# Piezoelectrically Actuated Transducer and Droplet Ejector

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*Abstract*— **This paper presents a variation on the design of a flextensional transducer that can be used to generate sound in air or water. By placing a fluid behind one face of the transducer, and an orifice in the center, a drop of the fluid can be ejected on demand, and for every cycle of transducer excitation. We report on an optimum design for the transducer based on finite element modelling, and we present results of ejection of water, ink, powder, and photoresist. We coat silicon wafers with photoresist with minimum waste, a very costly and expensive step in integrated circuit manufacturing. The ejector is harmless to sensitive fluids and can also be used to eject fuels, chemical and biological samples.**

## I. Introduction

VARIOUS kinds of droplet ejectors for ink jet printing have been reported in the literature, [1]. However, up to this time none of these has the potential for fabrication by silicon micromachining techniques in two-dimensional arrays. Some are also incompatible and harmful to sensitive fluids. Micromachining is necessary for high resolution and speed. Because of that, such improvements in ink jet printing technology strongly depend on the development of micromachined two-dimensional fluid ejector arrays. The novel ejector we developed is amenable to planar silicon micromachining in two-dimensional arrays. The ejector is harmless to sensitive fluids and can be used in high speed, high flow rate applications. We have demonstrated, in a scale model, ejection of low viscosity water based ink, powder, and photoresist. Because of the drop-on-demand nature of the printer, we anticipate its use in direct write applications where features are a few microns in lateral dimensions, ie. Micro Electromechanical Systems (MEMS).

## II. Device Schematic

A schematic of the proposed device is shown in Figure 1. A thin shim with a small orifice is attached to a piezoelectric ring. A cylinder is attached to the shim to serve both as a fluid reservoir and to clamp the ends of the compound membrane formed of the shim and piezoelectric. A small voltage is applied to the membrane and sets it into vibration. At the resonant frequencies of the fluid loaded compound membrane, the displacement in the middle is large. The fluid behind the orifice is accelerated as the membrane is moving, and when the inertial force is larger than the surface tension force that holds it to the orifice, a drop will be ejected from the orifice. The size of the drop, and its initial speed are a function of the size of the orifice and the energy applied to the transducer at the frequency of operation.

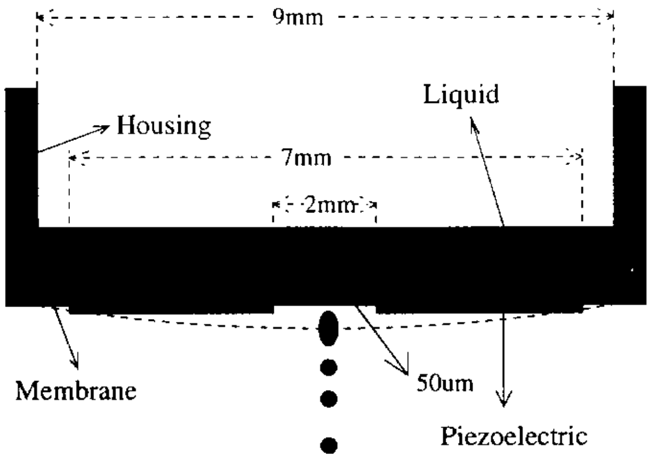


Fig. 1. A schematic of the proposed device.

## III. Design Parameters

We design the transducer to have a maximum displacement at the center of the membrane at the resonant frequency. Analyses of similiar devices such as those of Allaverdiev [2], Vassergiser [3], Okada [4], and Iulo [5] are helpful in giving a general trend for the design. However, the complexity of the structure and the fact that the piezoelectric we use is a ring rather than a full disk, necessesitates the use of finite element analysis to determine the resonant frequencies of the structure, the input impedance of the transducer, and the normal displacement of the surface.

It is well known that the transverse displacement $\xi$ of a membrane of uniform thickness obeys the following differential equation:

$$\nabla^4 \xi + \frac{\rho}{D}\frac{\partial^2 \xi}{\partial t^2} = 0 \quad (1)$$

Axisymmetric free vibration frequencies for edge clamped circular membrane are given by,

$$\omega = \frac{\lambda^2}{a^2\sqrt{\frac{\rho}{D}}} \quad (2)$$

where $\lambda$ represents the eigenvalues of Equation (1), $a$ the radius, $\rho$ the mass per unit area of the membrane and,

$$D = \frac{Eh^3}{12(1-\nu^2)} \quad (3)$$

where $E$ is Young's modulus, $h$ is the membrane thickness, and $\nu$ is Poisson's ratio.

The above equations suggest that the resonance frequency is proportional to the thickness of the membrane, and inversely to the square of the radius. However, we also know that the resonant frequency will be decreased by fluid loading on one or both sides of the membrane. The shift in the fluid loaded resonant frequency is given by Kwak [6],

$$f_w = \frac{f_o}{\sqrt{1+\beta\Gamma}} \quad (4)$$

where $\beta = \rho_w a / q_m h$ is thickness correction factor and $\rho_w$ is the density of water, $a$ is the radius of the circular membrane, $\rho_m$ is the mass density of the circular membrane, $h$ is the thickness of the circular membrane, and $\Gamma$ is the non-dimensional added virtual mass incremental (NAVMI) factor which is determined by boundary conditions and mode shape. With fluid loading, we expect the resonant frequency to shift down by 52% for one of our devices.

## IV. ANSYS Simulation

As mentioned before, because of the complex nature of the device, finite element analysis (FEA) were used to simulate the device. We use ANSYS, a finite element analysis commercial code to find the resonant frequency and displacement for our transducer. Figures 2,3, and 4 show typical results of such an analysis. The DC displacement is 1.48$\mu$m/V. The first resonance frequency is 2.604kHz and the second resonance frequency is 12.05kHz. The dimensions of the piezoelectric are: 2mm inner diameter, 7mm outer diameter, and 25$\mu$m thickness. These parameters give the maximum displacement at the center of the membrane at a resonance frequency of 2.604kHz. A number of iterations were used to determine this optimum design for the piezoelectric element. The membrane thickness and material were chosen from existing and easily available materials.

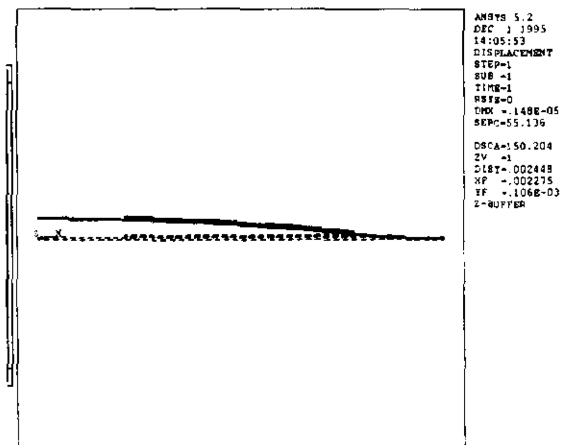


Fig. 2. ANSYS simulation for the DC displacement of the device.

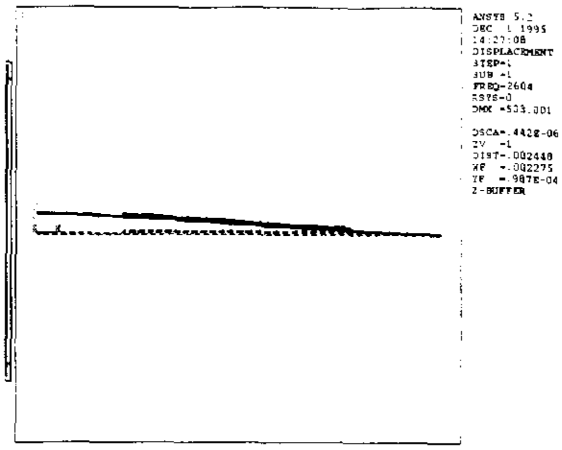


Fig. 3. ANSYS simulation for the first resonance frequency of the device.

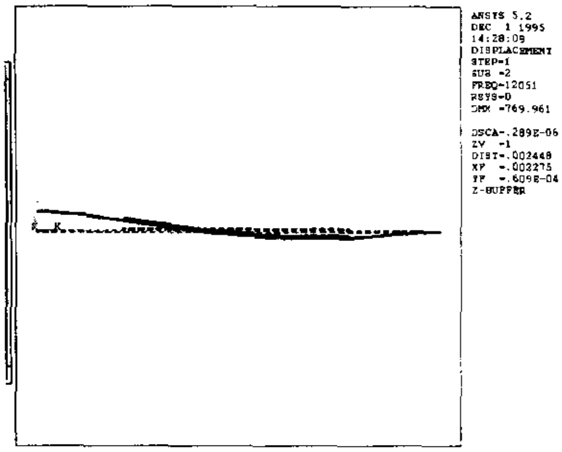


Fig. 4. ANSYS simulation for the second resonance frequency of the device.

## V. Device Fabrication

The scale model of the device was fabricated using piezoelectric material made by MURATA [7] and a membrane of brass. The reservoir was also made of brass. The dimensions of the device shown in Figure 1 are: 9mm diameter of brass shim, 25$\mu$m thickness of brass shim, 2mm inner diameter of MURATA PZT, 7mm outer diameter of MURATA PZT, 25$\mu$m thickness of MURATA PZT, and the reservoir height was 8mm. The orifice ranged in diameter from 50$\mu$m to 200$\mu$m. It was made using a drill in a small lathe. The measured resonance frequency of the device by fluid loading was 1.2kHz which is in aggrement with our model prediction (ANSYS plus water loadind equation reduction in resonance).

## VI. Experiments

Two transducers were used in air to generate and receive sound. The transducers were placed in a vacuum station and the amplitude of the transmitted signal was measured as the pressure was reduced from atmospheric pressure. We found that the signal decreased from 890mV at atmospheric pressure (190$\mu$m displacement at the center) to 24.4mV at 65mTorrs where the signal was at the same level as the electromagnetic feedthrough. A better detection scheme would allow us to measure lower pressures.

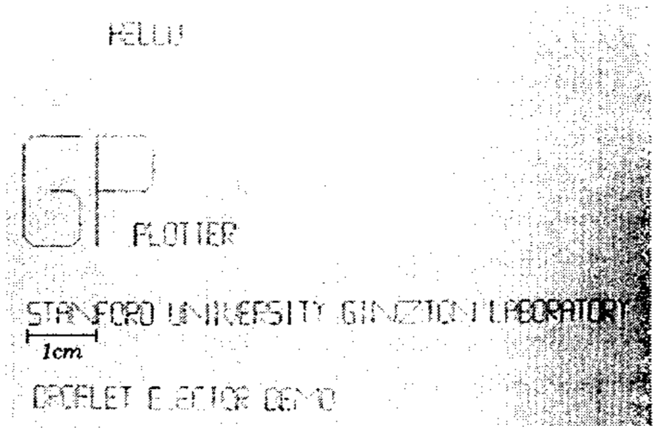


Fig. 5. Drop-on-demand ink jet printing sample.

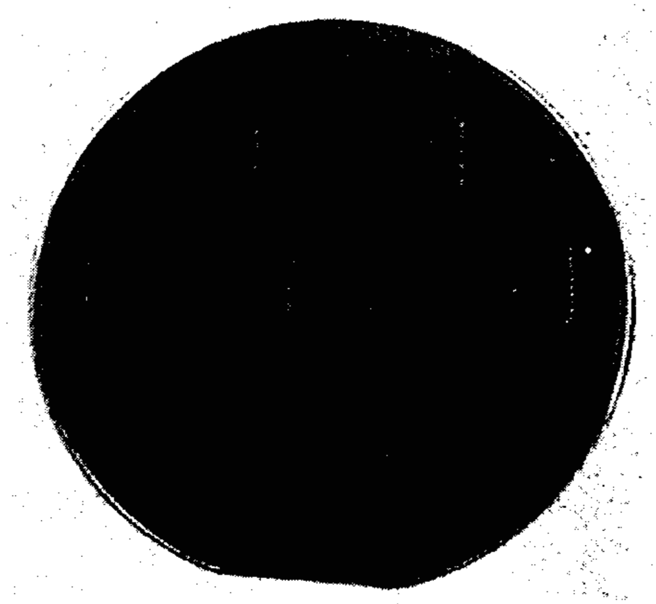

Fig. 6. Photoresist covered 3" wafer.

Low viscosity water based ink was ejected at 7.93kHz, 16.5kHz, and 31.9kHz using membranes with orifices of 50$\mu$m and 100$\mu$m. The ejector was placed above a white piece of paper that was scanned synchronously under the ejector. In the drop-on-demand mode, the ejector was turned on and off to write preprogrammed words such as shown in Figure 5.

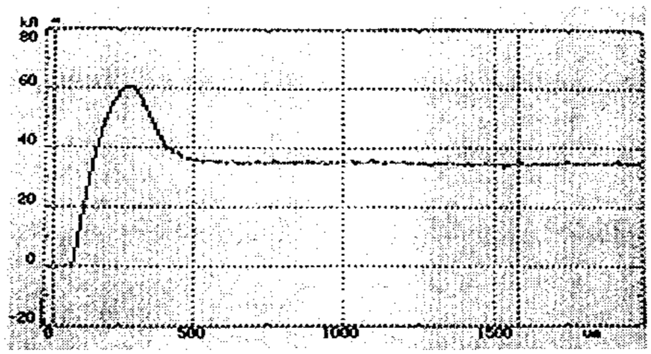


Fig. 7. Photoresist thickness measurement of the pattern in Fig. 6.

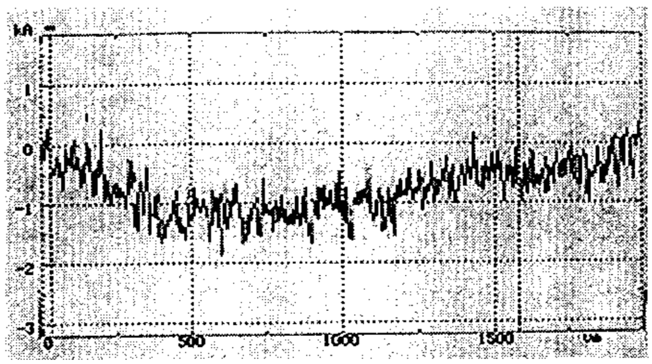


Fig. 8. Photoresist thickness variation of the pattern in Fig. 6.

Shipley 1400-27 photoresist was also ejected using the ejector. Figure 6 shows different patterns of coating of a 3" silicon wafer. The resist is 3.5$\mu$m thick and has a surface roughness of about 0.15$\mu$m. Figures 7 and 8 shows thickness profiles of the photoresist deposited in Figure 6. To obtain this thickness profile, we applied 108V amplitude sinusoidal tone burst with 2 cycles per burst. Each spot on the wafer was 540$\mu$m in diameter. To overlap the spots on the wafer, and obtain the profile of Figure 7, we synchronized the scanning and the ejector set for an overlap of 3%. The resist coating was done in a dry lab and contains dust particles, and nonuniformity due to the quick evaporation of the solvent in the resist. This drying results in nonuniformity as the wafer is coated. Using a chamber with solvent saturated environment will alleviate both problems of dirt incorporation and nonuniformity.

## VII. Conclusions

We have developed a novel ejector which can be silicon micromachined into two-dimensional arrays. The ejector is based on using a variation of a flextensional transducer. The transducer design was optimized using finite element analysis. And the ejector was demonstrated with water, ink, powder, and photoresist.

## Acknowledgments

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