Micromachined droplet ejector arrays for controlled ink-jet printing and deposition

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In this article, we present a variation on the design of the micromachined flextensional transducer for use to eject liquids. The transducer is constructed by depositing a piezoelectric thin film to a thin, edge clamped, circular annular plate. By placing a fluid behind one face of a vibrating compound plate that has an orifice at its center, we achieve continuous or drop-on-demand ejection of the fluid. We present results of ejection of water and isopropanol. The ejector is harmless to sensitive fluids and can be used to eject fuels, organic polymers, low-*k* dielectrics, chemical, and biological samples. Micromachined two-dimensional array piezoelectrically actuated flextensional droplet ejectors were realized using planar silicon micromachining techniques. Typical resonant frequency of the micromachined device ranges from 400 kHz to 4.5 MHz. The ejection of water through a 5 μm diameter orifice at 3.5 MHz was demonstrated by using the developed micromachined two-dimensional array ejectors.
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I. INTRODUCTION

A fast, reliable method for dispensing picoliters to femtoliters fluid volumes is needed in many emerging areas of biomedicine and biotechnology. There is also a continuing need for alternative deposition techniques of organic polymers in precision droplet-based manufacturing and material synthesis, such as the deposition of doped organic polymers for organic light-emitting devices of flat panel displays,[1–5] and the deposition of low-*k* dielectrics for semiconductor manufacturing. A reliable and low-cost droplet ejector array that can supply high quality droplets, e.g., uniform droplet size and ejection without satellite droplets, at high ejection frequencies, and high spatial resolutions is needed. The micromachined droplet ejector presented in this article can readily be scaled to an array of more than 10 000 ejectors per 1 cm^2, and the ejected drop size ranges in diameter from 5 μm at an ejection rate of 3.5 MHz to 150 μm at an ejection rate of 7 kHz.

II. DESIGN

We designed the transducer to have maximum displacement at the center of the plate at the resonant frequency. Similar ejector designs can be found in Ström,[6] Maehara *et al.*,[7,8] Ueha *et al.*,[9] Tetsuo,[10] and Ivri.[11] However, the complexity of the structure and the fact that the piezoelectric used is an annular disk rather than a full disk necessitate the use of a more complicated analysis to determine the resonant frequencies of the structure, the input impedance of the transducer, and the normal displacement of the surface as presented in Perçin and Khuri-Yakub.[12] In the absence of analytical expressions for the equivalent circuit parameters of a flextensional transducer, it is difficult to calculate its optimal parameters and dimensions, and to choose suitable materials. The influence of coupling between flexural and extensional deformation, and coupling between the structure and the acoustic volume on the dynamic response of piezoelectrically actuated flextensional transducer is analyzed using three analytical methods: classical thin (Kirchhoff) plate theory, Mindlin plate theory, and simple variational method. Classical thin plate theory, Mindlin plate theory, and variational methods are applied to derive two-dimensional plate equations for the transducer, and to calculate the coupled electromechanical field variables such as mechanical displacement and electrical input impedance. In these methods, the variations across the thickness direction vanish by using the bending moments per unit length or stress resultants. Thus, two-dimensional plate equations for a step-wise laminated circular plate are obtained as well as three different solutions to the corresponding systems. An equivalent circuit of the transducer is also obtained from these solutions.

III. EJECTION SIMULATION

A computational model which simulates droplet ejection has been also developed using a boundary integral method in Perçin *et al.*[13] The surface equations of motion were made dimensionless using the radius of the orifice as the characteristic length and the period of plate oscillation as the characteristic time. The only parameter which remains in the equations is the surface tension parameter S,

$$S=\frac{2\sigma}{\rho a^3 f^2}, \tag{1}$$

where a is the radius of the orifice, σ and ρ are surface tension and density of the liquid. This provides a scaling law for drop ejection. All other things being equal, such as am-

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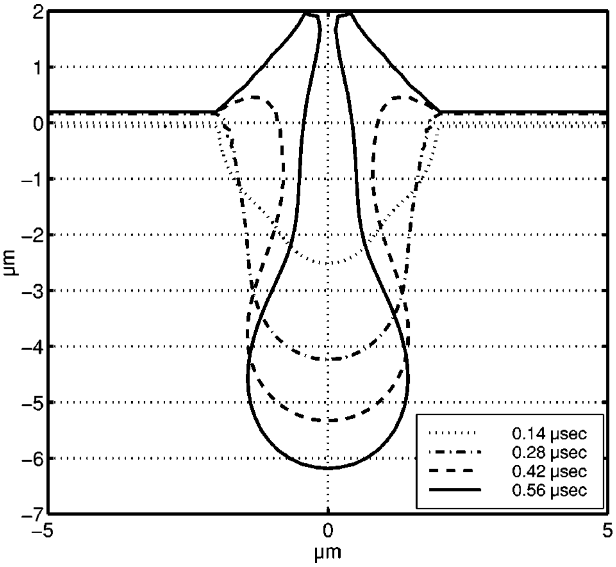

FIG. 1. Typical microelectromechanical systems device water ejection simulation through 4 μm diameter orifice at 1.4 MHz by using 112 μm diameter device. The drop formation is shown at different time intervals.

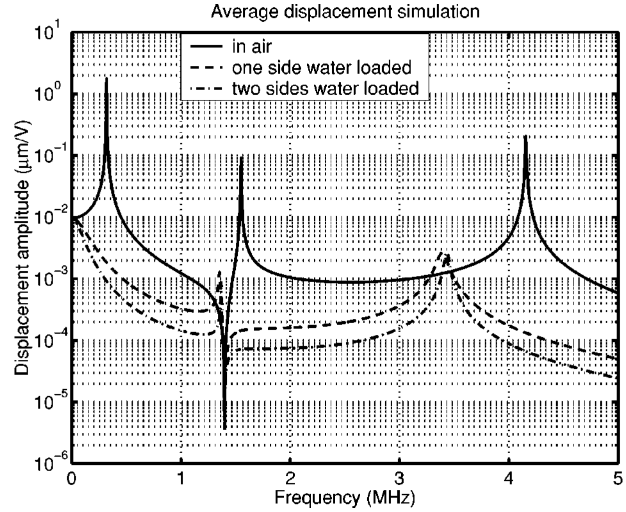

FIG. 2. Micromachined droplet ejector average displacement simulations for a single element for air and water loaded cases.

plitude and plate mode shape, this says that droplet size and shape are only a function of this single dimensionless parameter. For instance, if f is made larger then either the orifice radius should be smaller or σ made larger.

In the computation, drop ejection is initiated by pushing the membrane downward from an elevated stationary position to a depressed position where it is stopped. That is, it moves through a half cycle with a motion which produces a flowrate through the orifice of $q = q_{\max} \sin(2\pi t)$ with $0 < t < 0.5$. In Fig. 1, the simulated droplet ejection is shown, with actual dimensions, four times during a cycle. The orifice diameter is 4 μm, the amplitude of the plate displacement is 0.2 μm, the ejection frequency is 1.4 MHz (period 0.71 μs), the first flexural axisymmetric mode of the step-wise laminated plate is used for the ejection, and the ejected fluid is water. The diameter of the drop is 75% of the orifice diameter and the final velocity is about 5.3 m/s based on the distance between the heights of the last two frames. The calculated flow rate is 19.8 nl/s for an array element and the volume of the drop is 14.1 fl. In the computation, the drop pinch off time was 0.62 μs and the surface tension parameter was $S = 9.3$. This simulation shows that a 0.2 μm amplitude of displacement is needed to eject water through a 4 μm orifice. The average displacement simulations for the device used in the previous droplet ejection simulation are given in Fig. 2 for air, one side water loaded, and two sides water loaded cases.

IV. FABRICATION

The fabrication process for the micromachined two-dimensional array flextensional transducers and droplet ejectors is given in Fig. 3. On the right-hand side of the figure, actual pictures of one element from a two-dimensional array are given along with the process flow. The process starts with growing a sacrificial layer, chosen to be silicon oxide [8% phosphorus doped densified low-temperature oxide (LTO)]. A nonpiezoelectric carrier plate layer of low-pressure chemical vapor deposited silicon nitride is grown on top of the sacrificial layer. Ejection holes are patterned in the silicon nitride carrier plate layer at the front surface of the wafer by plasma etching. Later, back side access holes or fluid reservoirs are patterned in the silicon nitride and LTO layers at the back surface of the wafer, and the back side access holes are etched by deep reactive ion etching (DRIE) until reaching the sacrificial silicon oxide layer at the front surface as shown in Fig. 3. The DRIE of silicon has an SF_6 ambient with a flow rate of 130 sccm, a pressure of 35 mTorr, an rf power of 120 W in active cycle, and an C_4F_8 ambient with a flow rate of 80 sccm, a pressure of 18 mTorr in passive cycle. The etching rate is 3.8 μm/min. Because of the material compatibility with the DRIE equipment in our laboratory, we choose to etch the back side access holes in bulk silicon before defining the actual transducers at the front surface of the wafer. The bottom Ti/Au electrode layer is deposited on the nonpiezoelectric carrier plate by electron-beam (e-beam) evaporation at 240 °C. The degree to which the ZnO c axis, ⟨0002⟩ is oriented normal to the substrate surface is very sensitive to the degree to which the Au film is ⟨111⟩ oriented. The quality of the ZnO is measured by an x-ray rocking curve scan. The ZnO had a 5.5°-wide rocking curve above Au with a 5°-wide rocking curve. Later, the bottom electrode layer is patterned by wet etch, and a piezoelectric ZnO layer is deposited on top of the bottom electrode. The ZnO is deposited by dc planar magnetron sputtering from a 127-mm-wide target consisting of 99.99% Zn. The deposition is made in an 20%–80% argon–oxygen ambient with a flow rate of 26.6 sccm, a pressure of 7 mTorr, a substrate temperature of 150 °C, and a dc power of 350 W. The separation between the substrate and the target is 51 mm. The deposition rate is 10.5 Å/s. The top Cr/Au electrode layer is formed by e-beam evaporation at room temperature and patterned by liftoff. The last step is etching the sacrificial layer by wet etch, and this concludes the front surface micromachining of the devices.

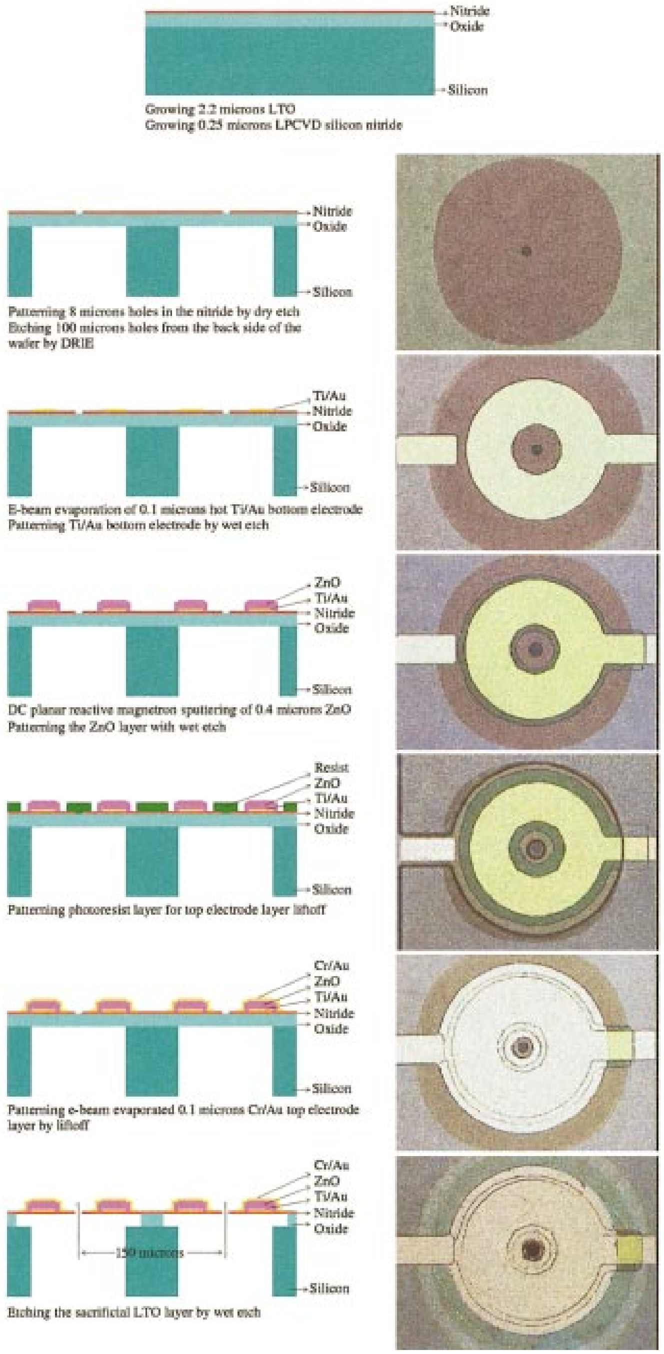

FIG. 3. (Color) Micromachined droplet ejector fabrication process flow.

V. EXPERIMENT

We have shown that the version of the ejectors shown in Fig. 3 neither have enough displacement nor actuation mechanism to eject some fluids at relatively higher frequencies. Due to this fact, a modified version of the device has been developed to provide a bulk actuation mechanism along with the individual array element actuation. Two different modes of operation of the devices are presented. The micromachined two-dimensional array droplet ejectors with bulk actuation mechanism are shown in Fig. 4. The bulk actuation mechanism consists of longitudinal thickness mode piezoelectric transducer. The piezoelectric transducer is in contact with the fluid, and bonded above the fluid reservoirs. In the first type of operation, the bulk actuation mechanism provides enough actuation to form a fluid meniscus around the orifice, so that individual array elements when actuated will cause fluid to eject through the orifice. In this mode of operation, the phases of bulk actuation and individual array element actuation should match at the liquid–air interface at the orifice. In the second type of operation, the bulk actuation mechanism is enough to eject the fluid by itself, and the individual array element when actuated out of phase will cause the existing ejection to stop. By using the bulk actuation mechanism shown in Fig. 4, the water ejection through 5 μm diameter orifice has been achieved, and the ejection picture for a single array element from 22×22 per 1 cm^2 array is shown in Fig. 5. The ejection is tilted with respect to the orifice due to asymmetric wetting problems. One droplet is ejected for each cycle of the input signal.

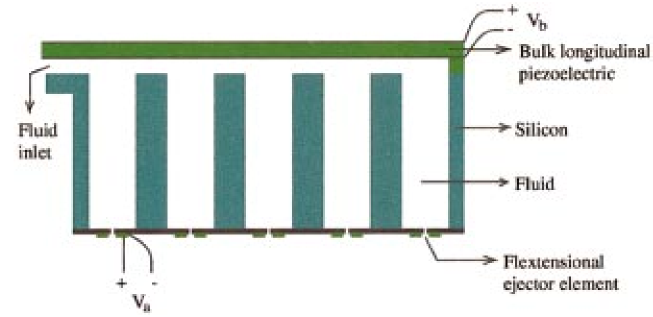

FIG. 4. (Color) Configuration of the micromachined droplet ejector. The device is bulk actuated by using the bulk piezoelectric material.

VI. DISCUSSION

In summary, a novel fluid ejector that can be used as miniaturized sample preparation module is designed and demonstrated in this article, and was also silicon micromachined into two-dimensional arrays. The ejector design, based on that of a flextensional ultrasound transducer, is optimized using both a finite element analysis and analytical model that was developed in Perçin and Khuri-Yakub.[12]

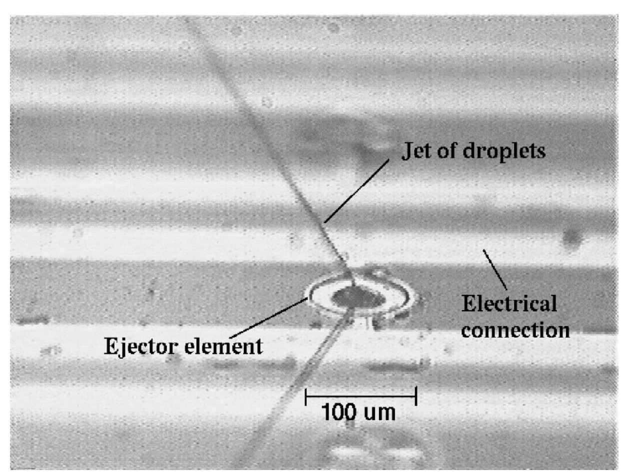

FIG. 5. Water ejection through 5 μm diameter orifice at 3.48 MHz by using both the first and the second type of operation.

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