A NOVEL SUB-PICOLITER MONODISPERSED DROPLET GENERATION DEVICE BASED ON LIQUID DIELECTROPHORESIS

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ABSTRACT
This paper reports a new phenomenon for jetting of droplets and demonstrates its use for generation and transfer of monodispersed droplets in sub-picoliter volumes. This technique obtains jetting at lower voltages (combination of $470V_{ac}$ and $-250V_{dc}$), even for high surface tension liquids. The reported technique is fast in achieving a dense transfer of micro-droplets (14,000/mm^2) in less than 10s. Compared to other microfluidic techniques, the new technique uses simpler fabrication and does not require bulky components (e.g. pumps). The technique is extremely easy and economical to scale making it suitable for portable applications.

INTRODUCTION
Generation of monodisperse droplets is of significant interest for many applications including aerosol formation, lab-on-chip, micro-nanoparticle creation etc. Electro-hydrodynamic jetting (electrospraying), a well-known technique for polar and conductive liquids[1] uses high voltages in the order of kV's and requires bulky setups for continuous fluid supply[2]. Use of high voltage often requires an inert environment further complicating the setup. Microfabricated electrospraying devices have been demonstrated, but require complex fabrication involving multiple wafers[3]. Dispensing micro-droplets in T-channel or flow-focusing devices requires external pumps[4] and transferring the generated droplets to a target substrate requires an additional mechanism which adds complexity. Pyroelectrodynamic jetting allows precise control but requires expensive laser[5].

Electrowetting-on-Dielectric(EWOD) and liquid Dielectrophoresis(L-DEP) are, respectively, the low- and high-frequency limits of the electromechanical response of an aqueous liquid to an electric field[6]. Even though EWOD is proven for controlled droplet generation[7], it is not suitable for sub-picoliter droplets. L-DEP is a phenomena in which a liquid drop sitting on dielectric coated coplanar electrodes experiences a non-uniform electric field when voltage is applied to the electrodes[8]. The force arising due to the non-uniform field causes the interface to move forward[9] and form a cylindrical neck which elongates along the gap of the coplanar electrodes. Generation of nanoliter droplets from a microliter droplet[10] has been achieved in L-DEP using hydrodynamic instability, where when the voltage is removed, the elongated liquid neck breaks up into sessile droplets. The generated droplets can be evenly spaced and are of fairly uniform size[11]. In this paper we report a new jetting phenomenon observed during the L-DEP actuation of a droplet interface that is capable to generate and transfer sub-picoliter droplets.

DEVICE FABRICATION
The device configuration is similar to coplanar EWOD, with the water droplet sitting centered on the gap between a pair of electrodes. Fabrication starts with the cleaning of the glass substrates using standard cleaning procedure in a Piranha solution. 20nm chromium and 100nm gold were sputtered on the cleaned substrates. Actuation electrodes (10×2.5mm^2) and contact pads were patterned lithographically and the metal layers were etched in wet chemistries. The gap between the electrodes was fixed at 100µm. SU8 2005 serves as the dielectric, isolating the droplet from the electrodes. SU8 was spin coated at 2000rpm for 40s to get a dielectric thickness of ~6µm. For the top plate, 150nm Indium Tin Oxide was sputtered on another glass substrate. Figure 1 provides the detailed description of the fabrication steps.

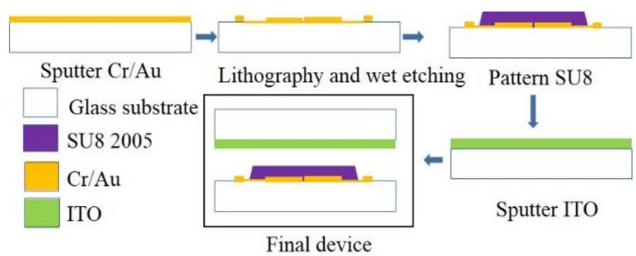

Figure 1: Fabrication steps

For driving the droplet two out of phase sine waves were generated by a two channel voltage waveform generator (Agilent 3350B). The signals were amplified by two high voltage amplifiers (Trek 2205) having a gain of 50. DC bias on the top plate was provided by a DC power supply. Droplet spreading and the jet formation was recorded using a high speed camera (Photron Fastcam SA4) at 6000fps. Figure 2 shows the schematic diagram of the experimental setup.

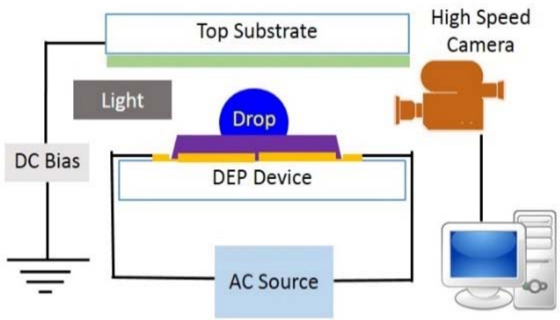

Figure 2: Schematic of the experimental setup

DROPLET SPREADING

A 10µl DI water droplet was placed in between the gap of two coplanar electrodes and an AC voltage at 50kHz was applied. As the AC voltage is increased the L-DEP actuation force on the droplet interface increases. When the actuation force overcomes the contact line stiction associated with contact angle hysteresis, the interface starts to move. At 470V_{ac} the droplet elongates to completely cover the gap between the electrodes. Figure 3 shows the top view imaging of droplet elongation. In case of fabrication defects the contact line gets pinned to the defect and the elongation is incomplete even for the highest voltage possible in our system.

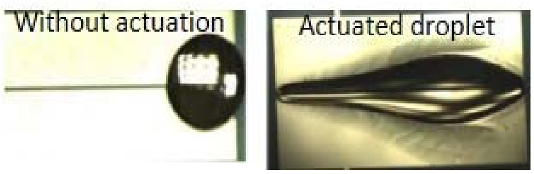

Figure 3: Top view of the spread drop

During the droplet spreading, we could observe satellite droplets along the interface which have been attributed to contact line instabilities. These instabilities are mostly observed at high actuation voltages[12] and are associated with contact angle saturation[13]. Figure 4 shows the zoomed bottom view at 50x of the interface of the drop during spreading along with the satellite droplets. For bottom view imaging ITO electrodes were used.

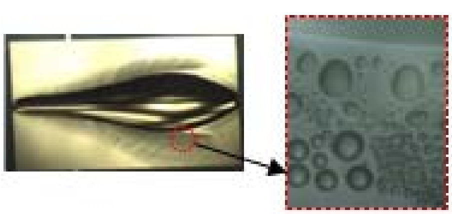

Figure 4: 50x view of the interface along with satellite droplets

JETTING PHENOMENA

During the initial spreading experiments captured using high speed camera a mist consisting of tiny flying droplets was observed. In order to identify the charge on these droplets an ITO coated top plate was placed ~3mm above the substrate. When a DC bias is applied to the top plate, a jet is observed implying the micro-droplets are charged. Figure 5 shows the experimental observations of jet formation from the satellite droplets.

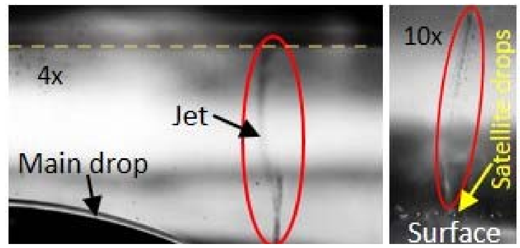

Figure 5: Jetting phenomena captured at 4x and 10x.

The jet is observed to originate in a region where the satellite drops are formed. Figure 6 shows the schematic diagram of the jet formation. Though satellite droplets are formed all along the contact line, the jet is found to be formed near the gap between the coplanar electrodes. The small size of the jetted droplets in addition to the uncertainty of the location for jetting adds to the difficulty in performing experiments to elucidate the exact phenomenon. Researchers have reported droplet jumping on super-hydrophobic surfaces due to coalescence[14]. Even though the phenomenon is still under investigation, one of the hypothesis under consideration is the release of surface energy during dynamic coalescence of charged satellite droplets allows the droplet to overcome surface adhesion and jump out of the surface.

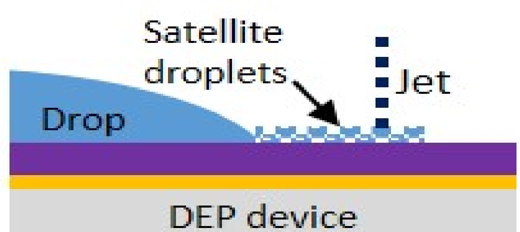

Figure 6: Schematic of the jetting phenomenon

Another hypothesis is related to formation of highly charged satellite droplets which then become unstable in the high electric field leading to jetting through formation of a Taylor cone. In contrast, for conventional electrospraying, where the main droplet is grounded and top plate is biased to form jets, the jet would have formed on the top of the droplet which is closest to the top-plate. Further experimentation and data analysis regarding the origin of jetting is under investigation.

DROPLET TRAPPING

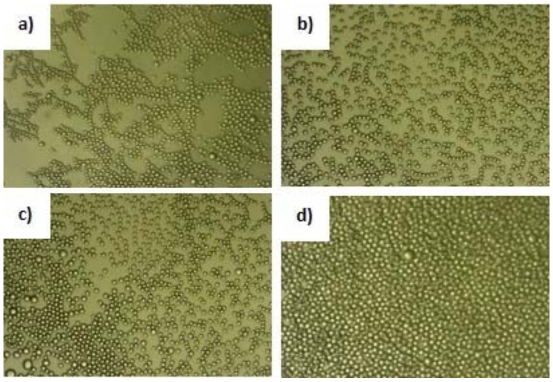

Figure 7: Water droplets captured on oil coated top plate for varying DC bias voltages: (a) -250V, (b) -500V, (c) -750V and (d) -1kV

By varying the DC voltage on the top plate, we could control the droplet deposition on the top plate. In order to capture the droplets the top plate was coated with silicone oil which reduced droplet merging and evaporation. We performed experiments with four different negative voltages and captured the optical images using a 10x lens. Figure 7 shows the trapping of droplets on oil coated top plate for different bias voltages over an area of $0.48 \times 0.34 mm^2$.

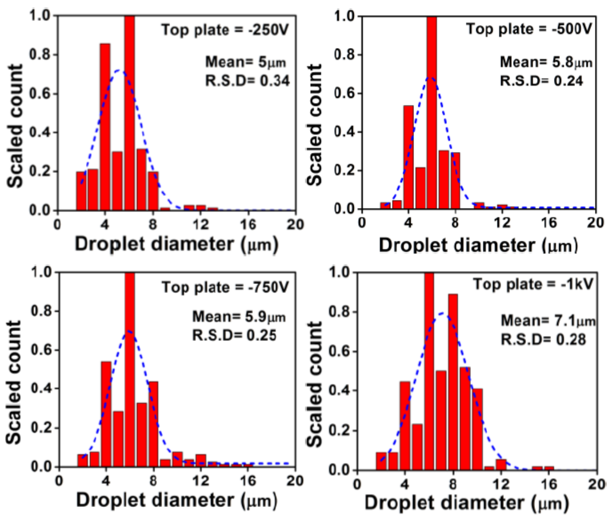

Figure 8: Droplet size distribution as measured using image analysis.

In order to estimate the size of the trapped droplets, 240 droplets were randomly selected and their sizes were measured manually using the ImageJ[15] software. Droplet size distribution was plotted for different bias voltages as seen in Figure 8. Mean droplet size increased from 5µm to 7.1µm as the top-plate bias voltage changed from -250V to -1000V. The relative standard deviation (RSD) is given by the ratio of the standard deviation to its mean. A minimum RSD of 0.24 means a reasonably good monodispersity. The calculated volume of individual drops assuming spherical droplets in the jet varies from 65 femtolitre to 190 femtolitre.

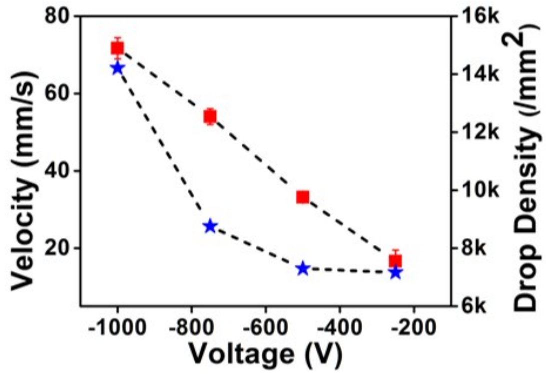

Figure 9: Density of droplets deposited on the top plate (★) and droplet velocity in the jet (■) as a function of the top plate voltage

At higher top-plate DC voltages larger numbers of droplets were able to overcome the retarding forces due to the AC field leading to increased density of the transferred droplets (see Figure 9). As individual droplets are difficult to observe the droplet velocities in the jet were estimated by measuring the speed of the tip of the jet at 1mm distance away from the top plate. At least five different jetting videos were used to measure the jet velocity. Droplet velocity in the jet increases linearly with increasing DC field, providing a method to control the droplet impact dynamics on the top-plate which is important for many applications like printing, pattern transfer, etc. Simple fabrication and actuation allows easy and economical scaling of this system to a multi-liquid jetting platform as conceptualized in Figure 10. The technique is suitable for integration with EWOD platforms with minimal design modifications.

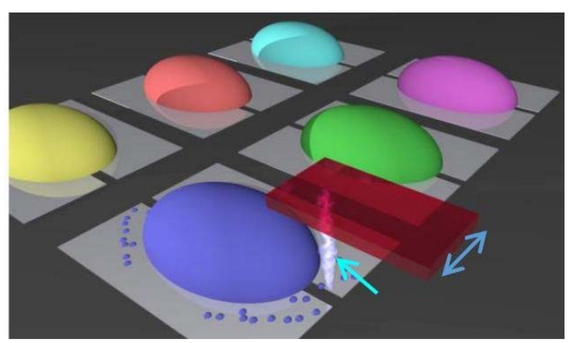

Figure 10: Schematic showing the concept of a multi-liquid jetting chip for lab-on-chip applications

CONCLUSION

We report a new phenomenon for jetting of droplets and demonstrates its use for generation and transfer of monodispersed droplets in sub-picoliter volumes using liquid dielectrophoresis. The reported jetting technique was achieved at lower voltages with a dense transfer of micro-droplets in less than 10s. The preliminary experiments are limited to water. After analyzing the complete physics behind the jetting origin, it can be extended to wide range of high viscous and high surface tension liquids. The technique is extremely easy and economical to scale making it suitable for portable applications.

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