

# Dielectrophoretic Microfluidic Devices

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## ABSTRACT

On the microscale, the dielectrophoretic (DEP) force may be used to control and manipulate sub-microliter volumes of liquid water using co-planar electrodes of very simple design. The basic phenomenology of liquid DEP on the microscale is familiar; water tends to collect in regions where the electric field is strongest. However, because capillarity and surface wetting become stronger as dimensions are reduced, certain important distinctions between microDEP and centimeter-scale DEP are observed. One important difference is that, in certain cases dependent on electrode geometry and dimensions, the water can assume either of two distinct, and apparently stable, cross-sectional profiles, "narrow" or "wide". For the narrow profile, the advancing water finger is confined to the immediate vicinity of the electrode gap, while for the wide profile, the liquid spans the entire width of the electrodes. This indeterminate behavior depends on the width of the electrodes, though the ratio of the electrode spacing to the width may be just as important. The existence of two stable hydrostatic equilibria seems to be related to the surface wetting. An hypothesis is presented that local electric field intensification near the edges of the electrodes is responsible for the behavior.

## INTRODUCTION

DEP liquid actuation uses non-uniform electric fields created by simple co-planar electrodes patterned on insulating substrates to manipulate and move sub-microliter volumes of water around a smooth substrate. The electrodes have feature sizes typically in the 50-100  $\mu\text{m}$  range and are covered by a  $\sim 10$   $\mu\text{m}$  polyimide layer [1]. One configuration has been employed successfully to form multiple droplets smaller than 10 nanoliters using programmed sequences of voltage application and changes of electrode connections. On moderately hydrophobic polyimide, with contact angle  $70-80^\circ$ , DEP actuation of small water volumes is extremely rapid: transient "meniscus" speeds exceed 5 cm/s, transient flow rates reach  $\sim 1$   $\mu\text{l/s}$ , and droplet formation times are less than 0.1 s. On the other hand, surface treatment with amorphous Teflon<sup>®</sup>, which has a contact angle of  $105^\circ$  against water, or agarose, a good wetting agent, blocks DEP actuation. The dielectric layer prevents electrolysis, but necessitates rf frequencies due to capacitive coupling; the minimum operating frequency for structures tested to date is  $\sim 60$  kHz and the required voltage is 500 to 700 V-rms.

This paper reports an experimental investigation of how the cross-sectional dimensions of the electrodes influence the behavior of flow structures used for dielectrophoretic (DEP) actuation of liquid water. In certain circumstances not always predictable, the liquid profile in these flow structures can assume either

a "narrow" or a "wide" configuration. The experiments reported here have been conducted to document this behavior and to clarify the critical geometrical parameters that control it. Improved understanding of these phenomena is crucial to successful exploitation of DEP actuation in new microfluidic devices.

## BACKGROUND

In the past ten years, microfluidics research, particularly  $\mu$ TAS (micro-total analysis systems) and the "laboratory on a chip", has rapidly advanced [2,3]. The dream of  $\mu$ TAS is fluidic/diagnostic microstructures fabricated on a substrate with the capability to perform chemical reactions and/or biological protocols on the microscale. Central to such schemes are systems programmed to manipulate, dispense, transport, and process very small inventories of fluid automatically without intervention. These structures will be integrated on a chip with necessary electronics, sensors, and measuring systems. The implications for such a technology are immense in health care delivery. Likewise, automated  $\mu$ TAS schemes offer new prospects for routine chemical analysis, drug testing, and bio-assay. Advantages include reduced handling of toxic or pathogenic substances, reduced waste of expensive reagents, and the capability to perform large numbers of separate, combinatorial reactions simultaneously.

Microfluidic systems rely on many different ways to move small liquid samples about. Those under investigation at present divide loosely into two categories: *closed* and *open* systems. Closed systems consist of tiny channels ( $\sim 10^2$  to  $\sim 10^3$   $\mu\text{m}$  in size) and a variety of pumps, including miniature piezo-electric devices, ion-drag [4], electroosmosis [5], and electrochemical reactions [6]. On the other hand are open systems, which manipulate and transport liquid upon structured surfaces, for example using capillary [7] or wetting [8] phenomena.

The DEP actuation scheme described in this paper is an open system. Microliter volumes of water, deposited on substrates underlain with arrays of planar electrodes, are manipulated, transported, and probably divided into nanodroplets using the DEP force exerted by non-uniform electric fields. Once formed, these nanodroplets are moved about on a substrate for subsequent mixing, separation, assay, and other processes, possibly via Washizu's electrostatic droplet transport scheme [9]. Another application for DEP actuation is as an interface with closed-channel systems. One important, long-term goal is DEP actuation of sub-nanoliter quantities of nutrient-rich, aqueous media containing biological cells and cell components.

## DIELECTROPHORESIS OF WATER

The electromechanical response of water resting atop the planar electrodes when voltage is applied is well-understood [10]. The electrodes create a non-uniform electric field, and the DEP force attracts the water, or any polarizable liquid, into regions where this field is strongest. One distinction of the DEP effect in water from earlier experiments using dielectric liquids [11] is that the electrodes must be coated with an insulative coating to prevent electrolysis. This capacitive coupling to the conductive water blocks current below some

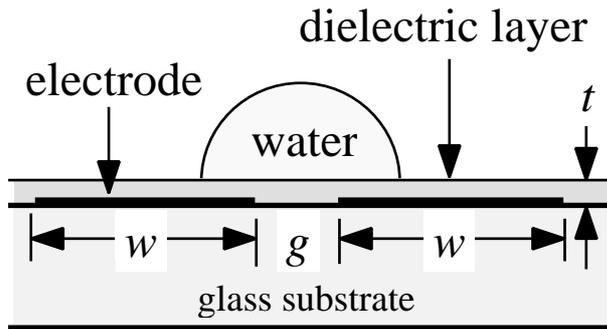


Fig. 1 Cross-section of co-planar DEP flow structure showing liquid profile observed only for frequency 60 kHz. The dielectric layer covering the electrodes prevents electrolysis. Sketch is not to scale.

critical frequency value  $f_c$ . We have used a simple series RC circuit model to estimate  $f_c$  [1]. Below this critical frequency, which is  $\sim 60$  kHz for de-ionized water of conductivity  $\sim 10^{-4}$  S/m, liquid fails to collect in the compact, semicircular profile of Fig. 1, and DEP actuation is not achieved.

It is easy to exemplify basic liquid DEP phenomenology with the simple strip electrodes shown in cross-section in Fig. 1. The sequence of video images in Fig. 2 shows the liquid response for a structure with width  $w = 1000 \mu\text{m}$ , spacing  $g = 100 \mu\text{m}$ , dielectric thickness  $t = 10 \mu\text{m}$ , and effective length  $L = 3 \text{ cm}$ . When voltage is applied, a finger of water, confined to the vicinity of the gap between the two strips, projects from the large droplet (at lower left), moving rapidly and turning two corners before arriving at the opposite end of the structure. This transient motion then stops, unless the structure has been tilted so that gravity-driven siphoning occurs. When voltage is removed, the water collects into large masses at each end, and sometimes one or more small droplets stranded along

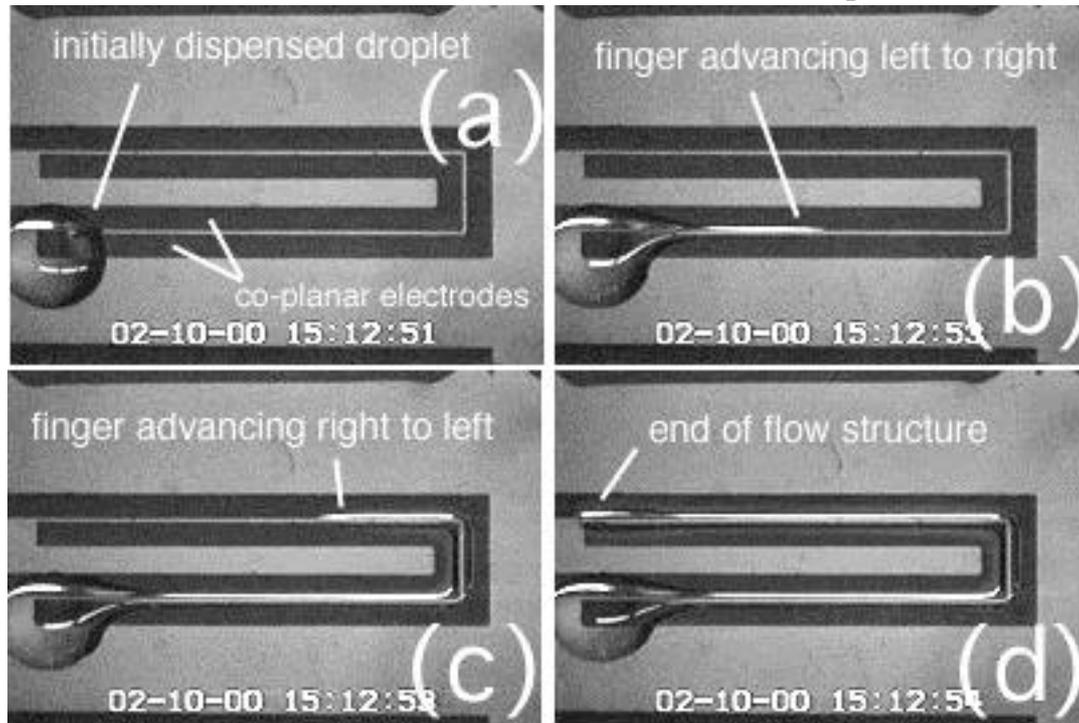


Fig. 2. Video micrograph sequence of flow structure (top view) with de-ionized water ( $\sim 10^{-4}$  S/m). Electrode dimensions:  $g = 100 \mu\text{m}$ ,  $w = 1000 \mu\text{m}$ ,  $t = 10 \mu\text{m}$ . Voltage at  $\sim 100$  kHz turned up by hand over several seconds to  $\sim 700$  V-rms. (a) Voltage off: microliter droplet dispensed by micropipette visible at lower left. (b) Voltage on: finger starting to extend to right along flow structure. (c) Voltage on: water finger has rounded two  $90^\circ$  turns. (d) Voltage on: water finger has reached the end of the structure.

the flow structure. If the voltage is turned on rapidly with a relay, then the tip of the finger moves at a speed  $>5$  cm/s. To record the sequence in Fig. 2, the voltage was actually turned up by hand, so the water was subjected to the strong electric field for several seconds, causing heating and some evaporation. Brief application of the voltage (a few tenths of one second) accomplishes the same net motion, but with much less heating.

The high-frequency behavior revealed in Fig. 2 is consistent with the predictions of liquid DEP theory. The liquid is confined within the region of maximum electric field strength in a column of semi-circular cross-section, centered on the midpoint between the two electrode strips and extending along the flow structure. Once formed, it is the strong fringing field at the tip that pulls the finger forward.

#### PROFILE IN NARROW STRUCTURES

The video sequence of Fig. 3 shows DEP-actuated transient flow in a much narrower flow structure. Here, the coplanar electrodes, ( $w = 50$   $\mu\text{m}$  and  $g = 100$   $\mu\text{m}$ ) are terminated by a bisected circle of diameter several times larger than the total structure width,  $2w+g = 200$   $\mu\text{m}$ . Again first, a microliter-sized droplet is dispensed manually, this time on the right side. When voltage is applied, a finger forms and moves left along the structure to create a hemispherical droplet of diameter  $\sim 60$  nanoliter. Of present interest to us here is the width of the liquid profile, rather than droplet formation. Unlike Fig. 2, where the water finger is confined to a relatively narrow region centered on the gap, here the finger spans the entire width of the structure, from the outer edge of one electrode to the outer edge of the other. This behavior, while distinct from the previous case, is probably not surprising because the electrodes in Fig. 3 are considerably narrower and only somewhat closer together. Nevertheless, this difference between "narrow" and "wide" profiles suggests that capillary forces do impose ultimate lower limits on useable structure dimensions and the size of droplets that can be formed by DEP actuation. It also means that there must be some transition in the width of the profile of a water finger as electrode width  $w$  is decreased from  $1000$   $\mu\text{m}$  to  $100$   $\mu\text{m}$ .

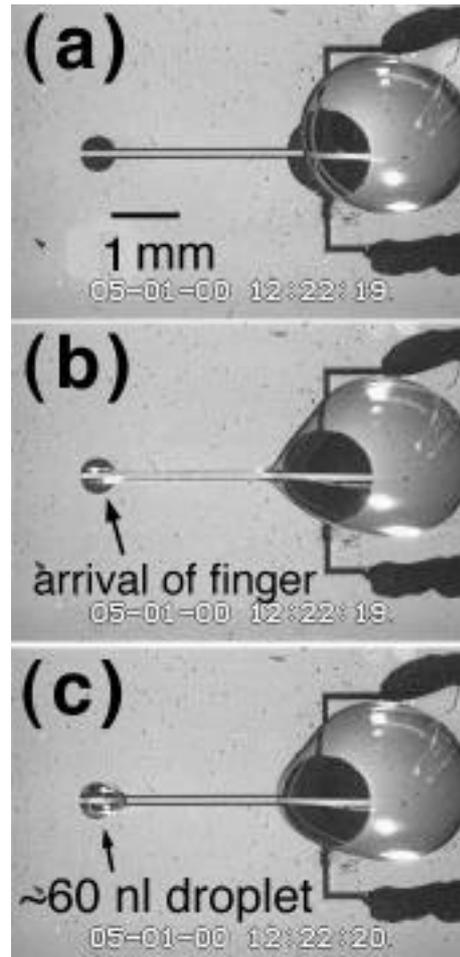


Fig. 3. Video micrograph sequence of narrow flow structure filling bisected circular electrodes with DI water ( $\sim 10^{-4}$  S/m) at  $\sim 100$  kHz. a) Voltage off: initial microliter droplet at right. b) Voltage on: finger filling bisected circular electrode at left. c) Voltage off:  $\sim 60$  nanoliter droplet formed at left; flow structure drained.

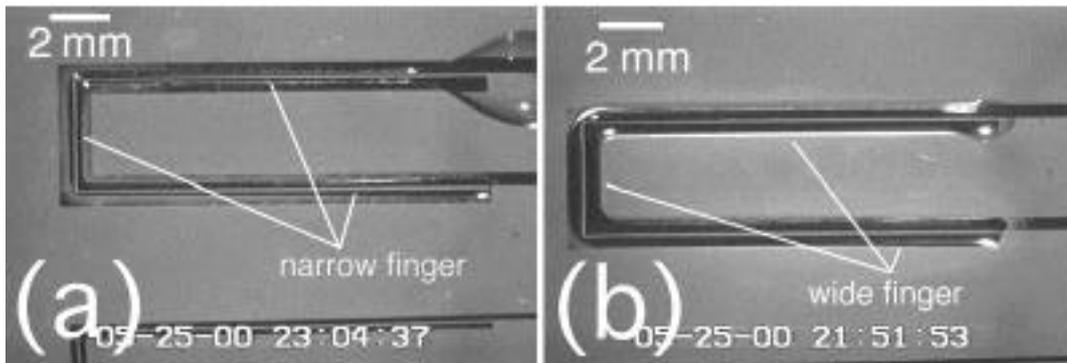


Fig. 4. Indeterminate behavior in co-planar geometry:  $w = 500 \mu\text{m}$ ;  $g = 100 \mu\text{m}$ ; polyimide layer  $t = 10 \mu\text{m}$ . Voltage is  $\sim 700 \text{ V-rms}$  at  $100 \text{ kHz}$ . a) "narrow" finger not much wider than gap. b) "wide" finger spanning entire width of structure.

The next set of experiments was carried out with the specific objective of studying the effect of electrode width on the profile of the finger. New electrodes were fabricated in the basic design of Fig. 2, with the same gap spacing  $g = 100 \mu\text{m}$  but electrode width:  $w = 500 \mu\text{m}$ . Figs. 4a and b show results of two identical experiments performed with identical structures having these dimensions and recorded on videotape. For each experiment, only the frame showing when the water finger has just reached the end of the structure is shown. In Fig. 4a, the finger has assumed the "narrow" configuration like Fig. 2. On the other hand, in Fig. 4b, the finger takes the "wide" configuration, spanning the entire structure like Fig. 3. Note that in Fig. 4b, the large droplet has been almost entirely drained, its liquid now distributed along the entire length of the flow structure.

A further set of experiments was conducted using the electrode structure shown in Fig. 5. Here, the gap is fixed,  $g = 100 \mu\text{m}$ , but the width of the electrodes  $w$  varies along the length of the structure from  $500 \mu\text{m}$  on the left side to  $1000 \mu\text{m}$  on the right side. Figs. 6 and 7 show video sequences of two distinct experiments with identical electrodes, performed as before except that now the microdroplet is placed initially at the left or right end, respectively. For the sequence in Fig. 6, the finger moves from left to right, initially with a "wide" profile, but changing to the "narrow" configuration near the transition. In Fig. 7, the finger moves from right to left, changing from the "narrow" to the "wide" configuration.

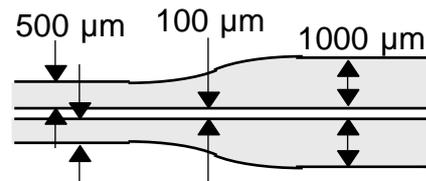


Fig. 5. Top view of electrode structure having a fixed gap  $g = 100 \mu\text{m}$  and smoothly varying electrode widths  $w$ , from  $500 \mu\text{m}$  on the left side to  $1000 \mu\text{m}$  on the right side.

The dynamic behaviors of the fingers advancing in opposite directions, as shown in Figs. 6 and 7, seem mutually consistent. However, in at least one attempt to repeat the experiment of Fig. 6, where the droplet was placed initially on the left side, the finger widened (rather than narrowed) at the transition and then proceeded to cover the surfaces of both electrodes. Fig. 8 shows this occurrence. Note that, in the last frame shown, Fig. 8d, the initially deposited

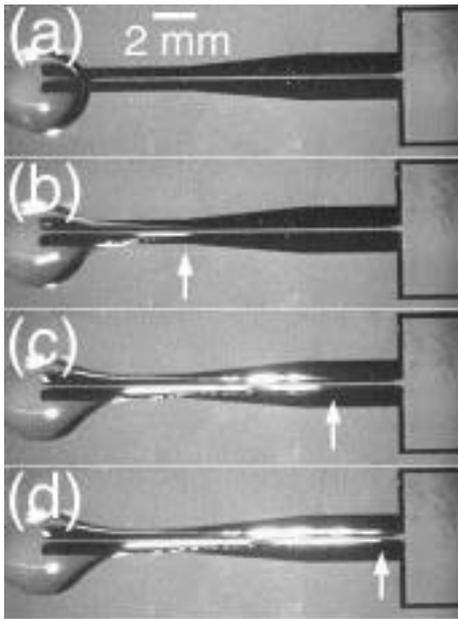


Fig. 6. Video micrograph sequence with variable width structure. With droplet placed at left, profile starts out "wide" on the left side but then becomes "narrow" on the right side. Arrows ( ) indicate leading edge of advancing water finger. (a) Voltage off: microliter droplet visible at left. (b) Voltage on: finger moving from left to right. (c) Voltage on: finger moving from left to right. (d) Voltage on: finger nearing end of structure.

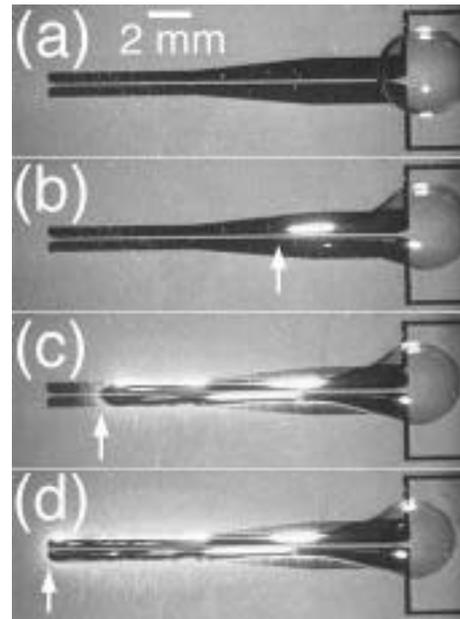


Fig. 7. Video micrograph sequence with variable width structure. With droplet placed at right, profile starts out "narrow" on the right side and then becomes "wide" on the left side. Arrows ( ) indicate leading edge of advancing water finger. (a) Voltage off: microliter droplet visible at right. (b) Voltage on: finger moving from right to left. (c) Voltage on: finger moving from right to left. (d) Voltage on: finger has reached end of structure.

droplet has been completely drained, and the water is now distributed over both electrodes.

## DISCUSSION

For structures with small aspect ratio,  $g/w \approx 0.1$ , and spacing  $g \approx 100 \mu\text{m}$ , the liquid profile almost always assumes a narrow profile, only somewhat wider than the electrode spacing  $g$  as shown in Fig. 2. On the other hand, for structures with aspect ratio  $g/w$  near unity and gap  $g \approx 100 \mu\text{m}$ , the liquid profile tends to span the entire structure width, as shown in Fig. 3. Between these limits lies a zone of unpredictable behavior. Figs. 4a,b show that, with aspect ratio,  $g/w \approx 0.2$ , and gap  $g \approx 100 \mu\text{m}$ , the finger can assume either a "narrow" or "wide" profile, even when the same procedure is followed using identical electrodes. This apparent indeterminacy forces us to attempt to identify other influential factors and then to learn how to control them. What could these factors be? There is little doubt that surface wetting of the polyimide is important; however, if wetting inhomogeneities were the only factor, then considerably more variation in the width of the finger would be expected. Instead, we note that the sides of the finger (the contact line) always seem to be constrained directly above *either* the two inside edges or the two outside edges of the electrodes.

The behavior exhibited in Fig. 8, where the finger spreads out and covers the entire structure at the wide end, might be anomalous. If so, then the flow pattern in the variable width structure, as revealed in Figs. 6 and 7, may be viewed as reasonably predictable. That we never observed narrow profiles on the left side of the variable width structures might be attributable to factors such as the dynamics of the finger, or possibly to alterations of surface wetting conditions in the critical transition region induced by rf discharge. It does seem that, for electrode structures with width  $w = 500 \mu\text{m}$ , the flow spans the entire structure, while for  $w = 1000 \mu\text{m}$ , the narrower profile is preferred. Still, these experiments have not provided us with definitive information about either the minimum usable flow structure width or how the electrode geometry actually influences the flow profile. Specifically, we do not know if it is the aspect ratio  $g/w$  or the total (absolute) structure width,  $2w+g$ , that determines whether a water finger is to assume the wide or narrow profile. If absolute width were determining, then capillarity would probably be responsible. But the indeterminate profile behavior we have encountered has been observed in structures much wider than the narrowest electrodes successfully tested to date.

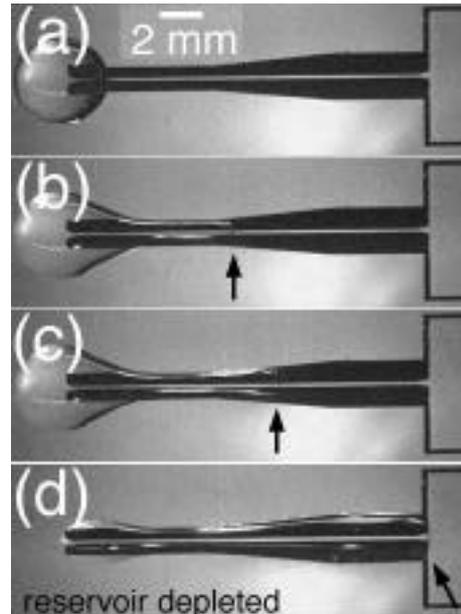


Fig. 8. Video micrograph sequence with variable width structure. Droplet placed at left end. Profile is "wide" on the left side and remains "wide" as it passes transition to the right. Arrows ( ) indicate the leading edge of advancing water finger. (a) Voltage off: microliter droplet dispensed by micropipette visible at left. (b) Voltage on: finger moving from left to right. (c) Voltage on: finger moving from left to right. (d) Voltage on: finger has reached end and has fully drained initial droplet

A possible explanation for why the sides of the finger are usually aligned very close to the edges of the electrodes is electric field intensification. The electrodes are very thin, vapor-deposited, aluminum strips imbedded beneath a  $\sim 10 \mu\text{m}$  polyimide layer. The electric field is very strong along both the inside and outside edges of these electrodes. Though diminished by distance, some intensification extends to the surface of the polyimide, where it could attract water and serve to pin the contact line directly above the edges. Refer to Fig. 9, which shows where this pinning might occur. The contact line of the water along the sides of the semi-circular column would then be constrained along either the two inside or the two outside edges of the electrodes, providing stabilization against capillary instability [12]. If this hypothesis is valid, then we have an explanation for the seeming indeterminacy of the water profile. It is simply a manifestation of the existence of two stable hydrostatic configurations; some sort of bifurcation would define the boundary between them in the appropriate parameter space.

Just as it might explain why the sides of an advancing water finger are constrained, electric field intensification might also be the mechanism that initially forms the finger and determines its width. A strong field could disrupt the initially deposited droplet along the contact line directly above the edges of the electrodes. For wide electrodes, the field will be most intensified along the inner edges, while for narrow electrodes, disruptions at the outer edges of the electrode

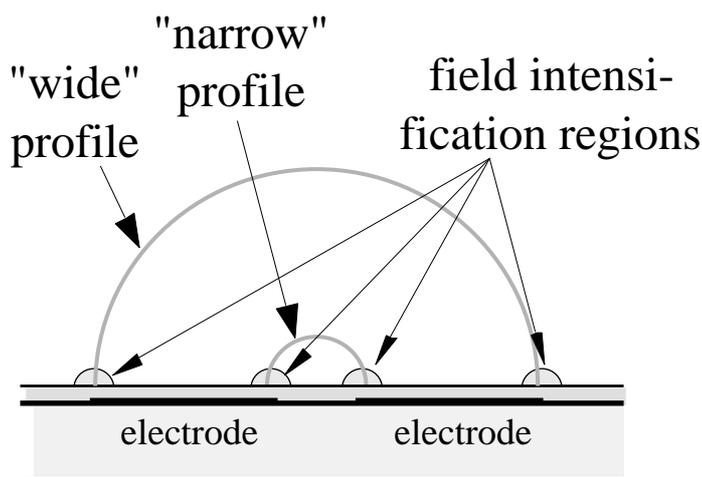


Fig. 9. According to the proposed electric field intensification hypothesis, the liquid contact line is pinned directly above the edges of the electrodes by the DEP force, thus constraining the finger against capillary instability and creating the possibility of two stable liquid profiles, the "narrow" and "wide" configurations.

stripes might dominate and initiate a wide finger. In other words, the width of the finger might be determined by the initial mechanism that disrupts the droplet when the voltage is first applied. The reason why no DEP actuation is observed on surfaces treated with amorphous Teflon®, which is more hydrophobic than polyimide, or with agarose, which is quite hydrophilic, is not known. It seems especially puzzling to us that DEP actuation can be blocked merely by increasing the contact angle from slightly acute ( $\sim 75^\circ$ ) to slightly obtuse ( $\sim 105^\circ$ ). The explanation for such strong dependence of DEP actuation on surface wetting may involve the mechanism that disrupts the droplet to form the finger.

It is only natural to seek some connection between our experiments and electrowetting. In electrowetting, voltage at rather low frequency is applied directly between a water droplet, which serves as one electrode, and a dielectric-coated, plane, metal surface [13]. At the frequencies typically used ( $\sim 1$  kHz), even pure water is virtually an equipotential. On the other hand, the DEP actuation phenomena we report is simply not in evidence below  $\sim 30$  kHz. At the high frequencies required ( $> 60$  kHz), the water is not an equipotential body. Furthermore, the water is capacitively coupled to the applied voltage.

## CONCLUSION

DEP actuation of nanoliter to microliter volumes of aqueous media suggests the possibility of a new class of open, microfluidic structures for the "laboratory on a chip". Controllability and speed may be its biggest advantages. An advancing finger of water moves at  $\sim 5$  cm/s, and transient flow rates are in the range of  $\sim 1$   $\mu\text{l/s}$ . We observe multiple nanoliter droplet formation to occur in 0.1 s. However, successful exploitation of liquid dielectrophoresis of water presents a number of technical challenges. First and foremost is Joule heating,

which, while significantly offset by the high actuation speeds already demonstrated, nevertheless may become limiting as aqueous cell media (which contain ions and therefore have much higher electrical conductivity) are used. Second is the problem of the minimum size of droplets that can be formed using surface electrodes. We must anticipate some lower limit imposed by capillarity, particularly because of the high surface tension of water.

The experiments described in this paper reveal unpredictability in how the water will respond when voltage is applied. There is a range of values of electrode thickness  $w$  for which the water finger has been observed to assume either a "narrow" or "wide" configuration. The field intensification hypothesis proposed here does offer at least qualitative explanations for two consistently observed aspects of the behavior: (i) the constraint imposed along the sides of an advancing water finger and (ii) the existence of two stable equilibria ("narrow" and "wide" profiles) for flow structures with electrodes of intermediate width.

For any practical application of DEP liquid actuation, we must decrease operating voltages substantially. Scaling down the planar electrode dimensions and the thickness of the dielectric layer should accomplish this goal. Reduced size facilitates production of sub-nanoliter droplets, a capability that in turn will ameliorate Joule heating. But scaling down structure size demands that we improve our understanding of the complex interplay of the DEP force with surface wetting (including electrowetting), capillarity, Joule heating, and conductive heat transfer. It is clear that better understanding is crucial to successful exploitation of DEP liquid actuation in  $\mu$ TAS.

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