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THERMO-KINETIC ACTUATION FOR HINGED STRUCTURE BATCH MICROASSEMBLY

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Abstract – Surface micromachined hinged flaps are assembled using thermo-kinetic forces in the molecular gas flow regime. Ultrasonic vibration energy is used to reduce static friction. The effective thermo-kinetic force is characterized as a function of pressure and temperature. The transition from the viscous to molecular flow regime is found to be flap size dependent. In the molecular flow regime the thermo-kinetic forces increase with increasing pressure and surface temperature. A suction based assembly jig suitable for automated MEMS batch assembly is also demonstrated.

INTRODUCTION

We report on the use of gas kinetic effect to actuate and assemble hinged microstructures. The actuation is due to differential pressure across the flap near heated surface in the molecular flow regime; a phenomenon also known as the "radiometer effect". In the past, different assembly methods have been proposed for surface micromachines. The structures can be assembled manually using a probe tip, but due to the labor and time cost of the manual assembly, more automated solutions are being investigated. One way is to use on-chip electrostatic [1] or thermal actuators [2]. 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 [3] and surface tension of wet solder [4] 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) [5] or by depositing magnetic material on them [6].

Since assembly method presented here is based on gas kinetics near heated surface that cause the flaps to lift up, the method is suitable for actuating devices from *any* surface micromachining process. Furthermore, no surface area is consumed nor are any interconnects required on the silicon die. The history of radiometer effect dates back to the original Crookes radiometer (1873), a four vaned device with dark and light surfaces, that rotates when a source of light is brought nearby. The radiometer mechanism was explained by Knudsen (1910) with energy transfer from heated dark surface to gas molecules generating recoil force. Knudsen also proposed an absolute namometer based on the momentum transfer between two heated surfaces although the device has not been commercially adopted due to its delicate nature.

For microstructures, friction forces are significant. To remove the static friction on hinged structures, the silicon sample was ultrasonically vibrated using a piezoelectric PZT (lead-zirconate-titanate oxide) plate. Ultrasonic vibrations have previously been used for assembly as a source of random energy input [7] or to impact actuate micromachines [10]. In the work presented here, however, the purpose of the vibrations was only to remove friction and not to move the microstructures. The sample was vibrated at high frequencies (>2.5 MHz), where the vibration amplitude is only a few nanometers and not sufficient to impact actuate the surface micromachines.

In MEMS2001, we reported on the initial results of assembling surface micromachined flaps using combination of heat and ultrasound [8]. The actuation mechanism was not determined conclusively at the time. One of the hypothesis was that the actuation was due to generation of friction induced charge and ultrasonic lubrication. Remarkably, friction induced charge and gas kinetic hypothesis give the same qualitative behavior in the molecular flow regime but gas kinetics hypothesis predicts the experimental results quantitatively in *all* pressure regimes. In addition to a new theoretical understanding, we report on the use of suction induced *mechanical* coupling of ultrasound instead of adhesive bonding enabling a new MEMS assembly tool.

ANALYSIS OF FORCES ON A HINGED STRUCTURE

For micron scale devices bulk forces, such as gravity, become less important and surface forces start to dominate. In this section the role of gravity, friction, ultrasonic vibrations, and gas-kinetic forces are compared in context of surface micromachined flaps and different pressure regimes are identified.

Gravity force and hinge friction

Gravity and other inertial forces are the dominant forces in the macro world. However, as the mechanical devices shrink to micron scale, surface forces dominate. For silicon plate with dimensions of 100 μm$\times$250 μm$\times$2 μm, the gravity force is only 0.4 nN while friction force can be many times larger. To remove the hinge friction, the substrate is vibrated ultrasonically at frequencies above 2.5 MHz. The vibrations cause the hinge-flap contact to break and the friction force vanishes momentarily [9]. This leads to nanoscale ratcheting at MHz frequencies and results in overall reduction in frictional force.

Impact from sonic pulses

The substrate vibrations can be used to actuate surface micromachines [10, 11]. This can be accomplished by exciting the substrate at the surface micromachine resonance for frequency selective actuation, or by pulsing the entire substrate for impact actuation. In the work presented here, however, the purpose of the substrate vibrations is to remove static friction and not to actuate. Therefore the vibration amplitude is kept below impact actuation threshold.

Thermo-kinetic forces

The origin of thermo-kinetic force is illustrated in Figure 1. The gas molecules from ambient gas with temperature $T_{ambient}$ bombard the die surface and flaps with average velocity $\bar{v}_{ambient} = \sqrt{8RT_{ambient}/\pi m}$ [12]. These molecules are absorbed and accommodated on the surface. After a finite amount of time they desorb leaving the surface with average velocity $\bar{v}_{particle}$ corresponding to the particle temperature $T_{particle}$. The particle temperature $T_{particle}$ of desorbing molecules can be expressed as

$$T_{particle} = \alpha(T_{surface} - T_{ambient}) + T_{ambient}, \qquad (1)$$

in terms of the accommodation coefficient α ($0 < \alpha < 1$) and the ambient and surface temperatures. The case of $\alpha = 0$ correspond to elastic surface-molecule interaction with no change in molecule temperature (ideally smooth surface). The case of $\alpha = 1$ correspond to full accommodations ($T_{particle} = T_{surface}$). Typically $\alpha > 0.5$ for engineering surfaces [13]. If the mean free path of the gas molecules is approximately the same as or larger than the flap-surface distance, the molecules leaving the surface will on average impact the flap with a higher velocity than the molecules from the ambient. This average net momentum transfer from particles ejected from surface leads to net force

$$F_{gas} = \frac{1}{2}CpA\left(\sqrt{\frac{T_{particle}}{T_{ambient}}} - 1\right) \qquad (2)$$

on the flap, where C is geometry constant, p is the ambient pressure and A is flap area. The geometry constant C can be calculated from 3-D gas dynamics and depends on the shape of the flap and the distance between the flap and the surface [14]. Here $C = 0.5$ is used. For flap dimensions of 100 μm$\times$250 μm, accommodation coefficient $\alpha = 0.8$ pressure of 500 mTorr, and temperatures $T_{surface}$=100°C and $T_{ambient}$=20°C, equation (2) gives $F_{gas} \approx 90$ nN. Although this force is small, it is still two orders of magnitude larger than the gravity force for silicon flaps with same area and thickness of 2 μm.

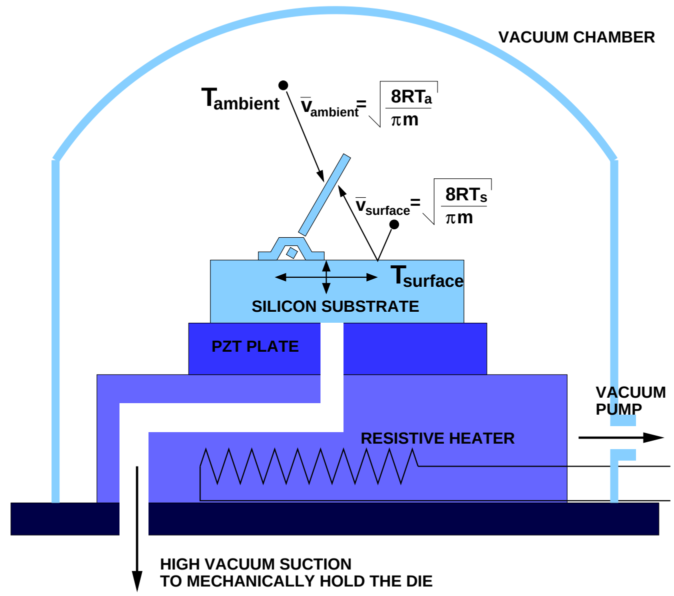

Figure 1. The origin of thermo-kinetic force. Gas molecules leaving the heated surface have higher momentum than those in the ambient gas. Also shown is the experimental set-up and the assembly jig, The two vacuum ports are for maintaining differential pressure over the die for hold down suction.

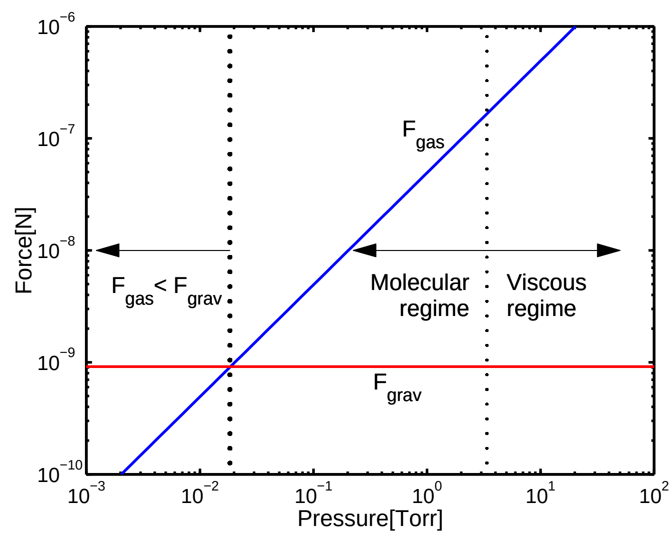

Figure 2. Thermo-kinetic force F_{gas} and gravity force F_{grav}. Above ~10 Torr (viscous regime), there is no net force on the flaps. Below ~10 Torr (molecular regime), the flaps feel net force upwards. The gravity force dominates below ~10mTorr.

Since the gas force depends on pressure, different regimes are observed as illustrated in Figure 2. In the viscous regime, the gas molecules leaving the substrate equilibrate with ambient before impacting the flap and there is no net force on the flap. As the pressure is decreased, the mean-free path ($\lambda = 5 \cdot 10^{-3} p^{-1}$ cm·Torr in air) increases and becomes comparable to the flap dimensions [15]. The molecules impacting the flap result in a net force perpendicular to the substrate. Thus, the flaps are lifted up at pressure corresponding to transition pressure from viscous to molecular flow at the flap scale (at $p = 1$ Torr, $\lambda \approx 50\ \mu$m). Short flaps are expected to lift up at higher pressure than long (tall) flaps. The flaps stabilize perpendicular to substrate surface as momentum from impacting molecules is equal on both sides of the flaps. Flaps near the edge are observed to stand at a slight angle. After the transition pressure, the force diminishes linearly with decreasing pressure in accordance with equation (2) as the particle density is reduced. Eventually the thermo-kinetic force becomes less than other forces such the gravity and ultrasonic ratcheting.

EXPERIMENTAL SETUP

For the experiments a temperature controlled PZT assembly mount shown in Figure 1 was fabricated. The PZT plate with dimensions of 10 mm$\times$10 mm$\times$0.2 mm was soldered to a hot plate with temperature control to adjust the substrate temperature. The assembly mount was placed in a vacuum chamber and the chamber pressure was adjusted in the range of 1mTorr to 750 Torr with a leak valve. The constant leakage of air into the chamber also helps keeping the chamber temperature near room temperature even with the heater on. The sample was monitored with an optical microscope and the video image together with substrate temperature and chamber pressure were recorded. Electrostatic forces on the hinges were minimized by sputtering 200 Å of gold to the released flaps.

In experiments requiring vacuum pressures less than 500 mTorr, the silicon die was mounted to the PZT with adhesive bonding. This can be undesirable in an industrial environment. Therefore vacuum suction for holding down the silicon die was investigated. It was found that even in moderate vacuum (>0.5 Torr), suction is enough to hold the die in place during the assembly. At lower chamber pressures, the pressure difference between the suction pipe and chamber was too low to hold the die during ultrasonic vibrations. Alternative to the suction would be to use mechanical clamping. The fact that imperfect mechanical coupling of ultrasonic vibrations without adhesive also leads to assembly indicates that the ultrasound serves only to reduce friction. This new vacuum jig allows quick attachment of the die to the assembly tool enabling automated assembly of MEMS.

The PZT/Silicon substrate resonances depend on device geometry and shift with temperature. To avoid complications of frequency tuning to the shifting resonances, the actuation frequency was swept from 2.5 to 5 MHz with excitation amplitude of approximately 10 V_{PP}. The swept frequency actuation also has the advantage over fixed frequency actuation that there are no fixed nodal patterns and micromachines are excited more evenly over the entire surface. The high frequency range was chosen

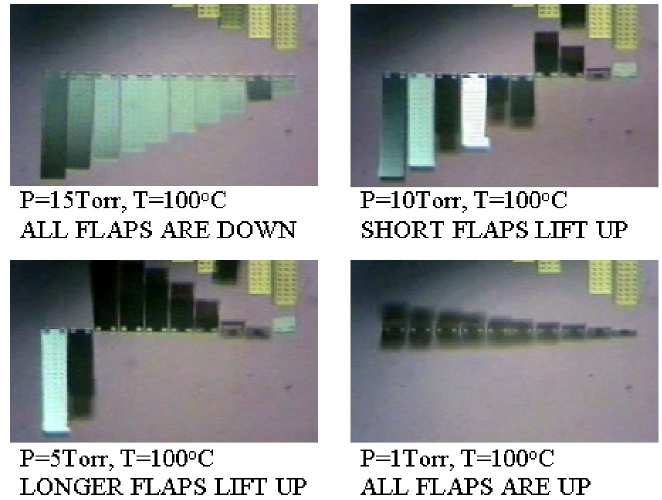

Figure 3. *The effect of flap length on the transition pressure from viscous to molecular flow. As the chamber pressure is lowered, shorter flaps are lifted before longer ones.*

because frequencies less than 1 MHz can excite strong lateral and bending vibrations of the substrate. These sub 1 MHz vibrations can have large vibration amplitude ($\sim \mu$m) at the anti-nodes, sufficient for impact actuation of the surface micromachines which is undesirable in these experiments.

EXPERIMENTAL RESULTS

In the first experiment, the substrate temperature was set to 100 °C and ultrasound was applied to reduce friction. In the viscous regime (10-750 Torr) the flaps stay down as expected as the mean free bath is too small to generate significant actuation force. As the pressure is lowered to below 10 Torr first short flaps, and then longer flaps lift up confirming that the transition pressure depends on the flap dimensions (Figure 3). Upon ultrasound removal, the assembled flaps remain up indefinitely even after cooling of the sample to the ambient temperature due to static friction at the hinges. Applying ultrasound to the samples after removing the thermo-kinetic force by cooling the sample resulted in flaps falling down. It should be noted that some of the flaps would lift up when heated at lowered pressure even without the ultrasonic friction removal due to statistical nature of friction. This shows that the ultrasound is not the source of actuation.

In the next experiment, the low pressure behavior of the flaps was verified. As equation (2) predicts, the flaps fall down as the pressure is lowered to 1-300 mTorr and the thermo-kinetic force becomes smaller than the gravity and ultrasonic forces. Further verification of equation (2) was obtained by measuring the threshold pressure at which the flaps fall down as a function of substrate temperature in the presence of the ultrasound. As expected the threshold pressure is reduced with the increasing substrate temperature (Figure 4). The measured pressure-temperature re-

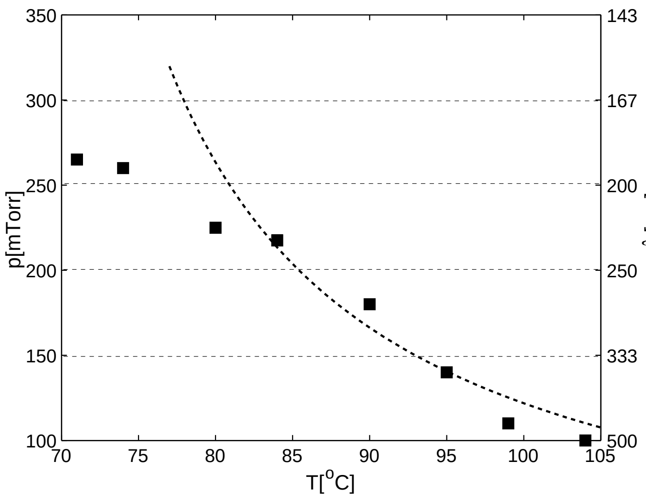

Figure 4. *Measured flap falling pressure thresholds versus substrate temperature and the theoretical p-T curve ($\alpha = 0.8$). Right y-axis shows the calculated mean free path at 25°C (flap length 400 µm).*

lationship, however, does not exactly follow equation (2) because at the low temperatures the transition pressure is fairly high and the mean free path of the gas molecules approaches the flap dimensions (flap length in the experiment was 400 μm). A fraction of molecules will undergo a collision before impacting the flap and the effective force will be lower. Also in deriving equation (2) it was assumed that the ambient gas temperature does not depend on substrate temperature. In practice, however, even with the constant air flow from the leak valve, the heated substrate will cause temperature gradients near the die surface. Another source of discrepancy can be the temperature dependency of the accommodation coefficient. Heating of the surface causes desorption, cleaning the surface and typically lowering the accommodation coefficient [13].

CONCLUSIONS

A new batch assembly mechanism for surface micromachines was demonstrated. The forces on the surface structures were characterized as a function of pressure and temperature and three pressure regimes were identified. In the viscous regime, the drag forces dominate. In the molecular flow regime, the thermo-kinetic forces are significant but decrease with pressure due to reduced particle density. At pressures less than 10 mTorr, the thermo-kinetic force becomes insignificant. Finally, a PZT vibrator/heater that does not require adhesive bonding to the silicon could enable assembly in an industrial setting.

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REFERENCES

[1] N. C. Tien, O. Solgaard, M.-H. Kiang, M. Daneman, K. Y. Lau, and R. S. Muller, "Surface-Micromachined Mirrors for Laser-Beam Positioning", *Sensors and Actuators A*, vol. A52(1-3), pp. 76–80, Mar. 1996.

[2] J. R. Reid, V. M. Brigth, and J. T. Butler, "Automated Assembly of Flip-Up Micromirrors", *Sensors and Actuators A*, vol. 66(1-3), pp. 292–298, Apr. 1998.

[3] T. Ebefors, E. Kälvesten, and G. Stemme, "New Small Radius Joints based on Thermal Shrinkage of Polyimide in V-Grooves for Robust Self-Assembly 3D Microstructures", *Journal of Micromechanics and Microengineering*, vol. 8(3), pp. 188–194, Sep. 1998.

[4] R. A. A. Syms, "Equilibrium of Hinged and Hingeless Structures Rotated Using Surface Tension Forces", *Journal of Microelectromechanical Systems*, vol. 4(4), pp. 177–184, Dec. 1995.

[5] I. Shimoyama, O. Kano, and H. Miura, "3D Micro-Structures Folded by Lorentz Force", *Proceedings of the 11th Annual International Workshop on Micro Electro Mechanical Systems*, pp. 24–28, Heidelberg, Germany, Jan. 25-29, 1998.

[6] Y. Li and C. Liu, "Assembly of Micro Optical Components Using Magnetic Actuation", *The 10th International Conference on Solid-State Sensors and Actuators*, pp. 1466–1469, Sendai, Japan, Jun. 7-10 1999.

[7] K. F. Bohringer, K. Goldberg, M. Cohn, R. Howe, and A. Pisano, "Parallel Microassembly with Electrostatic Force Fields", *IEEE International Conference on Robotics and Automation*, vol. 2, pp. 1204–1211, Leuven, Belgium, 16-20 May 1998.

[8] V. Kaajakari and A. Lal, "Electrostatic Batch Assembly of Surface MEMS using Ultrasonic Triboelectricity", *Proceedings of the 14th Annual International Workshop on Micro Electro Mechanical Systems*, pp. 10–13, Interlaken, Switzerland, Jan 21-25, 2001.

[9] F. Dinelli, S. K. Biswas, G. A. D. Briggs, and O. V. Kolosov, "Ultrasound Induced Lubricity in Microscopic Contact", *Applied Physics Letters*, vol. 71(9), pp. 1177–1179, Sep. 1997.

[10] V. Kaajakari and A. Lal, "Pulsed Ultrasonic Release and Assembly of Micromachines", *The 10th International Conference on Solid-State Sensors and Actuators*, pp. 212–215, Sendai, Japan, Jun. 7-10, 1999.

[11] V. Kaajakari, S. Rodgers, and A. Lal, "Ultrasonically Driven Surface Micromachined Motor", *Proceedings of the 13th Annual International Workshop on Micro Electro Mechanical Systems*, pp. 40–45, Miyazaki, Japan, Jan. 23-27, 2000.

[12] J. H. de Boer, *The Dynamical Character of Adsorption*, Oxford University Press, 1953.

[13] S. C. Saxena and R. K. Joshi, *Thermal Accommodation and Adsorption Coefficients of Gases*, vol. II-1 of *McGraw-Hill/CINDAS Data Series on Material Properties*, McGraw Hill, 1981.

[14] H. L. Eschbach and R. Y. Werz, "A Generalized Correction Factor for the Knudsen Radiometer Gauge with Arbitrary Vane and Heater Shape", *Vacuum*, vol. 26(2), pp. 67–71, Feb. 1976.

[15] A. Roth, *Vacuum Technology*, North-Holland, 2nd ed., 1982.