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Pulsed Ultrasonic Release and Assembly of Micromachines

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ABSTRACT

We report the first ever use of ultrasonic pulses for probeless release and mass actuation of micromachined devices. The pulses were created by a piezoelectric PZT (Lead Zirconate Titanate) plate, making the method suitable for packaged structures. Polysilicon beams 0.9μm thick, 15μm wide, 10-150μm long, and spaced by 1.3μm oxide were released from a stiction state. No dimples were used. We also actuated various surface micromachined parts including hinged structures and rotors. In this paper we will provide an analysis of plausible mechanisms for the observed phenomena and discuss implications for reliability and assembly of micromachines.

INTRODUCTION

Various stiction phenomena cause major problems in micromachined devices due to the micromachine's large surface to volume ratio. As parts are released, liquid forces can pull the devices to the surface of the die, where they get permanently stuck. Several methods for releasing microstructures have been developed, including dry release and self assembled monolayers (SAMs) [1]. A significant problem is in-use-stiction, where released micromachines get stuck. Often high voltages are required for speed and sensitivity in micromachined devices. These voltages can pull the released part to the surface where they get stuck. Various methods have been tried to overcome the problem including SAM and Lorentz force. The Lorentz force has been used to release stuck parts but this method requires an external magnetic field [2]. SAMs can reduce the problem but they may have a degrading effect on the device performance. Furthermore, they wear out over time. A method to re-release stuck micromachined parts is therefore of significant interest.

Assembly of large arrays of surface micromachines is another challenge in commercializing MEMS technology. Series assembly is too slow and costly. On chip robots have been used but they consume valuable surface area [4]. Ultrasonic vibration has been used to overcome friction and shake parts around for assembly [5]. Liquid forces have been used for assembling GaAs lasers on silicon die [3]. However, the ultrasonic vibration and liquid assembly offer little directional control. Also, the use of liquid forces might not be suitable for surface micromachined parts due to surface tension and stiction effects.

Here we present results of applying ultrasonic pulses to the surface of silicon dies. These pulses were used to release and actuate surface micromachines. The pulses were generated by using a back-mounted PZT-plate of similar shape and size as the die. Unlike previous uses of ultrasonic shaking, the pulses were incident to the surface of the die. Also, since we used discrete pulses instead of continuous vibration, we had more control over the applied forces. This method is suitable for re-releasing stuck micromachines that are already packaged and can thus greatly improve the reliability of micromachines. We also successfully actuated several micromachines. It is possible to move micromachined parts in a desired direction by design or by applying a pulse that has an amplitude variation across the die. In addition to horizontal motion, it is possible to have micromachined parts to pop up. An analysis of two mechanisms of release and actuation are presented: spalling and ultrasonic impact. Spalling occurs when a wave is reflected at the front surface of the die producing tensile stress on the stuck parts. Impact coupling occurs when moving the surface of die exerts force on the released micromachined parts.

ANALYSIS OF ULTRASONIC RELEASE AND ACTUATION

Spalling

Spalling can occur when an initially compressive ultrasonic pulse is reflected at a free surface. Since there cannot be any stress at the free surface, the compressive wave is reflected, producing a tensile wave that cancels the compressive wave at the surface as shown in figure 1.

The sum of the reflected and incident waves produces a tensile stress beneath the surface. This stress reversal has been used in characterizing pulses by attaching small pellets at the end of rods with a grease interface [6]. The compressive pulse propagates through grease and is reflected at the free surface of the pellet. Since the grease cannot sustain the tensile stress, the pellet flies of due to the incident wave momentum. Spalling has also been considered for mining purposes [7]. The idea is that the shock waves would cut off pieces of rock to flatten mountains.

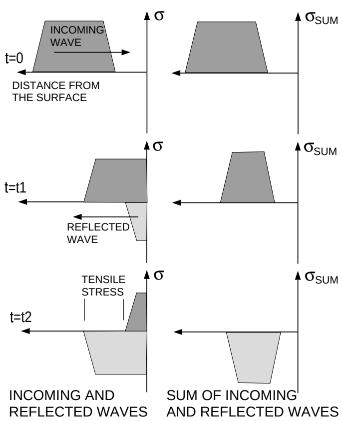

Figure 1. *Reflected wave produces tensile stress under the surface.*

The stress wave was generated by using a PZT-plate at the back of the wafer. To obtain significant tensile stress beneath the surface, the pulse fall time has to be small and the incident stress magnitude has to be large. To optimize the generated pulse, we carried out an analytical derivation of the tensile stress magnitude beneath the surface.

The maximum stress we can generate is given by

$$\sigma_{MAX} = d_{33} Y \frac{V}{T_{PZT}}, \tag{1}$$

where d_{33} is the piezoelectric constant, Y is Young's modulus, V is the voltage at the PZT electrodes, and T_{PZT} is the thickness of the PZT. The fall time t_{FALL} is determined by the PZT capacitance C and the discharge current I:

$$t_{FALL} = \frac{CV}{I} = \frac{\varepsilon_{PZT} A}{T_{PZT}} \frac{V}{I}. \tag{2}$$

Here ε_{PZT} is the permitivity and A is the area for the PZT.

The discharge current is assumed to be constant and is limited by the the power absorption of the driver. In our case this was 17 amperes. Since the distance L_{FALL} is figure 2 is related to time by $L_{FALL} = c_{Si} t_{FALL}$, where c_{Si} is the silicon speed of sound, we can express for the stress at point x as

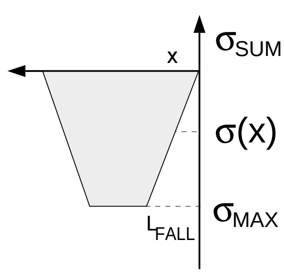

Figure 2. *Wave after it has fully reflected.*

$$\sigma(x) = \sigma_{MAX} \frac{x}{c_{Si} t_{FALL}} \tag{3}$$

Substituting equations (1) and (2) into equation (3) we get

$$\sigma(x) = \frac{d_{33} Y I}{c_{Si} \varepsilon_{PZT} A} x. \tag{4}$$

It is interesting to note that the stress does not depend on the thickness of the PZT but on the maximum current drive of the circuit. For the optimum performance the PZT should have a large piezoelectric coefficient and low permitivity.

To show plausibility of spalling using PZT we carried out finite-element time-domain simulations using commercial software (PZFlex [8]) that is designed to model ultrasonic and piezoelectric effects. The actual measured voltage pulse generated at the PZT electrodes was used for the simulations. Figure 3 a shows a typical pulse. We believe that parasitic capacitances and inductances in addition to PZT self resonances caused the fine features in the pulse. Even with relatively long rise and fall times we could achieve stress levels of several kiloPascals beneath the surface. The data also indicates that thicker micromachines should be easier to release by spalling.

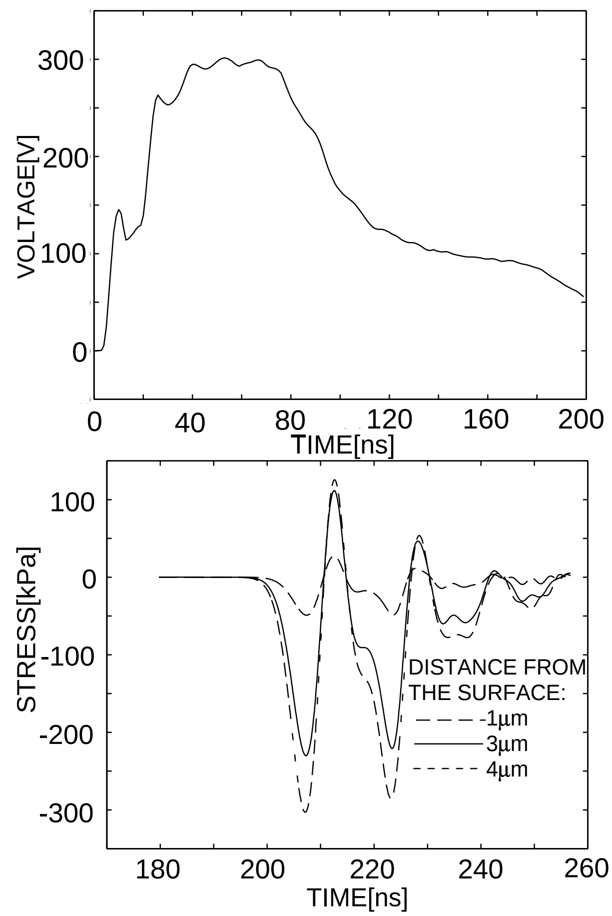

Figure 3. *Finite element time-domain simulation of the stress characteristics. A) Measured voltage pulse. B) Simulated stress response.*

Ultrasonic Impact Actuation

In the previous discussion we assumed that the micromachines were attached to the surface and the wave propagated into them. However, if the the part is released and only in contact with the surface, it moves with surface as long as the surface acceleration is positive. When the surface velocity has reached its maximum and starts retreating, the released part maintains maximum velocity and is in effect ejected (see figure 4).

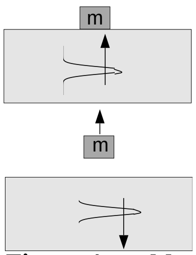

Figure 4. *Momentum transfer to surface micromachine.*

However, the part quickly slows down due to the air resistance. Solving Newton's equation

$$ma = -F_{DRAG} \tag{5}$$

we can get the approximate distance the part moves into air. If the Reynolds number is small (< 2000) the drag force in equation (5) is given by

$$F_{DRAG} = Bv, \tag{6}$$

where B is a constant and v is the part velocity. For spheres the constant B is

$$B = 12D\mu, \tag{7}$$

where D is the diameter and μ is the viscosity of air [9]. Our finite element simulations gave a peak surface velocity of 0.3m/s. The resulting distance traveled by an object with a diameter of 10μm, initial velocity 0.3m/s, and density 2030kg/m^3 is then

$$s = \frac{v_0 m}{B} \approx 100\mu\text{m}. \tag{8}$$

In this calculation we have neglected the gravity force since it is two orders of magnitude smaller that the initial drag force. The initial direction of the motion is upwards causing only vertical displacement of parts. However, we can also get sideways motion by creating pulses with a spatial amplitude gradients.

EXPERIMENTS ON SPALLING

Fabrication and Setup

To demonstrate the release of stuck micromachined structures we fabricated polysilicon beams on a silicon substrate. The silicon was deposited at 580^{o}C followed by 3 hour anneal at 600^{o}C [10]. A 100Å layer of gold was evaporated on the beams to minimize that electrostatic stiction effects. The substrate was then mounted on a PZT plate ($4mm \times 4mm \times 0.5mm$) by two different methods: adhesive bonding and by using a special packaging jig. For bonding we used cyanoacrylate The measured bond thickness was 2-10μm measured under a microscope. A schematic of the packaging jig together with the driving circuit is shown in figure 5. The jig has an advantage over the bonding because the silicon PZT sandwich can be precompressed for better coupling.

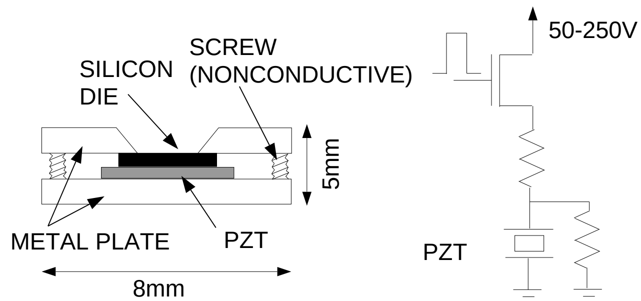

Figure 5. *Special packaging jig for mounting.*

Experiments

Our goal was to show that successfully released parts could be re-released if stuck again. Hence our first step was to release our beams and dry them in a critical point dryer. To simulate in-use-stiction discussed in reference [11], the beams were pushed on the surface of the substrate where they remained stuck. The beams could be repeatedly forced to stick and unstick by using a probe tip proving that the stiction was not electrostatic.

To test the spalling mechanism, the stuck beams were released by applying voltage pulses on the PZT. The pulse amplitude was varied from 50 volts and increased to as high as 250 volts. The results are shown in figure 6. The voltages in the figure indicate the voltage at which the beam was released. The release threshold seemed not dependent on the number of pulses applied – it was only dependent on voltage. The experiment was repeated for 8 samples with similar results. In each case all beams were successfully unstuck.

The release voltage did not depend on the beam length. This indicates that the release was really due to spalling since

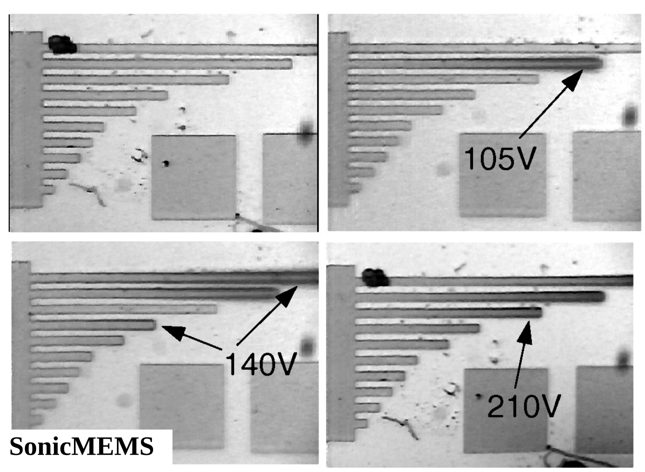

Figure 6. *Poly-beams before and after applying an ultrasonic pulse to release them.*

this effect is not dependent on shape or area of the stuck structure. It is possible to get an estimate of the bonding force by correlating the pulse voltage to the maximum simulated stress level in PZFlex as shown in figure 7. In the future we will measure the surface velocity using optical methods to verify the simulations.

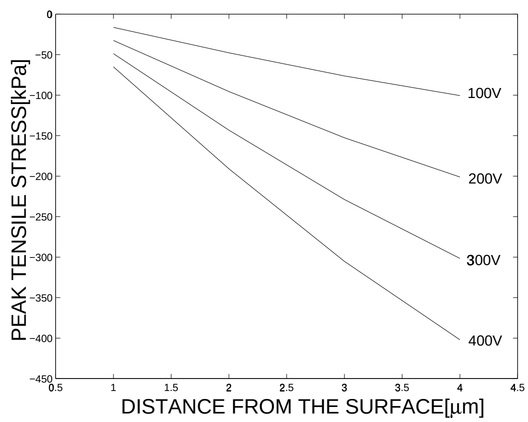

Figure 7. *Calculated maximum tensile stress for different pulse amplitudes.*

ACTUATION OF RELEASED STRUCTURES

In this section experiments on bulk actuation by pulsing are presented. We used the jig described in the previous section for optimum coupling. The PZT was pulsed using voltages between 100 and 400V.

The first first experiment was carried out in atmospheric pressure. We observed released parts moving on the silicon surface. In our experiment we did not have control over the direction that the parts would travel. However, it should be feasible to move parts in desired directions by applying pulses with amplitude gradient and/or possibly adding some constraints.

In the previous experiment the motion was mainly in spatial directions due to drag force. To reduce this force experiments were done in vacuum. This time we were able to lift hinged structures to an upright position as shown in figure 8. The parts stayed in the vertical position indefinitely.

CONCLUSIONS

We have shown the first ever use of ultrasonic pulses for release and actuation of micromachined devices. Since the pulse is applied from the back of the die using a PZT-plate the process is completely IC compatible. Using the demonstrated methods it is possible to re-release micromachined parts as necessary and thus improve the reliability of micromachined devices. The pulsing can also be used to actuate micromachines. Bulk assembly is therefore possible without consuming any surface area.

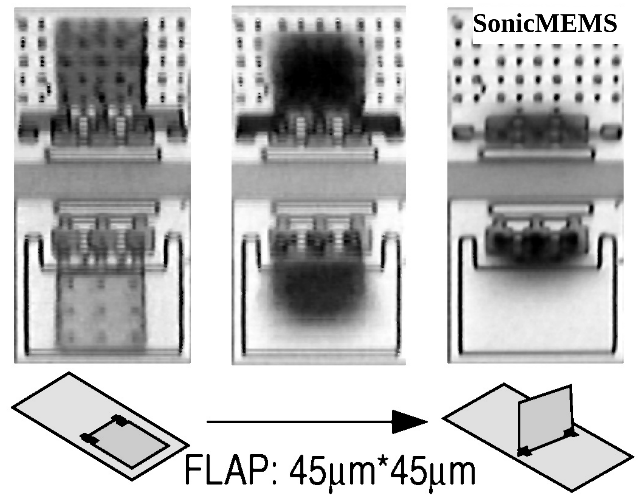

Figure 8. *Micromachined flaps being raised by ultrasonic pulsing (fabricated using MCNC-MUMP).*

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