Particle Line Assembly/Patterning by Microfluidic AC Electroosmosis

Meng Lian, Nazmul Islam and Jie Wu
The University of Tennessee, Knoxville, Tennessee, USA
Email: jaynewu@utk.edu

Abstract: Recently AC electroosmosis has attracted research interests worldwide. This paper is the first to investigate particle line assembly/patterning by AC electroosmosis. Since AC electroosmotic force has no dependence on particle sizes, this technique is particularly useful for manipulating nanoscale substance, and hopefully constructs functional nanoscale devices. Two types of ACEO devices, in the configurations of planar interdigitated electrodes and parallel plate electrodes, and a biased ACEO technique are studied, which provides added flexibility in particle manipulation and line assembly. The paper also investigates the effects of electrical field distributions on generating microflows for particle assembly. The results are corroborated experimentally.

1. Introduction

Manipulation and assembly of microscopic objects, such as colloidal particles, cells, and molecules play a crucial role in fabricating an emerging paradigm of devices. Precise placement of particles at nanoscale has been envisioned to be the strategy to construct functional nanoscale devices, in order to overcome fundamental and throughput limitations of lithography-based fabrication. Such a capability is also useful in the development of miniature environmental/medical/chemical diagnostic kits. These kits need to concentrate a small number of bio-particles, molecules and chemicals in a small sample to detectable level. Recent research indicates that AC electroosmosis (ACEO) can be used to transport and assemble micro- or nano- particles above surfaces.

So far, the choice of maneuvering particles and (to a less successful degree) molecules is DC electrophoresis (EP) or AC dielectrophoresis (DEP) [1], which depend either on particle charge or field-induced charge on the particle. However, EP often has bubble generation and contamination problems because of the steady and large potential gradient. DEP scales as the third power of the particle radius and is therefore rather size sensitive. Consequently, DEP force is weak for bioparticles unless a large field gradient is established. This large gradient can only be realized using microelectrodes with small spacing and the range of DEP force normal to the electrode is small at no more than 20 microns typically.

In contrast, ACEO convection on electrode surfaces does not depend on particle sizes and E-field gradients. Hence, particle manipulation by electroosmosis has much longer range than the aforementioned methods – over 1 mm in some of our experiments reported below. The induced particle surface velocity can exceed 100µm/s. Moreover, ACEO flow is a surface flow that is highest at about 10 nm to 100 nm, the thickness of the electrode double layer, from the electrode surface. Hence, micron-sized particles are conveyed at the surface by the maximum fluid velocity in the microfluidic chamber.
As a result, ACEO manipulation is most effective at the surfaces of substrates, independent of substance (such as reactants) /particle or pattern dimensions down to nanometer, and capable of parallel processing over a large area. ACEO devices can have in-plane or out-of-plane configuration, providing extra flexibility in forming complicated patterns or layer-by-layer composite materials. ACEO assembly technique that we are currently developing is well suited for maneuvering nanoscale materials, compared with other techniques such as pressure driven fluids, optical tweezers, or electrostatic force.

ACEO has been observed to induce particle aggregation on electrode surfaces [2, 3, 4, 5], however the mechanism has not been clearly understood, especially for the particle line assembly on an isolated pair of electrodes observed in our experiments. This paper investigates the electrical field distributions around electrodes, its effects on microfluidic motions, and the mechanisms of particle line assembly. Using finite element analysis (FEA) of electric field distribution and Navier-Stoke fluid dynamics (FEMLAB, www.comsol.com), particle line assembly is shown to be caused by electric field singularities. The simulation results were corroborated by experimental work. Later on, the paper presents new development in this field by us, namely biased ACEO and arbitrary line patterning.

2. AC Electroosmosis and simulation

ACEO refers to the microfluidic motions generated at electrode surfaces when AC signals are applied [6]. A nanometer layer of charges/ions is induced by an AC electric field at the interfaces of electrolytes and solids. The key of ACEO is to have tangential electrical fields over this nanolayer of charges/ions. Ions are driven along electrode surfaces by tangential field, producing osmotic microflows due to fluid viscosity. Because the E-field distribution is non-uniform in ACEO, as opposed to DC EO, flow rates vary over the electrode surface.

Figure 1 Experiment result of planar electrode configuration. Light areas are the electrodes.

While there are several groups working on ACEO [4, 5, 7, 8], our research focuses more on directed depositing and line patterning of particles. For an isolated pair of electrodes, our experiments observe two particle lines on the electrodes, as shown in Fig. 1, which was not explained in the literature. To better understand the particle line assembly mechanism, an isolated pair of electrodes on silicon wafer was used to study ACEO.

The electrodes were microfabricated at 0.1 µm thick, 80 µm wide with 20 µm separation. There is no limit to the length of electrodes and hence assembled particle lines. When AC signals are applied over the electrodes, non-uniform and synchronous electric fields both normal and tangential to the electrodes are generated to induce microflows. It is commonly believed that two vortices were formed over the electrodes. Our hypothesis is that another two minor vortices are generated beside the
center loops to focus particles into lines. Consequently, particles deposit at locations where flow rates are slower than elsewhere, thus realizing particle assembly and patterning.

Figure 2 (a) Computed contour plot of tangential component of electrical field over electrode surface. (b) Plot of tangential field with respect to left electrode. It is maximized at two edges of electrode. (c) Normalized velocity profile of ACEO simulation on left electrode surface with respect to horizontal x axis; (d) Simulation of fluid velocity distribution inside the chamber using FEMLAB shows the side view of fluid chamber. Particles are accelerated at the electrode-gap edge and deposited at the stagnation point.

ACEO fluid motion is clearly related to the magnitude and direction of electric field, so we investigated the electric field distribution around electrodes and its effects on microfluidic motions. Simulation was performed by using 2D electrostatic calculation from FEMLAB multiphysics modelling package (COMSOL, Burlington, MA). The simulation is as follows. The electrode geometries used are 80 μm and separated by a 20 μm gap. The dielectric subdomains are water ($\varepsilon = 80$) and electrode ($\varepsilon = 2$). The left electrode is given a voltage of positive one volt and the other negative one volt. All the other boundaries are taken to be electrically symmetrical. Next is to
triangulate the system into conformal mesh. After that, the solver was then initiated to solve the Poisson equation to obtain electrical field distribution.

The fluid velocity on the electrode surface is given as

$$u = -(\varepsilon / \eta)(\xi - \varphi_b)E_t$$

(Eq1, [8]), where $\varepsilon$ is the permittivity, $\eta$ is the viscosity of bulk solution, $(\xi - \varphi_b)$ is the difference of potential between the double layer and the bulk solution, $E_t$ is the tangential component of electrical field. The null points occur at a position

$$\frac{1}{\sqrt{2}} \sqrt{(L + a)^2 + a^2}$$

$L$ is the electrode width; $a$ is half of the gap distance) away from the electrode inner edge and is approximated as $\frac{1}{\sqrt{2}}$ of electrode width [9]. When particles approach such points, they lose momentum due to the existence of counter flows and settle down at the electrode surface. Thus, they are trapped by ACEO in a short time.

Figure 2a illustrates the distribution of tangential electric field. Two null points occur at approximate $\frac{1}{\sqrt{2}}$ of electrode width away from inner edges. Figure 2b clearly shows that the tangential field reaches its maximum at the edge of electrode and gap and decreases rapidly as it gets away from the edge towards the electrode. At the null point, it changes its direction to negative. The tangential component inside the gap can be approximated by zero. Therefore, particles can be predicted to have its largest velocity at the electrode gap edge. Then the velocity decreases toward null point and a counter flow is produced. The particles have the lowest velocity at the null points and are likely trapped at the stagnation area.

In order to model the fluid motions as described above, the 2D Incompressible Navier and Stokes module is called in FEMLAB. In this case, the hydrodynamic property in the chamber is given as density=1000 kg·m$^{-3}$ and viscosity=110$^{-3}$ kg·m$^{-1}$·s$^{-1}$. According to Equation 1, the velocity on the surface of double layer is proportional to the tangential field and potential difference between the double layer and fluid, which corresponds to the normal component of electrical field. Therefore, normalized boundary conditions on both electrodes are given as $u = -E_x E_y$. The fluid velocity distribution is then obtained by solving Navier-Stokes equation with calculated field profile. The result is shown as Figure 2c. Figure 2d simulates the vortices generated over the electrode. The locations of particle aggregation correspond to the experimental observations.

3. Biased AC Electroosmosis and Arbitrary Particle Line Assembly

The knowledge on how electric fields play a role in particle aggregation helps us to design new ACEO devices for more efficient and effective particle manipulation. An addition to ACEO is our “biased ACEO” technique [10, 11], in which a DC offset has been added to the AC signal with the form of $V = V_0 + V_0 \cos \omega t$ and $V = -V_0 - V_0 \cos \omega t$, so that one electrode has a positive offset with the potential always greater than zero, while the other one lower than zero. For the positively biased electrode, when peak positive potential exceeds certain threshold, Faradaic reaction occurs and co-ions are generated following Faraday’s law. For the other electrode with a negative offset, counter ions are attracted to the electrode. Therefore, for two electrodes, same polarity of ions is induced. A unidirectional fluid loop is consequently formed by tangential fields. Because most particles acquire negative charges in an aqueous environment, they adhere to the stagnation line on the positively biased electrode. Henceforward, biased ACEO exhibits directional particle assembly.

The biased ACEO simulation has also been performed in our research work. The whole process results in the main fluid motion in a unidirectional fashion, as been illustrated by the arrows in Figure 3a. Note that particles now are trapped only in positive electrode, agreeing with experimental results (Figure 3b).
Another ACEO device we investigated is similar to a pair of parallel plates, and an electric field is applied between the parallel plate electrodes. However, instead of uniform electric field normal to the electrode surface as in typical parallel plates, for this device, one plate in the pair has patterns on it, and tangential electric fields are generated by asymmetric electrode patterns on the plates. The tangential electric field induces electro-osmotic fluid motion. It is the microfluidic flow that conveys particles from the bulk of the fluid onto the fluid surface. The particles are trapped at the stagnation points of the fluid in motion [11].

FEMLAB simulation shows that induced osmotic flows direct from the outer edge of bottom electrode to the centre. Therefore, two main loops are formed with particles trapped onto the centre of bottom electrode (Figure 3a). This is proved experimentally. The particle movement was observed using a camera through the glass top plate, which is coated with indium tin oxide (ITO) to conduct electricity. Figure 3b shows that particles form lines along the central line of conductive electrode strips. Various line patterns can be realized by pattern the electrode differently.
3. Conclusion

This paper investigates various methods for particle line assembly lines by AC electro-osmosis. A better appreciation of the role of electric field distribution in ACEO is reached through FEA simulations. New ACEO devices were designed, and experimental results agree with simulations. With two different electrode configurations (interdigitated and parallel plates) and biased ACEO, a variety of particle line patterns can be realized. Many applications are expected for ACEO particle manipulation technique.

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