Micromachined Piezoelectrically Actuated Flextensional Transducers For High Resolution Printing And Imaging

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Abstract - In this paper, we present a technique for the deposition of inks, toners, organic polymers, fuels, small solid particles, biological and chemical fluids, using a fluid ejector. The ejector design is based on a flextensional transducer that excites the axisymmetric resonant modes of a clamped circular plate. It is constructed by depositing a thin piezoelectric annular plate onto a thin, edge clamped, circular plate. Liquids or solid-particles are placed behind one face of the plate which has a small orifice at its center. By applying an ac signal across the piezoelectric element, continuous or drop-on-demand ejection of fluids has been achieved. The ejected drop size ranges in diameter from 4 µm at 3.5 MHz to 150 µm at 7 kHz, the corresponding ejected drop volume ranges from 34 fl to 1.5 nl, and the corresponding flow rate ranges from 117 nl/s to 10 µl/s. 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. The device is manufactured by silicon surface micromachining and implemented in the form of two-dimensional arrays. Individual elements are made of thin silicon nitride membranes covered by a coating of piezoelectric zinc oxide. Classical thin plate theory and Mindlin plate theory 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 two different solutions to the corresponding systems. An equivalent circuit of the transducer is also obtained from these solutions.

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.

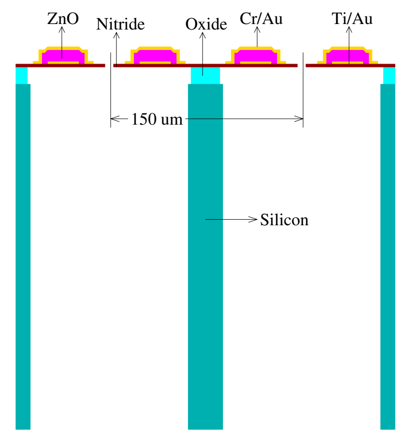


Figure 1: Side view of two adjacent elements of the developed micromachined two-dimensional array of ejectors

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 4 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.

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, since only a thin piezoelectric film is driven. Furthermore, the device can readily be scaled to an array of more than 10,000 ejectors per 1 cm^2.

II. Large Scale Prototype

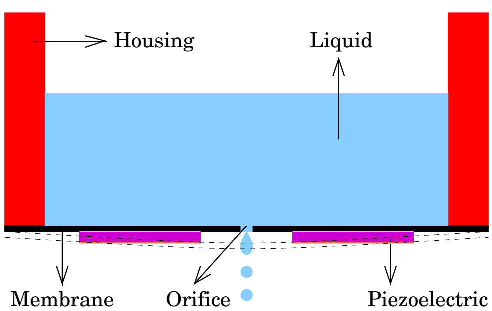


Figure 2: A schematic of the large-scale prototype ejector: the lateral extent is 9 mm

Earlier, we developed a technique for the deposition of inks, organic polymers and solid-particles[5]-[7], using the large-scale prototype fluid ejector shown in Fig. 2. The ejector uses a flextensional ultrasound transducer that excites axisymmetric resonant modes in a clamped circular plate. It is constructed by bonding a thin piezoelectric annular disk to a thin, edge clamped, circular plate. Liquids or solid-particles are placed behind one face of the membrane that has a small orifice (50-200 µm diameter) at its center. By applying an ac signal across the piezoelectric element, continuous or drop-on-demand ejection of water (Fig. 3), photoresist (Fig. 4), oil-based ink, and talcum powder (Fig. 5) is achieved. Successful deposition of photoresist was accomplished without spinning, and thus without waste. Patterning of 10 µm features, by baking, exposure and developing, revealed no defects in the deposition process.

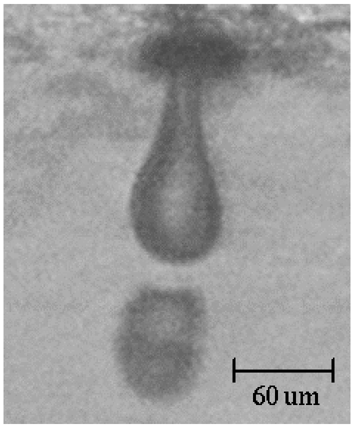


Figure 3: Water droplet ejection through 60µm diameter orifice by using the large-scale device

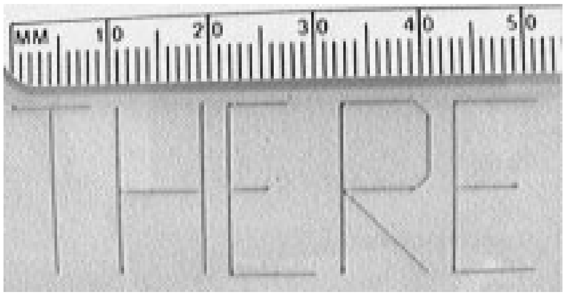


Figure 4: Drop-on-demand direct write with photoresist by using the large-scale device: the lines are 350 µm wide

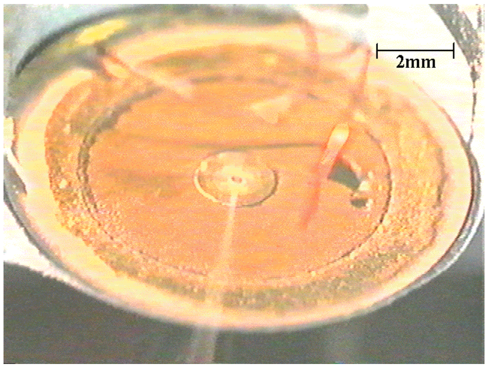


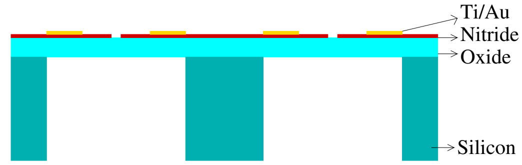
Figure 5: Small solid particle ejection through 150 µm orifice at 2.9 kHz

III. Device Fabrication

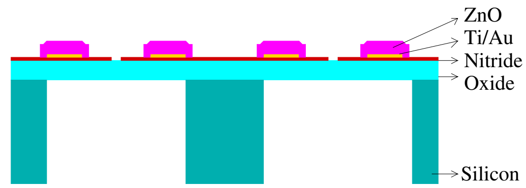
The fabrication process for the micromachined two-dimensional flextensional ejector arrays is given in Fig. 6. The process starts with growing a sacrificial layer, chosen to be silicon oxide (LTO). A non-piezoelectric carrier plate layer of LPCVD silicon nitride is grown on top of the sacrificial layer. Ejection holes are patterned in the silicon nitride carrier plate layer at the front surface of the wafer by plasma etching. Later, 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 RIE until reaching the sacrificial silicon oxide layer at the front surface. Because of the material compatibility with the RIE equipment, we have to choose to etch the backside 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 non-piezoelectric carrier plate by e-beam evaporation at relatively high temperature. 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. 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 zinc target. The deposition is made in an argon-oxygen ambient with a substrate at relatively high temperature. 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.

Growing 2.2 microns LTO
Growing 0.25 microns LPCVD silicon nitride

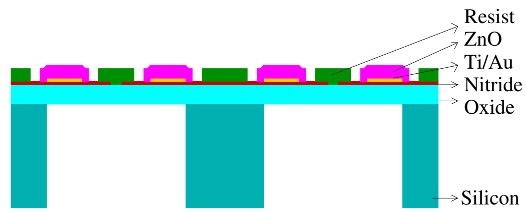
Patterning 8 microns holes in the nitride by dry etch
Etching 100 microns holes from the back side of the wafer by DRIE



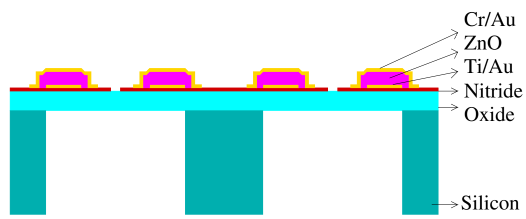
E-beam evaporation of 0.1 microns hot Ti/Au bottom electrode
Patterning Ti/Au bottom electrode by wet etch



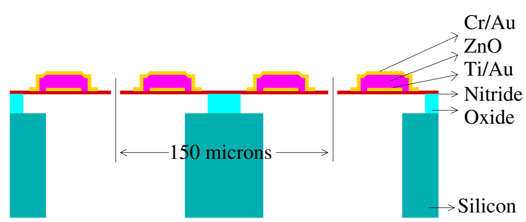
DC planar reactive magnetron sputtering of 0.4 microns ZnO
Patterning the ZnO layer with wet etch



Patterning photoresist layer for top electrode layer liftoff



Patterning e-beam evaporated 0.1 microns Cr/Au top electrode layer by liftoff



Etching the sacrificial LTO layer by wet etch

Figure 6: Developed micromachined device process flow

IV. 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[7]. 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.

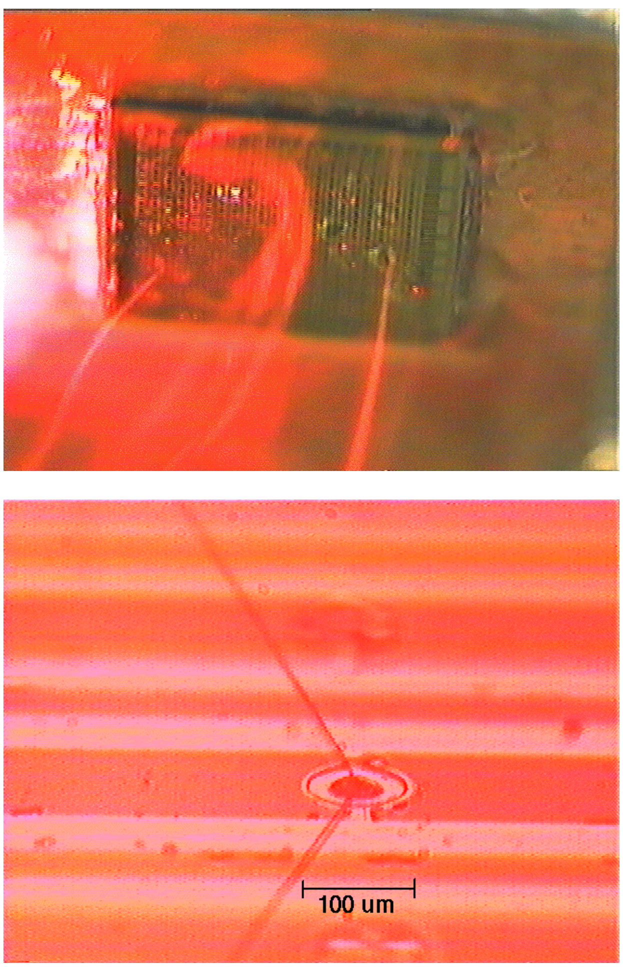


Figure 7: Water ejection by using a micromachined fluid ejector, 3.5 millions 4 µm diameter water droplets per second are ejected

Fig. 7 shows the water ejection thru 5 µm diameter orifice by using the realized prototype micromachined device that has been developed for pulmonary drug delivery applications (where all of the array elements are ejecting the same fluid), and individual array elements are 100 µm in diameter.

V. Conclusion

In summary, a novel fluid and solid particle ejector that can be used as cost-effective miniaturized sample preparation module is designed and demonstrated, 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 models that was developed.

VI. References

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