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ELECTROSTATIC BATCH ASSEMBLY OF SURFACE MEMS USING ULTRASONIC TRIBOELECTRICITY

Ville Kaajakari and Amit Lal
Department of Electrical and Computer Engineering, University of Wisconsin Madison,
1415 Engineering Dr., Madison, Wisconsin, 53706
http://www.cae.wisc.edu/~sonicmem

ABSTRACT

In this paper we present a novel method for batch assembly of polysilicon hinged structures. The method uses ultrasonic vibrations generated with an attached piezoelectric actuator to vibrate polysilicon plates on silicon nitride or polysilicon surfaces. We believe that the rubbing between the substrate and the structures creates contact electrification charge that results in hinged flaps to be stabilized vertically on the substrate at elevated temperatures. Furthermore, the ultrasonic triboelectricity is shown to be the most likely explanation due to the observed "memory effect" in which assembly occurs even without further ultrasonic actuation after the initial ultrasonic assembly. This method has been used to batch assemble an array of hinged flaps, retroreflectors, and plates with retaining springs.

INTRODUCTION

This paper reports on the initial investigation and use of ultrasonic triboelectricity (frictional charging) to actuate and assemble polysilicon surface micromachines. In the past, different methods have been proposed for micromachine assembly. Two different approaches can be taken: 1. The micromachines can either be fabricated with a single process with the assembly being the final step. 2. The micromachine parts can be fabricated with multiple parallel processes with the final step of combining the parts from the different processes. Examples of the latter approach are the integration of GaAs lasers on matching silicon slots using fluid carriers [1], fluid assembly micromachines using shape matching and patterned self-assembled monolayers [2], and laser driven release of components from one wafer to the desired position on another wafer [3]. However, the economics and yield of polysilicon surface micromachining have made the integrated process approach more popular. For example several optical components (mirrors, diffraction gradings and Fresnel lenses) [4] and suspended RF inductors [5] have been made by folding or lifting surface micromachined polysilicon structures above silicon substrate enabling 3D structures. In this paper a new approach of using ultrasonic vibration induced triboelectricity to assemble polysilicon 3D structures is presented.

Several different assembly methods have been proposed for surface micromachines. The structures can be assembled manually using a probe tip, but due to the delicate nature of the structures and cost of manual assembly, more automated and economic solutions are being investigated. One way is to use on-chip electrostatic [6] or thermal actuators [7]. This is attractive especially if the resulting devices need to be actuated during the device operation. A major drawback is the large die surface areas consumed by the actuators. Other methods have been proposed that use special processing or external actuation forces. Thermal shrinkage of polyimide in V-grooves [8] and surface tension of wet solder [9] have been used to lift micromachined flaps to the upright position. External magnetic forces can be used to actuate surface micromachines either by passing current through them (Lorentz force) [10] or by depositing magnetic material on them [11]. Yet another approach is to use electro-chemical forces to assemble micromachined boxes in electrolyte solution [12].

The method presented here does not require special processing, nor does it consume any chip surface area. The ultrasonic pulses required to assemble the surface micromachines are provided from the back of the silicon die using a piezoelectric plate (PZT-4H, Lead-Zirconate-Titanate). We have previously reported on the use of stress pulses to release and actuate surface micromachined beams, flaps [13] and micromotors [14]. Since the actuation is done from the back of the die, no electrical connections to the front surface are required and interconnectless actuation of sealed micromachines is possible. In this paper we report on the use of similar Si/PZT composite but a different actuation principle to assemble and actuate polysilicon surface micromachines. Instead of using stress pulse momentum transfer, we use triboelectric charge generation for electrostatic actuation: The PZT plate is driven in the MHz range which cause the PZT, silicon substrate and polysilicon micromachines to vibrate. Resulting friction between polysilicon structures and the substrate causes surface micromachines to charge and lift due to the repelling of like charges. Also, the charge repulsion effectively stabilizes the surface micromachined flaps to the upright position and nearly perfect yield over the entire die area can be achieved barring flaps with mechanical defects.

EXPERIMENTAL SETUP

After release and critical point drying the silicon die containing MUMPS fabricated micromachines was mounted on a 500 μm thick piezoelectric plate (PZT-4H, Lead-Zirconate-Titanate) using a cyanoacrylate adhesive. The sample was placed in a vacuum chamber and the PZT was actuated by applying a swept frequency signal with 3-20 V_{PP} amplitude. High frequency (2-4.5 MHz) signal excites several modes of the PZT/silicon sandwich with most of the vibrational energy being in the thickness direction. The low impedance of these resonances result in significant heating of the PZT. Low frequency (100kHz to 1 MHz) excites the bending like modes of the PZT/silicon composite with much less heating due to higher impedance of these resonances. The swept frequency actuation was chosen to avoid the need for tuning at the PZT resonances. Although the electrode configuration did not affect the experimental outcome, the top PZT electrode was connected to the ground potential to reduce the possibility of parasitic field effects on the micromachines (Figure 1). A miniature 34 gauge thermocouple was adhesively mounted on the PZT top electrode to monitor the sample surface temperature.

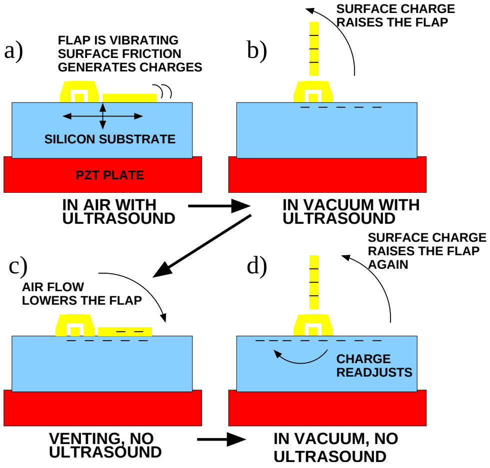

Figure 1. *Sequence of actuation. a) Ultrasonic vibrations charge the polysilicon parts and heat the PZT. b) Electrostatic repulsion forces the hinge up. c) Venting induced air flow causes the flap to lower. d) Surface charge remains on the flap and lowering the pressure will raise the flap again with no ultrasound.*

RESULTS

In this section experimental results are presented. First an overview of the experiment is given followed by detailed analysis of the assembly.

Assembly of structures

The experimental procedure is shown in Figure 1. The parts were first actuated in ambient pressure using a high frequency (2-4.5 MHz) signal with the mean voltage of 5-15 V_{PP}. The actual instantaneous voltage across PZT varied because of the frequency dependent impedance of the PZT and the output impedance of the generator (50 Ω). The mean value was recorded using an oscilloscope. The substrate vibrations transferred momentum to the surface micromachines which was evident from a rattling observed under a microscope. However, at atmospheric pressure they would not lift up due to air drag on the flaps [13]. As the pressure was lowered to about 1 Torr with the ultrasound still on, the hinged polysilicon flaps were lifted up. At this stage, the PZT surface temperature was measured to be 70-120 ^{o}C due to the heating of the PZT depending on the drive voltage. The flaps stayed up indefinitely even after the samples were brought back to the atmospheric pressure. However, if the venting was done rapidly, air flow was able to knock the flaps down. Surprisingly some of the flaps would rise back up again as the pressure was lowered even in the absence of the ultrasonic actuation! We believe this "memory effect" to be a new novel phenomena. The memory effect shows that the assembly is due to a force other than the direct ultrasonic actuation. The memory effect wore off after two or three venting cycles and the flaps would remain down showing that the memory effect is not permanent. At this point the sample temperature had also been lowered to room temperature.

Low frequency (100 kHz to 1 MHz) actuation did not yield similar results. At low voltages the flaps rattled but increasing the voltage in vacuum caused the flaps to bounce from side to side without preferring the upright position as a stable point. The actuation mechanism here is due to the direct impulse transfer. Also, the low frequency actuation did not significantly heat the sample due to much lower power dissipation in PZT. The measured temperature increase was within 1 ^{o}C.

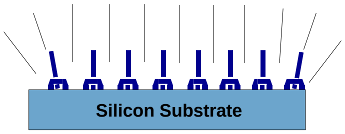

Figure 2. *Hypothetical field lines and experimentally* ***observed*** *flap angles. The flaps at the edge are in a small angle.*

Further insight to the memory effect was obtained by combining the high and low frequency actuation. The flaps were assembled to the vertical position using the high frequency signal. Next the low frequency signal was applied to vibrate the flaps. If this rattling signal was applied immediately after the high frequency assembly, the flaps would stay up even though they would visibly shake 5-15 degrees around the stable point of upright position due to momentum coupling at the hinge. However, after 30-60 s the rattling force would knock the samples down and the temperature had returned to room temperature.

Based on these initial observations, it was postulated that the assembly is due to triboelectric charging. The charging is due to the ultrasonic vibration induced contact electrification at the plate-substrate interface. The repelling of like charges effectively stabilizes the flaps at an upright position as shown in Figure 2. We believe that the charge is mobile due to the surface defects and the charge readjusts to balance the flap as shown in Figure 1d. The flaps on the edge of the die were observed to stand at a small angle in agreement with this hypothesis. After the high frequency ultrasound was turned off, the charge decayed with time and flaps would come down if disturbed by air flow or the small frequency vibrations.

An attempt to visualize the charge with a SEM was made placing the entire structure inside the SEM. Parts were successfully assembled at low magnification and low beam current at a vacuum of $4 \cdot 10^{-6}$ Torr. The low magnification did not allow measurement of the charging effect. Unfortunately, at larger magnification the flaps were excessively charged by the beam current and were stuck, most likely due to the mirror charges in the substrate.

Ultrasonic power and temperature effects

Figure 3 shows the effect of ultrasonic power on the assembly for high frequency actuation. At voltage levels less than 4.5 V_{PP} the parts failed to assemble. As the voltage was increased, assembly was observed with correspondingly shorter time. With further increase, the time to assemble saturated to a few seconds.

Figure 4 shows the time span of the memory effect. The flaps were assembled in vacuum with the high frequency signal, knocked down with air venting, and assembled again in vacuum. The first assembly took about 21 s. If the dormant time between two assembles was small, the flaps would rise up immediately with the applied high frequency signal during the second assembly. After 45 s dormancy, the second assembly time would increase with increasing dormancy time and eventually it saturated at 21 s.

Figure 5 shows the PZT surface temperature as a function of time for a typical experiment. The sample was first actu-

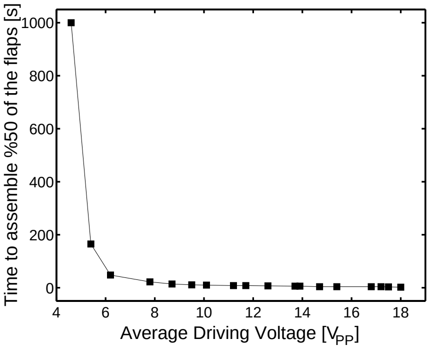

Figure 3. *Time to assemble 50% of the flaps versus mean actuation voltage*

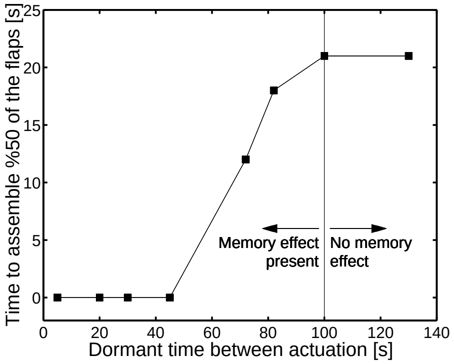

Figure 4. *Time to assemble 50% of the flaps versus dormant time between actuation*

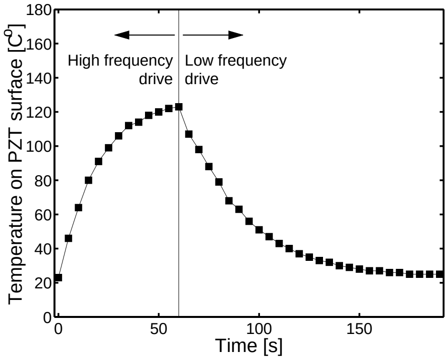

Figure 5. *Recorded PZT temperature versus time*

ated using high frequency swept signal that heated the sample and assembled the flaps. Next low frequency signal was applied with low voltage level sufficient only to shake the sample. The temperature rise and fall time was found to correlate very accurately to the assembly time and duration of the memory effect with flaps falling down as the temperature decreased to less than $\sim 50^o$C.

Two explanations are possible to explain the measured data: The heating could drive away the moisture that shields the charged surfaces or the heat might cause local pressure differences and air streaming [15]. It is well established that for pressures less than $1/2$ atm, only a monolayer of H_2O molecules remain on a glass surface. Furthermore, quantity of the absorbed H_2O decreased by order of magnitude with temperature increase from room temperature to 100^oC. Hence, the scenario of PZT heating leading to the H_2O desorption and unshielding of the charge is a likely explanation.

To further clarify the effect of the temperature, the sample was mounted on a heater inside the vacuum chamber. Heating the sample without the ultrasound showed no flap movement indicating that heat alone cannot actuate the flaps. Next the PZT temperature was set to 120 ^{o}C. As expected, immediately after the high frequency assembly, low frequency rattling was not enough to knock the parts down. However, if the low frequency signal was applied after 30 minutes of dormancy at 120 ^{o}C, all the flaps would fall down. This indicates that the memory effect is not caused by high temperature alone. On the other hand, charge decay over time can still occur at high temperature. Furthermore, after initially falling down, the flaps started to rise up again even with the low frequency, low power actuation signal. It should be noted that this rattling signal was too small to cause further heating but might be large enough to cause charging once the H_2O molecules have been removed with the heat. This supports the theory that higher temperature is only needed to remove moisture of the surfaces and that the actuation force itself is electrostatic.

ASSEMBLY OF FLAP STRUCTURES

For permanent assembly one requires the assembled structures to stay in their final position even after the memory effect goes away. Therefore different structures with locking mechanisms were also fabricated. Such locking structures have been used extensively in manual assembly procedure [16]. The structures would stay up even after the triboelectric effect wore off. Figure 6 shows examples of assembled flap arrays and retroreflectors. One observed problem was that locking latch also stayed up due to charge repelling. This can be solved by using a spring latch anchored to the substrate. Nearly 100% assembly yield was obtained in 30 s as shown in Figure 7. The flaps that failed to assemble were either not released properly during the release process or jammed in the retaining lever. These problems may be solved with more careful device design.

CONCLUSIONS

We have demonstrated a novel method of batch assembly of hinged polysilicon flaps. The method relies on electric charge generated between the hinges and the substrate due to ultrasonic vibration induced rubbing. The residual oxide on polysilicon flaps and the insulating silicon nitride are believed to retain charges after contact electrification. A swept frequency drive of the piezoelectric plate allowed a robust method to generate motion of the micromachines without the need for a tuning circuitry. The heat generated in the PZT/Si laminate is believed to drive away charge shielding molecules on the sample surfaces. The unshielded charge and its redistribution due to surface mobility cause the flaps to be stabilized in the vertical position. The dual role of temperature and ultrasonic actuation was clarified by experiments that showed that the assembly could not take place with only higher temperature or actuation. Further experiments using electrostatic AFM probes to measure the nature and location of the charge creation are underway to quantify and validate the role of ultrasonic triboelectricity for micromachine assembly. In addition to the significance of surface charges for assembly, this paper also points towards possible hazards of surface charging in MEMS structures.

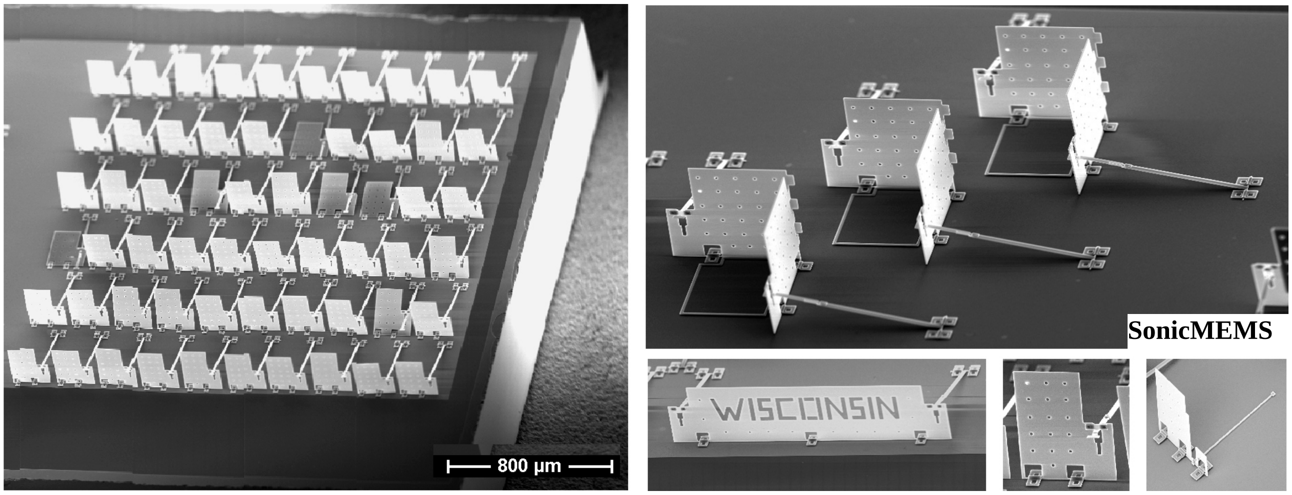

Figure 6. *Examples of assembled devices: Array of assembled micromachined flaps, polysilicon corner cube reflectors (200x200µm) with lock-in structure, and "micro-art" Wisconsin banner. Lower right shows a flap with a retaining spring latch anchored to the substrate.*

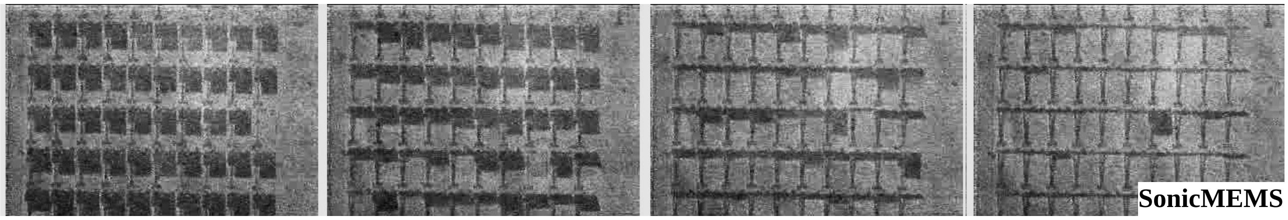

Figure 7. *Snapshots of a flap array assembly (50x200µm flaps, 10x5 array). 1. Flaps are vibrating on the surface. 2-4 charged flaps are lifting up. 5. All but one flap are lifted (SEM photo identified the problem to be a dirt particle).*

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