Micromachined droplet ejector arrays

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In this article we present a micromachined flextensional droplet ejector array used to eject liquids. By placing a fluid behind one face of a vibrating circular plate that has an orifice at its center, we achieve continuous 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, photoresists, low-*k* dielectrics, adhesives, and chemical and biological samples. Micromachined two-dimensional array 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 ejections of water through a 4 μm diameter orifice at 3.45 MHz and a 10 μm diameter orifice at 2.15 MHz were demonstrated by using the developed micromachined two-dimensional array ejectors. [DOI: 10.1063/1.1517145]

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 array presented in this article can readily be scaled to an array of more than 20 000 ejectors per 1 cm^2, and the ejected drop size in diameter is as small as 3 μm at an ejection rate of 3.45 MHz.

II. DESIGN

We designed the droplet ejector to have maximum displacement at the center of the flexurally vibrating circular plate at its resonant frequency when loaded with fluid. The vibrating plate that has an orifice at its center is actuated by forming an acoustic cavity resonator in the fluid reservoir for each array element. Longitudinal thickness mode piezoelectric material shown in Fig. 1 is used as an actuation mechanism. The resonances of the flexurally vibrating plate, the cylindrical acoustic cavity (the fluid reservoir), and the piezoelectric material were chosen to be the same for obtaining the smallest energy required to eject fluid droplets. The resonant frequencies of the circular plate are decreased by fluid loading on one side of the vibrating plate.

The vibrating plate sets up capillary waves at the liquid–air interface and raises the pressure in the liquid above atmospheric (as high as 1.5 MPa) during part of a cycle, and if this pressure rise stays above atmospheric pressure long enough during a cycle, and this is high enough to overcome inertia and surface tension restoring forces, drops are ejected through the orifice. If the plate displacement amplitude is too small, the meniscus in the orifice simply oscillates up and down. If the frequency is too high, the pressure in the fluid does not remain above atmospheric long enough to eject a drop.

III. EJECTION SIMULATION

A computational model which simulates droplet ejection has been also developed using a boundary integral method in Perçin *et al.*[6] 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*,

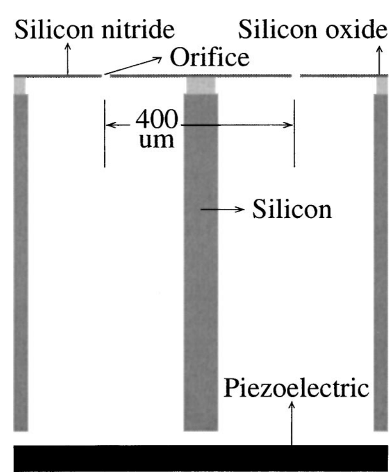

FIG. 1. Configuration of the micromachined droplet ejector. The spacing between the adjacent array elements ranges from 150 to 400 μm. The orifice diameter ranges from 4 to 10 μm. The vibrating plate diameter ranges from 90 to 500 μm.

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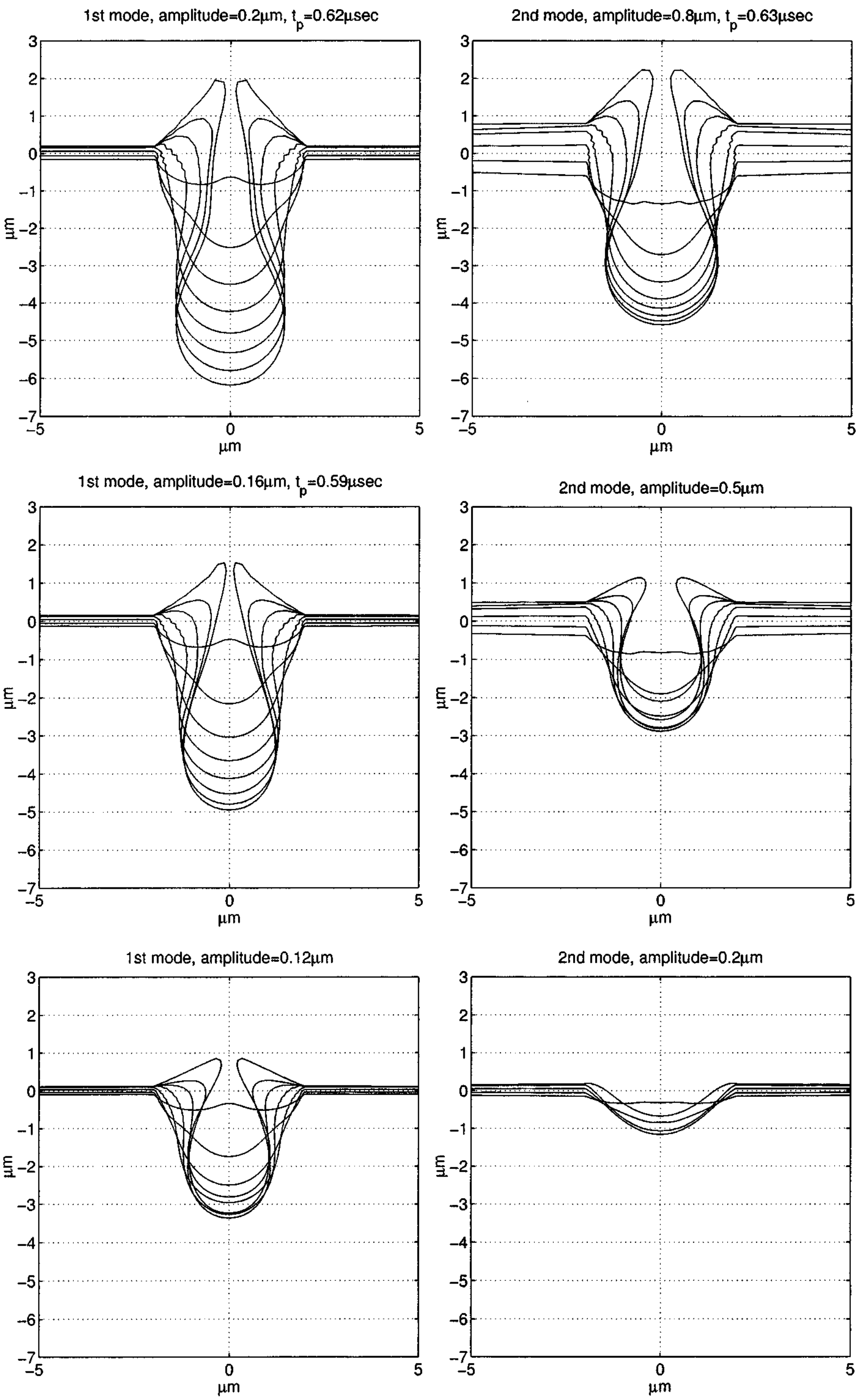

FIG. 2. Water ejection simulations through a 4 μm diameter orifice at 1.4 MHz by using a 112 μm diameter device. The drop formations are shown at every 0.071 μs intervals for different modes and excitation displacement amplitudes. t_p is the drop pinch off time.

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

where a is the radius of the orifice, f is the frequency of oscillations, and 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 amplitude 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. It should be emphasized that viscous effects have been neglected in this analysis given that the ejection velocity scales with af. A Reynolds number,

$$\mathrm{Re}=\frac{a^2 f}{\nu}, \tag{2}$$

which describes the ratio of inertial forces to viscous forces, should be sufficiently large for the analysis to be valid, where ν is kinematic viscosity of the liquid.

In Fig. 2 the simulated droplet ejections are shown, with actual dimensions, at every 0.071 μs intervals, for different mode shapes and excitation displacement amplitudes. In the

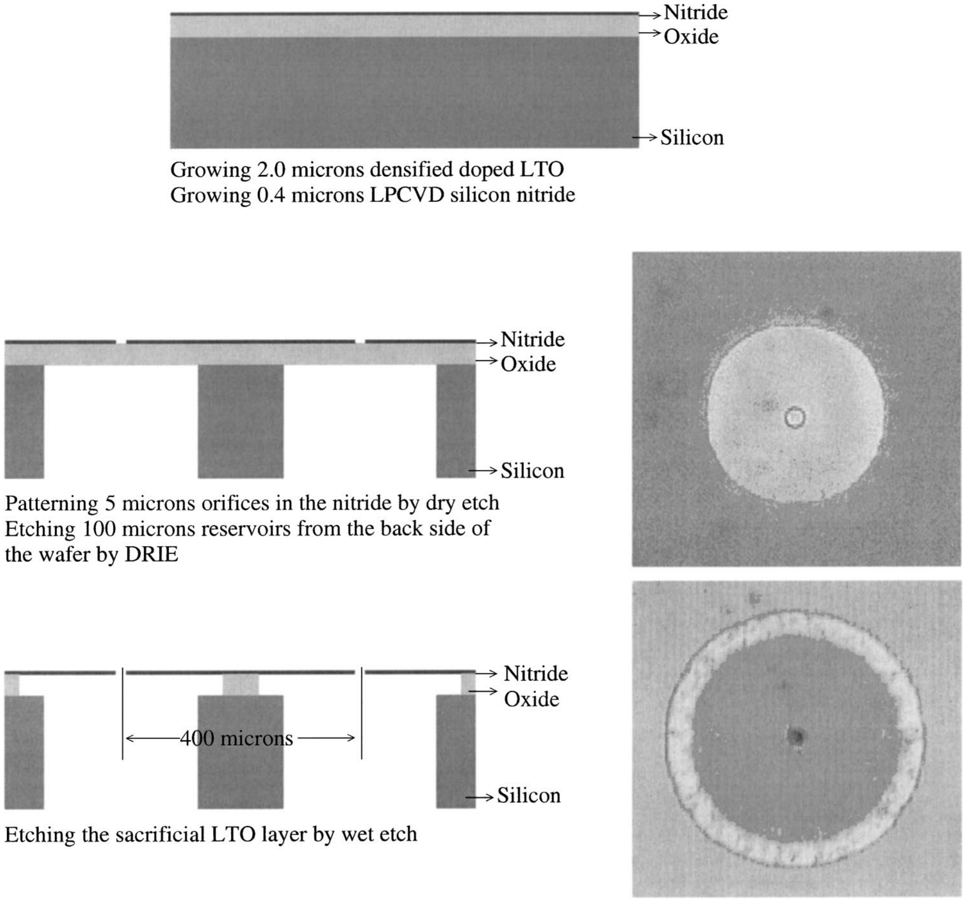

FIG. 3. The fabrication process flow for the realized micromachined droplet ejector array.

upper left simulation plot, 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 circular plate (fluid loaded) 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 for the upper left plot in Fig. 2, the drop pinch off time was 0.62 μs, Re=5.6, and the surface tension parameter was $S=9.3$. These simulations show that a 0.16 μm amplitude of displacement for the first mode is needed to eject water through a 4 μm orifice. As shown in Fig. 2, the second mode requires more displacement to eject the same fluid than the first mode. For the first mode and an excitation displacement of 0.12 μm, the plate displacement amplitude is so small that the meniscus in the orifice simply oscillates up and down and collapses onto itself. This also happens for the second mode and excitation amplitudes of 0.5 and 0.2 μm, and the liquid droplet cannot pinch off from the liquid–air interface.

IV. FABRICATION

The fabrication process for the micromachined two-dimensional array flextensional droplet ejectors is given in Fig. 3. At the right side of the figure, actual pictures of an 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 den-

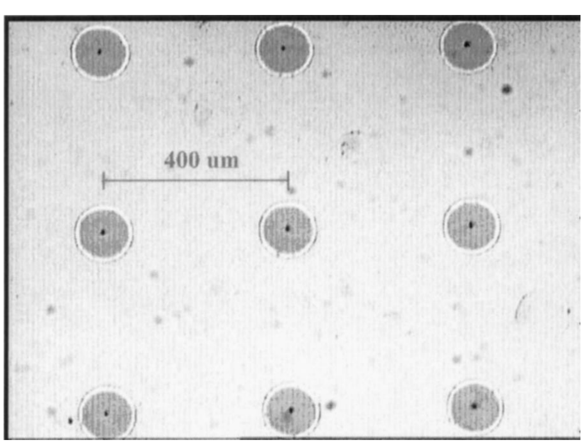

FIG. 4. Realized micromachined device. Section of 22×22 per 1 cm^2 array.

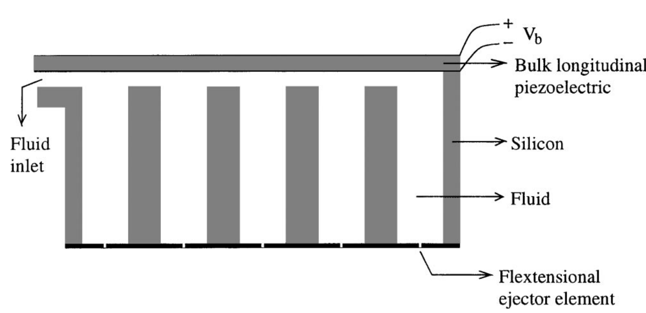

FIG. 5. Configuration of the device.

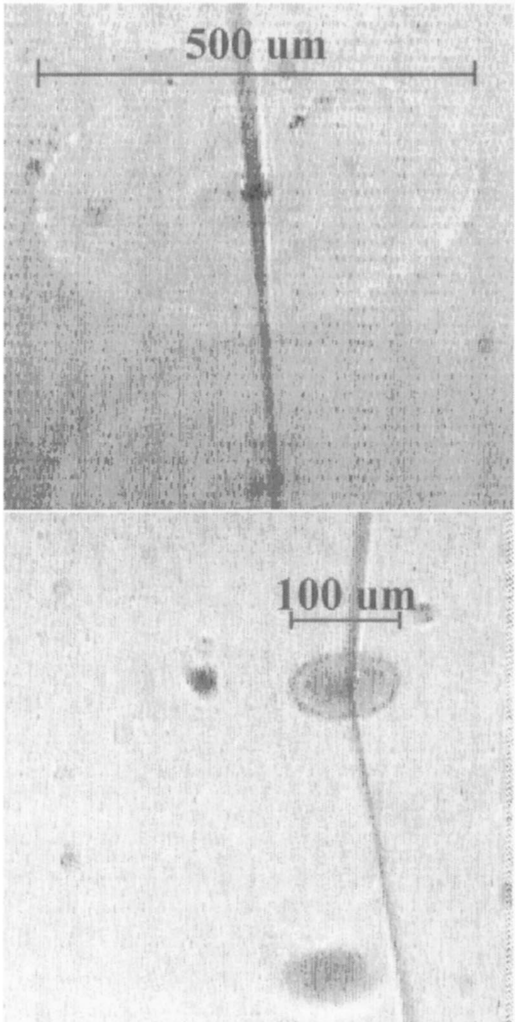

FIG. 6. Water ejections through a 10 μm diameter orifice at 2.15 MHz and a 4 μm diameter orifice at 3.45 MHz. The reflections of the fluid jets are located at the top of each picture.

sified low temperature oxide (LTO)]. A vibrating plate layer of low pressure chemical vapor deposited (LPCVD) silicon nitride is grown on top of the sacrificial layer. Ejection holes (orifices) are patterned in the silicon nitride vibrating plate layer at the front surface of the wafer by plasma etching. Later, the fluid reservoirs are patterned in the silicon nitride

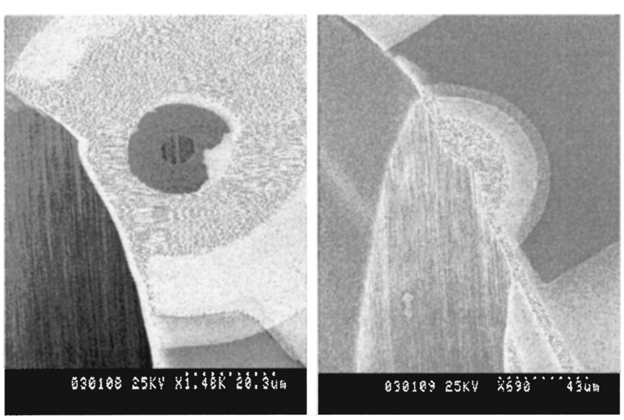

FIG. 7. SEM images of the micromachined droplet ejector array element.

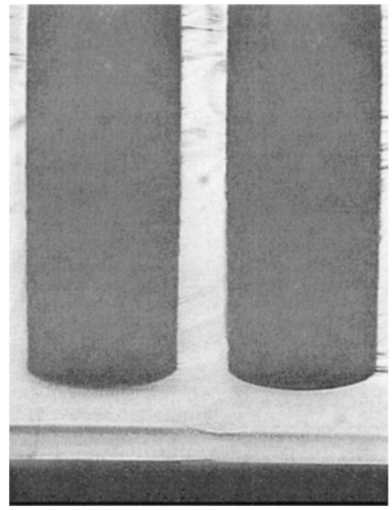

FIG. 8. Sideview of the fluid reservoirs of the micromachined droplet ejector array. The spacing between the adjacent fluid reservoirs is 150 μm.

and LTO layers at the back surface of the wafer, and the fluid reservoirs are etched by deep reactive ion etch (DRIE) until reaching the sacrificial silicon oxide layer (also etch stop layer) at the front surface as shown in Fig. 3. The DRIE of silicon has a sulfur hexafluoride (SF_6) ambient with a flow rate of 130 sccm, a pressure of 4.7 Pa, a rf power of 120 W in active cycle, and a perfluorocyclobutane (C_4F_8) ambient with a flow rate of 80 sccm and a pressure of 2.4 Pa in passive cycle. The etching rate is 3.8 μm/min. The last step is etching the sacrificial layer by wet etch, and this concludes the front surface micromachining of the devices. Figure 4 shows a section of realized 22×22 per 1 cm^2 two-dimensional array droplet ejectors.

V. EXPERIMENT

The micromachined two-dimensional array droplet ejectors with bulk actuation mechanism are shown in Fig. 5. The bulk actuation mechanism consists of a longitudinal thickness mode piezoelectric transducer. The piezoelectric transducer is in contact with the fluid and bonded above the fluid reservoirs. The bulk actuation mechanism is used for ejecting the fluid. By using the bulk actuation mechanism shown in Fig. 5, the water ejections through 4 and 10 μm diameter orifices have been achieved, and the ejection pictures for a 500 μm diameter array element with a 10 μm diameter orifice driven at 2.15 MHz and a 100 μm diameter array element with a 4 μm diameter orifice driven at 3.45 MHz are shown in Fig. 6. The ejection is tilted with respect to the orifice due to asymmetric wetting problems caused by the particles left from the microfabrication process. Figure 7 shows scanning electron microscope (SEM) images of the fabricated array element. Figure 8 shows a sideview of the fluid reservoirs of the micromachined droplet ejector array.

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 a flexurally vibrating circular plate, is optimized using the analytical model that was developed in Perçin *et al.*[7] An individually addressed two-dimensional array version of the droplet ejector is presented in Perçin *et al.*,[8,9] where each array element has its own actuation mechanism, and individual array elements are made of a thin silicon nitride plate covered by a coating of piezoelectric zinc oxide rather than having a bulk piezoelectric material bonded above the fluid reservoirs.

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