Electrostatic Droplet Ejector with Monolithic Fabrication of nozzle

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ABSTRACT

This paper presents a novel mechanism of electrostatic micro droplet formation and ejection of fluid. Unlike conventional electrostatic jetting which requires a high operating voltage, we offer a low operating voltage for droplet-on-demand operation based on a monolithically layered electrode structure of nozzle. The layered electrode structure of nozzle allows the formation, acceleration, and ejection of a droplet to be controlled by the voltage signals applied to individual electrodes

Keywords: electrostatic, micro droplet, ejection, monolithic nozzle, layered electrode

1 INTRODUCTION

During past several decades, there have been a lot of researches for generation and ejection of fluid micro droplets. Its primary commercial implementation today is in the field of inkjet image printing. Recently, there has been a tremendous increase in the use of micro droplets in physical, chemical, biological and engineering research areas [1]. Due to the increased sensitivity of detectors, the need for large scale combinatorial chemistry assays using very high cost chemicals, and the need for microdispensing of small sub-nanoliter volumes of fluids for the making of sensors, flat panel displays, and biochips, there has been an increased interest by both industry and basic research field [1-4].

A micro scale of jetting device based on thermal bubble or piezoelectric pumping has shown a great commercial success in digital printing [5-6]. The conventional jetting devices based on thermal bubble or piezoelectric pumping, however, have some fundamental limitations to overcome to meet the aforementioned requirements for the future generation of jetting devices[7] : 1) Thermal bubble jetting is under a fundamental limitation on the size and density of nozzle array, as well as the ejection frequency. 2) Mechanical jetting in general has a fundamental limitation on the density of nozzle array, as well as the ejection frequency.

Alternatively, electrostatic jetting in the form of mechanical pumping by electrostatic actuator carries similar fundamental limitation to that of mechanical jetting, even worse in scaling pumping power in terms of size. It may be the type of electrostatic jetting based on the direct manipulation of liquid by an electric field, instead of indirect pumping, that appears to be more promising. A droplet can be separated from a pinnacle covered with a liquid film, where the strong electric field concentrated around the pinnacle induces dielectric charge separation [8]. Without the need of indirect pumping, the electrostatic jetting based on direct liquid-field interaction seems promising [9]. However, the approaches to the direct electrostatic jetting presented to date have two major drawbacks to overcome: 1) the need of high operating voltage, often over 1 KV, to be applied and 2) the need of one electrode to be placed externally to the device.

This paper aims at solving these two major issues associated with the direct electrostatic jetting approach to a droplet-on-demand operation.

2 MICRO JETTING SYSTEM

The approach taken here to the solution of the above issues is to design a nozzle with a micron scale of layered electrode structure, as shown in figure 1, such that an operating voltage of less than 1 kV can produce an electric field sufficient enough for forming and ejecting a droplet, while no externally placed electrode is required. The micro jetting system consists of a tip-shaped ground electrode, monolithic nozzle, sequential electrodes, and reservoir. Driven by capillary attraction, liquid gets through the hydrophilic micro channel and reaches the interface between the hydrophilic and hydrophobic surfaces in the nozzle, where is just before the electrodes.

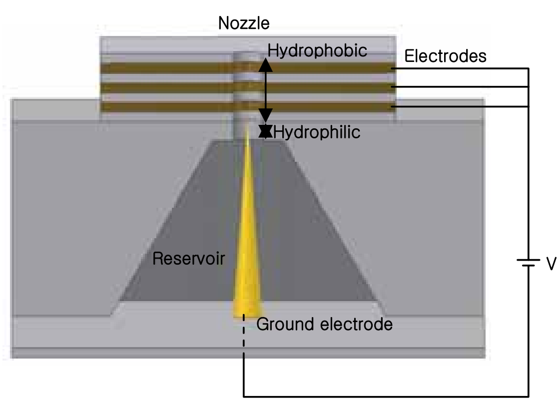

Figure 1: Schematic of electrostatic microdroplet ejector

The intense electric field between the electrode and the ground induce the liquid meniscus at the interface to form a micro droplet due to electrostatic force. When the force is stronger than the surface tension on the liquid meniscus, the

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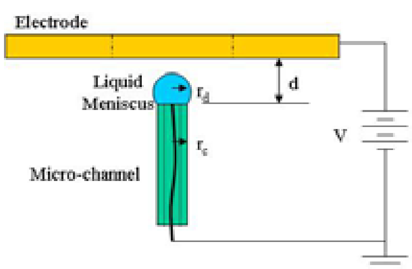
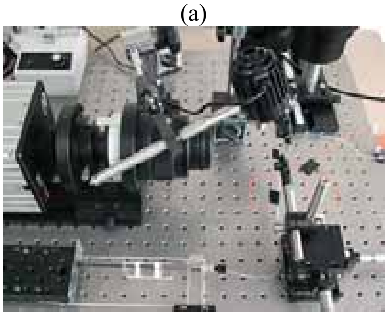
liquid breaks up into micro droplet and eject the droplet. Then since it allows individual electrodes to have different levels of voltage, an optimal voltage distribution across the electrodes, as well as its variation in time, can be set in such a way as to maximize the efficacy of droplet formation, acceleration and ejection. So we present a novel mechanism of electrostatic micro droplet ejector based on a layered electrode structure of nozzle.

3 EXPERIMENT

To examine the feasibility of the novel mechanism proposed here as an electrostatic micro droplet ejector, which is presented in Figure 1, and investigate the critical condition of droplet formation and ejection, we performed simple micro-scale experiment before we fabricate monolithic system using MEMS technology. Figure 2 shows the schematic and picture of the experimental set-up. The glass micro channel is used and its diameter is 100 ㎛. The Al electrode is connected to power supply and the Pt wire is used as a ground electrode. A high speed camera(IDT XS-3) with a micro-zoom lens and a halogen lamp were used to visualize droplet ejection. The high speed camera can image 4000 frames in a second at a 160 x 1280 resolution. A high voltage power supply (maximum voltage of 36kV) was used with a relay switch to control electrostatic field. Liquid was supplied to a grounded nozzle by a micro-syringe, and an electrode was placed above the nozzle.



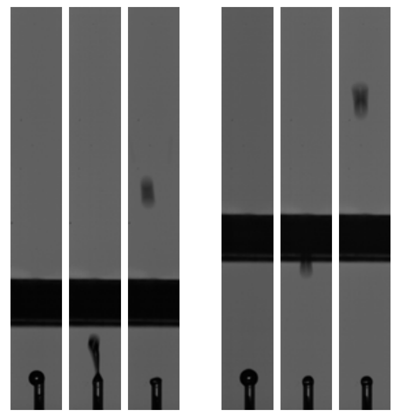
(a)



(b)

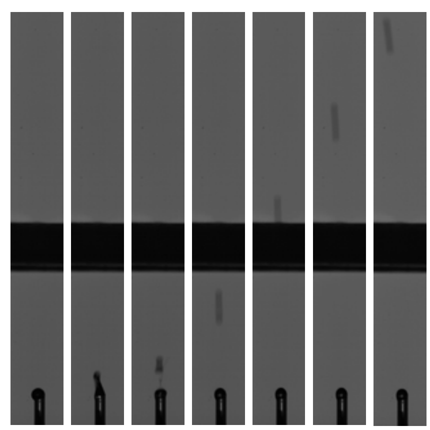
Figure 2: Schematic of experimental setup

Figure 3 shows sequence photographs of the motion of a droplet which is formed and ejected from the meniscus of the liquid. Droplets are observed to be formed and ejected from the initial state of meniscus for several conditions, i.e. voltage and the distance between the electrode and the micro channel. When the voltage is up to 3000 V, the droplet can be formed from the meniscus and ejected through the hole of the electrode. When the distance is 2 mm and the voltage 3000 V, the droplet is completely formed and starts to move to upward at 3/4000 sec. As the vertical distance between the electrode and the nozzle decreases and the voltage increases, the droplet can be more easily formed and ejected as shown in figure 3. Figure 3 shows the dripping mode[9] of electrostatic droplet ejection and the droplets take the shape of regular spheres detaching from the nozzle because the electrostatic force overcome the surface tension forces. After the droplet detachment, the meniscus attracts back forming a hemispherical shape.



Time = 0 3 9 0 7 12

(a) d=1mm, V=3kV (b) d=2mm, V=6kV



Time = 0 2 3 5 7 9 11

(c) d=2mm, V=3kV

Figure 3: Sequence of formation and ejection of droplet (time=1/4000 sec)

Figure 4 depicts the regime of ejecting droplet showing the effect of voltage, meniscus shape, and distance between electrode and micro channel. When voltage was down to 2000V, no ejection phenomena could be observed. And the threshold voltage of electric breakdown is around 4000 V so that spark phenomena can be shown above the voltage. Xiong et al.[10] presented the effect of the ambient pressure on the electric break down. The threshold voltage increases remarkably when air pressure was far below a standard atmosphere pressure. When surrounding air pressure is as high as 10^{-3} Pa, electric breakdown phenomenon does not occur, although voltage between two electrodes increase to 8000V.

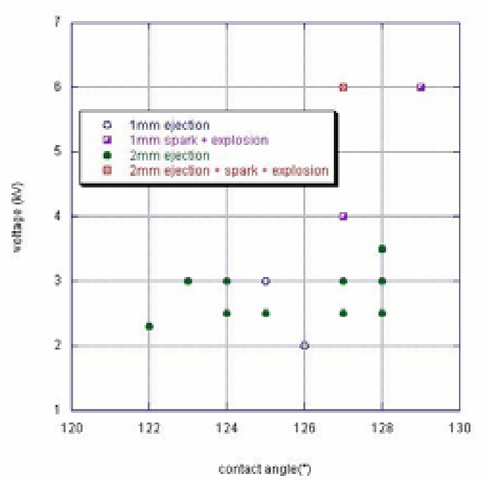


Figure 4: Effect of voltage, meniscus shape, and distance between electrode and micro channel

4 SIMULATION

Micro droplet is formed from the liquid meniscus due the induced electric field. At the direction of ejecting the micro droplet, the liquid meniscus suffers two forces: electric field force and surface tension force.

We assumed that the shape of the meniscus is a sphere. The surface tension force f_1 and the electric field strength f_2 can be described as

$$f_1 = 2\pi r_c \sigma \tag{1}$$

$$f_2 = \int_0^{2\pi} \frac{1}{2} E \cos\theta \rho_s 2\pi r_d \sin\theta r_d d\theta \tag{2}$$

where E denotes electric field, σ is the fluid surface tension coefficient, ε_0 the permittivity of free space, r denotes the radius of the channel and the droplet, q denotes the net charge of the droplet. E and ρ_s can be expressed by

$$E = \frac{q}{4\pi\varepsilon_0 r_d^{\ 2}} \tag{3}$$

$$\rho_s = \frac{q}{4\pi r_d^{\ 2}} \tag{4}$$

If the electric field force is balanced by surface tension force, we have

$$E = 2\sqrt{\frac{\sigma r_c}{\varepsilon_0 r_d^2}} \tag{5}$$

Equation (5) indicates that when the electric field on the liquid surface is larger than a threshold value, the liquid droplet will become instability. This can be called critical electric field.

When we assume that radii of the droplet and the nozzle are equal, the results from equation (5) are shown in table 1 for the 300 and 3 micro meters, respectively. The electric field on the droplet surface as high as $7.39\text{x}10^6$ and $7.39\text{x}10^7$ must be meted to start an ejection. As the droplet size decreases, the effect of surface tension increases so that the stronger electric force is needed.

R=r_c=r_d(μ m)	E (V/m)
300	7.39 x 10^6
3	7.39 x 10^7

Table 1: critical electric field

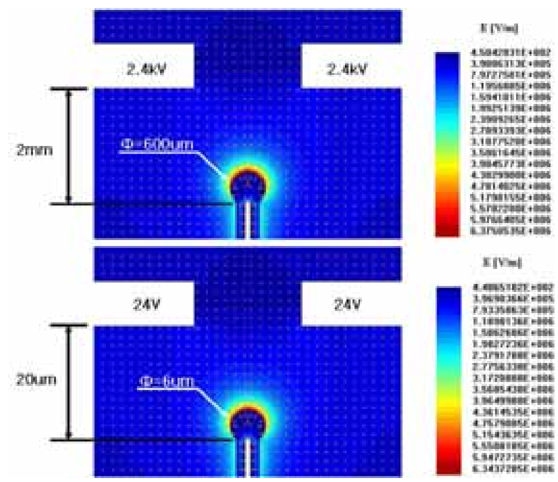


Figure 5: Contours of electric field

The electric field is obtained by solving the following governing equations.

$$\nabla \cdot \varepsilon \nabla \varphi = -\rho_{e0} \tag{6}$$

$$\vec{E} = -\nabla \varphi \tag{7}$$

These equations are solved by FEM(finite element method) and then the electric field can be simulated as shown in Figure 5. Because the electric field is strongest at the top of the meniscus, the droplet can be easily generated.

Voltage(V)	2000	2800	3000
Max. E(V/m)	$5.75\text{x}10^6$	$8.05\text{x}10^6$	$8.63\text{x}10^6$

Table 2: Values of maximum electric field (r_d=300μ m, d=2 mm)

Voltage(V)	100	200	300
Max. E(V/m)	$2.88\text{x}10^7$	$5.75\text{x}10^7$	$8.63\text{x}10^7$

Table 3: Values of maximum electric field (r_d=3μ m, d=20 μ m)

Table 2 and 3 show the values of the maximum electric fields according to droplet size, voltage, and the distance between the electrode and the nozzle. From comparisons of table 2 with the table 1, the electric fields are strong enough to start a formation and ejection of droplet, when the diameter is 600μ m and the applied voltage between electrodes is over 2.8 kV. This phenomenon can be already illustrated from the experimental works. As we see figure 4, when the voltage is over 2.5 kV for this geometry and droplet condition, the micro droplet can be formed and ejected.

Similarly, when we compare the table 1 and table 3 for the smaller droplet (6 μ m diameter), we can guess the critical voltage over which the formation and ejection of droplet is possible. Results shows that the voltage as high as 300 V can form and eject very small droplet. Therefore, as described in figure 1, we can offer a low operating voltage for droplet-on-demand operation based on a monolithically layered electrode structure of nozzle.

5 CONCLUSIONS

We've suggested a noble concept of the electrostatic micro droplet ejector with monolithic nozzle, which can generate and eject the micro liquid droplets. Unlike conventional electrostatic jetting which requires a high operating voltage, we offer a low operating voltage for droplet-on-demand operation based on a layered electrode structure of nozzle. To examine the feasibility, the analytic and experimental works are performed. Investigation includes the effects of the meniscus shape, voltage, and electrode distance on the droplet formation and ejection.

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