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REVIEW ARTICLE

Dependence of Shape and Geometry of Microelectrodes in Manipulating Polarisable Particles like DNA through Electro-kinetic Effects

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ABSTRACT

Recently electro-kinetics, namely AC electro-osmosis and dielectrophoresis have been judiciously utilised to manipulate movement of polarisable particles like DNA suspended in aqueous solution and placed between electrically fed microelectrodes. Researchers around the globe have tried to fabricate electrodes of different geometries to understand how electric field owing to sharpness of the electrodes has influenced the aforementioned electro-kinetic properties. Presented a chronological development in design of patterned electrodes used to align and trap DNA molecules in and around the electrodes. We have examined the pros and the cons of such geometry of the set of the micro-electrodes and also tried to provide a solution in terms of shape and sharpness of the electrode that would facilitate DNA molecules to bridge between the electrodes for further application of conducting DNA as molecular wire.

Keywords: AC electro-osmosis, dielectrophoresis, transport dynamics, patterned electrode geometry, Microelectrodes

1. INTRODUCTION

Recently there has been a huge interest in manipulating polarisable particles like DNA using electrical forces in micro devices as it finds novel applications in lab-on-a-chip technology or in DNA diagnostics[1]. It is well understood that in a suitable condition, DNA molecules suspended in electrolytic solution would develop a strong electric dipole moment[2] and this induced dipole allows trapping and manipulation of the molecule, when placed between two micro-electrodes due to a process known as dielectrophoresis (DEP)[3,4]. In this context it is worth mentioning that the dielectrophoretic motion of DNA molecules requires alternate current (AC) electric field to suppress the electrophoric effect of the molecules' net charge[5]. However, the motion of the DNA molecules and hence their trapping/manipulation possibilities within a set of microelectrodes will also be countered by the flow of the electrolyte known as AC electro-osmosis (ACEO)[6]. This in turn implies that a balancing of DEP and ACEO should be a promising and non-destructive technique to probe non-contact manipulation/trapping of DNA molecules suspended in an electrolyte solution and placed within electrically fed microelectrodes[7]. In the text later, the processes ACEO and DEP is discussed.

Washizu[2], *et al.* adapted a set of interdigitated sinusoidally corrugated aluminium microelectrodes to experimentally observe site-specific immobilisation of double-stranded DNA molecules under AC electric field. The study exhibited that the orientation of DNA molecules depended strongly on the electric field strength. Similar inter-digitated rectangular metal microelectrodes of different dimensions and gap lengths were later investigated, both experimentally and numerically, by several researchers[8] with an aim to understand movement of DNA molecules within microelectrodes under electro-kinetic effects. However, from these investigations, it was not apparent if such geometries of electrodes could serve the purpose of bridging the electrode with a single DNA molecule out of several such species suspended in the solution. This is of paramount interest as it is well established that DNA molecules of some typical length and having specific combinations of base pairs do behave like a metal[9] and once one is bridged between two metal electrodes, it would behave as a molecular wire.

Since the manipulation/trapping of polarisable particles like DNA molecules depends strongly on the strength of the applied electric field, it is expected that the sharpness or bends of the electrode edges would influence the overall electro-kinetic process. In this regard, it appears that one might further exploit state-of-art lithographic technique to fabricate smaller electrodes with sharper bends which would intensify the non-uniformity of electric field and significantly influence DNA manipulation. A chronological development in fabrication of microelectrodes that are used by several researches in order to manipulate/trap polarisable particles like DNA is presented. Commonly used numerical simulations of the dielectrophoretic concentration of DNA particles and the effect of AC electro-osmosis and experimental methods adopted to analyse the observation is presented. Experimental observations of electronic manipulation of polarisable particles for potential circuit assembly are also presented.

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2.1 AC Electro-osmosis

When AC voltage is applied to the electrodes, having an electrolyte in between them (KCl is taken as a typical electrolyte), each electrode attracts ions of opposite charge. The electric field exerts electric force on these ions which points in opposite directions on both electrodes. This electrical force causes movement of ions which in turn produces stress on the surrounding fluid which thus moves from the gap between the two electrodes onto the surface of the electrode on either side. The schematic of the system explaining the mechanism of AC Electro-osmosis (ACEO) is shown in Fig. 1 where the x-component of electric field and the direction of resultant Coulombic force are shown clearly.

If one considers a set of symmetric rectangular parallel electrodes like that used by Green[10], *et al.* then for the frequency of applied voltage at 500 Hz, a typical plot of electric potential and ACEO flow, generated numerically using COMSOL multiphysics could be realised as depicted in Figs. 1 and 2 respectively. It is to be noted that coplanar parallel electrodes are placed in a closed glass chamber. It is customary to exploit the symmetry of the system and only one electrode is used for simulation. The schematic of the simulation region (top view) is shown in Fig. 3. For this typical electrode having a width of 100 µm, the plane Y = 0 is the plane of symmetry. The distance of the electrode from plane of symmetry is 12.5 µm. This geometry is also used by Green[10], *et al.* As it can be observed from the Fig. 2.

It is to be noted that Comsol Multiphysics software is based on finite element method where, a mesh consists of triangular elements for the two-dimensional parallel electrodes. Finer meshing might be more appropriate if an electrode has bend or sharp edges due to the discontinuity of electric field at edges.

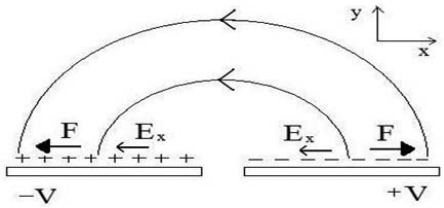


Figure 1. Schematic of the ACEO mechanism[11].

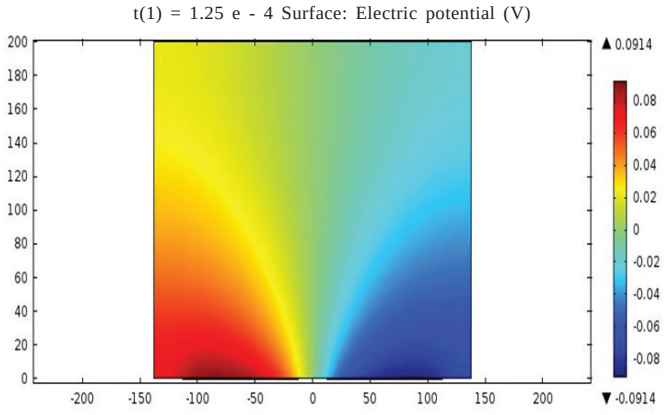


Figure 2. Electric Potential at 500 Hz[11].

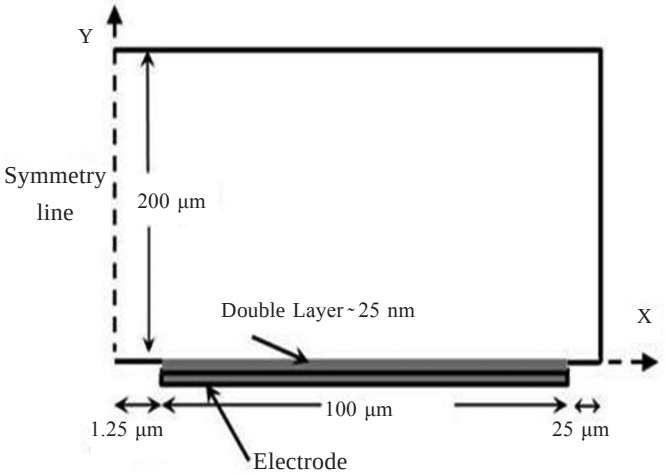


Figure 3. Schematic of problem space showing cross-sectional view[11].

This is in general, termed as 'the coplanar parallel electrode (CPE) geometry'. A simplified linear model proposed by Green, *et al.* adequately provides a qualitative understanding of the system[12,13,14]. In other words it is based on a linear RC circuit model where the double layer is modelled as a capacitor and the bulk region as a resistor[15].The low applied voltage falls within the domain of the linear model. The electrical double layer (EDL) formed above the surface of electrode is taken to have a thickness equal to the Debye length given by the thin layer approximation,

$$\lambda_d = \frac{\varepsilon k_B T}{2N_a e^2 C} \tag{1}$$

where ε is the permittivity, k_B is the Boltzmann constant, T is the absolute temperature (~298K), N_a is the Avogadro number, e is the electron charge and C is the concentration of one ion at infinite dilution in the medium calculated using the following equation,

$$C = \frac{\sigma}{\lambda_\infty} \tag{2}$$

λ_d is the molar conductivity of KCl at infinite dilution at room temperature. Only the bulk region (after EDL ends) is simulated and the potential and the fluid flow equations are used as boundary conditions. The charge density in the bulk region is assumed negligible and hence potential V, in the domain is governed by the Laplace's equation:

$$\nabla^2 V = 0 \tag{3}$$

The following boundary condition is applied at the top of the EDL,

$$\vec{n}.\vec{J} = i\omega C_{DL}\left(V - V_{ref}\right) \tag{4}$$

where the term on the left hand side pick out the normal component of current density, C_{DL} is the capacitance per unit area of the double layer and V_{ref} is the potential applied to the electrodes which is sinusoidal in nature. The capacitance is estimated using the linear *RC* circuit model for the system as in Debye Huckel theory,

$$C_{DL} = \frac{\varepsilon_0 \varepsilon_r}{\lambda_d} \tag{5}$$

The potential at the image plane is taken to be zero. Once the electric potential is solved, the coupled time-dependent Navier-Stokes (NS) equation given below is solved for fluid flow, considering incompressible fluid.

$$\rho \frac{\partial \vec{u}}{\partial t} + \rho\left(\vec{u}.\vec{\nabla}\right)\vec{u} = \vec{\nabla}.\left[-p\vec{I} + \eta\left(\vec{\nabla}u + \left(\vec{\nabla}u\right)^T\right)\right] + \vec{F} \tag{6, 7}$$

$$\rho\vec{\nabla}.\vec{u} = 0$$

where ρ refers to mass density of fluid, taken to be mass density of water, 1000 kg/m^3, p refers to pressure, I refers to Identity matrix. F refers to the external force on the fluid, which for this case is the electrical force that arises out of potential applied to the electrodes. The region of interest being the bulk region where charge density is negligible, allows one to assume, F = 0 for simulation purposes. As Reynolds number for microelectrodes is less than 10^{-2}, inertial term (second term on left hand side of the equation) is neglected in the Eqn. 6. The walls and electrodes are assumed impervious and therefore have no normal component of the fluid velocity at their surface. On the top of the double layer, horizontal fluid velocity is given by Helmholtz-Smoluchowski formula for electro-osmotic velocity[12]

$$\vec{u} = -\frac{\varepsilon_0 \varepsilon_r \Lambda \varsigma \vec{E}_t}{\eta} \tag{8}$$

where $\varsigma = V_{ref} - V$

This is the potential difference between the outer and inner sides of the diffuse layer, is the ratio of potential drop across di use layer and potential drop across double layer. E_t is the tangential component of electric field just outside the double layer, η is the viscosity of the medium. Owing to symmetry, at the image plane, normal component of velocity as well as the sheer stress is zero.

As the ACEO flow is unidirectional with respect to the AC voltage, for experimental purposes, time-averaged velocity is usually taken by averaging out the 6-8, which then become,

$$\nabla.\left[-p_{avg}\vec{I} + \eta\left(\nabla u_{avg} + \left(\nabla u_{avg}\right)^T\right)\right] = 0$$

$$\rho\nabla.u_{avg} = 0$$

$$u_{avg} = \frac{\varepsilon_0 \varepsilon_r}{2\eta}\mathrm{Re}\left(\varsigma E_t^*\right)$$

where * denotes the complex conjugate

2.2 Dielectrophoresis

DEP is a phenomenon where a force is exerted on a polarisable particle like DNA molecule by a non-uniform electric field which in most practical cases is sinusoidal in nature[3]. Surface charges get induced in the polarisable particle in the electric field with positive in one side and negative on the other. The charges are of the same magnitude. This produces a Coulombic interaction between the induced surface charges and the electric field. It is worth mentioning that in a uniform electric field the net force due to the Coulombic interaction is zero but becomes significant in non-uniform electric field. Depending on the magnitude of the particle polarisability with respect to the surrounding, a DEP process is named as 'positive DEP' or 'negative DEP'[3]. The dielectrophoretic force acting on a spherical particle is given by[10]

$$F_{DEP} = 2\pi\varepsilon_m r^3 \,\mathrm{Re}\left[K(\omega)\right]\nabla E_{rms}^2 \tag{9}$$

where r is the particle radius, ε_m is the permittivity of the medium, E_{rms} is the rms value of the applied field and $Re[K(\omega)]$ is the real part of Clausius-Mossotti (CM) factor. This, in case of a homogeneous spherical dielectric particle is given by,

$$K(\omega) = \frac{\varepsilon_p^* - \varepsilon_m^*}{\varepsilon_p^* + 2\varepsilon_m^*} \tag{10}$$

where, ε_p^* and ε_m^* are the complex permittivities of the medium and the particle, respectively which are related to the conductivity σ and the angular frequency ω of the applied field through the equation:

$$\varepsilon^* = \varepsilon - i\left(\frac{\sigma}{\omega}\right) \tag{11}$$

3. EXPERIMENTAL OBSERVATION ON ELECTRO-KINETIC MANIPULATION OF POLARISABLE PARTICLE

Washizu and Kurosawa[2] first presented experimental observation of the electrostatic orientation and dielectrophoresis of λ-phase DNA molecule under high intensity electric field produced in a microfabricated electrode system of two types: One parallel strip electrode with spacing 60 μm and the other right-angle edge-to-strip electrode having minimum spacing of 70 μm. The former is intended to produce a uniform and the latter a non-uniform field. The fluorescence technique was adopted to visualise the orientation. It was observed that the orientation of DNA molecules in the form of number of thin filament-like agglomeration, parallel to the field took place under field strength of 10^6 V/m and the frequency around 1 MHz for parallel electrodes. The whole process took only one second. Interestingly, when the voltage was turned off, the band diffused and disappeared in about one minute. Although similar phenomena was also observed for edge-to-strip electrode, but molecules were attracted to the region near the edge where the field is the strongest. Figure[2] shows the electrostatic orientation of DNA under (a) uniform field and (b) non-uniform field. They thoroughly investigated the frequency dependence of the orientation of the DNA molecules wherein they concluded that for the frequency range between 0.1 MHz and 1 MHz, the orientation took place parallel to the field, while at 40 kHz, it occurred parallel to the field. Through stretch/shrink of an individual molecule when the field is on/off, they provided a clue to determine the molecular size (i.e. number of base pairs) of a DNA molecule.

This work by Washizu and Kurosawa paved way to novel applications in genetic engineering. Methods were developed to immobilise stretched DNA onto a substrate, including

(a) immobilisation onto conducting substrate for observation with scanning tunnelling microscope and
(b) anchoring onto a substrate only at the both ends of DNA

using special electrode configuration.

To achieve site-specific immobilisation of DNA molecules, Washizu[8], *et al*. fabricated an electrode configuration as shown in Fig. 4 which was less likely to induce flow of the medium than a simple parallel strip.

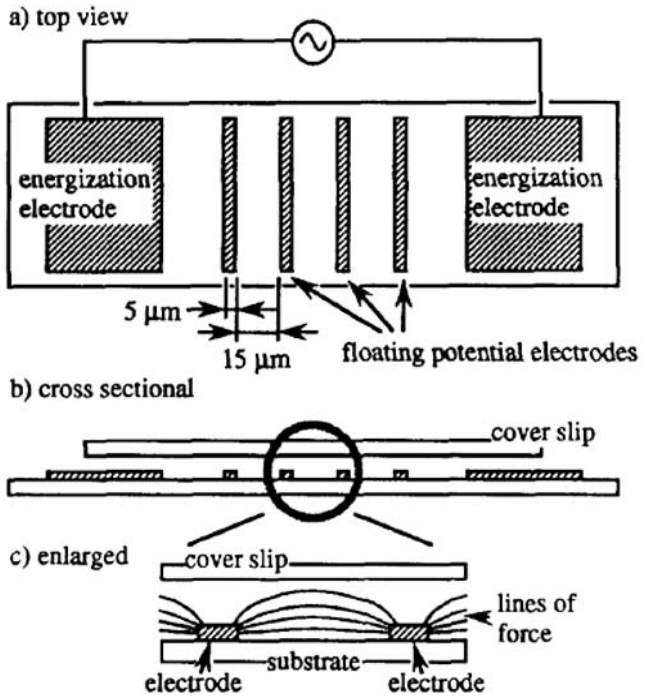


Figure 4. Schematic of the electrode configuration. Taken from Washizu[8], *et al.*

In a simple parallel strip electrode configuration, the flow pattern in the gap started from the electrode edges towards the center of the gap, and went apart from the from the plane of the electrodes and circulated back. One end of DNA pulled into the high field region might be fixed to an edge, but the other end was prevented from approaching to the other electrode due to the flow. The electrode set up fabricated by Washizu[8], *et al.* consisted of two outermost electrodes and several strip electrodes between the gap. The power supply was connected only to the outermost electrodes and the thin strip electrodes have no electrical connections giving rise to 'floating potential electrode geometry'. This electrode configuration did not reduce the electric field induced flow at the edge of the energised outermost electrodes, but the flow at the edge of the floating electrodes was substantially suppressed. With this field geometry, DNA was found to get anchored at both ends, bridging over the two adjacent floating potential electrodes.

As mentioned before, DEP plays a crucial role in manipulation of polarisable particles like different biopolymers, Washizu[16], *et al.* used the fluid integrated circuit (FIC) concept to fabricate micrometer-sized electrodes with which a very high intensity, high frequency field over 10^6 V/m at 1 kHz to 10 MHz could be created. The experimental set up was a kind of interdigitated sinusoidally corrugated electrodes. The observation of molecular DEP using avidin (68 kD) and other biopolymers were made and it was found that DEP occurred at the field strength of 0.4-1.0 x 10^6 V/m which was lower than that was predicted from theory.

Within a few years, Asbury and van den Engh showed that DNA molecules could be manipulated in aqueous solution in a manner analogous to optical trapping[17]. They experimentally exhibited that molecules were locally trapped in an oscillating field using strips of very thin gold film, fabricated using standard photolithographic technique, to generate strong electric fields with steep gradient. They suggested that spatial control over the trapped molecules was possible because they were confined to a width of about 5 μm along the edges of the gold-film strips. As this study revealed that high field gradient would easily induce a dipole moment in DNA and cause it to aggregate, based on this this, Asbury[18], *et al*. later developed two methods for measuring the strength and capacity of dielectrophoretic DNA trapping.

In the first method, CCD camera and fluorescent microscope were used to take sequence of digital images as trapping voltage is turned on and then off again. The second method used was a micro-fludic channel placed over the trapping electrodes and a photomultiplier to measure the fluorescence from a small quantity of DNA trapped and subsequently released upstream of the measurement point. Figure 5 shows the fluorescence profile of typical time behaviour of DNA trapping following the first method. As soon as the trapping field was switched on, narrow peaks (width ~5 μm) of fluorescence grew rapidly in the profile where DNA molecules became concentrated over the edges of the gold film. The field was switched off again after 30 s and the peak broadened and shortened as the DNA molecules dispersed.

Figure 5 shows the plot of fluorescence intensity as a function of elapsed time during a typical experiment on T2-phase DNA (164 kb) following method two where the frequency of the applied field was varied for each measurement. At each frequency, 3 $V_{p\text{-}p}$ was applied for 60 s, followed by a 30 s

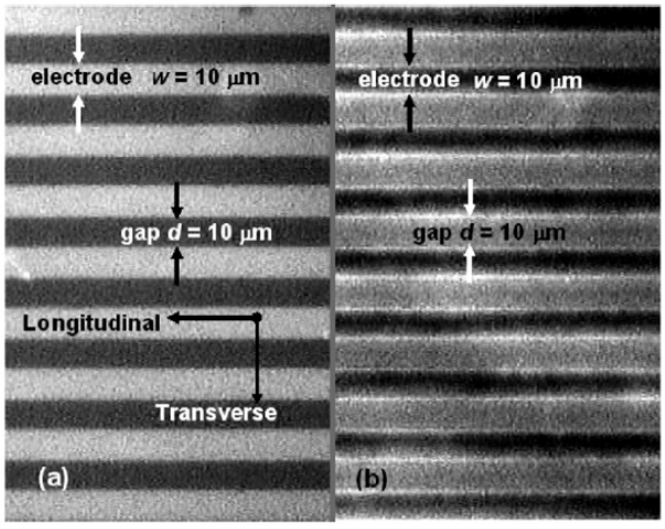


Figure 5. Photographs showing DAPI labeled DNA plasmid suspension collecting onto the interdigitated electrode array. (a) Array before the onset of DEP, (b) 4.2 s after onset of DEP with The gold electrodes in (a) appear bright because they reflect the fluorescence from the DNA suspension. In (b), the DNA collects between the electrodes, so the gaps appear bright. Taken from Bakewell[19], *et al.*

interval with no voltage. A slight decrease in fluorescence was evident during voltage application, indicating that a significant fraction of molecules flowing past the upstream electrode were being trapped. Bright spikes occurred immediately after the voltage was switched off as the previously trapped molecules flown past the detector. The height of the peak was used as a measure of the quantity of the DNA trapped.

Bakewell and Morgan[19] reported measurements that characterised the collection of DNA onto interdigitated microelectrodes, as shown in Figure 5, employing high frequency dielectrophoresis. The electrodes were fabricated using standard photolithographic technique from Gold with a Tiunder layer and were 10 µm wide with a 10 µm gap. The use of Ti was to improve adhesion of gold on to the substrate.

The fluorescence microscopy was used to dielectrophoretic collection of pTA250 plasmid DNA within the above-mentioned electrode structure. Figure 5(a) shows the two half frame width (60 per cent height) video images of the fluorescently labelled DNA suspension before and ~4 s after the onset of DEP. From Figure 5(b), it is clear that DNA plasmids are getting collected between the electrodes.

Zheng[20], *et al.* fabricated quadrupole electrode geometries to manipulate DNA, protein and nanoparticles for potential circuit assembly. The gap between the electrodes ranged between 3 µm and 100 µm and field strengths were typically 10^6 V/m. The DNA used for experiment was λ-phage (48.5 kbp). Through fluorescence technique, they observed that DNA at chosen experimental condition underwent positive DEP for a range of frequencies between 100 kHz and 30 kHz. The images of the fluorescently labelled DNA are shown in Fig. 6. The four images were taken in on/off/on/off sequence in a time span of about 30 s (f = 1 MHz and applied voltage = 8 V). Jiong-Rong Du[21] utilised asymmetric T-shaped quadrupole electrode configuration, very similar to that used by Zheng[20], *et al.* which was capable of trapping and concentrating a trace amount of DNA molecules efficiently. The gap between the adjacent electrodes was 75 µm. This strategy evoked non-linear

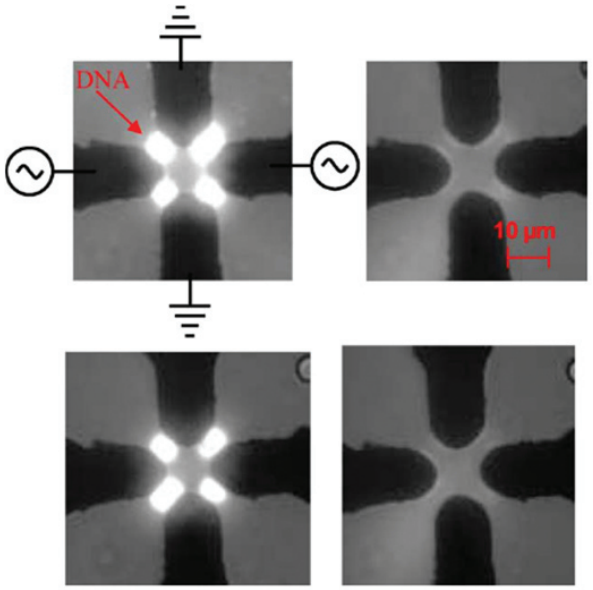


Figure 6. Images of fluorescently labelled DNA take in on/off sequence, Zheng[20], *et al.*

electro-osmotic flow induced by charge polarisation under high frequency ac fields and the motion of DNA molecules was observed using an inverted fluorescence microscope. The progress of trapping with time was examined through temporal evolutions of the fluorescent intensities at different locations of a focussed spot which showed trapped molecules.

Experimental investigations of DEP particle concentration by Bakewell and Morgan[19] also revealed a difference between experimental and numerical results which were attributed to other factors like ACEO flow, caused by the interaction of the ions in the electric double layer with tangential electric field on the electrode surface. The manipulation problem scales up by the fact that ACEO fluid flow is induced in the system that disturbs the DEP concentration of the particle. It opens up a necessity to investigate on ACEO coexistence with DEP. Loucaides[24] presented numerical simulation of dielectrophoretic concentration of DNA molecules and the effect of ACEO. DNA molecules were suspended in a solution within a system of parallel electrodes where particles were found to be attracted to the edges of the electrodes.

When logarithm of steady state concentration was studied as a function of dipole moment using Smolochowski Equation[12], the results were remarkably different with DEP alone and with joint DEP and ACEO. As soon as ACEO was introduced the concentration dramatically decreased while very modest collections of DNA on the array were observed in comparison predicted experimentally[19]. Through numerical simulations, Loucaides later showed there did exist trapping points in parallel electrodes and configurable asymmetric electrode systems under the combined effect of ACEO and DEP[23]. They also pointed out that asymmetric configuration might be more suitable to generate trapping points though it would depend on the number of electrodes in the array and device characteristic scale.

Electrical measurements through a single DNA molecule trapped and bridged between two with 10 nm triangular metal electrodes was reported by Porath[24], *et al.* Electrodes were fabricated using ultra-modern electron beam lithography. The work clearly exhibited that the electric field strength which was extremely large at the vertices of the triangular electrodes, coupled with polarisation properties of DNA molecules, played a crucial role to guide the flow of molecules in and around the tips. Moreover the triangular shape of the electrode facilitated the chance of a single molecule being bridged between the electrodes. Recently, Vahidi[25], *et al.* confirmed that triangular metal electrodes were the most suitable form of electrode configuration which would result in attachment of DNA molecules at the electrodes with high aspect ratio. Figure 7 shows SEM images of λ-DNA being bridged between two metal electrodes.

However, there is an interesting point to ponder. Though electron beam lithography is successfully used to pattern nanometer gap electrodes, there is an inherent limit of accuracy with the instrument. That is to say, bends and sharpness of the electrodes may not be as designed after standard development and lift-off processes. Now, with sharp and blunt edges, non-uniformity of the electric field would vary, which in turn should affect the combined effect of ACEO and DEP. As a result the

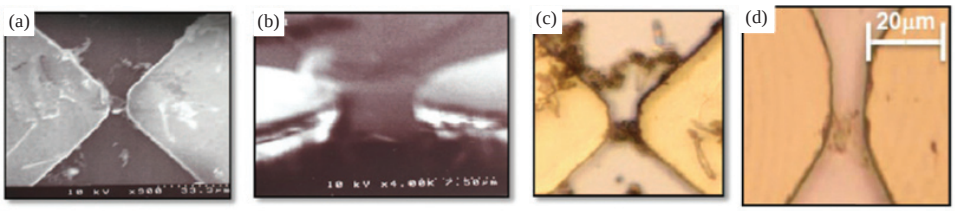


Figure 7. SEM images of the λ-DNA. Taken from Vahidi[25], *et al.*

positions as well as the strengths of the trapping points in the electrolyte solution, facilitating stretched DNA molecules to bridge across the electrodes would vary. Recently we studied in detail, through simulations how those minute bends of the electrodes and sharpness of the edges could affect the sites of the trapping points as well as its strength[26,27].

The electrode geometry used byus[26] is as shown in Fig. 8. where simulations, using COMSOL Multiphysics is done to systematically study the behaviour of the system by varying three parameters:

(i) The apex angle θ which governs the notion of convexity,
(ii) The fillet radius *r* which governs the notion of sharpness of the rounded tip and
(iii) The electrode separation *d*.

An increase in θ while keeping the other two parameters constant would cause a decrease in convexity. Similarly an increase in *r* causes a decrease in sharpness. Numerical studies were done using mirror image symmetry as mentioned in the text before, by varying each parameter while keeping the other two fixed to explore the possibility of obtaining trapping points and to analyse the strength of these trapping points as a function of these parameters.

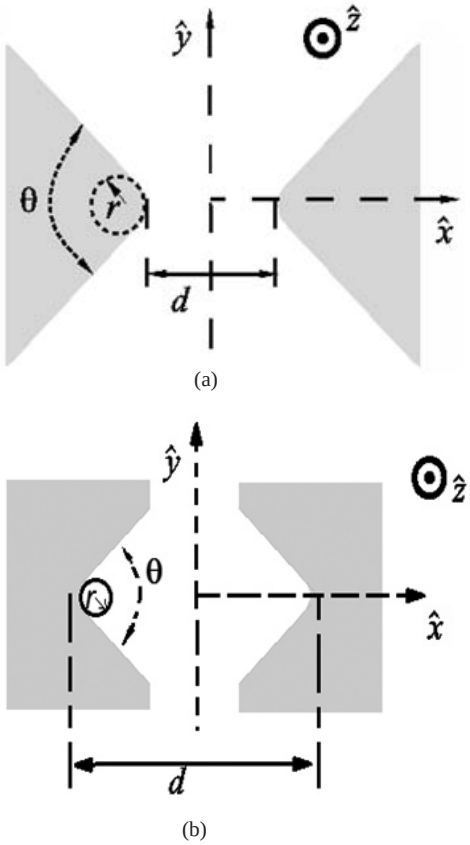


Figure 8. Schematic representation of the top view of the (a) convex and (b) concave triangular electrodes, Ghonge[26], *et al.*

Decreasing the apex angle leads to increasing an electric field density near the tip. The presence of a tip causes a sudden rise and fall in the value of the electric field – this causes the formation of trapping points as is observed in the plot of the *x* component of the net force plotted against the *x* coordinate. Figure 9 shows a typical variation.

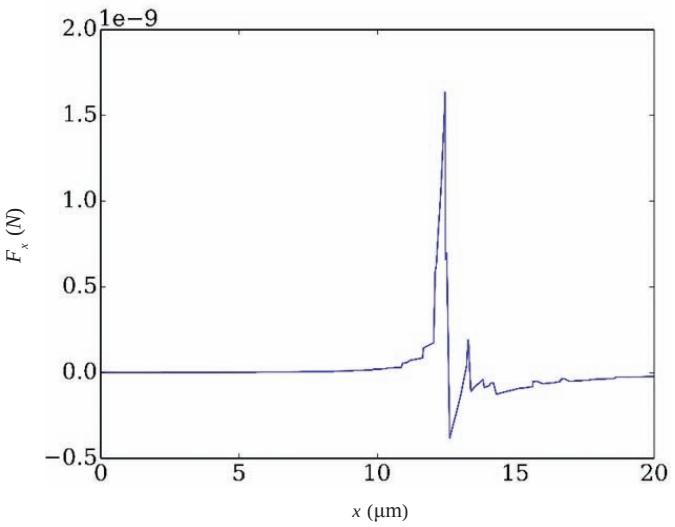


Figure 9. Variation of the x-component of the force on a stretched DNA molecule along the x-axis. The specific parameters used are *d* = 25 μm , *r* = 0.5 μm , θ =102. Taken from Ghonge[26], *et al.*

The figure shows a sharp peak followed by a sharp trench at $x = 12.5$ μm. The force around $x = 12.5$ μm is a trapping point as the force is restoring in nature. The strength has been defined as absolute value of the average slope calculated between the extrema. For the convex electrode case, an increasing apex angle implies decreasing convexity, while for the concave cases, it means increasing convexity. Figure 10 shows that an increase in convexity implies an increase in the strength of the trapping points.

A variation of the fillet radius r also changes the electric field density around the tip of the electrodes. A sharper electrode tip produces a stronger electric field and strengthens the DEP force. Thus, the net force across the vortex is expected to change faster for sharper electrodes. It is tested by plotting

The variation of *x*-component of the force F_x as a function of the fillet radius *r* at the center of the vortex keeping electrode separation $d = 25$ μm and apex angle $\theta = 102°$. Figure 11 shows the variation of the slope of the x-component of the force as a function of *r* for the convex (dashed curve) and the concave (solid curve) electrodes. Specifically, the slope was calculated

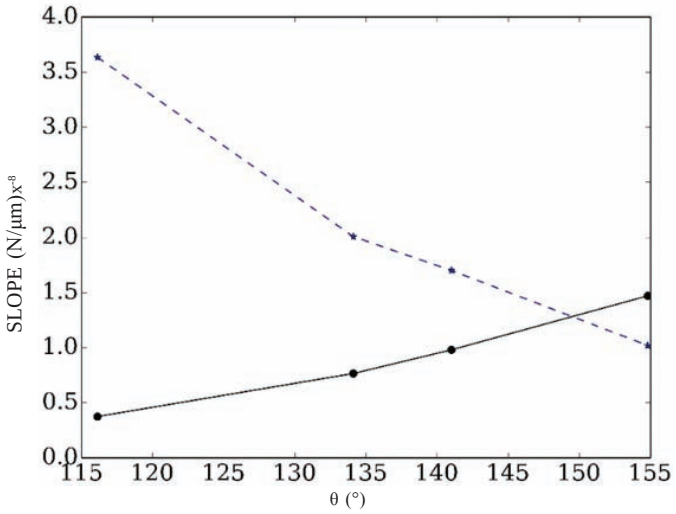


Figure 10. Variation of the slope of the x-component of the force as a function of the apex angle θ for the concave (solid curve) and convex (dashed curve) electrodes. Taken from Ghonge[26], *et al.*

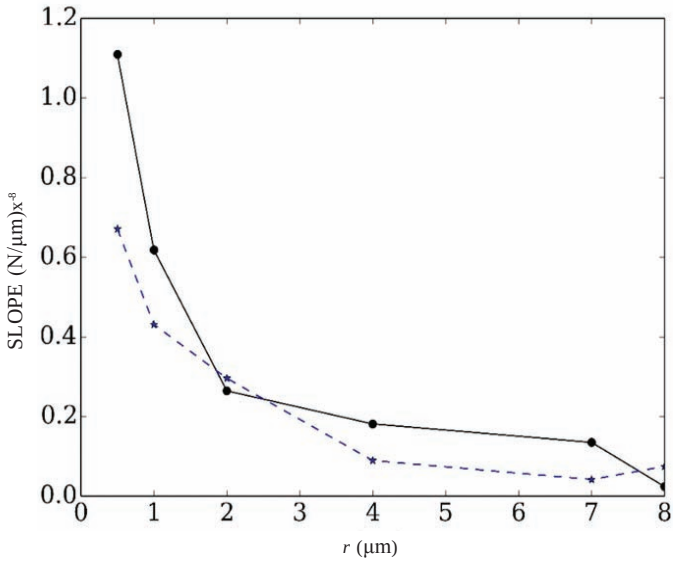
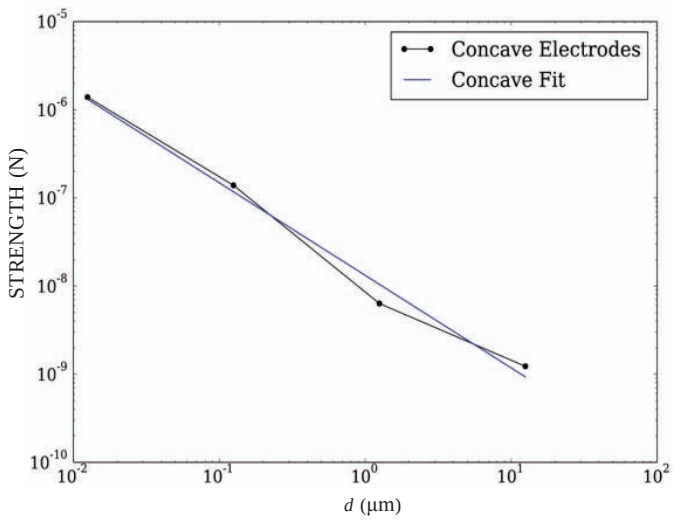


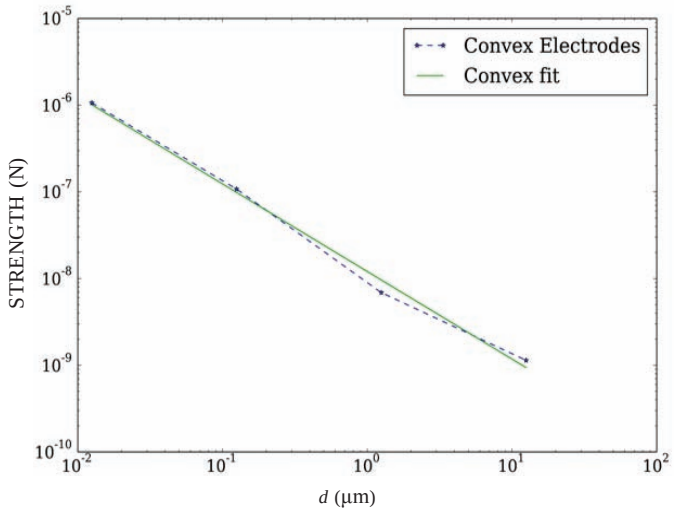
Figure 11. Variation of the slope of the x -component of the force as a function of the fillet radius *r* for the concave (solid curve) and convex (dashed curve) electrodes. Taken from Ghonge[26], *et al.*

by taking a linear approximation of the curve between the two points where the force reaches its extremal values. F_x varies with d at a rate of $0.48\times10-10$ *N/μm* for flat electrodes ($r \to \infty$). The decrease of the stiffness of the force with the fillet radius occurs for all angles checked in the range of 116.1° to 154.8°. The plot (Fig. 11) suggests that electrodes with smaller r (i.e. having sharper tip) would produce stronger vortices within the electrolyte.

The behaviour of the trapping points as a function of electrode separation, having a fixed convexity and properly scaled sharpness of tips are presented by Prasad[27], *et al.* Figures 12(a) and 12(b), respectively show the plot of the strength of the x-component of the force on a DNA molecule as a function of the parameter d for convex electrode and concave electrode. The convexity of the electrodes is maintained at a value of θ



(a)



(b)

Figure 12. Variation of the strength of the x component of force v/s the electrode separation *d* for the system of (a) convex and (b) concave electrodes, Prasad[27], *et al.*

equal to 102° and its sharpness is kept constant by scaling down the size of the entire system for a decrease in *d*. From the Figs. 12(a) and 12(b), it is clear that the magnitude of force increases with a decrease in distance d between the electrodes. It would be interesting to verify these results through experiments to confirm the predicted trapping behavior of the polarisable molecules.

4. CONCLUSION

Examined how polarisable particles like DNA molecules could be electro-kinetically controlled when placed in suspended form in between two micro/nano electrodes fed by ac voltage. It opens up a challenge to researchers from theoreticians to experimentalists, from a designer to a fabricator, as it holds high promise to novel applications in applied physics, electrical engineering, and biotechnology. Experiments are necessary to validate the simulations done which are already underway in many research laboratories including that of ours.

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In the current study, he has defined the problem and overviewed it over the time to fruit results. He has also drafted the review article.