Dielectrophoresis (DEP) Based Microfluidic Particle Separator

Zhuxin DONG

Abstract-This report introduces a microfluidic system for manipulation and separation of micron-sized particles based on the combined use of negative dielectrophoresis (DEP) and hydrodynamic forces. A 2-D micro-electrode structure has been constructed on the bottom surface on glass wafer 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 carrying by laminar flow can either penetrate the gate or settle down 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 an electrode array sitting on the channel has been fabricated using micro-fabrication techniques. Polystyrene beads were used to study the performance of the device. Experimental results including the concentration and separation of particles are presented.

I. 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 two-dimensional electrode structure for separation and accumulation of micron-sized particles based on negative DEP and hydrodynamic force. The electrode structure is constructed by aligning one layer of microelectrode on the 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.

II. Theoretical Background [7]

A. Theory

DEP is a phenomenon in which a force is exerted on a dielectric particle when it is subjected to a non-uniform electric field. This force does not require the particle to be charged. All particles exhibit dielectrophoretic activity in the presence of electric fields. However, the strength of the force depends strongly on the medium and particles' electrical properties, on the particles' shape and size, as well as on the frequency of the electric field. Consequently, fields of a particular frequency can manipulate particles with great selectivity. This has allowed, for example, the separation of cells or the orientation and manipulation of nanoparticles and nanowires.

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

$$F_{DEP} = 2\pi\varepsilon_m r^3 Re(f_{cm})\nabla E^2 \qquad (1)$$

where ε_m is the permittivity of the surrounding medium, r is the particle radius, E is the root-mean square (RMS) value of the electric field, and fcm is the Clausius-Mossotti factor.

Negative DEP 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. 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 (Eq. 1) and the drag force on the particle:

$$F_{Drag} = 6\pi\eta r v \qquad (2)$$

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

B. *Verification of Negative DEP*

DEP can be further classified by direction. If the force is in the direction of increasing field gradient, it is termed positive DEP. Its opposite effect, negative DEP, acts to repel the particle from regions of high electric field, moving it "down" the field gradient. Whether a particle experiences positive or negative DEP is dependent on its polarizability relative to its surrounding medium; differences in the quantity of induced charge at the interface between particle and medium lead to dipoles oriented counter to the applied field (and hence positive dielectrophoresis) where the polarizability of particle is more than that of the medium, and in the same direction as the applied field (and hence negative dielectrophoresis) where it is less. Since relative polarizability is a complex function dependent not only on the permittivity and conductivity of the particle and medium, but also on the applied field frequency, it has a strong frequency dependence and particles may experience different dielectrophoretic behavior at different frequencies.

In other words, negative DEP, which is going to be applied in the separator, takes place when $Re(f_{cm}) < 0$. Eq.3 gives the method how to calculate the Clausius-Mossotti factor. Then we substitute the parameters of the particle – Polystyrene beads, and the medium – DI water as shown in Tab.1. Finally, we can conclude during what frequency range of the AC power the negative DEP can be guaranteed. From Fig.1, it is obvious that frequency in unit of MHz is proper to generate negative DEP for Polystyrene bead as particle while DI water as the medium.

$$f_{cm} = \frac{\varepsilon_p^* - \varepsilon_m^*}{\varepsilon_p^* + 2\varepsilon_m^*} \qquad (3)$$

where, ε^* is the complex dielectric constant $\varepsilon^* = \varepsilon + \frac{\sigma}{jw}$, σ is the electrical conductivity, w is the angular frequency and j is the imaginary number.

Tab.1. Parameter constant of particle and medium

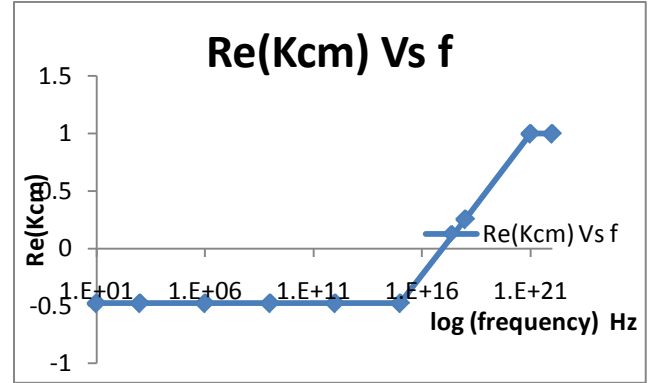| item	dielectric constant	electrical conductivity
polystyrene (p)	2.5	1.00E-16
DI water (m)	78	5.00E-03

Fig.1. Real part of the Clausius-Mossotti factor versus frequency

C. *Condition of Separation*

Fig. 2 & 3 illustrate the design of the electrode for the separator and acting force analysis of a particle. The two force components are acting on the particle simultaneously and compete against each other. The particle will be deflected from the direction of flow as long as $F_{DEP} > F_{Drag\perp} = 6\pi\eta r v(\sin\theta)$. If flow velocity v is less than v_{th}, where $v_{th} = \frac{F_{DEP}}{6\pi\eta r(\sin\theta)}$, the particle will be deflected. Since F_{DEP} is proportional of cubic r, it implies that the bigger the radius is, the larger v_{th} the particle has. Therefore, we can conclude that eventually, those particles with smaller radius can penetrate the electrode array first when the flow velocity keeps increasing.
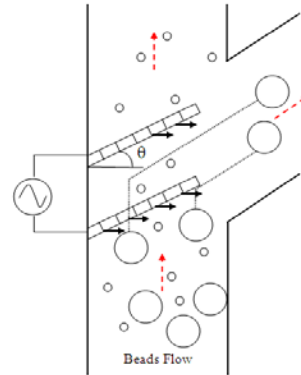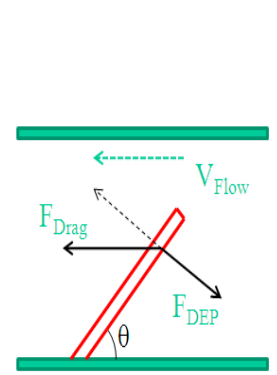

Fig.2. Design of the separator   Fig.3. Force analysis on top-view

III. µChannel

A. Size of µChannel

The µchannel is fabricated on a glass wafer and the electrode, made up of Cr and Au, is deposited and patterned on the top. Then a PDMS layer extruded with channel shape in advance is used as the top lid for the channel. Each channel is 1cm long, 800µm wide and 75 µm high. Fig.4 illustrates the dimensions of the channel.
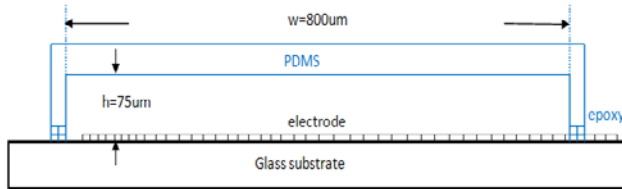

Fig.4. Cross-section view of the µchannel

B. Fabrication of Electrode

To fabricate micro-electrode for separating usage on a glass wafer, first of all, two layers of metal are deposited by evaporation. The first one is Cr layer, 25nm thick; the other is Au layer, 100nm thick. Then 4µm thick AZ4330 positive photo-resist layer is coated and patterned by photolithography. Then the metals are etched. Finally, after stripping off the rest of photo-resist, the electrodes are ready. Fig.5 shows the MEMS technique process to fabricate the electrode, where all the procedures are done in HiDEC. Fig.6 illustrates the electrodes on the wafer. Actually, there are six different shapes for the electrodes. They can be divided into 3 main parts: 30°, 45° and 60°, which give the decline angles. For each angle type, there are parallel and not-parallel ones for each pair of electrode.

C. PDMS Top Lid

PDMS is poured and cured on an Al base mode, which can be fabricated by a Computer Numerical Control (CNC) machine. Before fabrication, the mode of the aluminum base is designed by SolidWorks as shown in Fig.7. The SolidWorks .part file is converted into another one by MIL to be read by CNC. After that, a rectangular aluminum slide is ready to be fabricated. At last, the channel shape on the aluminum surface is examined by DEKTAK and Fig.8 illustrates the result: 2mm long to scan the channel cross-section, the width of channel is about 700µm and the height at the measure point is 64.6µm. Although it is a little bit different from what it is expected, the CNC fabrication result is acceptable.
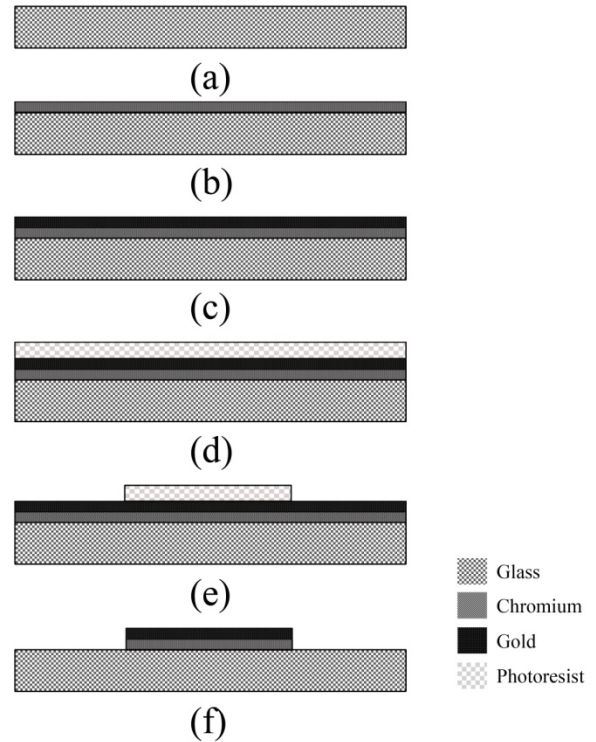

Fig.5. Fabrication process of micro electrode: (a) glass substrate; (b) & (c) both chromium and gold are deposited on the glass surface by evaporation; (d) cover the metal surface by photoresist layer; (e) photoresist is patterned ; (f) the metals are etched as patterned and the rest of photoresist is stripped off completely.
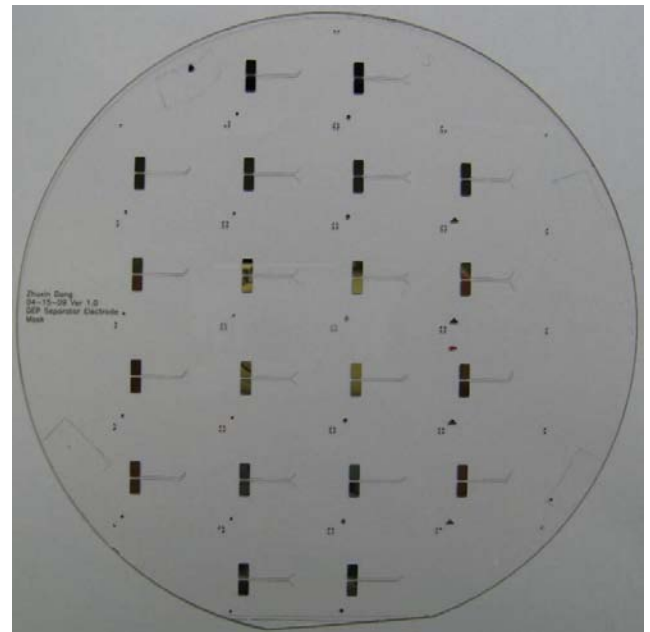

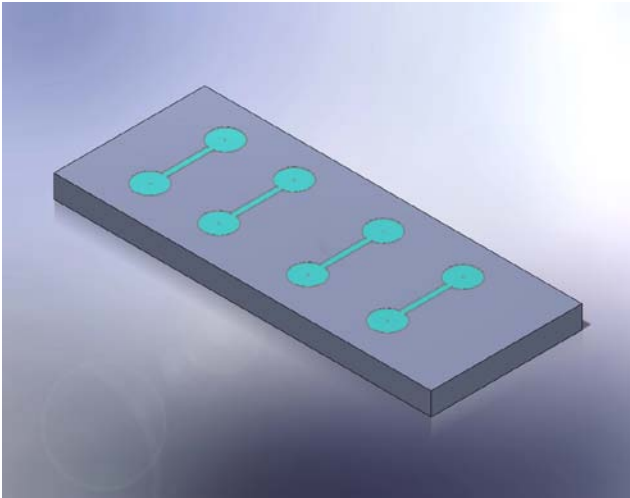Fig.6. Top-view of the glass wafer with Au electrodes on the top surface
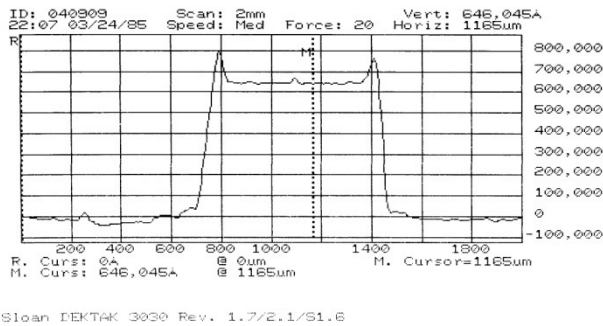
Fig.7. Al-Mode design of the µchannels

Fig.8. Scan result of a channel height and width

D. The Channel

After the Al mode is ready (see Fig.9), PDMS is cured on its surface. The cure can be divided into 2 parts. First to do is curing with the Al mode on a hotplate at 60C for 50mins, where PDMS is not completely cured, it's still sticky. At the same time, the glass chip is drilled for 2 holes through Dremel Tool. Then, the PDMS is cut into 4 pieces and stick into the glass chip, make sure the channel is crossed by the electrode and do the thermal cure at 80˚C for ~10 hours. The wires are bonded on the pads by conductive epoxy before drilling the holes. When curing is done, two connectors for inlet and outlet of the channel are built with epoxy. Fig.10 shows the final shape of a micro channel with one pair electrode in the middle.
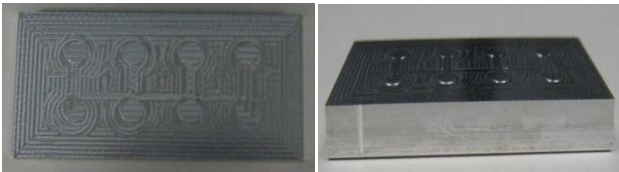
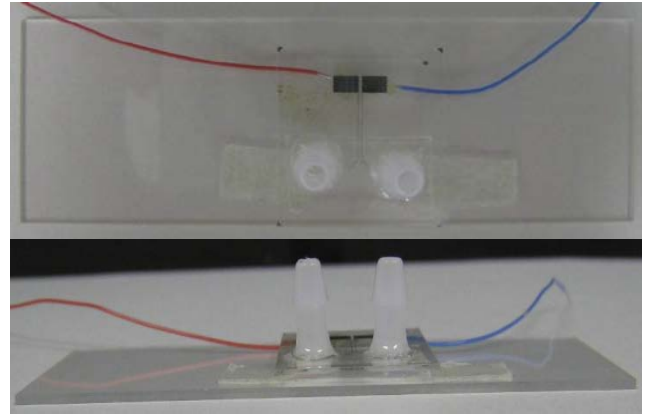

Fig.9. Top-view of aluminum mode for µchannel manufacture

Fig.10. A µchannel on a glass slide

IV. Experimental Results

Fig.11 shows the experimental setup for separation. 1.5ml solution with polystyrene beads suspending is prepared and loaded into the syringe. In this solution, two kinds of beads are mixed: 1 vs. 10µm in diameter. The pump is programmable for flow-rate. Two wires are connected to a function generator, which provides an AC power at 1.5MHz with 5V p-p. Currently, there is a limitation of the function generator that if the frequency goes high, the p-p voltage must be lowered accordingly. The microscope is focused on the channel area to observe the motion of the beads inside. Unfortunately, the deflection does not happen to either kind of beads when the AC power is applied (please see the videos attached for results). At the beginning, the flow-rate is set 50µl/hour and it is increased to 120µl/hour, nothing changes. Therefore, this separator is not functional as I expected.

Fig.11. Experimental setup for separation

V.   Conclusion and Future Work

Through this project, I have learned the fundamentals of DEP application for separation of particles in fluid as well as some MEMS fabrication skills. In chip design and fabrication, a mask for electrodes is made; metal evaporation, pattern of photo resist, metal etching and glass wafer dicing are complete in HiDEC. Aluminum mode design & fabrication, cure of PDMS and connectors build-in for manufacturing μchannels are practiced. However, owing to lack of experience, some mistakes should be paid attention to, for example, the length of the channel here is only 1cm which should have been made longer. Otherwise, I will suffer from a problem of building the connector too close and that is dangerous to block seeing the channel. To make the separator work, in the future, I will fabricate another structure of electrodes inside the channel: a pair of electrodes fabricated on both bottom and top layers. In addition, the parameters of the AC power should be tuned into proper values. According to [7], both frequency and p-p voltage are supposed to be raised in order to separate beads.

Reference

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