AC electrothermal manipulation of conductive fluids and particles for lab-chip applications

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Abstract: AC electrokinetics has shown great potential for microfluidic functions such as pumping, mixing and concentrating particles. So far, electrokinetics are typically applied on fluids that are not too conductive (<0.02 S/m), which excludes most biofluidic applications. To solve this problem, this paper seeks to apply AC electrothermal (ACET) effect to manipulate conductive fluids and particles within. ACET generates temperature gradients in the fluids, and consequently induces space charges that move in electric fields and produce microflows. This paper reports two new ACET devices, a parallel plate particle trap and an asymmetric electrode micropump. Preliminary experiments were performed on fluids with conductivity at 0.224 S/m. Particle trapping and micropumping were demonstrated at low voltages, reaching ~100 μm/s for no more than 8 Vrms at 200 kHz. The fluid velocity was found to depend on the applied voltage as $V^2$, and the maxima were observed to be ~20 μm above the electrodes.

1 Introduction

Microfluidic electrokinetics (EK) is gaining popularity as an actuation mechanism for lab-on-a-chip, owing to its simple implementation and reliability from no moving parts. EK can be applied with DC or AC electric sources. Direct current electrokinetics (DC EK) has a long history of development, being investigated and applied extensively [1]. However, DC EK suffers from high voltage operation (several kilovolts) and consequently excessive electrolysis as AC EK [2, 3]. AC EK mainly includes dielectrophoresis (DEP), AC electro-osmosis (ACEO) and AC electrothermal (ACET) effect. DEP refers to the interaction between a dipole moment on a particle and a non-uniform field [4]. DEP velocity is size dependent, and decreases rapidly with the distance to the electrode.

Both ACEO and ACET apply a non-uniform electric field to produce fluid flow [2, 3]. In some cases, ACEO and ACET produce very similar flow patterns, but they are of different origin. ACEO [9, 10] arises from the movement of ions in the electric double layer at the electrode/electrolyte interface, producing microflows because of the fluid viscosity. Pioneer work and comprehensive review on ACEO can be found in [2, 3, 9, 10]. The fluid velocity is approximately given by $u_{ACEO} = -\eta e/\varepsilon \Delta \xi / E_i$, where $e$ and $\eta$ are the permittivity and viscosity of the medium, $E_i$ is the electric fields parallel to the solid surface, and $\Delta \xi$ is the voltage drop over the charge layer, which is proportional to induced charge density. So ACEO requires both normal and tangential components of electric field at the electrode surface, which leads to the frequency dependency of ACEO effect. At low frequencies, most of the applied voltage drops across the double layer, ACEO is important. At high frequencies, electrode charging is negligible and ACEO becomes insignificant. Data in [9] also show that ACEO is pronounced for frequencies lower than 100 kHz, beyond which its effect is minimal and can be neglected. The optimal frequency for ACEO operation can be estimated as $\Omega \simeq (\sigma/2\eta)e\lambda_D/l$, where $\lambda_D$ is the Debye length, typically less than 10 nm, and $l$ is the characteristic length of the system, for example the electrode spacing. $\lambda_D/l$ represents the process of charging the double layer through the resistive fluid bulk.

ACEO velocity $u_{ACEO} \sim V^2/r$, and the resulting fluid flow exerts a drag force on particles. Therefore ACEO can be used to transport particles as well as fluids, and there is no size dependency. Particle manipulation and fluid flow control using ACEO have been reported in various forms, such as biased ACEO [11, 12], and 3D ACEO pump [13, 14], travelling wave ACEO pump [15], asymmetric electrode ACEO pump [16] and particle traps [17–20]. ACEO has been demonstrated to generate surface velocity of 50–100 μm/s by applying AC signals in the order of 1 Vrms with an electrode spacing of 5–25 μm. However, complexity in fluid dynamics takes place at higher voltages, for example, flow reversal. It was tentatively attributed to Faradaic charging of the double layer (i.e. generation of
The concept of particle trapping is to induce microfluids to convey particles from the bulk of the fluid onto the electrode surface, where the fluid slows down and deposit the particles. Although DEP has been extensively used for particle manipulation, the technique will be much more effective if it works in conjunction with ACET or ACEO [19]. The effectiveness of DEP, or DEP force, scales with the particle volume, which makes DEP unfavourable when handling submicron particles, whereas ACET and ACEO use fluid flows to convect particles to certain locations, hence has no dependence on particle sizes. Moreover, DEP decreases much faster than ACET/ACEO with respect to the distance from the electrode (approximately $1/r^3$ for DEP and $1/r$ for ACET).

There are prior reports on convecting and trapping particles with electrophoretic methods. Most of them use a side-by-side electrode configuration [25], and are based on ACET [18–20], which limits their application to low ionic strength solutions and the trapping range into the fluid is in the order of the system characteristic length. Our ACET particle trap consists of a pair of electrodes that face each other. The electrodes have a spacing of 500 μm, exerting force on the micro-litre fluid between them for particle collection, which is desirable for many types of lab-chip sample processing.

Our work demonstrates ACET microfluidic devices capable of manipulating fluids and particles at a fluid conductivity of interest to biochemical analysis and environmental monitoring. Preliminary data on the ACET particle trap and pump will be presented for working fluids with $\sigma = 0.224$ S/m. ACET experiments have been successfully performed on fluids with conductivity as high as 1.58 S/m (phosphate buffered saline). However, the flow motion was not recorded well enough to be analysed, as flow rate increases linearly with fluid conductivity and becomes too high to be measured.

2 ACET effect

ACET effect refers to fluid motion induced by temperature gradients in the fluid in the presence of AC electric fields. When an electric field $E$ is applied over the fluid with electrical conductivity $\sigma$, Joule heating of the fluid will take place according to the energy balance equation

$$k \nabla^2 T + \frac{1}{2} (\sigma E^2) = 0$$

where $T$ is temperature and $k$ is the thermal conductivity. For microsystems, heat convection is small compared to heat diffusion [2, 3]. So here the temperature equation assumes the simplified form with Joule heating as the energy source. If the field strength $E$ is non-uniform, there will be spatial variation in heat generation, which leads to temperature gradients $\nabla T$ in the fluid. The temperature gradient $\nabla T$ produces spatial gradient in local conductivity and permittivity by $\nabla e = (\sigma / \nabla T) \nabla T$ and $\nabla \sigma = (\sigma / \nabla T) \nabla T$. Further, $\nabla \sigma$ and $\nabla e$ generate mobile space charges, $\rho$, in the fluid bulk, by $\rho = \nabla \cdot (\sigma E) = \nabla \cdot E + e \nabla \cdot E$ and $\rho / \nabla T + \nabla \cdot (\sigma E) = 0$ with $\partial / \partial t + i \omega$. The free space charges experience a volume force $f_v$ in the electric field $E$, $f_v = \rho E - 1/2 E^2 \nabla e$, exerting force on fluid through viscosity and leading to fluid transport. The time average of electric force on fluid is given as [10]

$$\langle F_{et} \rangle = - \frac{1}{2} \left[ \frac{\nabla \sigma}{\sigma} - \frac{\nabla e}{e} \right] - \frac{e |E|^2}{1 + (\sigma \tau)^2} - \frac{1}{4} \nabla |E|^2$$

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where $\sigma$ and $\varepsilon$ are the electrical conductivity and permittivity of the medium, $\tau = \varepsilon/\sigma$ is its charge relaxation time, and $\omega = 2\pi f$ is radian frequency. For aqueous media at 293K, we have [22]

$$\frac{1}{\varepsilon} \frac{\partial \varepsilon}{\partial T} = -0.004 \nabla E \frac{\partial E}{\partial T} = \frac{1}{\sigma} \nabla \sigma \frac{\partial \sigma}{\partial T} = -0.004 \nabla T = -0.004 \nabla T \quad (3)$$

$$\frac{1}{\sigma} \frac{\partial \sigma}{\partial T} = 0.02 = \frac{\nabla \sigma}{\sigma} = \frac{1}{\sigma} \nabla \sigma \frac{\partial \sigma}{\partial T} = -0.02 \nabla T \quad (4)$$

giving

$$\langle F_{e\sigma} \rangle = -0.012 \cdot \nabla T \cdot \frac{\varepsilon |E|^2}{1 + (\omega T)^2} + 0.001 \cdot \nabla T \cdot \varepsilon |E|^2 \quad (5)$$

The two terms at right hand side of (2) and (5) represent the Coulomb force and dielectric force, respectively. At low frequency, $1/1 + (\omega T)^2 \approx 1$, Coulomb force is much stronger (about 11 times) than dielectric force. Coulomb force decreases with frequency, and becomes less than dielectric force at high frequency. Consequently, the flow will reverse its direction. The crossover frequency can be expressed as $f_c = \sqrt{11}/2\pi$. The solution used in our experiments has a conductivity of $\sigma = 0.224 \text{ S} \cdot \text{m}^{-1}$, so its crossover frequency is estimated to be $\sim 1.7 \times 10^5 \text{ Hz}$. With AC signals at 200 kHz, the dielectric force is much smaller than the Coulomb force, so the flow direction is dictated by the Coulomb force. In the meanwhile, the applied AC signals have high enough frequency, so that doubly layer charging can be ignored and ACEO is negligible. The charging time of the double layer is estimated as $(\varepsilon/\sigma) \cdot (l/\lambda_D)$. In this work, the electrode separation is 500 $\mu m$ (parallel plate) and 20 $\mu m$ (pump). At an ionic strength of 17.8 mM NaCl ($\sigma = 0.224 \text{ S} \cdot \text{m}^{-1}$), the Debye length is calculated to be less than 2.3 nm, and the double layer has a charging frequency much lower than 200 kHz.

The induced fluid motion is described by Navier-Stokes (N-S) equation

$$\rho \frac{\partial u}{\partial t} + \rho (\nabla \cdot u) u = -\eta \nabla^2 u + \nabla P = F_{e\sigma} \quad (6)$$

where $\rho$ is the fluid density, $\eta$ is the dynamic viscosity of the fluid, $P$ is the external pressure and $u$ is the velocity of the fluid. Since we are considering fluid motion in a microsystem, that is, low Reynolds number, the time-averaged fluid velocity can be found by the simplified N-S equation as

$$-\eta \nabla^2 u + \nabla P = \langle F_{e\sigma} \rangle \quad (7)$$

Together with $\nabla \cdot u = 0$ for incompressible fluid, (7) is later used in numerical simulation to obtain the fluid flow fields in our ACET devices.

This paper presents two new ACET devices, a long range particle trap and a micropump for conductive fluids. Both numeric simulation and experiments have been performed to design and prototype the new microfluidic devices, and functional devices have been demonstrated with preliminary experiments.

### 3 Parallel plate particle trap

Our ACET particle trap consists of a pair of parallel plate electrodes at a spacing of 500 $\mu m$, as shown in Fig. 1a. The bottom electrode is shorter than the top one in order to create a non-uniform electric field, which in turn induces non-uniform temperature field and, further, fluidic flow field. Microflows convey particles in the bulk solution to the shorter electrode and deposit them in its centre, increasing particle count at that location.

![Schematic of parallel plate particle trap and its simulation model](image)

*Fig. 1 Schematic of parallel plate particle trap and its simulation model*

(a) Schematic of microfluidic chamber

(b) Simulation model

#### 3.1 Numerical simulation

Parallel plate ACET trap was simulated with Femlab/Comsol Multiphysics package (www.comsol.com; Stockholm, Sweden). The model used in the simulation is shown in Fig. 1b, including one bottom electrode with a length of 600 $\mu m$. Periodic boundary conditions for all the variables (electric fields, temperature and velocity) were applied to the sides.

There are several steps involved in the numerical simulation. The first one is to use Laplace’s equation $\nabla^2 T = 0$ to derive the electric field distribution in the fluidic chamber. The resulting electric field distribution is used to calculate the temperature field according to the energy equation (2). Then the fluid volume force in the chamber is calculated using the temperature gradient and the electric field distribution from the first two steps. Lastly, the fluid flow field is obtained by N-S equation (7).

In electric field simulation, the top and bottom electrodes are set at certain electric potentials, whereas other boundaries are left at neutral and insulative. Then the heat transfer module is invoked, using the resulting $E$ to calculate the temperature field. The top and bottom boundaries along with electrodes are set at ambient temperature. Treating the electrodes as isothermal is appropriate considering their sub-micron thickness [25]. In the fluid dynamic module, an AC frequency of 200 kHz is used to calculate the fluid volume force, which corresponds to our experimental conditions. The top and bottom boundaries are treated as non-slip, that is, $\nu = 0$, and the left and right walls are defined to be periodic.

The electric field simulation (Fig. 2a) indicate the existence of electric field strength ($E = -\nabla V$) maxima around the edge of the bottom electrode, with both tangential and normal components. Since there is no flow into the electrodes, it is the tangential component of the electric field that induces the microflow. For a potential difference of 20.3 $V_{\text{rms}}$, the highest electric field strength is calculated as 0.522 $V/\mu m$ (Fig. 2a). Accordingly, the temperature gradient takes the highest value of 0.609 $K/\mu m$ at the same locations, shown by the arrows in Fig. 2b. The peak temperature rise is calculated to be 2.44 K, comparable to 2.3 K by the analytical predictions $\Delta T = \sigma V_{\text{rms}}^2/8k$ in [2].
The result of fluidic simulation is shown in Fig. 3, where the arrow length scales with the fluid velocity. Two counter-rotating vortices are produced above the bottom electrodes. The flow direction is upwards in the middle and downwards at the sides. Global velocity maxima are seen at the edge of bottom electrode, where the electrical field strength is at the highest. Flow velocity decreases along the electrode inwards until it becomes zero at the middle. Fluid motions in the middle of bottom boundary are cancelled out by flows in opposite directions and consequently producing stagnation. It is expected that micro/nano particles are deposited in that area.

3.2 Experiments

Parallel particle trap presented uses a silicon wafer with patterned Au layer as the bottom electrode and an indium-tin oxide glass slide as the top electrode, as shown schematically in Fig. 1a. A 500μm thick spacer (PC8R-0.5, Grace Bio-Labs, Inc.) is placed between the electrodes to form the microfluidic chamber. NaCl solution (σ = 0.224S/m) seeded with 500 nm fluorescent particles (molecular probes) is used as the working fluid. Particle motion is recorded through a Nikon eclipse LV100 microscope and a CCD camera in real time. The images are then processed by Image Pro 3DS (www.mediacy.com, Cybernetics Inc.) to extract particle velocity information. A signal generator (Agilent 33220A function generator, Agilent Technology, CO, USA) and an amplifier (Model 354-1-50, Heico Company) are used to provide a desired voltage level for electrothermal experiments. Voltages of 11.9–22.7 V_{p–p} at 200 kHz were used in the experiments.

Particles started to make fast circular movements after an AC signal is applied (e.g. 12 V_{p–p}, 200 kHz). At the wafer surface, the particles moved from the edge of the conductive area towards its centre. When the focal plane of the microscope was elevated to be above the wafer, the flow directions were reversed. So it is certain that the fluid was moving in vortices.

Figs. 4a and b compare the wafer surface before and 5 min after applying an AC signal. Within a few minutes, a large proportion of the particles became immobilised and accumulated at the stagnation points/lines. As shown in Fig. 4b, particles deposited along the field minima,
forming the cell-like structures. For the same reason, particles also form smaller clusters at the centres of non-conductive regions. It can also be seen that some particles accumulate at the edges of electrodes (bright lines), indicating the existence of positive DEP effect.

The trapping effect was also quantified. A rectangle area of $360 \times 225 \, \mu m^2$, with its location indicated in Fig. 4b, was used to measure the particle deposition. Fig. 5 shows the number of trapped particles as a function of time. A particle concentration of $6 \times 10^5$ particles/mm$^3$ was used in the experiment. At the beginning of experiment ($t = 1 \, s$), an initial reading of 30 particles was obtained in the specified rectangle. The number of trapped particles shows a linear relationship with time at a positive slope with a trapping rate of about 0.5 particles/s. The particle count tripled at $t = 120s$.

4 ACET micropump

The above experiments also demonstrate that ACET provides an effective method to manipulate fluids. With an applied voltage of $20 \, V_{p-p}$, the velocity of ACET flow is in the order of $100 \, \mu m/s$ at the edge of the electrode. So it is natural to explore ACET effect for micropumping.

Our research indicates that the net pumping motion can be achieved by asymmetric co-planar electrode arrays. Prior research has shown that reflective-symmetric, counter-rotating vortices can be generated over a pair of identical electrodes [22]. Unequal width of electrodes in a pair breaks the symmetry of electric and thermal field distribution, resulting in net velocity vector and therefore the net flow.

The electrode array used in our simulation and experiments has the dimensions of $100 \, \mu m$ narrow electrode/20 $\mu m$ gap/180 $\mu m$ wide electrode/100 $\mu m$ in-pair gap. The height of the chamber is 500 $\mu m$. One period of the ACET pump was simulated, with periodic boundary conditions applied to the sides (inlet and outlet). For other boundaries, boundary conditions similar to the parallel trap were applied.

Fig. 9 shows the fluid field profile from 0 to 500 $\mu m$ above the electrodes. The initial fluid velocity is set to zero. The fluid motions are generated by applied electric signals, and the net flow is directed from the narrower electrode towards the wider one.

The simulation results have been verified by experiments. Asymmetric electrode arrays were patterned by lift-off onto silicon wafers. Polymer channels were used. Solution of sodium chloride ($\sigma = 0.224 S/m$) was again used as the working fluid. To indicate the microflow, $1 \, \mu m$ latex particles were injected into one end of a pre-filled channel. The particles were carried along by the fluid and transported from one end of the channel to the other (Fig. 6), when an...
AC signal of 18.8 V\textsubscript{p-p} at 200 kHz was applied. Image sequence in Fig. 10 illustrates the pumping action on a particle cluster advancing through electrode pairs (Fig. 7), which was taken at \(\sim 20 \, \mu\text{m}\) above the wafer surface. The height of the focal plane was controlled through a computerised stepper (Optic scan II, CS152Z, Prior Scientific Instrument LTD). The average fluid velocity was approximately 117 \(\mu\text{m/s}\).

Fig. 6  
Simulated flow pattern over a pair of asymmetric electrodes by AC electrothermal effect  
Net fluid transport is generated. Maximum velocity is 162 \(\mu\text{m/s}\) at 15.6 V\textsubscript{p-p}.

AC signal of 18.8 V\textsubscript{p-p} at 200 kHz was applied. Image sequence in Fig. 10 illustrates the pumping action on a particle cluster advancing through electrode pairs (Fig. 7), which was taken at \(\sim 20 \, \mu\text{m}\) above the wafer surface. The height of the focal plane was controlled through a computerised stepper (Optic scan II, CS152Z, Prior Scientific Instrument LTD). The average fluid velocity was approximately 117 \(\mu\text{m/s}\).

Fig. 7  
Image sequence showing a particle cluster advancing through the electrodes  
The focal plane is \(\sim 20 \, \mu\text{m}\) above the wafer. The image colour was reversed to illustrate the particle more clearly (Dark areas are electrodes at 400 \(\mu\text{m}\) pitch.)  
\(a\) \(t = 0 \, \text{s}\)  
\(b\) \(t = 1 \, \text{s}\)  
\(c\) \(t = 1.8 \, \text{s}\)  
\(d\) \(t = 2.5 \, \text{s}\)  
\(e\) \(t = 2.9 \, \text{s}\)  
\(f\) \(t = 3.4 \, \text{s}, \text{ } \text{ } V = 18.8 \, \text{V}_{\text{p-p}} \text{ at } 200 \text{ kHz}\)

The micropump design presented here has not been optimised. Research on asymmetric ACEO micropumps indicates that a width ratio of \(\sim 7\) for the electrode pair seems to produce a high flow rate for a given voltage [16]. Since both types of micropumps are based on the geometry asymmetry, various ratios will be investigated in the future to improve pumping efficiency.

The channel height is another important factor. Our study shows that fluid motion becomes suppressed when the channel height is reduced from 500 to 200 \(\mu\text{m}\). This is in agreement with other groups’ observation [2]. This attribute is opposite to that of ACEO pumps, which produce higher surface velocity with decreased channel height.

5 Discussion

In theory, ACET velocity is expected to follow a quartic relationship with respect to applied voltage. The voltage dependency of fluid velocity was experimentally studied in this research by varying the applied voltage from 11.9–22.7 V\textsubscript{p-p} at 200 kHz. These voltages are the actual potential drop across two electrodes, measured by an oscilloscope. For each voltage settings, four velocity readings were taken and averaged to reduce the effect of Brownian motion.

Our experiment has shown that the fastest particle motion, that is, fluid velocity, occurs at \(\sim 20 \, \mu\text{m}\) above the wafer surface, which is in agreement with the simulation results. This is consistent with the characteristics of ACET flows, since electrothermal effect induces volume force on the fluid, and fluid velocity at the boundaries is zero according to no-slip condition.

Fig. 8 gives a comparison between velocities from theoretical prediction (quadratic dependency to applied voltage \(0.000303 \, V^{2}\) or \(0.0194 \, V^{4}\), simulation and experimental measurements. The three sets of data exhibit a close agreement. Simulated velocities are slightly higher than experimental data. However, at 12 V\textsubscript{p-p}, the experiments yielded a velocity slightly higher than calculation and simulation. That is probably because of other forces such as ACEO and DEP. ACEO can generate almost identical fluid flow patterns. Even though ACEO is weak in fluids with high ionic strength, it is possible that it contributes to the slightly higher velocity. As the applied voltage increases, ACEO fluid velocity goes up as \(V^{2}\), whereas \(u_{\text{ACET}} \propto V^{4}\), the contribution from ACEO becomes less noticeable.
Our work also uses impedance analysis to assess the relative importance of double layer charging (ACEO) at the electrode surfaces and space charge force (ACET) in the fluid bulk. A pair of electrodes in a fluidic cell can be electrically represented by the equivalent circuit as shown in Fig. 9. At the interface of electrolyte and electrodes, there are double layer capacitances, $C_{dl}$, for charging at the interface (which do not behave ideally, but act like a constant phase element (CPE) as defined in [9, 14]). The fluid bulk is treated as a resistor $R_{solute}$ and electricity passing it generates heat according to Ohm’s law. It is in series with the interfacial impedances on both ends. $C_{cell}$ represents direct dielectric coupling between electrodes and its value is determined by dielectric properties of the fluid.

At low frequencies, the impedance from $C_{dl}$ is much larger than that from $R_{solute}$. The system exhibits mostly capacitive characteristics, and most of the voltage drop across the interfacial double layer, which is desired for ACEO techniques. As the frequency increases, the impedance from double layer capacitances and constant phase impedances decrease, and less voltage drops over the electrode/electrolyte interfaces. More voltage drops across the fluid bulk, resulting in higher current flowing through the resistive fluid, and consequently larger temperature gradient. As a result, fluid volume force from ACET effect starts to dominate. Therefore resistive characteristics at a sufficiently high frequency indicate the dominance of ACET effects. As the frequency increases further, the dielectric coupling between the two electrodes will become dominant. The whole system exhibits capacitive characteristics again.

Impedance analysis from 100 Hz to 30 MHz was applied to both the parallel plate particle trap and the asymmetric micropump (Fig. 10). For the plate trap, the magnitude of impedance decreases from 1472 $\Omega$ at 100 Hz to 79 $\Omega$ at 50 kHz and remains constant to several MHz (Fig. 10a) and the phase angle changes from $\sim 74.831$ to $\sim 2.149$ at corresponding frequencies (Fig. 10b). The same characteristics are also observed for the pump. The impedance measurement shows a frequency range from 50 kHz to a few MHz to be suitable for ACET operation. The phase angle at low frequency does not go to 90°. It is because of the non-ideality of the double layer capacitance (CPE) and also the frequency is not low enough. The impedance analysis has also been performed on micropump presented above. The overall impedance gives 26 $\Omega$ / $\sqrt{2}$ at 200 kHz. Therefore at the operating frequency of 200 kHz, the system is electrically functioning as a resistor and electrothermal effect dominates.

Electrothermal effect, as the name implies, will lead to temperature rise in the device. The electrodes are deposited on a 4” silicon wafer, which is a good thermal conductor. During the experiments, the silicon wafer acting as a heat sink dissipates the heat generated in fluid. The temperature rise was measured by an infrared thermometer (model 52224, Mastercool, Inc.) to be $\sim 2.1$ K for the set up in Fig. 2b, close to the predicted value. This small temperature rise is insufficient to produce observable buoyancy phenomenon.

6 Conclusion

This paper presents two new ACET devices to achieve microfluidic functions of particle trapping and pumping at a fluid conductivity of interest to biochemical analysis. Preliminary experiments of ACET devices were successful. As theoretically predicted, fluid velocity scales to the fourth power of applied voltage, and it increases with fluid conductivity. Effective particle and fluid manipulation were demonstrated. Improved performance of ACET devices is expected with optimised design. The advance with ACET devices will greatly expand the application scope of electrokinesis in microfluidic chips.

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