Pulsed Ultrasonic Actuation of Polysilicon Surface Micromachines

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ABSTRACT

We report on the use of ultrasonic pulses for actuation of surface micromachined devices. The pulses were generated by an attached piezoelectric PZT plate making the method suitable for IC-packaged structures. In this paper we investigate the effect of different parameters on the actuation: pulse width and amplitude, ambient pressure and size of the micromachines. Applications for the pulse actuation method include assembly and release of stuck micromachines.

INTRODUCTION

Various actuation methods have been investigated for surface micromachines: electrostatic, thermal, magnetic, and piezoelectric. Magnetic actuation has not gained popularity due to difficulties in fabricating coils with planar processing. Piezoelectric thin films are attractive because they can generate large forces even at micron scale. Unfortunately they require special processing that can be costly and conflict with other processes used in fabrication. Hence, electrostatic and thermal actuation has proven to be the most popular of these alternatives.

Our approach has been to use piezoelectric bulk PZT (Lead Zirconate Titanate) plates mounted at the back of a silicon die to actuate surface micromachines [1]. The PZT plate is of similar shape and size as the die. The composite can be mounted in a standard IC package. Bulk PZT plates have previously been used to actuate bulk micromachined devices such as silicon based ultrasonic surgical tools [2] and micromachined pumps [3]. Since the PZT plate is mounted after the device processing, the actuation method is suitable for micromachines from any fabrication process. Also, in the case of surface micromachines, no die surface real estate is consumed by the actuator. This can give a significant cost advantage over electrostatic actuation where the actuator often consumes more surface real estate than the parts actually being actuated.

The effect of ultrasonic pulses on surface micromachines is due to impact transfer from the moving die surface. The pulses are used to actuate surface micromachines such as hinged flaps and beams. The effect of pulse width, amplitude and pressure is identified. The pulse shape, duration, and magnitude affect the mechanism of actuation. The ambient pressure affects the drag forces on the micromachines.

ACTUATION THEORY

The stress pulse is generated at the back of the die using a PZT plate as shown in figure 1. As the pulse is reflected at the surface of the die, momentum is imparted on surface micromachines. This momentum is upwards, perpendicular to the die surface. However, side ways motion is also possible by generating pulses with spatial amplitude difference.

Our previous work indicates that we can generate surface particle velocities of order of

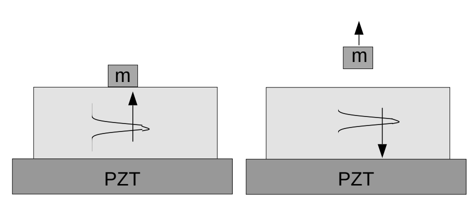

Figure 1: *Impact actuation of a micromachine.*

0.1 m/s [1]. Although this is quite large the parts will quickly slow down in atmospheric pressure due to the drag forces, which is a function of the Reynold's number. The Reynold's number is given by [6]

$$R = \frac{\rho L_c}{\mu} v, \tag{1}$$

where ρ is the density of air, L_c is the characteristic length, μ is viscosity and v is the velocity. Since for micron sized devices this is below 1000, we can use the theory of laminar flow to calculate the drag force:

$$F_{DRAG} = 1/2 C_D \rho A v^2, \tag{2}$$

where C_D is given by $C_D = 24/R$ and A is the area. We are interested in flaps so the area is given by $A = L \cdot W$, where L is the length and W is the width. Solving the Newton's equation

$$m \frac{\mathrm{d}v}{\mathrm{d}t} = F_{DRAG} + F_{GRAV} + F_{FRIC} \tag{3}$$

we get the distance traveled by the particles to be

$$s = \frac{m v_0}{12 \mu L}, \tag{4}$$

where v_0 is the initial velocity. The gravity and friction forces, F_{GRAV} and F_{FRIC}, have been neglected for simplicity. The impact coupling between the micromachines and the surface is not perfect and some energy is lost due to adhesion forces. If we assume that the the micromachines leave the surface at velocity that is 10% of the peak surface velocity we and use width and length of 100 μm, the plates will lift approximately 5 μm from the surface of the die. Due to this drag force most of the experiments were done in vacuum.

Experimental Setup

To demonstrate the actuation of surface micromachines, test structures were fabricated using the MCNC process. These structures were released with hydrofluoric acid and dried using a critical point dryer to prevent micromachines from sticking to the substrate during the release. The released dies were then mounted on a PZT plate using cyanoacrylate as shown in figure 2. After mounting the sample was placed in a vacuum chamber and the PZT was pulsed with the MOSFET circuit. The vacuum could be controlled with the pressure range of 60 mTorr to 700 Torr. The MOSFET circuit used with these experiments could generate pulses with the amplitude of 50-250 V and the rise and fall times of 25-30 ns.

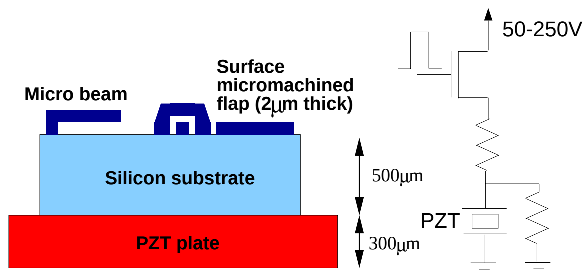

Figure 2: *A die with surface micromachines mounted on a PZT plate with MOSFET driving circuit.*

Experimental Results

In order to study the impact actuation on surface micromachines, the test structure shown in figure 3 was actuated. All flaps were 100μm wide, and the length was $78 - 528\mu$m. In the experiments, pulse width, amplitude and chamber pressure were varied.

Effect of the Pulse Width

The pulse width was varied between 50 ns to 10 μs at a pulse amplitude of 100 V and pressure of 80mTorr. Short, less than 600ns, pulses did not fully actuate the flaps although the flaps jiggled on the surface of the die. As the pulse width was increased to 800ns, the flaps started to bounce shown in figure 4. After this threshold, increasing the pulse width slightly enhanced the actuation with longer flaps also being lifted off the surface. However, increasing the pulse width beyond 2 μs had little or no effect.

To understand this behavior, we simulated the impulse response of the PZT-adhesive-silicon structure using finite-element time-domain simulation program [5]. The resulting surface displacement is plotted in figure 5 as a function of time for different excitation pulse widths. The displacement amplitude initially increases with increasing pulse width until it reaches maximum. After this pulse width, the displacement amplitude does not

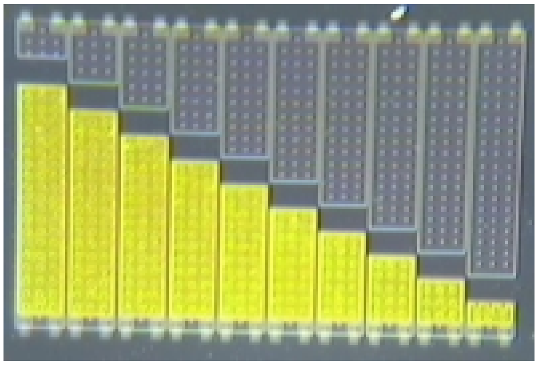

Figure 3: *Micromachined flap test structure*

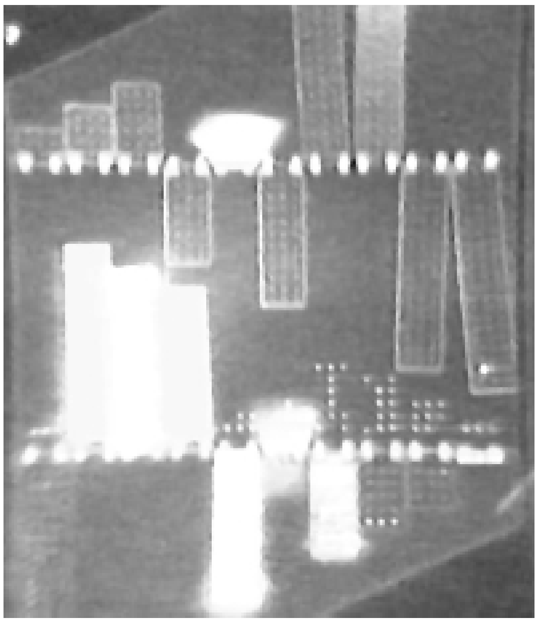

Figure 4: *Test structure being actuated*

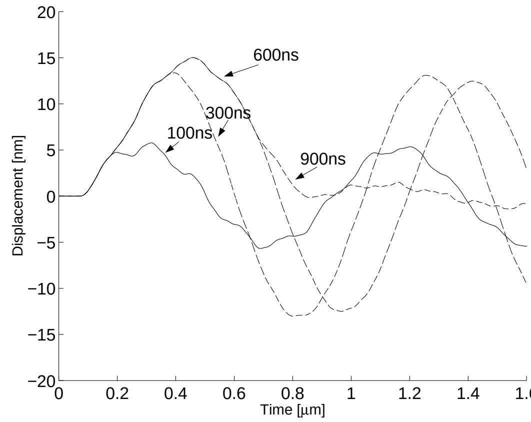

Figure 5: *Simulated surface displacement responce for different pulse widths.*

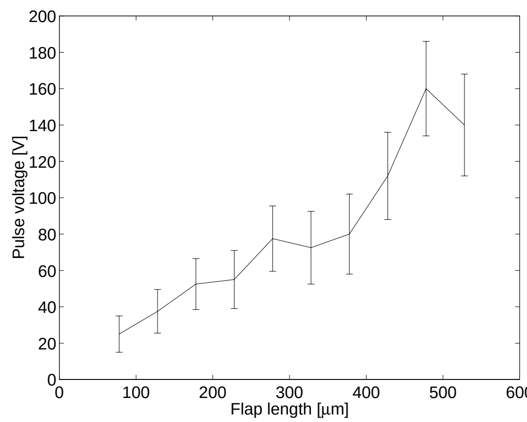

Figure 6: *Size dependancy of the actuation*

increase. The reason for this nonlinear behavior is that the PZT and silicon are weakly coupled with adhesive and it requires time for the energy to transfer from PZT to silicon.

Effect of the Pulse Amplitude

The pulse voltage was varied between 50 to 250 volts with constant pressure and a pulse width of 80 mTorr and 800 ns. Longer flaps required larger pulse voltages to flip over as indicated in figure 6.

Effect of Pressure

At room pressure the drag forces were too high and the flaps were not lifted. As the pressure was lowered, the flap motion increased. At pressure of 4-6 Torr the flaps could be fully raised. Lowering pressure below this point had little effect. Also, we did not observe significant difference on how pressure affected flaps of different sizes.

The pressure threshold can be correlated to the transition from viscous to molecular drag [9]. This transition happens because in low pressures the mean free path of gas molecules approaches the physical dimensions of devices. The transition pressure can be approximated using the theory of laminar flow in pipes. For tubes with diameter D the transition pressure in air is given by

$$P = \frac{6.7 \times 10^{-2}\text{Torr} \cdot \text{cm}}{D}. \qquad (5)$$

Equating the diameter D to the flap width of 100μm gives pressure of 6.7Torr which is in agreement with the observed threshold.

DISCUSSION

There are a number of interesting applications for die level pulse actuation. Parallel assembly of micromachines is perhaps most intriguing. Effort has been put into electrostatic and magnetic self assembly of micromachines [7, 4]. However, pulsed ultrasonic actuation is attractive because no special processing or on die motors are required. We can raise small flaps repeatedly to an upright position as shown in figure 7. These flaps will stay up even after the pulsing stops. Large, 500 μm, flaps can also be lifted up, but currently this is not controllable. However, it is possible to fabricate locking structures that will latch the structures in the desirable position.

Another possible application is to use the stress pulses to release stuck micromachines. Due to their large surface to volume ratio, the micromachines can become stuck if they become in contact with the surface of the die or other micromachines [8].

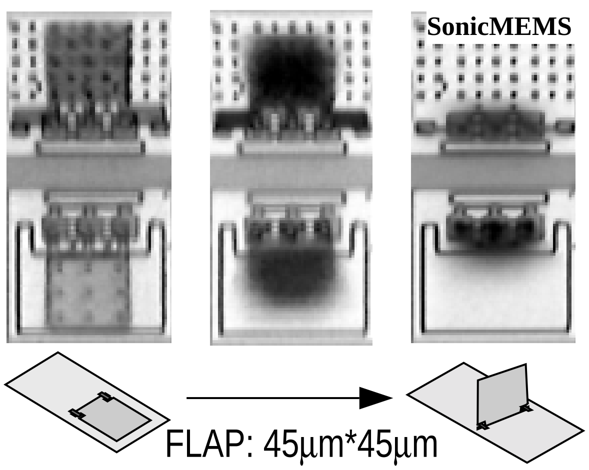

Figure 7: *Micromachined flaps being raised by ultrasonic pulsing (fabricated using MCNC-MUMPs).*

CONCLUSIONS

We have shown pulse actuation of surface micromachined structures. The effect of pulse parameters, device size, and pressure were investigated. It was shown that small flaps are easier to actuate while larger flaps require higher pulse voltages. There appears to be a threshold in pulse width and pressure for the actuation. These thresholds can be explained by resonant effects and transition from viscous to molecular drag respectively. Since the pulse is applied from the back of the die using a PZT-plate, the process is completely IC compatible. Bulk assembly is therefore possible without consuming any surface area.

ACKNOWLEDGMENTS

The authors acknowledge Mr. D. Christensen, Mr. D. Jones, and Ms R. Bauer of Wisconsin Center of Applied Microelectronics (WCAM) for technical support.

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