were re-suspended at low concentration in de-ionized water. Conductivity of the medium was adjusted by adding phosphate buffer solution. The conductivity was measured using a conductivity meter with graphite sensor electrodes (Dist3WP, Hanna Instruments Inc., RI). Medium conductivity from 1 mS/m to 10 mS/m was used.

3.2. Microfabrication and packaging

The microfluidic system comprising 3-D microelectrodes was fabricated using conventional microfabrication techniques (Figure 2). The fabrication began with a 4-inch glass wafer (Pyrex 7740) and a silicon wafer with 1 μm silicon dioxide (SiO_2) thermally grown on the surface as the insulation layer. The electrode layer of 25 nm Cr/ 100 nm Au was deposited using magnetron sputtering process, and patterned with lift-off technique. An ultrasonic source was used to expedite the lift-off process. To fabricate the fluidic inlet and outlet of 600 μm in diameter, the silicon wafer coated with microelectrodes on the surface was etched through using ICP deep reactive ion etching. Meanwhile, a microchannel of 75 μm in height, 800 μm in width was constructed using the epoxy-based photosensitive resist SU-8. SU-8 was used for it can yield very well defined channel structure. For bonding, alignment marks were defined on the two chips previously in the microelectrode fabrication step. The electrode face-to-face alignment were performed under an optical microscope and found to be of micrometer precision.An epoxy-based adhesive with 3 hours curing time was used. The adhesive provided a bond of good coverage, high bonding strength, and small adhesive thickness. Typical thickness of the adhesive layer less than 2 μm was determined by microscopic examination of the cross-section of a sample.

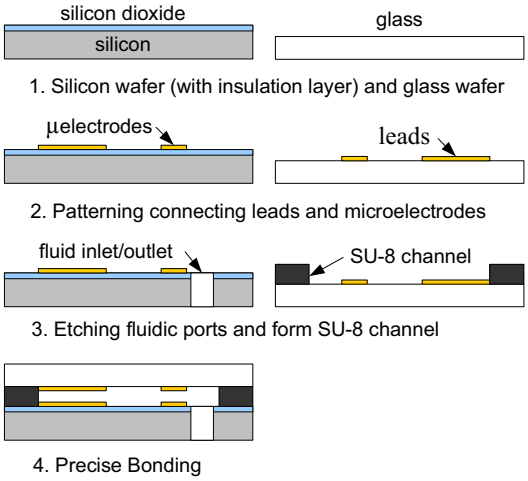

Figure 2. Microfabrication of the DEP device.

A completed DEP-based microfluidic system comprising the 3-D microelectrode array is shown in Figure 3. Two diced slides containing planar electrode arrays were bonded together with electrode precisely aligned facing each other. Polypropylene fittings attached to the holes on the bottom slide server as fluidic ports. A PMMA block with fluidic holes cut in was used to as a mechanical support for the system. One advantage of this package is low profile, in that there are no protrusions above the plane of the top slide, which makes it easy to mount the package under a conventional microscope for observation.

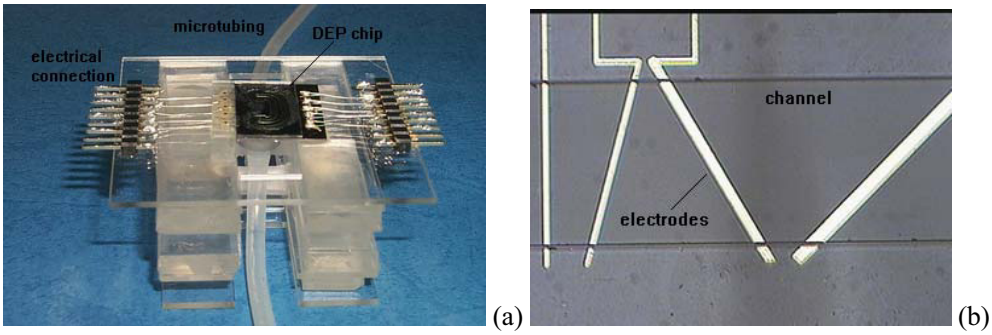

Figure 3. The microfabricated microfluidic system comprising 3-D deflector array. The insert (b) shows an array of electrodes of different width and aligning angles (top view).

3.3. Electrical excitation and fluidics

Sine wave excitation up to 20 MHz and 15 V_{pp} (into 50 Ω) was generated by a Wavetek 90 Function Generator (Wavetek Wandel & Goltermann, Inc., NC, USA). Fluidic connection to the package was made via fitting and silicone tubing (Cole-Parmer, In. Co, Illinois). A syringe pump (Model NE-1000, New Era Pump System Inc, NY, USA) was used for precise control of the buffer and particle stream at a flowrate of 10 – 500 µl/hour, in combination with a four-way valve (V-101D, Upchurch Scientific, Oak Harbor, WA) and an injection valve (V450, Upchurch Scientific, WA).

4. Results and discussion

4.1. Threshold velocity

The threshold velocity was measured in a bi-directional manner, in which the flowrate was gradually increased up to the point where particles held began to penetrate the electrode, and the flowrate was gradually decreased down to the point where particles began to stop at the gate. The flowrate was readily set through keypad of the syringe pump. The average value of the measurements was used.

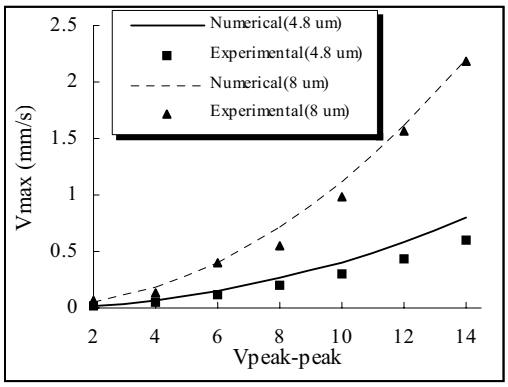

Figure 4. Threshold velocity for the latex particles with radius of 4.8 µm and 8.0 µm, respectively. The aligning angle was 45^0 and electrode width was 40 µm. Both the numerical values and measured values are shown.

Figure 4 shows the threshold velocity for the latex particles with radius of 4.8 µm and 8.0 µm, respectively. The velocity was calculated from $V_{\max} = 1.5Q_{fr}/(w \times h)$, where Q_{fr} is the flowrate (µl/hour) indicated from the syringe pump; w and h are the width and height of the channel,

respectively. The threshold velocity was higher for larger particle, and increased with higher applied voltages. Different particles can be separated on the basis of the difference in the threshold velocity.

4.2. Particle accumulation and separation

All the particles will be deflected by the dielectrophoretic gate at the flowrate lower than the threshold velocity. Since the particles have lateral movement along the electrode caused by the hydrodynamic force, particles will be collected at the location formed by the electrodes and channel wall. Figure 5 shows the two types of particles with radius of 4.8μm and 8.0 μm accumulated by the paired electrode array. A flowrate of 50 μl/hour resulting in a mean flow velocity of ~213.5 μm/s was used, which was below the threshold velocities of both the particles. The electrode width was 60 μm and the electrode was aligned at 45^0 with respect to direction of the flow. The flow was running from the left to the right. The particles running with the flow were stopped by the paired electrode structure when they were near the electrode, and continued to move in the direction parallel to the electrode, till to the collection area as indicated by 'A' in Figure 5. It was noticed that the accumulated particles were in high concentration. The accumulation was enhanced by the previously collected particles, probably due to the dipole-dipole interaction. They can be released from the accumulation area by either turning off the applied voltage or reversing the direction of the flow.

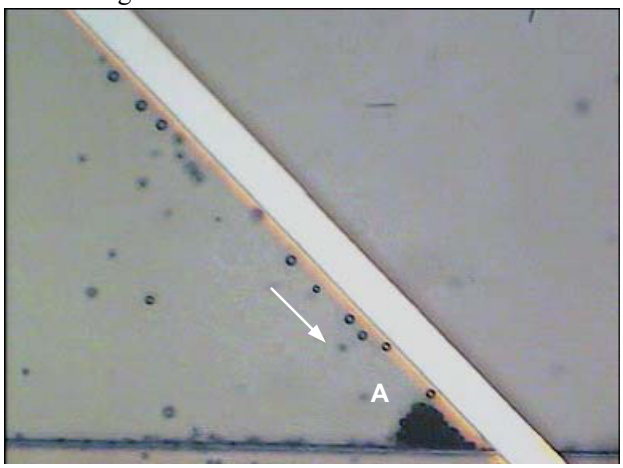

Figure 5. Particles were collected by the paired electrode array at the flowrate of 50 μl/hour.

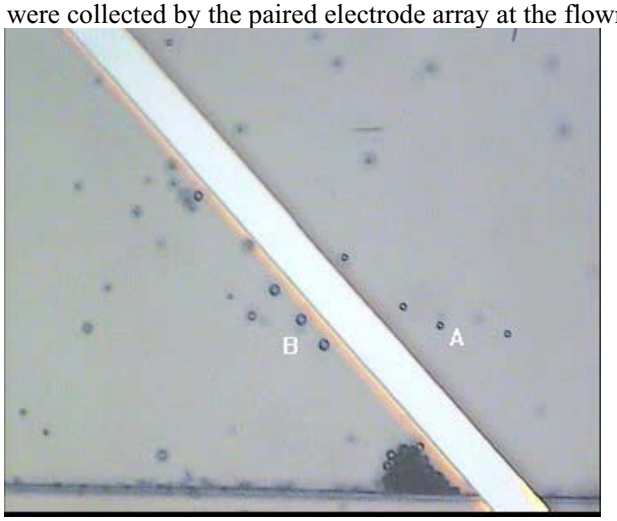

Figure 6. Particles of 4.8 μm penetrated the gate and were carried away by the flow.

As the flowrate was increased, the particles had the potential to escape from the collection area and run through the dielectrophoretic gate. As discussed in 4.1, the smaller particles (4.8 μm) will first begin to penetrate the gate since they have lower threshold velocity. Using a proper flowrate, which is between the threshold velocities of the two particles, can separate them into two subpopulations. Figure 6 shows the separation of the two particles using the paired electrode system. At the flowrate of 120 μl/hour, the particles of 4.8 μm (indicated by 'A') escaped and ran through the gate, while the other particles of 8.0 μm ('B') remained in the collection area. The 4.8-μm particles were carried by the flow to the external container via the outlet. Then particles of 8.0 μm were collected by turning the voltage off. In this way, particles of different sizes were successfully separated. Note that it would also be possible to separate particles of equal sizes but with different dielectric properties.

5. Conclusion

A DEP-based microfluidic device for separation and accumulation of micro-sized particles has been presented. Two layers of microelectrode structures were constructed face to face on the top and bottom sides of the microchannel and driven with high-frequency AC voltage to generate dielectrophoretic gates. Threshold velocity of particles with radius 4.8μm and 8.0 μm respectively was studied. The velocity at which the gates still work depends on a number of parameters such as channel height, particle size, electrode width etc. The microfluidic device consisting of the paired electrode array sitting on the channel has been fabricated using standard microfabrication techniques. Particle accumulation and separation have been achieved with the microfabricated device. The present system has potential applications in separating particles differing in sizes or dielectric properties.

Reference

[1] T. B. Jones, *Electromechanics of particles*. Cambridge ; New York: Cambridge University Press, 1995.

[2] H. A. Pohl, "Dielectrophoresis," *Cambridge University Press*, 1978.

[3] H. B. Li and R. Bashir, "Dielectrophoretic separation and manipulation of live and heat-treated cells of Listeria onmicrofabricated devices with interdigitated electrodes," *Sensor Actuat. B - Chem.*, vol. 86, pp. 215-21, 2002.

[4] D. F. Chen, H. Du, W. H. Li, and C. Shu, "Numerical modeling of dielectrophoresis using a meshless approach," *J. Micromech. Microeng.*, vol. 15, pp. 1040-1048, 2005.

[5] Y. Huang and R. Pethig, "Electrode design for negative dielectrophoresis," *Meas. Sci. Technol.*, vol. 2, pp. 1142-6, 1991.

[6] R. Pethig, Y. Huang, X. B. Wang, and J. P. H. Burt, "Positive and negative dielectrophoretic collection of colloidal particles using interdigitated castellated microelectrodes," *J. Phys. D: Appl. Phys.*, vol. 25, pp. 881-8, 1992.

[7] T. Schnell, T. Muller, G. Gradl, S. G. Shirley, and G. Fuhr, "Paired microelectrode system: dielectrophoretic particle sorting and force calibration," *Journal of Electrostatics*, vol. 47, pp. 121-132, 1999.