Parallel Assembly of Microstructures with a High-Speed Spinner

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ABSTRACT

This paper describes the possibility of parallel assembly of three-dimensional microstructures on a high-speed spinner. According to our calculation, centrifugal the force and aerodynamic force developed by the spinning can be utilized to rotate hinged mirrors out of plane. The centrifugal force and aerodynamic force applied on a 100 µm by 200 µm mirror could reach micro-Newton range with a photoresist spinner rotating at 5000 rpm. In addition, the forces applied on microstructures can be easily adjusted by changing the rotational rate or the radius of rotation. Successful experiment has been done by King Lai, et al, and their publication is in progress [1]^{*}. Rotational assembly has great potential for high-volume low-cost manufacturing and of threedimensional systems.

INTROCUCTION

Surface micromachining process is a very powerful approach for fabricating twodimensional thin-film structures. Rotating these thin-film plates out of plane on hinges makes three-dimensional structures possible with the current planar process. Numerous of complex microsystems have been demonstrated utilizing this technique.

However, difficulties in assembly have limited the manufacturing of three-dimensional structures. Currently available assembly techniques include manually probing [2], water assembly [2], magnetic actuation [3], and electrostatic assembly [4]. Assembly of an entire micro-system by flipping a single plate was also demonstrated [5]. Drawbacks of these techniques are time consuming, low-yield, highcost, and difficulty in implementation. We propose to assemble microstructures with a high-speed spinner where the centrifugal force and aerodynamic force are utilized to lift up microstructures. Spinning assembly would be a fast and low-cost parallel process.

PRINCIPLE

Microstructures undergoing uniform circular motion feel a hypothetical inertial force -centrifugal force with the direction away from the center of motion. This centrifugal force has the magnitude of:

$$F_c = mr\omega^2 \tag{1}$$

Where m is the mass of the microstructure, r is the radius of motion, and ω is the angular velocity of the microstructure.

In addition to the centrifugal force, the microstructures moving in a viscous fluid – air also feel dragging force due to the viscous shear stress on the surface of the structure. This dragging force is in the direction of the airflow with the magnitude given by:

$$F_{d} = \frac{1}{2}\rho v^{2}A$$

$$= \frac{1}{2}\rho \omega^{2}r^{2}A$$
(2)

Where ρ is the density of the air, v is the velocity relative to the air, A is the cross sectional area perpendicular to the airflow.

^{*} We came out with the idea of rotational assembly independently. We found out about King Lai's work later and read his pre-print paper for MEMS 02. We had some discussion with his group.

From Equation (1) and (2), we can see both centrifugal force and aerodynamic force are quadratic functions of the rotation rate. Also, centrifugal force and aerodynamic force are linear and quadratic functions of the radius of rotation, respectively. Therefore, increasing rotational rate and radius could make centrifugal force and aerodynamic force large enough to overcome surface forces [6], and generate torques to lift up microstructures. On the other hand, the centrifugal force and the aerodynamic force are limited by the maximum tensile stress of polysilicon, 1.2 ± 0.15 GPa, to prevent breakage of hinges.

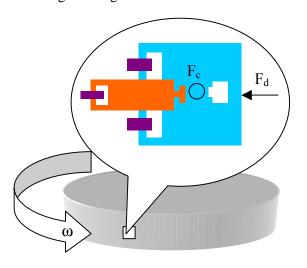


Figure 1: Conceptual drawing of the rotational system.

DESIGN

Rotational system

A simple and handy rotational system for parallel assembly could be a manually operated photoresist spinner. Microstructures released with critical point drying are mounted perpendicular to the spinning disc (shown in Figure 1). The layer to be flipped up is open towards the airflow direction. This orientation is chosen such that the torques generated by the centrifugal force and aerodynamic force are maximized.

90° Test structure

Test structure that needed to flip up by 90° would be a hinged mirror. A hinged latch is chosen as the lock-in structure in order to minimize its pull-down force exert on the mirror. The enlarged portion in Figure 1 is an example of the test structure. There are also dimples underneath the mirror plate to minimize the surface forces. Parameters of the structure are listed in Table 1.

Mirror Size (µm×µm)	100×200
Latch Size (µm×µm)	15×40
Thickness (µm)	2
Angular Velocity (rpm)	5000
Radius of Rotation (m)	0.1
Centrifugal Force (µN)	2.55
Aerodynamic Force (µN)	3.53×sinθ
Tensile Stress on Hinges (Pa)	~10 ⁵

 Table 1: 90° test structure parameters.

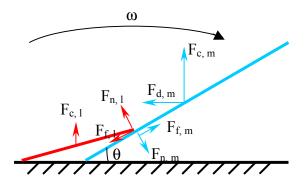


Figure 2: Free-body-diagram of hinged mirror in uniform circular motion.

A free-body-diagram showing the major forces applied on the systems is in Figure 2. In this diagram, frictional force at the hinges is not drawn since its moment arm is too small to contribute to a torque. Also note that the air dragging force is ignored for the latch since the mirror blocks most of the airflow. The centrifugal force exerted on the latch is an order of magnitude smaller than that of the mirror. The normal force and frictional force at the point of contact are in the same order of magnitude as the centrifugal force exerted on the latch. Consequently, the normal force and the frictional force are small compare to the air dragging force and centrifugal force exerted on the mirror. To the first order approximation, we consider the centrifugal force and air dragging force as the major forces determining the motion of the mirror. The torque generated by the two forces can be express as:

$$T = F_c \frac{L}{2}\cos\theta + F_d \frac{L}{2}\sin\theta \qquad (3)$$

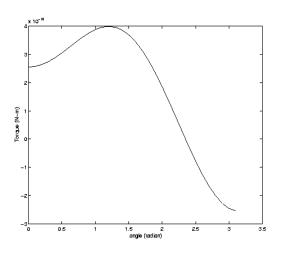


Figure 3: Plot of torque vs. θ .

Figure 3 shows the torque applied on the mirror by the centrifugal force and air dragging force during its flip up rotation. Note that the torque remains positive until 135°. However, after the mirror rotates up to 90°, the latch locks the mirror in position, and the normal force, which exerted by the latch on the mirror, increases significantly to prevent the mirror from further rotation. The upper limit for this normal force is also the maximum tensile stress of polysilicon. In our example, the tensile stress on the latch is in the order of 10^5 Pa, under the limit.

180° Test structure

It is also good to be able to rotate hinged plates 180 degree. By flipping a single plate by 180 degree, some complex three-dimensional systems can be entirely assembled [5]. The detail analysis of the flipping the pop-up structure is beyond the scope of this paper. We would like to examine the possibility of 180° rotation of a single plate. From Figure 3, we can see the torque generated by the centrifugal force and air dragging force decreases below zero after 135° due to the fact that centrifugal force provides negative torque as the angle of rotation increases beyond 90°. To overcome this negative torque, we can increase the angle of rotation by introducing an angular acceleration α . If we look at the hinged mirror as the reference, the mirror would feel a hypothetical inertial force:

$$F_i = ma = m\alpha R \tag{4}$$

Where a is linear acceleration, and α is angular acceleration. This inertial force adds a positive torque to the mirror. The free-body-diagram of the mirror under angular acceleration is shown in Figure 4. The total torque applied on the mirror can be express as:

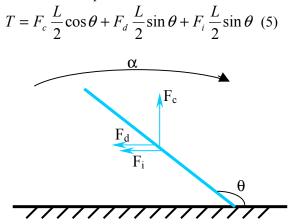


Figure 4. Free-body-diagram of hinged mirror under angular acceleration.

When the torque equals zero, the mirror rotates to its final position. The final position θ_{max} of the mirror depends on the acceleration of the spinner. Using the parameters listed in Table 1, we can calculate the final values F_c and F_d . Setting the torque equal to zero, we can then find out the value of θ_{max} as a function of angular acceleration α , shown in Table 2. Notice that rotating the mirror all the way to 180° requires infinite acceleration, which cannot be achieved. However, rotating the plate 179° makes the distance between the plate and the substrate less than 3.5 µm. Hopefully, surface force and pull the plate down to 180° . We can also verify that the tensile stress on the hinges is in the order of 10^7 Pa with the inertial force, still under the limit of maximum tensile stress of polysilicon.

α (s ⁻²)	$F_{I}(N)$	θ_{max}
0	0	134.4°
2.85e5	2.65e-6	150°
3.10e6	2.88e-5	175°
7.83e6	7.28e-5	178°
1.57e7	1.46e-4	179°
∞	~	180°

Table 2: θ_{max} as a function of α

In order to flip a plate by 180°, huge acceleration is required as shown in Table 2. A regular photoresist spinner cannot achieve this acceleration. Other special instrument is required to complete the task.

POTENTIAL PROBLEMS

The airflow assumption is over simplified in the above analysis. The fluid velocity vector close to the surface of the substrate is threedimensional, and there might be turbulent flow at high speed of rotation. Structure breakage might occur due to the complex airflow. To avoid breakage, assembling in vacuum with a higher speed of rotation might be necessarily.

CONCLUSION

Parallel assembly of three-dimension structure with a high-speed spinner is a high yield and low cost process. Rotating polysilicon plate 90° out of plane is very promising, and flipping plate 180° could be done with further investigation. Very complex MEMS structure can be batch assembled by high-speed spinning. Rotational assembly makes the high-volume manufacture of three-dimensional structures more attractive.

ACKNOWLEDGEMENTS

The authors are thankful to the friendly discussions with Brian Bircumshaw, Eliot Hui, Sunil Bhave, Karen Cheung, Rocky Mai, Wen Li and Roger Howe.

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