Parallel Plate Particle Trapping with Application to Cantilevers

Jie (Jayne) Wu
Department of Electrical and Computer Engineering, The University of Tennessee, Knoxville, TN, USA
jaynewu@utk.edu

Abstract. Recent years have witnessed many developments in microfluidic and micro-total analysis systems (μTAS) by applying microfabrication technology to biological and chemical processing. The paper reports an alternating current electro-osmotic (ACEO) particle trap for use in lab-on-a-chip. It is the first to demonstrate an integrated particle trap on cantilevers. It is expected that with the use of pre-concentrator (particle trap), the sensitivity of real-time detection can reach into sub-parts-per-trillion range. Also multiplexing detection can be achieved by coating cantilevers with various sensitive layers.

1. Introduction
The world is becoming increasingly concerned with toxin/pathogenic contamination in food, water and environment from infectious diseases and bioterrorism. Therefore an urgent need for the security of this country is to develop a multiplex sensor that is portable, real-time, in-situ for the detection of chemical and biological warfare agents/pathogens with exceptional sensitivity.

Recently, the detection of biowarfare agents, ricin (biotoxin) and Taluremia (bacterium), has been demonstrated with antibody coated cantilevers by research teams around the world. The success with micro- cantilever sensors suggests that in the years to come, cantilevers will be an integral part of many physical, chemical, and biological sensors. However, current real-time detection typically has a detection limit several orders of magnitude higher than an infectious dose. The time required for detection is generally much longer than desired, due to time involved in the diffusion process of those agents. Consequently, pre-concentrating biological analytes such as proteins, viruses, and bacteria, is important in real-time detection. This is especially true for the detection of bio-analytes that occur at very low concentration, for example biowarfare agents. The sensitivity as well as the detection time could be improved by orders of magnitude if a concentration trap could be embedded with cantilevers.

Recently AC electro-osmosis (ACEO) has emerged as a promising strategy to capture, manipulate and transport (bio)particles in microfluidic devices. A variety of ACEO microfluidic techniques and devices have emerged [1, 2, 3, 4] in the last few years. Among them are particle trapping by biased ACEO [6] and parallel plates for particle assembly/ line patterning [5].

Prior reports of ACEO traps adopt co-planar interdigitated electrodes for trapping bacteria and other charged particles to enhance detection sensitivity [6, 7]. However there are applications where interdigitated electrodes are not applicable or difficult to implement. For such applications, we have investigated parallel plate configuration. Based on that, we have developed the integration of trapping mechanism with cantilever detection. A prototype was demonstrated and preliminary experiments
were performed to concentrate particles onto cantilevers. It is expected that with the use of pre-concentrator (particle trap), the sensitivity of cantilever detection can further improved, reaching into sub-parts-per-trillion range.

2. Parallel Plate ACEO Particle Trap

2.1. AC electroosmosis (ACEO)

ACEO is based on the fundamental principle that a nanometer layer of charges/ions is induced by an AC electric field at the interfaces of electrolytes and solids, whether the solid is a metal or a cell membrane. The interactions between this nano-layer of charges and electrical fields will generate a variety of fluid/particle motions. When an AC potential is applied over the electrodes in an electrolyte, the charges in the double layer will change with the potential as a function of time. If there also exists an electric field parallel to the electrodes, the induced ions will migrate under the influences of the tangential field, and produce osmotic microflows due to fluid viscosity.

The fluid velocity on the electrode surface is given as

\[ u = \frac{-\epsilon}{\eta} (\xi - \phi_h) \]  

(Eq1, [8]), where \( \epsilon \) is the permittivity, \( \eta \) is the viscosity of bulk solution, \((\xi - \phi_h)\) is the difference of potential between the double layer and the bulk solution, also an indication of amount of charges induced at the interface, \( E_t \) is the tangential component of electrical field, which is responsible for generating EO flows along the electrode surfaces.

2.2. Parallel plate ACEO devices

For ACEO devices, it is essential for the electric field distribution to be non-uniform with both normal and tangential components synchronously, which can be achieved inherently with planar interdigitated electrodes. For parallel plate ACEO devices, electrodes are facing each other, similar to a pair of parallel plate capacitors, and an electric field is applied between a pair of parallel plate electrodes to generate EO microflows. As shown in Fig 1, the electrode on one plate has been patterned or has a different area (as particle trapping electrode). Because electrodes are asymmetric (such as different areas or with patterns), tangential electric fields are generated in addition to fields normal to the electrode surface.

Electric fields normal to the electrodes induce electric charges close to the electrode surface, which move under the tangential fields from the electrode edges towards its center, thus inducing electro-osmotic fluid motions [9]. Because of mass conservation, fluids above the electrode edges flow down to compensate the flow, forming convective vortices. Induced microflows then convey particles from the bulk of the fluid onto the fluid surface. Since electric fields are not uniform across the electrodes,
the microflows reduce their velocity as they go from the edge to the center, and the particles are trapped at the stagnation points of the fluid in motion. With this parallel plate configuration, more fluid volume can be influenced by ACEO flows. Basically, it will be the volume between the two electrodes.

2.3. Particle concentration experiments

Figure 2 shows the experimental setup used to explore the research idea. The particle movement was observed using a camera through the glass top plate, which is coated with indium tin oxide (ITO) to conduct electricity, serving as the top electrode in Fig. 1. A metal coated silicon wafer is used as the bottom electrode. The patterns on the trapping electrode were shown as the inset of Fig. 2. The squares are 600 microns on a side. The insulated regions were either coated by dielectrics (e.g. photoresist) or etched away. The fluid (De-ionized water) is contained within the polymer spacer (Grace Bio-Labs, Inc.) between the top plate and the bottom silicon wafer.

Particle concentration experiments have been performed using polystyrene particles (1~3 mm, Fluka Chemica) and clay particles (bentonite clay, which are nanoscale fine particles and normally stay suspended in the fluid). An HP33120 signal generator was used to apply electrical potential to electrodes. Signals of frequency from 50 Hz to 5 kHz, of magnitude 1 to 4 Vpeak-peak were used to induce electroosmotic flows. Figure 3 gives four snapshots of particle distribution at 60 second interval after the electric field is turned on. The square is the exposed metal surface, while the sides are covered with photoresist. The directions of generated electroosmotic flows are from the sides towards the center of the square. As a result, particles will be concentrated at the center. As it can be seen in Fig. 3, the particles accumulate along the square diagonals, which are the stagnation points of micro-flows, and eventually into a dot at the center.

Our experiments have used separation up to 2 mm and still generate microflows of sufficient strength to concentrate particles, and without hydrolysis. On the other hand, it is generally believed that ACEO flows from planar electrodes can reach about several hundred microns away from the electrodes. So parallel plates can accommodate more volume.
3. Cantilever Particle Trap

Since cantilevers are widely used in bio-chemical analysis, and a pre-concentration step is in demand to bridge the gap between the detectable level and infectious level of sample solutions, it will of great interest to embed particle traps onto cantilevers to take advantage existing expertise with cantilever

![Fig. 4 Schematic of cantilever particle trap.](image)

Fig. 3 Snap shots of concentrating particles on Si wafer at 60 seconds interval, with the leftmost as the initial state.
Because particle trapping/concentrating effect is more obvious with the smaller electrode, our design is to use metal-coated cantilevers as the lower electrode in Fig. 1 to attract particles onto the cantilevers. The schematic of the cantilever trap is shown in Fig. 4. The metal-coated cantilevers are facing one large electrode (ITO glass slide covering a whole fluid chamber). Based on the information we gained from planar electrode trap, the particles are expected to deposit onto the center of the cantilever where metal surface is exposed.

Finite element analysis has been performed with commercial software FEMLab to simulate electroosmotic flows generated around a cantilever. Detailed simulation procedure can be found in [5]. 2-D simulation results are shown in Fig. 5, in which the arrows indicate the flow directions. As it can be seen, two counter-rotating vortices are formed, and stagnation points occur at locations where the vortices meet.

Figure 6 shows experimental results of fluorescent particles being captured onto cantilevers. The distance from the cantilever to the glass cover is 200 μm. AC signals of 4 V peak-peak at 500 Hz have been used between the cantilever and the ITO top cover to concentrate particles for comparison. That cantilever traps were able to capture a variety of particles. The locations where particles are attracted to can be manipulated by patterning of the metal layer or its dielectric coating on the cantilever, so particles can be focused only onto the tips or any other locations of cantilevers for maximum sensitivity.
4. Conclusions

The paper presents a first particle trap integrated on cantilevers. The particle trapping can be realized using metal layers on cantilevers by applying ac signals with little adverse effects on cantilever detection. So this concept can be readily incorporated into existing cantilever detection system (such as optical deflection or piezo resistivity). Given the sensitivity in cantilever detection, ultra high sensitivity can be realized with our device. Experiments with DNA analysis are currently under way.

Experiments have also shown that (dielectric) coating on metal will not keep electroosmosis from happening. The flow velocity will reduce as compared with no coating, but this can be adjusted by operating conditions and device designs. The significance here is that detection sensitivity can be achieved as well by applying different sensitive layers onto various cantilevers to form an array of multiplex sensors.

References

[1] A. Ramos, H. Morgan, N.G. Green and A. Castellanos, “The Role of Electrodynamic Forces in the Dielectrophoretic Manipulation and Separation of Particles,” J. Electrostatics, Vol. 47, pp. 71 – 81, 1999.
[2] P.K. Wong, C.-Y. Chen, T.-H. Wang and C.-M. Ho, "An AC Electroosmotic Processor for Biomolecules", TRANSDUCERS’ 03, June 8-12, 2003, pp. 20-23
[3] V. Studer, A. Pepin, Y. Chen and A. Ajdari, “An Integrated AC Electrokinetic Pump in a Microfluidic Loop for Fast and Tunable Flow Control,” Analyst, 129, 944-949 (2004)
[4] J. Wu and H.-C. Chang, “Asymmetrically Biased AC Electrochemical Micropump,” AIChE annual meeting 2004, Nov. 7 – 12, Austin, TX, USA.
[5] M. Lian, Nazmul Islam and J. Wu, “Particle Line Assembly/Patterning by Microfluidic AC Electroosmosis,” Int’l MEMS Conf., May 9-12, 2006, Biopolis, Singapore, in press.
[6] J. Wu, Y. Ben and H.-C. Chang, “Particle Detection by Micro-Electrical Impedance Spectroscopy with Asymmetric-Polarization AC Electroosmotic Trapping,” Microfluidics & Nanofluidics, 1(2), pp. 161-167, 2005.
[7] J. Wu, Y. Ben, D. Battigelli nd H.-C. Chang, “Long range AC Electrokinetic Trapping and Detection of Bioparticles,” Industr. Eng. Chem. Research, vol. 44, pp. 2815 – 2822, 2005.
[8] K. H. Bhatt, S. Grego and O. D. Velev, “An AC Electrokinetic Technique for Collection and Concentration of Particles and Cells on Patterned Electrodes,” Langmuir 21, pp. 6603-6612, 2005.
[9] J. Wu, N. Islam and M. Lian, “High Sensitivity Particle Detection By Biased AC Electro-Osmotic Trapping on Cantilever,” 19th IEEE Int'l Conf. Micro Electro Mechanical Systems (MEMS 2006), Jan. 22-26, 2006, pp. 566 – 569, Istanbul, Turkey.