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Micromachined Fluid Ejector Arrays for Biotechnological and Biomedical Applications

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Abstract **- In this paper, we present a micromachined flextensional droplet ejector array for use 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 and 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, photoresists, low-*k* dielectrics, adhesives, 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 thru 4 μm diameter orifice at 3.45 MHz and 10 μm diameter orifice at 2.15 MHz were demonstrated by using the developed micromachined two-dimensional array ejectors. The unique features of the device are that the fluid is not pressurized, the fluid container is chemically or biologically compatible with most fluids, and the vibrating plate contains the orifice as the ejection source.**

I. INTRODUCTION

During the past few years, the application of microfabrication techniques has entered the medical field and has initiated the development of powerful new diagnostic devices used for cancer, AIDS, and genetic diseases[1]. A reliable, fast method for dispensing small volumes of biological and chemical fluids is needed in many emerging areas of biotechnology and biomedicine[2],[3],[4]. Economical, simple, inexpensive, and fast deposition of materials would have a great impact on the cost and quality control of drug delivery, drug discovery, high throughput screening, assaying, and combinatorial chemistry.

The developed micromachined arrays of droplet ejectors will enable the manufacturing of biochips such as immunoassays and DNA diagnostic assays. Lab-on-chip systems require reliable and robust methods for dispensing the reagents and biological agents on the substrates[2],[3]. Conventional pipetting, aspirating syringe, and capillary techniques (pins) have been used to withdraw or inject samples in automated analysis systems, such as high throughput screening systems. Conventional dispensing is difficult to use in high-density micro-array plates, such as 1536 and 3456-well plates. The developed ejector can deliver femtoliter to nanoliter scale samples of the biological and chemical fluids and small solid particles. By using the developed micromachined ejectors, it is possible to develop a microspotter system wherein the DNA oligos are deposited directly on each cell under computer control. Droplets (as small as 3 μm or smaller) can be deposited from a parallel array of orifices. The linear array of ejectors combined with mechanical scanning will be capable of depositing single bases (nucleoside phosphoramidites), predetermined sequences (oligonucleotides), cDNAs, or proteins over the full size of a biochip in a time interval that is compatible with the manufacturing process.

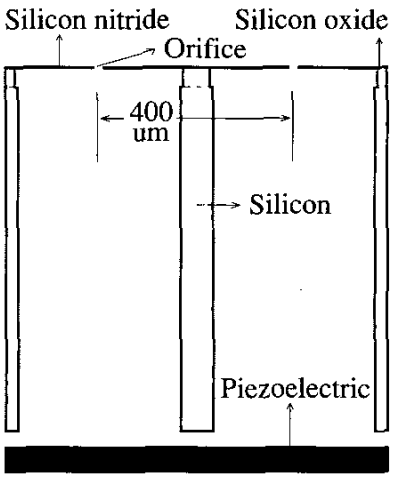


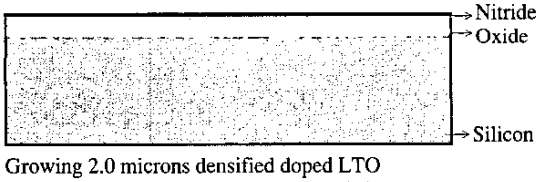
Fig. 1: Configuration of the micromachined droplet ejector. The spacing between the adjacent array elements ranges from 150 μm to 400 μm. The orifice diameter ranges from 4 μm to 10 μm. The vibrating plate diameter ranges from 90 μm to 500 μm.

The main mechanisms of ejecting ink droplets are categorized into two groups: bubble jet (thermal) and piezoelectric printheads. Thermoelectric actuation (bubble jet) is the dominating ink propulsion mechanism used in inkjet printheads on the market today. A small volume of ink is rapidly superheated forming a vapour bubble. The expansion of the bubble pressurizes the surrounding fluid causing a drop to be ejected from a nearby nozzle. Piezoelectric actuation causes acousto-hydraulic resonance in the ink chamber, i.e. the piezoelectric element is used to abruptly compress the enclosed volume producing a pressure wave which causes ejection of drop at a nozzle. Both printhead configurations suffer from some drawbacks,

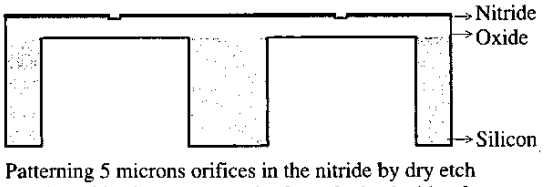
specifically, the piezoelectric printhead requires too much power to drive a large array of nozzles, and the bubble jet printhead has limited lifetime due to cavitation damage and burning of heater resistor. In the piezoelectric printhead design, it is difficult to reduce printhead size and to increase the spatial density of array elements. In the micromachined droplet ejector design shown in Fig. 1, the electric power consumption is very small. Furthermore, the device can readily be scaled to an array of more than 10,000 ejectors per 1 cm^2.

II. DEVICE FABRICATION

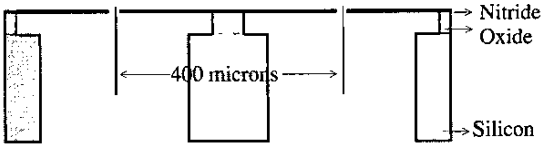
The fabrication process for the micromachined two-dimensional flextensional ejector arrays is given in Fig. 2. The process starts with growing a sacrificial layer, chosen to be silicon oxide (LTO). A vibrating plate layer of LPCVD silicon nitride is grown on top of the sacrificial layer. Ejection holes are patterned in the silicon nitride vibrating plate layer at the front surface of the wafer by plasma etching. Later, backside access holes are patterned in the silicon nitride and LTO layers at the back surface of the wafer, and the backside access holes are etched by DRIE until reaching the sacrificial silicon oxide layer at the front surface. The last step is etching the sacrificial layer by wet etch, and this concludes the front surface micromachining of the devices. Fig. 3 shows a section of a realized 22x22 per 1 cm^2 two-dimensional array droplet ejectors.



Growing 2.0 microns densified doped LTO
Growing 0.4 microns LPCVD silicon nitride



Patterning 5 microns orifices in the nitride by dry etch
Etching 100 microns reservoirs from the back side of the wafer by DRIE



Etching the sacrificial LTO layer by wet etch

Fig. 2: The fabrication process flow for the realized micromachined droplet ejector array.

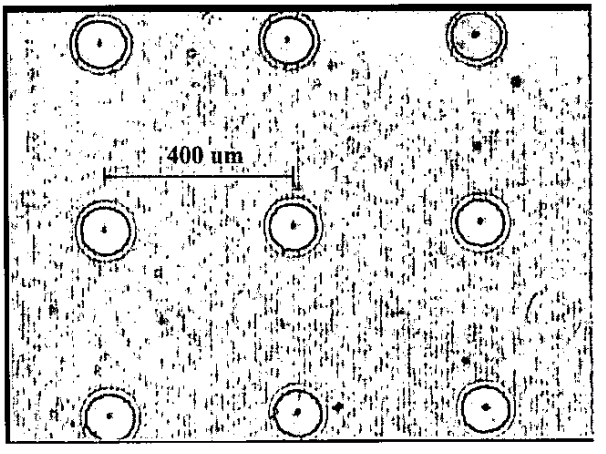


Fig. 3: Realized micromachined device. Section of 22x22 per 1 cm^2 array.

III. EXPERIMENTS

The vibrating plate sets up capillary waves at the liquid-air interface, and raises the pressure in the liquid above atmospheric 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. A computational model which simulates droplet ejection has been developed using a boundary integral method[5]. 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.

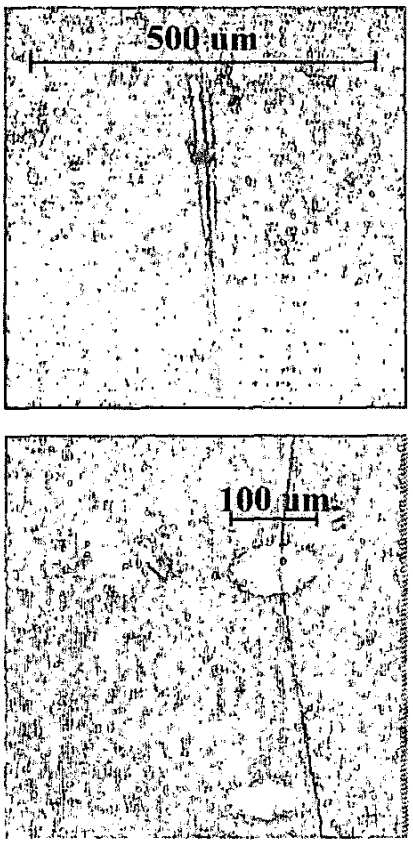


Fig. 4: Water ejection by using a micromachined fluid ejector, 3.5 millions 4 µm diameter water droplets per second are ejected.

The micromachined two-dimensional array droplet ejectors with bulk actuation mechanism are shown in Fig. 1. 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. The bulk actuation mechanism is used for ejecting the fluid. By using the bulk actuation mechanism shown in Fig. 1, the water ejections thru 4 µm and 10 µm diameter orifices have been achieved, and the ejection pictures for 500 µm diameter array element with 10 µm diameter orifice driven at 2.15 MHz and 100 µm diameter array element with 4 µm diameter orifice driven at 3.45 MHz are shown in Fig. 4. The realized micromachined device that has been developed for pulmonary drug delivery applications where all of the array elements are ejecting the same fluid. Individually addressed two-dimensional array version of the droplet ejector is presented in Perçin *et al.*[6] where each array element has its own actuation mechanism, and individual array elements are made of thin silicon nitride plate covered by a coating of piezoelectric zinc oxide rather than having a bulk piezoelectric material bonded above the fluid reservoirs.

VI. CONCLUSION

In summary, a novel fluid and solid particle ejector that can be used as a cost-effective miniaturized sample preparation module is designed and demonstrated in this paper and was also silicon micromachined into two-dimensional arrays.

V. REFERENCES

[1] J. Voldman, M. L. Gray, and M. A. Schmidt, "Microfabrication in biology and medicine," Annu. Rev. Biomed. Eng., vol. 1, pp. 401-425, 1999.

[2] C. M. Roth and M. L. Yarmush, "Nucleic acid biotechnology," Annu. Rev. Biomed. Eng., vol. 1, pp. 265-297, 1999.

[3] J. M. Jaklevic, H. R. Garner, and G. A. Miller, "Instrumentation for the genome project," Annu. Rev. Biomed. Eng., vol. 1, pp. 649-678, 1999.

[4] Ph. Luginbuhl, P.-F. Indermuhle, M.-A. Gretillat, F. Willemin, N. F. de Rooij, D. Gerber, G. Gervasio, J.-L. Vuilleumier, D. Twerenbold, M. Duggelin, and R. Guggenheim, "Micromachined injector for DNA mass spectrometry," in Proc. Transducers '99, 1999, pp. 1130-1133.

[5] G. Perçin, T. S. Lundgren, and B. T. Khuri-Yakub, "Controlled ink-jet printing and deposition of organic polymers and solid-particles," Appl. Phys. Lett., vol. 73, no. 16, pp. 2375-2377, Oct. 19, 1998.

[6] G. Perçin and B. T. Khuri-Yakub, "Piezoelectrically actuated flextensional micromachined ultrasound droplet ejectors," in IEEE Trans. Ultrason., Ferroelect., Freq. Contr., vol. 49, no. 6, pp. 756-766, June 2002.