# 2D ACOUSTICALLY ACTUATED MICROMACHINED DROPLET EJECTOR ARRAY

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*Abstract*— Most of the semiconductor and MEMS fabrication processes require deposition of organic polymers on wafers. The current state-of-the-art method is the spin coating. However, more than 95% of the expensive coating material is wasted. To reduce waste, we proposed to use a novel two-dimensional micromachined droplet ejector array to deposit photoresist and other spin-on materials used in IC manufacturing.

Each element of the two-dimensional ejector array consists of flexurally vibrating circular membranes with orifices etched at their centers. Droplets are ejected through these orifices. The actuation is performed by a piezoelectric transducer placed parallel to the array.

We observed that achieving simultaneous ejection from all the array membranes was difficult. The problem was associated with non-uniform membrane displacements across the array due to an uneven pressure distribution within the individual fluid reservoirs. Finite Element Method (FEM) modeling was used to investigate the problem. Our simulation results showed that in the presence of individual fluid reservoirs the membrane resonance frequency shifted and the quality factor of the resonance is decreased. These simulations indicated that an ejector design free of individual reservoirs would achieve more uniform membrane displacements across the array. The simulation results of two designs were verified by vibrometer measurements.

## I. INTRODUCTION

In semiconductor and microelectromechanical systems (MEMS) manufacturing, deposition of organic polymers is the most employed process step [1]. There is also a need for alternative deposition methods, such as deposition of doped organic polymers for organic devices, e.g. LED's and flat panel displays, and for deposition of photoresist or dielectric materials for semiconductor manufacturing [2]. Moreover, a reliable and rapid method for dispensing femtoliters to picoliters of fluid emerges as a basic need in the fields of biomedicine and biotechnology [3].

Various techniques have been reported for deposition of organic polymers such as photoresist and low-*k* or high-*k* dielectrics in semiconductor and MEMS processes [4]. Spin coating is widely employed in current applications, since it can fulfill the throughput and quality requirements of the IC industry [5]. However, this method causes extensive waste of expensive chemicals. For instance, photoresist deposition by spin coating wastes more than 95% of the resist consumed during the process [4].

A photoresist film deposited onto a wafer should be uniform in thickness and chemically isotropic in order to ensure uniform light response during photolithography [1]. One source of variation of the physical properties of a deposited film is the spin coating [1,6]. Direct deposition can reduce waste, production cost and environmental pollution. Therefore, deposition by droplet generation emerges as an attractive alternative method to spin coating.

Several methods for droplet generation exist. One of these methods is thermal ink-jet printing [7]. However, the problem with thermal ejection for the applications of interest here is that the heating may damage thermo-sensitive fluids such as photoresist, and low-*k* or high-*k* dielectrics. Another ejection method is based on piezoelectric actuation. However, this method pressurizes the reservoir at every ejection cycle with possible adverse effects on baro-sensitive fluids. Moreover, both the aforementioned device types are difficult to fabricate as 2D arrays [7,8]. Furthermore, it is hard to reduce the printhead size and to increase the spatial density of the array elements used in these two types of devices. In general, these devices operate at frequencies between 10 kHz and 100 kHz and eject 10-20 μm diameter drops [7].

Previously, various actuation methods have been used to eject fluids from a small orifice in a membrane. Maehara et al. demonstrated an ultrasonic atomizer [9]. Percin et al. used a piezoelectric ring fabricated on top of the membranes of a large-scale device, where the piezoelectric ring initiated the displacement of the membranes [9]. Although these devices allow the individual addressing of each array element, their fabrication requires extra lithography steps for the piezoelectric ring formation [9].

Demirci, et al. demonstrated acoustically actuated 2D micromachined ejector arrays [10-12]. In this design each membrane of the array had access to a fluid reservoir.

We propose to use acoustically actuated 2D micromachined ejector arrays to deposit organic polymers onto wafers. The ejector array does not damage sensitive fluids and it produces equi-sized droplets. Further, it does not increase the static pressure in the fluid volume and it is compatible with various chemicals. Moreover, the arrays operate in the 0.3 MHz to 5 MHz frequency range. Therefore, they provide high flow rates and a capability to eject 3-7 μm diameter droplets [10-13].

For low power consumption and uniform displacement operation of the ejector arrays the design parameters such as

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membrane diameter, reservoir height should be optimized. In order to do this we constructed an FEM model of the device. The effect of the reservoirs on the membrane resonances and on the quality factor of these resonances was simulated.

## II. THEORY

We used FEM simulations (ANSYS 5.7) to predict the resonance frequencies of the device and the membrane displacement at these resonance frequencies. The simulations were used to explore the effects of the fluid reservoirs and array geometry on the device operation. The FEM simulations performed a harmonic analysis of the 2D and 3D structures shown in figure 1. The frequency step was chosen to be 5 kHz in order to distinguish the resonances. The mesh density was chosen so that there were at least ten nodes per wavelength in the structure. The device was simulated by loading one side of a membrane clamped at the end of a reservoir with an infinitely long fluid space eliminating undesired reflections (FLUID 129). The structure-fluid interaction was taken into account by solid/fluid interface elements (FLUID 29). The ejection holes were not included in the geometry since they were observed not to change the resonance frequency and displacement of the membranes. The simulations were performed with $Si_xN_y$ membranes with characteristic material values: density of 3290 kg/m$^3$, Young's Modulus of 310x10$^9$ N/m$^2$ , and Poisson's Ratio of 0.27 [14].

*(i) Effect of the fluid reservoir*

It is important to determine the resonance frequencies of the device, since at these resonances, the displacement of the orifice is maximal. When this displacement is larger than the critical minimum displacement required for breaking a droplet from the orifice, fluid is ejected through the orifice [13]. The maximum orifice displacement as a function of frequency for a 160 µm in diameter 2.1 µm thick water loaded $Si_xN_y$ membrane is shown in figure 2 in the presence and absence of the individual reservoirs.

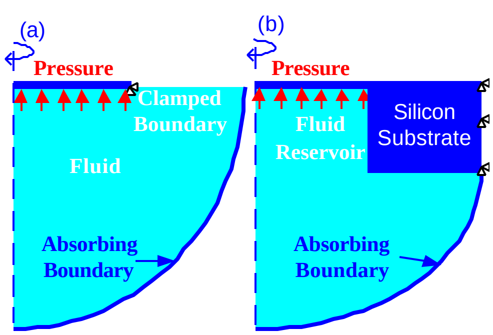



Figure 1. Unit Cell of an ejector array for 3D FEM simulations: (a) No Reservoir, (b) With reservoirs.

The two geometries, shown in figure 1, feature identical membrane diameter and thickness. They were simulated with identical pressures applied to each node of the membranes (ideal plane wave excitation), so that the effect of the reservoir on a single ejector array element performance could be determined. Figure 2 shows that a 160 µm in diameter 2.1 µm thick water loaded $Si_xN_y$ membrane, located at the end of a 500 µm long cylindrical fluid reservoir, resonates at lower frequencies as compared to the case where there is no fluid reservoir. Removing the fluid reservoir increased the amplitude of the maximum orifice displacement at the second resonance by 6 dB, when the same amount of actuation energy is used. Moreover, it was observed that the fluid reservoir modulates the quality factor of the device resonance. The quality factors for the first and second resonances were calculated to be 35, 8 and 47, 33 for the devices with a 500 µm long individual reservoir and without a reservoir, respectively. In this particular device the fluid reservoir reduces the quality factor of the resonance.

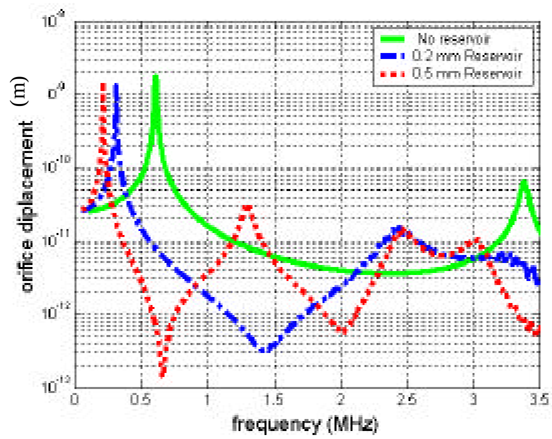



Figure 2. 3D FEM results: Maximum orifice displacement of a single membrane vs. frequency of an ejector array of 160 µm in diameter $Si_xN_y$ membranes with and without reservoir.

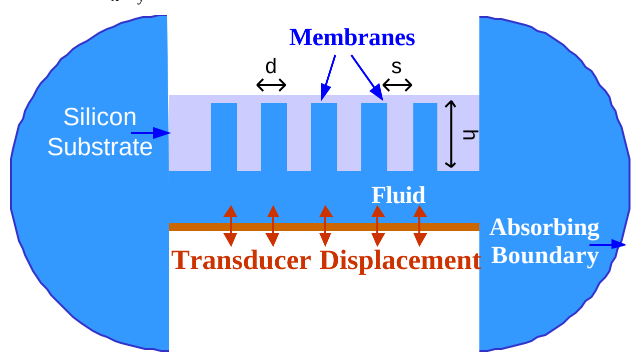


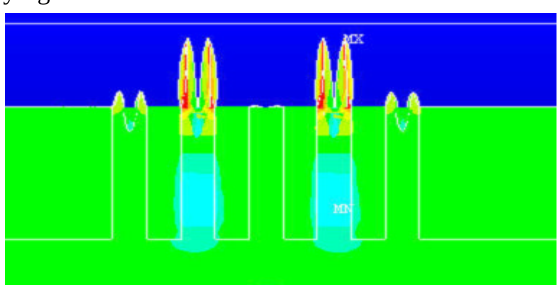

Figure 3. FEM model of 1x5 ejector array with transducer.

*(ii) Effect of the fluid reservoir on displacement uniformity*

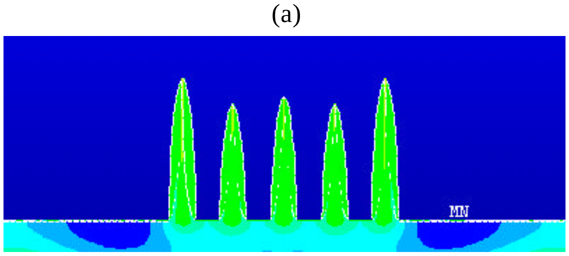
Figure 3 shows the model of a 1x5 ejector array actuated by a flat ultrasound transducer immersed in the fluid. The ejector array was 10% of the transducer area. Therefore, plane wave actuation was employed in this model. The transducer actuated the membranes at their 1.7 MHz resonance frequency. It was placed at 4.5 mm away from the membrane surface in both geometries, which corresponds to a Seki parameter of 0.4. The maximum orifice displacement of each array membrane was monitored as the reservoir height was modified as shown in figure 4. The ratio of the maximum to the minimum membrane displacement observed simultaneously across the array elements was 1.2 and 6 for devices with 500 µm reservoirs and without reservoirs, respectively. The non-uniform pressure distribution in the fluid reservoirs is shown in figure 5.

## III. METHODS

In order to verify the predictions of the simulations, an array without individual reservoirs with 160 µm in diameter, 21 µm thick $Si_xN_y$ membranes was tested experimentally. Maximum membrane displacements across the array were obtained by a Polytek OFV 502 (Walderbourn, Germany) laser vibrometer. The vibrometer could measure a maximum amplitude of ± 75 nm linearly. The 2D micromachined ejector array was aligned parallel to the transducer surface within less than 4° of error in order to form standing waves between the device and the transducer surface. A monochromatic sinusoidal waveform generated by a function generator (HP 33120A, CA) was applied to the transducer through an amplifier (EIN 300L, Rochester, NY). A transducer was utilized (Panametrics, A303 S, Atlanta, Georgia, center frequency 1.1 MHz, 0.39 MHz 6dB bandwidth). A vertical micrometer stage controlled the separation between the transducer and the device, figure 2. A block diagram of the experimental setup is shown in figure 6. The measurements were taken when the membranes were loaded with either distilled water or ethyl alcohol. The measurements were repeated on three membranes of the array without changing the transducer location. One of the membranes was chosen from the middle of the array, and two to the side of the array to explore displacement non-uniformity of the displacement of the membranes across the array. Each membrane displacement was maximized by sweeping the applied frequency until the strongest resonance was reached applying 0.5 V across the transducer.



(a)



(b)

Figure 4. Orifice displacement of array membranes at resonance (a) with a 500 µm reservoir (b) without an individual reservoir (not to scale).

## IV. RESULTS and DISCUSSION

The measurements with the vibrometer obtained from three membrane centers of the array near the orifice are as shown in figure 7. Current membrane based micromachined actuators have a fluid reservoir inherent to their design geometry [9-12]. These devices are actuated by acoustic waves that couple to the array membranes through individual cylindrical fluid reservoirs. However, the rims of the reservoirs act as scatterers for the incident acoustic plane waves [15]. Moreover, there is possibly coupling of acoustic energy to the walls of the fluid reservoir [16]. These facts represent inefficient use of the actuation energy. Furthermore, the cavity resonances of the cylindrical reservoir should overlap as seen in figure 2 with the membrane resonances of the ejector to achieve maximum displacement at the membrane orifice. This modifies the quality factor of the resonance. Matching the cavity height to the membrane dimensions increases the design complexity and adds a fabrication step.

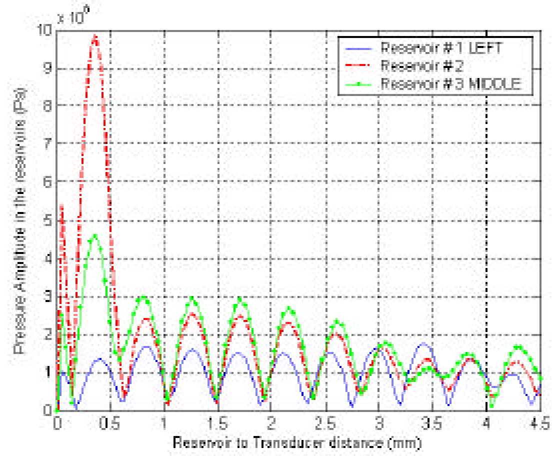



Figure 5. Pressure amplitude along a line across three reservoirs of the ejector array during actuation.

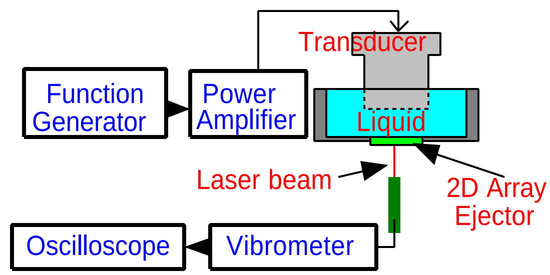
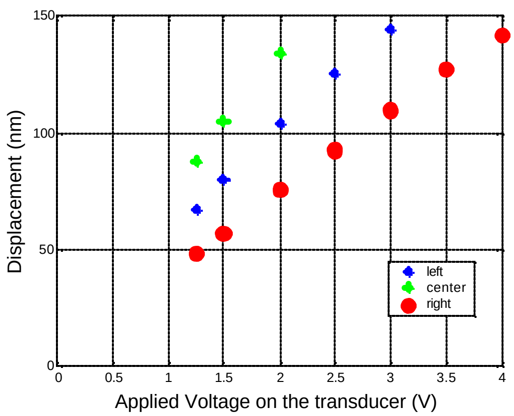


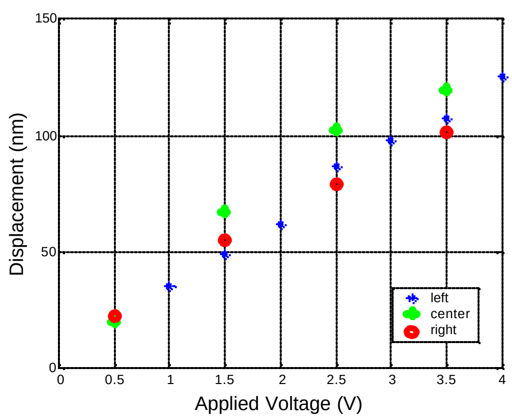

Figure 6. Experimental setup.

The FEM simulation demonstrates the inefficient use of the actuation energy due to the individual fluid reservoirs. The two geometries, shown in figure 1, have identical membrane diameter and thickness. They were simulated with an identical actuation mechanism. Figure 2 shows that removing the fluid reservoir increases the amplitude of the orifice displacement at resonance by more than 6 dB with the same actuation pressure. The FEM simulations of the array geometry indicated that the pressure amplitude distribution within the fluid reservoirs of the array was uneven. It was also observed that the membrane displacements were more uniform across the array, when the individual fluid reservoirs were removed as shown in figure 4. The membrane displacement non-uniformity could be due to the fact that there is interaction between the resonating array elements, which result in an uneven distribution of the pressure field behind the membranes. Scattering from the rims of the reservoirs of the acoustic waves could further contribute to the pressure non-uniformity. The design without the individual fluid reservoirs is more likely to form a uniform standing wave pattern between the transducer and the device.

The simulation predictions were supported by the vibrometer measurements. It was observed that the membrane displacements across the array were more uniform when the individual reservoir were removed from the ejector array design, figure 7. The maximum displacement dispersion was reduced from 80 nm to 20 nm. Removing the individual reservoirs from the ejector design removes the previously mentioned disadvantages originating from the presence of individual fluid reservoirs in the micromachined ejector device design. This makes an even ejection pattern easier to achieve.
Our proposed deposition method has potential to provide fast surface coverage since the ejection frequencies are in the megahertz frequency range. This effective droplet ejection method should be able to solve some of the practical problems associated with the spin coating technique. One such problem is the inability to cover deep trenches with uniform photoresist. By reducing waste, fabrication costs decrease, resulting in increased productivity and reduced environmental burden.




(a)




(b)

Figure 7. Maximum displacements on three membrane centers across the array (a) with 500 µm reservoirs (b) no reservoirs.

## V. CONCLUSIONS

We demonstrated that the non-uniform membrane displacements across the array was due to an uneven pressure distribution in the individual fluid reservoirs. FEM simulations indicated that an ejector design free of individual reservoirs would achieve more uniform membrane displacements across the array. Moreover, the simulations demonstrated that in the presence of the individual reservoirs the resonance frequency shifted and the quality factor of the resonance was decreased. We verified the simulation results with vibrometer measurements. Future work will focus on photoresist ejection, and optimization of the 2D micromachined ejector array design.

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