A Surface Micromachined Electrostatic Drop Ejector

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SUMMARY

Ejectors have applications ranging from ink-jet printing to drug delivery. A novel electrostatic ejector was surface micromachined; and satellite-free, 2 pl drops were ejected at 10 m/s using an electrostatic field (E-field) of 20 V/µm. The E-field is applied across the ejected liquid, which simplifies device design, but allows the possibility of dielectric breakdown and electrolysis in the liquid. These challenges were overcome in the prototype described herein.

Keywords: Ejector, Electrostatic, Surface-micromachining.

INTRODUCTION

A microfluidic chip typically contains flow channels of the same depth that are fabricated simultaneously. These co-planar flow channels are designed to accomplish a specific task. For instance, two intersecting glass channels can be utilized as an on-chip electrophoretic separation system [1]. There are applications, however, where precise fluid volumes must be delivered from one plane to another. For these applications an on-chip ejector that is integrated into a microfluidic system can be useful. Such applications include ink-jet printing [2], delivery systems for inhalers [3] and mass-spectrometry [4], and patterning of evaporative self-assembly systems [5].

Herein we report on surface micromachined, electrostatically actuated MEMS drop ejectors. Electrostatic actuation has advantages when compared to other actuation methods (piezoelectric [4] and thermal [2]). One advantage is that the fabrication process allows isolated conducting surfaces to be placed very close to each other, allowing large field strengths to be applied at moderate voltages. In our ejection system the actuating field is between two layers of polysilicon that are initially 5 µm apart. The actuation system is built into the mechanical structure so that no further assembly is required. Electrostatic actuation allows for a longer actuator stroke than for piezoelectric actuation; and for variable stroke, potentially resulting in the ejection of different size drops from the same ejector. Since the driving voltage is applied across the liquid, the power dissipated depends on the properties of the liquid. This configuration simplifies ejector design, but also leads to the possibility for dielectric breakdown of the liquid and electrolysis.

THEORY

The conceptual design is shown in Fig. 1. A voltage is applied to the piston. The nozzle plate is at ground. The electrostatic force between the piston and the nozzle plate pulls the piston towards the nozzle plate fast enough to eject a drop. The E-field required for the electrostatic force must be less than the dielectric breakdown strength of the liquid.

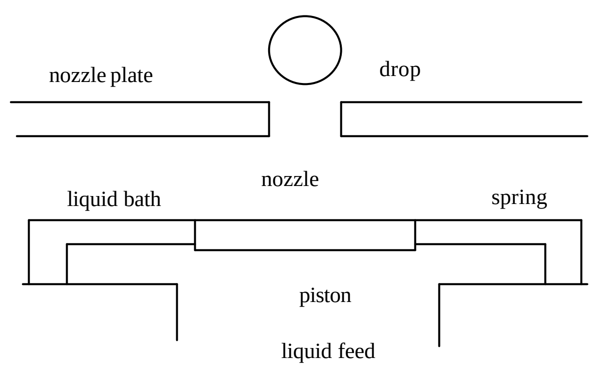

Figure 1. Design Concept.

The activating force is electrostatic attraction between the piston and the nozzle plate [6]:

$$F_E = 1/2\,(K\varepsilon_0)(V^2/x^2)A, \qquad (1)$$

$K\varepsilon_0$ is the dielectric constant of the liquid, V is the voltage, x is the gap between the piston and the nozzle plate, and A is the piston area. Opposing this activation force is the viscous force required to push the liquid through the nozzle, the surface tension force that develops as the drop forms, and the squeezing force caused by the pressure rise in the gap between piston and nozzle plate associated with pushing fluid out from this gap. The most significant force opposing piston motion is the squeezing force, which can be approximated to first order as [7]:

$$F_{SF}=(3w^2\mu\dot{x}A)/(2x^3), \qquad (2)$$

w is the piston lateral dimension, μ is the liquid viscosity and $\dot{x}$ is the piston velocity. This expression overestimates the squeeze film force because it ignores the pressure relief resulting from fluid escaping through the center hole. The squeeze film force is inversely proportional to the gap cubed. Therefore as the piston gets close to the nozzle plate (on the order of 1 μm) the squeeze film force gets large, slowing down and eventually stopping the piston. At this point the piston support springs pull the piston back to its original position (assuming the drive voltage has been turned off) and liquid flows around the piston to refill the piston/nozzle plate gap.

The simplest drive signal is a constant voltage pulse just long enough to eject a drop. There are two problems with this signal. First, even a small voltage (<2V) applied to an aqueous solution can lead to electrolysis. If this reaction proceeds far enough to produce micron diameter gas bubbles it will impede piston motion. In addition, electrolysis limits the amount of charge that can be stored at the piston surface, reducing the actuating potential difference. To minimize the effects of electrolysis we use an AC actuation signal. The same attractive electrostatic force is generated independent of the polarity. By reversing the polarity of the drive signal, the electrolysis reaction is reversed and any gas bubbles are removed.

The second problem is dielectric breakdown of the liquid. Breakdown provides a path for current transport between electrodes significantly reducing the actuating potential difference and possibly damaging the structure. For a constant voltage pulse, as the gap between the piston and the nozzle plate is reduced, field strength increases as 1/gap and eventually the dielectric strength of the liquid is exceeded. To avoid this occurrence constant E-field actuation can be used (applied voltage decreases linearly with gap spacing).

To calculate the field strength required for drop ejection equate Eqns (1) and (2) and solve for E:

$$E=\{(3w^2\mu\dot{x})/(x^3K\varepsilon_0)\}^{1/2}. \qquad (3)$$

For typical MEMS device dimensions w=50 μm and x=5 μm. Assuming fluid properties of water (K=80, μ=0.001 kg/m-s), for a drop velocity of 5 m/s the required field strength is E=20 V/μm. This field strength is below the dielectric breakdown strength of water [8] for micron length-scale gaps. Therefore there should be an operating window at approximately this drive signal field strength that will result in drop ejection.

MEMS EJECTOR DESIGN

The ejection system was fabricated using SUMMiT - www.mdl.sandia.gov/Micromachine. This process utilizes 5 levels of polycrystalline silicon (polysilicon, poly0 to poly4) – 4 structural layers and 1 layer on the silicon wafer substrate for electrical connection (poly0) [9]. The surface films are electrically insulated from the substrate by a layer of silicon nitride. The polysilicon layers are deposited, photo-patterned and etched to create three-dimensional structures. Between each polysilicon layer is a layer of silicon dioxide, which is also deposited, photo-patterned and etched. The final step of the fabrication process is the removal of the sacrificial silicon dioxide in an acid bath to release the polysilicon structures – freeing them to move. The entire process is monolithic, minimizing the assembly required, and can potentially be fabricated on the same substrate with high voltage CMOS to create a highly integrated electro-microfluidic MEMS ejection device.

The key parts of the design are the piston and the nozzle plate. The nozzle plate consists of a polysilicon layer with a series of nozzles in it. The nozzles are 20 μm in diameter and the nozzle plate is 2 μm thick. Thirteen ejectors are grouped together in a single fluid bath surrounded by an isolating sidewall that keeps liquid from leaking out the sides of the device. Electrical connection is made by wire bonding to bond pads outside of the fluid bath. Electrical traces feed through the sidewalls underneath the nozzle plate to each piston. The traces are isolated electrically from the nozzle plate using trapped silicon dioxide. Cuts in the bottom nitride are made for ground connection to the substrate.

Fig. 2 is an SEM image of one set of ejectors with sections of nozzle plate removed. Several nozzle cover support posts are shown, as are the electrical traces to the pistons, and the isolating sidewalls. The pistons, which are formed in poly1, have a “waffle iron” pattern. This pattern is due to a set of stiffening ribs on the bottom of each piston. Due to the conformal nature of the fabrication process, a dip can be seen in the upper layer of polysilicon (in this case the top of the piston) at every point where a rib is positioned. The pistons are supported by springs on two sides that are anchored directly to the electrical traces. Therefore the springs not only provide structural support for the piston, but also the electrical connection between the piston and the traces. The springs shown are designed for a stiffness of 10 N/m, and act to pull the piston back to its original position.

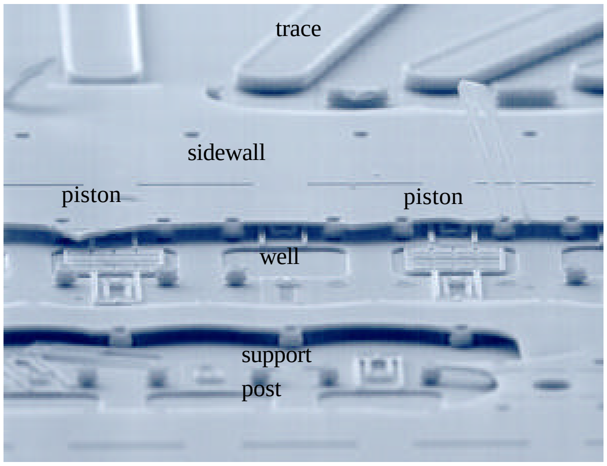

Figure 2. SEM of Ejectors (cover removed).

The pistons appear to be sitting in small wells. These wells are due to cuts through the bottom layer of nitride and allow fluid to fill the fluid bath from the back of the wafer once a through wafer etch is completed that intersects the wells. The through wafer etch is accomplished using the Bosch process [10]. This reactive ion etch (RIE) process allows the fabrication of high aspect ratio, 90 degree sidewall passages through the wafer. The final step in the fabrication process is the removal of the encasing oxide in an acid (HF:HCl) bath. This etch is timed (approximately 1 hour) so that not all of the oxide between the piston and the outside of the sidewall is removed. The remaining trapped oxide provides a seal around the liquid bath that prevents any leaks.

EJECTOR TESTING

Ejector testing was conducted to determine drop volume and velocity, and evaluate the effect of different voltage waveforms. Fig. 3 shows drop ejection. The drop is illuminated using a high power LED (Stanley Electric, NY) activated at 1 KHz, the same frequency at which the drive voltage is applied.

Figure 3. Strobed image of drops.

An arbitrary waveform generator (Pragmatic 2414A, CA) sends a 1 KHz, 1% duty cycle square wave timing signal to both the strobe pulse generator (Trabor Electronics 8500, Israel) and the arbitrary waveform generator (Wavetek 395, UK) used to create the signal sent to the piston for drop ejection (Fig. 4). The strobe pulse generator has controllable time delay allowing illumination of the drop ejector at different times during voltage waveform application. This capability allows one to follow the evolution of drop formation and ejection (Fig. 5), and to measure the drop velocity. The images are average images at the video frequency of 35 Hz. The sharpness of the drop images is an indication of the consistency of drop size, shape and location. There were no satellite drops observed during ejector testing.

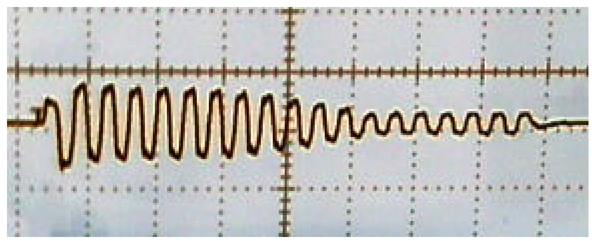

Figure 4. Waveform. 200 +/- 20 V_{pp} and > 2.5 MHz internal frequency for ejection.

The arbitrary waveform generator was programmed using Wavetek's DSP2 software to produce the voltage waveform shown in Fig. 4. This signal was sent to the ejector being fired at 1 KHz, 1 % duty cycle after amplification. The internal signal frequency was experimentally determined to be high enough to avoid electrolysis. Electrolysis was typically observed (2 μm diameter bubbles) when the internal signal frequency was lowered below approximately 2.5 MHz.

The length of the waveform was also adjustable. Drops were ejected for waveforms from 5 to 10 μs long. The shape of the waveform was critical for ejector operation. In the first few microseconds of signal application, the voltage was kept high to develop significant piston velocity before the squeeze film force became dominant. Later in the waveform as the gap between the piston and the nozzle plate decreases, the voltage must be reduced sharply to avoid breakdown.

The driving voltage waveform was amplified approximately 2 orders of magnitude using an RF amplifier (ENI 2100L, NY) prior to sending it to the piston for actuation. The actuation voltage for drop ejection was 200 +/- 20 V_{pp} (maximum voltage, Fig. 4). At lower voltages bulging of the meniscus was observed (beginning at 50 to 100 V_{pp}). Drop size and position were measured using a video measurement system (Boeckeler V1A100, AZ). The drop diameter was measured as 15.65 μm with a corresponding volume of

2 picoliters. A shift in drop location of 50 microns was measured for a strobe phase shift of 5 microseconds, indicating a drop velocity of 10 m/s.

CONCLUSIONS

We have presented a novel concept for drop ejection that utilizes electrostatic actuation applied across the liquid to be ejected. In this first prototype the potential problems of electrolysis and dielectric breakdown were overcome to eject drops. The monolithic, surface micromachined piston/nozzle plate design can potentially produce variable diameter drops using very low power, and may provide an alternative to thermal or piezoelectric actuation systems for some applications.

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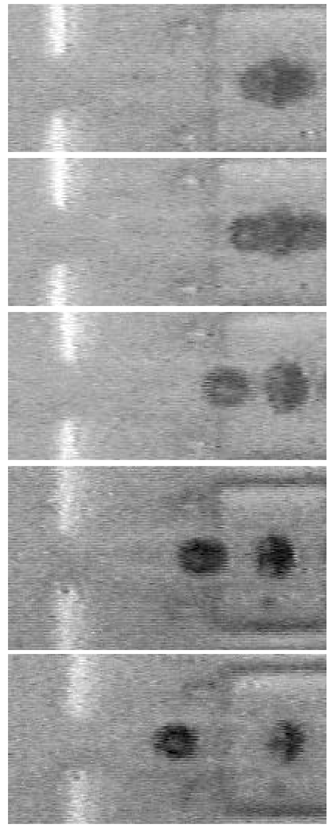

(a) 2 µs strobe delay

(b) 3 µs strobe delay

(c) 4 µs strobe delay

(d) 5 µs strobe delay

(e) 6 µs strobe delay

Figure 5. Close-up of drop ejection. Strobe delay from beginning of ejection signal (Fig. 4).