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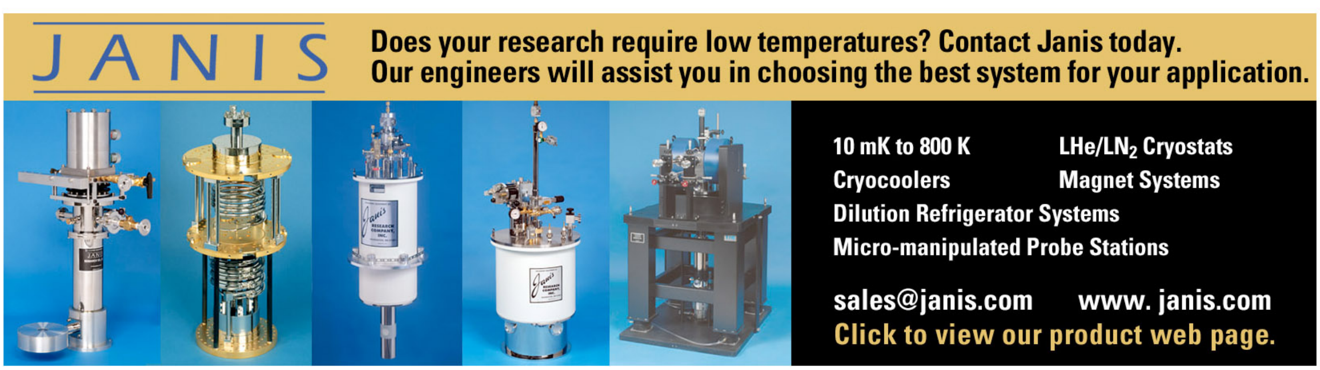

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Piezoelectrically actuated droplet ejector

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This article presents a novel piezoelectric fluid ejector that is based on a variation of the design of a flextensional transducer that excites axisymmetric resonant modes in a clamped circular membrane. The transducer is made by bonding a thin piezoelectric ring to a thin, fully supported, circular membrane. The transducer design is optimized for maximum flexure at the lowest order resonant frequency using finite element modeling. The fluid ejector is formed by placing a fluid, at atmospheric pressure, behind one face of the membrane and an orifice in its center. We achieve continuous or drop-on-demand ejection of the fluid by applying the appropriate voltage to the piezoelectric transducer. We present results of ejection of water, ink, powder, and photoresist. The application of photoresist with minimum waste on silicon wafers is one of the motivations for developing this device. In present applications, over 95% of the photoresist is wasted and has to be disposed as a toxic material, thus making this one of the more expensive steps in integrated circuit manufacturing. The ejector is harmless to sensitive fluids and can also be used to eject fuels, chemical and biological samples. The ejector configuration is unique in that it can be implemented using silicon micromachining as a microelectromechanical system, thus allowing the manufacture of true two-dimensional arrays of ejectors. © *1997 American Institute of Physics.*
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I. INTRODUCTION

Various types of droplet ejectors for ink jet printing have been reported in the literature.[1] None of the existing ejectors, however, have the potential for being fabricated by planar silicon micromachining techniques in true two-dimensional arrays. Some are also incompatible with and harmful to sensitive fluids. We propose a novel ejector which overcomes the limitations of existing ejectors. The ejector is harmless to sensitive fluids and can be used at high speeds (MHz range) in high flow rate (up to 100 mL/s range) applications with multiple devices. 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 ejector, we anticipate its use in direct write application of photoresist where features are a few microns in lateral dimensions.

II. SCALE DEVICE

A schematic of the novel ejector is shown in Fig. 1. A thin shim with a small orifice is bonded 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. The reservoir is open, and the fluid is at atmospheric pressure. An ac voltage is applied to the membrane to set it into vibration. At the resonant frequencies of the fluid loaded compound membrane, the displacement in the center 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 is ejected from the orifice. The size of the drop and its initial speed depend on the fluid, the size of the orifice, and the energy applied to the transducer at the frequency of operation. A unique feature in the device is that the fluid is unpressurized, and the vibrating membrane also has the orifice for the ejection. Thus, the device can be manufactured by surface micromachining and is amenable for implementation in two-dimensional arrays. Indeed, a silicon micromachined version of the device is presently under development in our laboratory.

We design the transducer to have a maximum displacement at the center of the membrane at the resonant frequency. Analyses of similar devices such as those of Allaverdiev *et al.*,[2] Vassergiser *et al.*,[3] Okada *et al.*,[4] and Iulo *et al.*[5] are helpful in identifying the important parameters of the device. However, the complexity of the structure and the fact that the piezoelectric we use is a ring rather than a full disk necessitate 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.

III. THEORY

It is well known that the transverse displacement ξ of a simple membrane of uniform thickness, in vacuum, obeys the following differential equation:[6]

$$\nabla^4 \xi + \frac{\rho}{D}\frac{\partial^2 \xi}{\partial t^2} = 0. \tag{1}$$

The axisymmetric free vibration frequencies for an edge-clamped circular membrane are given by

$$\omega = \frac{\lambda^2}{a^2\sqrt{\rho/D}}, \tag{2}$$

where λ represents the eigenvalues of Eq. (1), a is the radius of the membrane, ρ is the mass per unit area of the membrane, and

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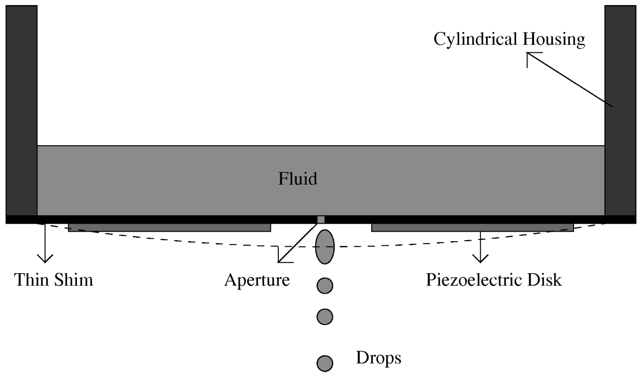

FIG. 1. A schematic of the proposed device.

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

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

The above equations suggest that the resonant frequency is directly proportional to the thickness of the membrane and inversely proportional to the square of the radius. However, it is also known 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 of a simple membrane is shown by Kwak[7] to be

$$f_w=\frac{f_a}{\sqrt{1+\beta\Gamma}},\qquad(4)$$

where $\beta=\rho_w a/\rho_m h$ is a thickness correction factor, ρ_w is the density of the liquid, ρ_m is the mass density of the circular membrane, and Γ is the nondimensional added virtual mass incremental (NAVMI) factor, which is determined by boundary conditions and mode shape. For the first-order axisymmetric mode and for water loading on one side of the membrane, Γ is 0.746313. Assuming the composite will behave similarly to the single membrane, we expect the resonant frequency to shift down by 52% for one of our devices.

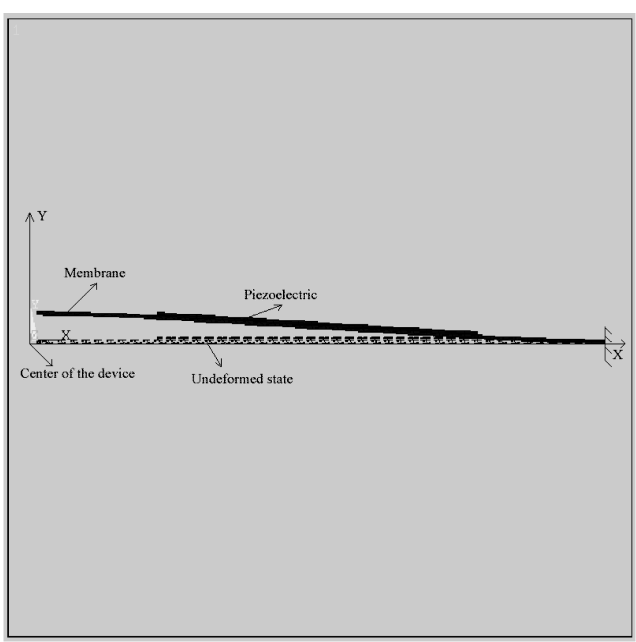

FIG. 2. ANSYS simulation for the first resonance frequency of the device.

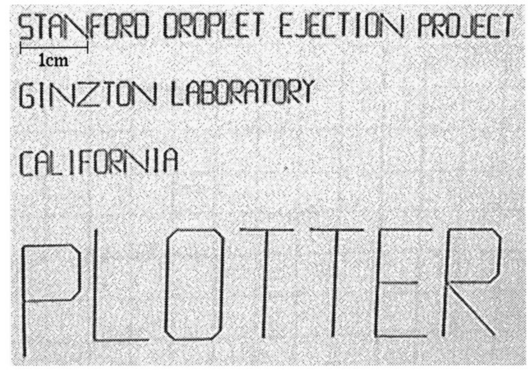

FIG. 3. Drop-on-demand ink jet printing sample.

IV. DESIGN AND MODELING

We use ANSYS, a finite element analysis commercial code, to find the resonant frequency and displacement of the composite transducer in vacuum. We use a brass shim and a piezoelectric material made by Murata.[8] The piezoelectric was chosen because it retains its properties when polished to a thickness of 25 μm, whereas the shim was chosen because it is easily available. Several iterations were run to maximize the displacement of the membrane as a function of the dimensions of the piezoelectric ring. Maximum displacement is obtained when the piezoelectric ring has an inner diameter of 2 mm and outer diameter of 7 mm, for a brass shim with a diameter of 9 mm. Figure 2 shows a typical result of the finite element analysis; namely, the vertical displacement of the membrane as a function of radial position. The dc displacement at the center is 1.48 μm/V, and the first two axisymmetric resonant frequencies are at 2.604 and 12.05 kHz.

V. EXPERIMENT

Scale model devices were fabricated using the optimum configuration described earlier. The reservoir was made of brass with a height of 8 mm. A 25-μm-thin shim was bonded to the 25-μm-thick piezoelectric ring. The inner and outer diameters of the ring were 2 and 7 mm, respectively. The orifice ranged in diameter from 50 to 200 μm and was made using a drill in a small lathe. The measured resonant frequency of the device was 2.5 kHz in air and 1.2 kHz with fluid loading on one side. Both resonant frequencies are in agreement with the model prediction.

The scale model devices were first tested as simple air transducers. Two transducers were set to transmit and receive sound as a function of pressure inside a vacuum station. This test was carried out to highlight the efficiency and sensitivity of the transducers. We found that the signal decreased from 890 mV at atmospheric pressure (190 μm displacement at the center) to 24.4 mV at 65 mTorr, where the signal was at the same level as the electromagnetic feedthrough. Thus, the transducer performed quite efficiently, and a better detection scheme would allow us to use these devices as vacuum gauges in the atmospheric to 1 mTorr pressure range.

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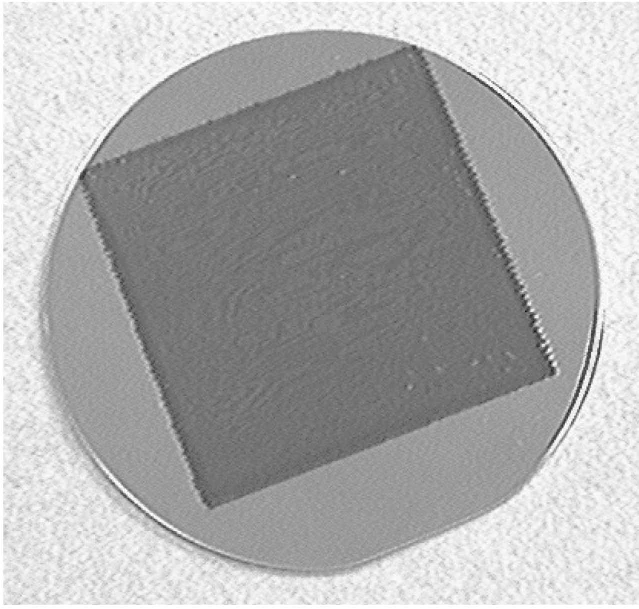

FIG. 4. Photoresist covered 3 in. wafer.

Next, low viscosity water based ink was ejected at 7.93, 16.5, and 31.9 kHz using membranes with orifices of 50 and 100 μm and with a voltage of 32 V peak to peak. 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 Fig. 3.

Shipley 1400-27 photoresist was also ejected using the ejector under the conditions described in the previous section but with a voltage of 200 V peak to peak. Figure 4 shows a square coating of a 3 in. silicon wafer. The resist is 3.5 μm thick and has a surface roughness of about 0.15 μm. 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 a solvent saturated environment will alleviate both problems of dirt incorporation and nonuniformity.

VI. DISCUSSION

In summary, 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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