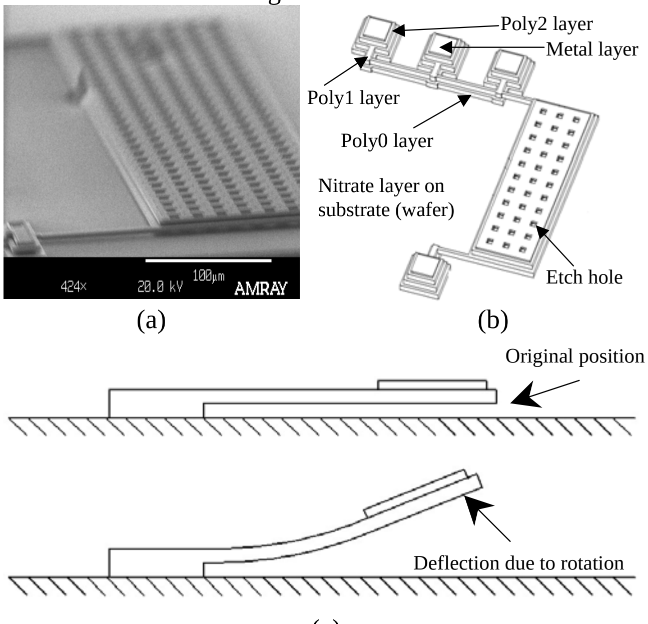
Centrifugal force is a good choice to perform micro-assembly because the force applied on the micro structures could be evenly distributed so that the micro structures would not be destroyed easily. Since the mass of a typical micro structure is very small, a 3cm radius disc rotating at 6250rpm will generate ~$3x10^{-6}$N force on a 250µmx100µmx4µm (see Fig. 2 for thin film layer composition) MUMPs fabricated mass-platform. The orientation of the chips were considered during the rotation-assembling process, i.e., the micro chips were placed perpendicular to the rotating axis, and the surface micromachined micro structures were faced outward as shown in Fig. 1. With this configuration, the micro structures could be pulled away from the substrate once rotation was initiated. On-chip micro locking structures were used to prevent the micro structures from detaching from the substrate during rotation.



(a) (b)

(c)

Fig. 2. (a) SEM picture of a rotation sensor. (b) Illustration showing the multi-layered MUMPs structure used in our experiments. (c) Conceptual drawing for the side view of the rotation sensor.

III. SURFACE FORCE MEASUREMENT

To study the limitations of the centrifugal assembling method, systematic experiments were performed to ascertain the surface force interactions of the micro mass-platforms during the rotation assembling process. The structures tested consist of a simple mass platform supported by two cantilevers as shown in Fig. 2. These platform-cantilever structures were designed as piezoresistive sensors capable of wirelessly transmitting motion information under rotation up to 6250rpm (similar to our prior work reported in [5]). Basically, these MUMPs rotation sensors can convert mechanical deflection of the polysilicon cantilevers into a change of electrical resistance, which can further be converted into a measurable change of voltage by connecting the sensors in a Wheatstone-bridge configuration. The voltage output from the bridge is then transmitted by a wireless transceiver after a voltage to frequency conversion. So, by using the setup as shown in Fig. 1, the appropriate centrifugal force needed to *free* a structure that is initially adhered to the substrate by surface forces can be measured.

Representative dynamic motion of a structure as a function of the angular velocity of a spinning disc is shown in Fig. 3. The *freed-state* (defined as the state when a platform is released from the substrate) is typically found at a high angular velocity when the disc speed is increased. However, if the angular velocity is decreased, the platform will *snap down* to the substrate at a lower angular velocity than the *freed-state*. This hysteresis characteristic is repeatable and may be attributed to surface-force effects. The force required to free the structure is the force required to overcome the surface force for different size of masses.

The relationship between the *freed-state* and the *snap-down-state* of the platform is also analyzed for various platform geometries. In general, the *freed-state* angular velocity is usually larger than *snap-down-state* angular velocity as shown in Fig. 4.

Although platform sizes as small as 320µmx160µm are all freed successfully, the range of required angular velocity to free them is more sporadic than the large platforms (greater experimental error bars as shown in Fig. 5). This phenomenon may be an indication of surface forces, which depend on many factors such as humidity and temperature, becoming more dominate as a mass becomes smaller.

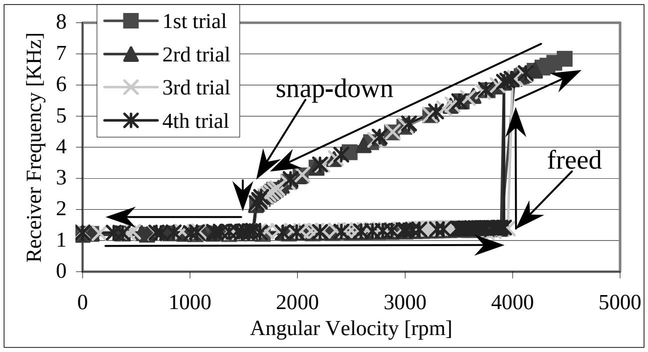


Fig. 3. Typical motion of a platform suspended by two cantilevers beams under rotation (receiver frequency is the wireless signal received and is proportional to the position of a platform).

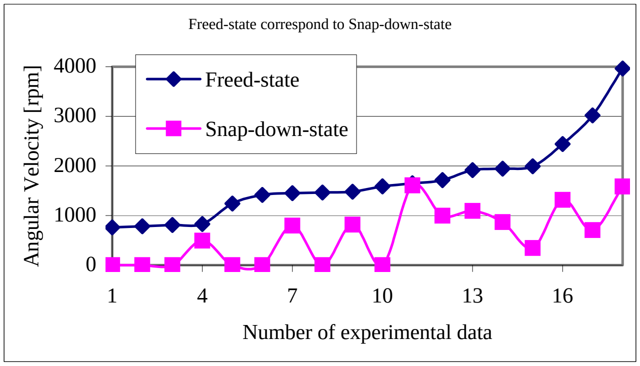


Fig. 4. Comparison between *freed-state* and *snap-down-state*.

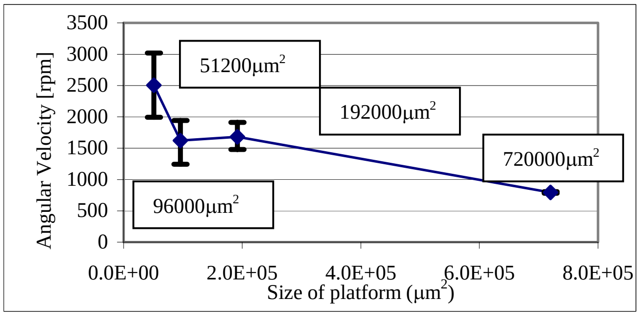


Fig. 5. The *freed-state* for 4 different sizes of MUMPs platforms. The angular velocity at which each platform type is freed from the substrate can be related to the centrifugal force acting on the micro platforms.

IV. ASSEMBLY OF VERTICAL MICRO MIRROR

A number of MUMPs platforms that could potentially be used as micro mirrors were fabricated for centrifugal assembly tests. These mirrors were classified into three types based on their mass sizes as given in Table 1.

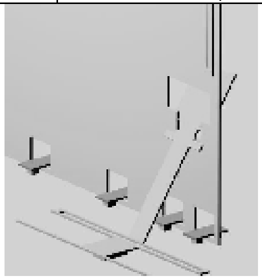
Type	Size of mirrors
I	600x300μm^2
II	300x200μm^2
III	250x100μm^2
 Traditional latch	

Table 1. Different sizes of micro mirrors tested using traditional latch as locking mechanism.

By increasing the angular velocity, different sizes of mirrors were lifted up from horizontal to vertical position until the traditional latches were engaged. When the rotation system reached the maximum angular velocity of about 6250rpm (a limitation of our current rotation system), most of the Type I micro mirrors have locked successfully into vertical position. Since centrifugal force applied on larger masses is greater than smaller masses at a given angular velocity, Type I mirrors could be assembled at a smaller angular velocity than Type II and III mirrors. When angular velocity is running at 6250rpm, the centrifugal forces applied on Type I, Type II and Type III mirrors are approximately 2.23×10^{-5}N, 7.45×10^{-6}N and 3.10×10^{-6}N, respectively. In Fig. 6, arrays of assembled micro mirrors are shown after a MUMPs chip was rotated under a certain angular velocity.

By counting the number of assembled micro mirrors (as shown in Fig. 7) for all three types of mirrors with respect to increment of angular velocity at 1200rpm, the yield of the centrifugal processes could be studied. The percentage of each type of lifted micro mirrors varies with angular velocity is shown in Fig. 8. Type I micro mirrors started to be lifted (*freed-state*) at about 1200rpm. On the other hand, Type II and Type III started to be lifted at greater angular velocities.

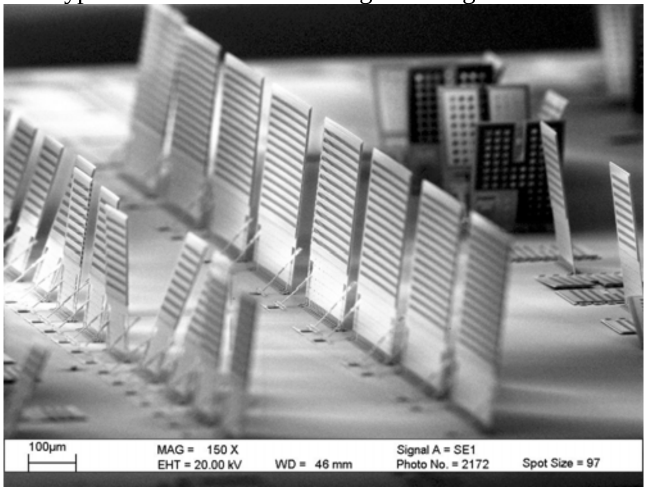


Fig. 6. SEM picture of the batch micro-assembled micro mirror arrays.

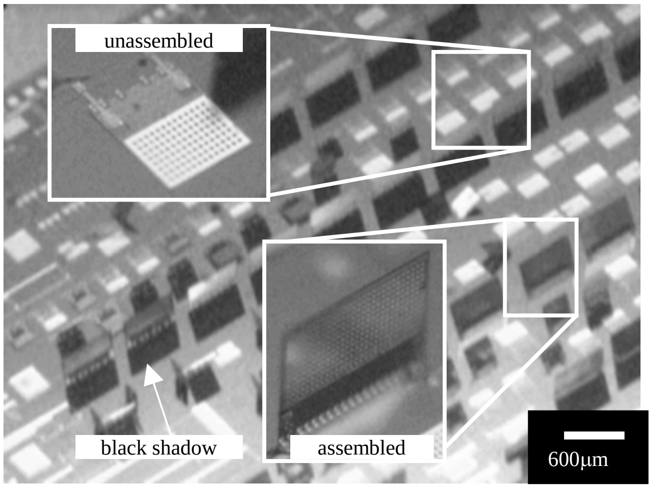


Fig. 7. Different sizes of micro mirrors assembled by centrifugal force. The white structures in the picture represent the unassembled structures (the white color is due to reflection from gold layer as observed under a 3D microscope), and the gray structures are the assembled structures with black shadows.

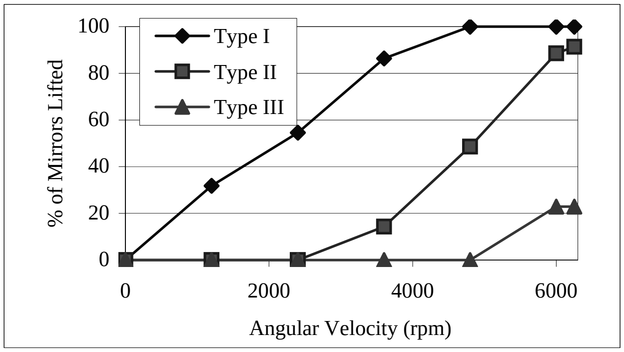


Fig. 8. Percentage of micro platforms lifted versus angular velocity, with platform size as a parameter.

Since Type III micro mirror have the smallest mass, a minimum of 4800rpm was needed to assemble the first mirror. The fact that even the same size of mirrors were assembled at different angular velocities which can be explained by the presence of other counter-acting forces such as frictional force between the hinges and the rotating platforms and the capillary force between the mass platforms and the substrate. All Type I mirrors were lifted at 4800rpm. About 50% of Type II mirrors were lifted at this angular velocity, and more than 90% were lifted when the angular velocity reached 6250rpm. The percentage of Type III platforms lifted increased from zero to 22% at 6250rpm.

To sum up, the success rate to lift up all the micro mirrors was about 70% when angular velocity reached 6250rpm as shown in Fig. 9. The success rate could be increased by increasing angular velocity or rotational radius because larger centrifugal force could be applied on Type III micro mirror.

The centrifugal self-assembly process was verified to be very successful and gave high yield. None of the micro mirrors were damaged (see Fig. 6 for example) during the assembling process because the applied centrifugal force was small (~$2\text{x}10^{-5}$N for Type I platforms, based on Eq. 1) and did not exceed the maximum tensile strength of polysilicon hinges holding the platforms(our prior work reported in [6]).

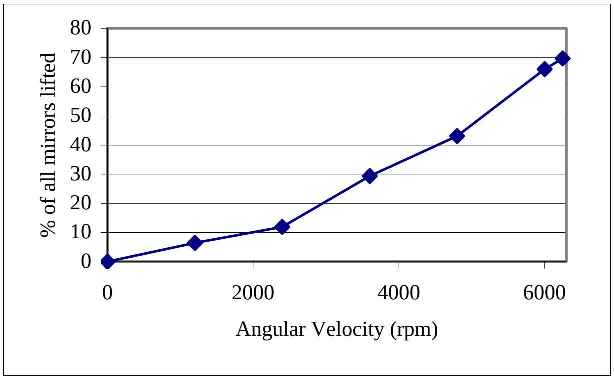


Fig. 9. Percentage of mirrors lifted on a MUMPs43 chip.

V. ASSEMBLY OF MOVABLE MICRO MIRROR

Movable (2-Dimensional) micro mirror has been designed to illustrate that the centrifugal assembly could be applied to assemble complex structures. One unassembled 2D micro mirror is shown in Fig. 10. The center part is the mirror plane which is $200\text{x}200\mu\text{m}^2$, which can be used to perform lightwave reflection. It is surrounding by the supporting structure frame and 8 identical lockers and has an overall size of about $1000\text{x}1000\mu\text{m}^2$ (not including the bond pads). The mirror plane is needed to be lifted up (assembled), so that sufficient space, between the mirror and substrate, could be provided for the mirror to move as shown in Fig. 11. When the mirror moves, the lightwave will be reflected to different directions, such that the mirror could be used as an optical ON/OFF or channel switch. The 2D micro mirror is driven by the electrostatic force between the mirror plane and the substrate.

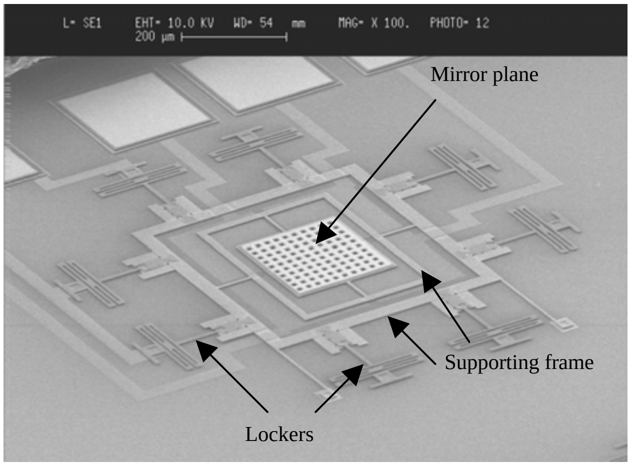


Fig. 10. Isometric view of an unassembled 2D micro mirror.

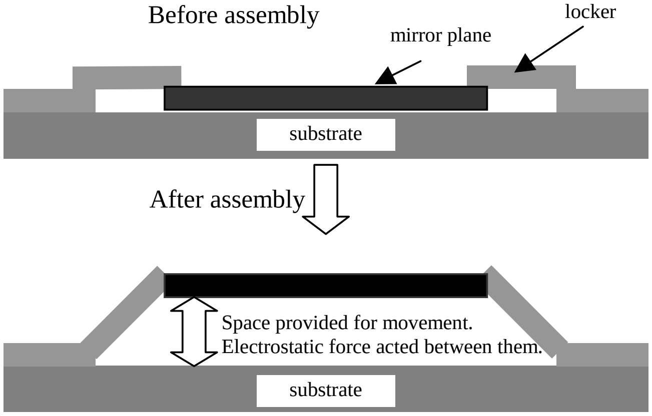


Fig. 11. Conceptual drawing of the side view of a 2D micro mirror before and after assembly.

The fabrication was also done by MUMPs and each chip was diced into 1cmx0.5cm dice. 3x6 micro mirrors were fabricated on each die. One row of micro mirrors was used as "control micro mirrors" that would not be lifted during assembly as shown in Fig. 12.

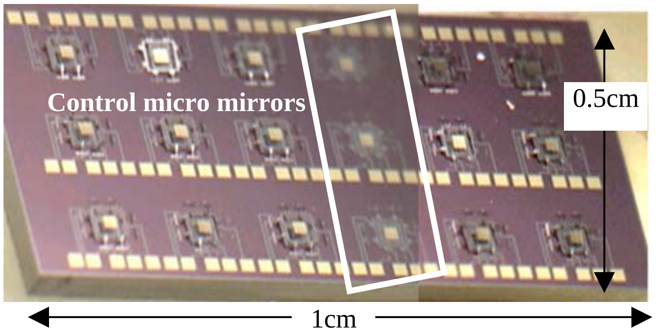


Fig. 12. 2D micro mirrors on each die. One row is used as control micro mirrors during the assembling process.

Six identical dice were tested by the centrifugal assembly running between 4300rpm–4700rpm angular velocity. Neglecting the control micro mirrors, a total of 90 micro mirrors were tested and the results are summarized as shown in Table 2.

Table 2. Results of centrifugal assembly on 2D micro mirrors.

Situation	No.	Percentage
8 locked (fully assembled)	23	25.56%
4-7 locked (partly assembled)	32	35.56%
1-3 locked (partly assembled)	2	2.22%
Not lifted	18	20.00%
Broken	15	16.67%
Total tested micro mirror	90	100%

Although the yield of fully assembled 2D micro mirrors (as shown in Fig. 13) was not as high as the vertical micro mirrors, this is relatively a very good result (25% success rate) compare to conventional manual assembly by micro probes, i.e., often, excessively large force will damage the surface MEMS structures easily. Besides, partly assembled micro mirrors (as shown in Fig. 14) achieved 35% success rate, and they could potentially be fully assembled when angular velocity can be increased to induce larger centrifugal force to lift up the micro mirrors. So, the yield could be potentially increased by increasing the angular velocity.

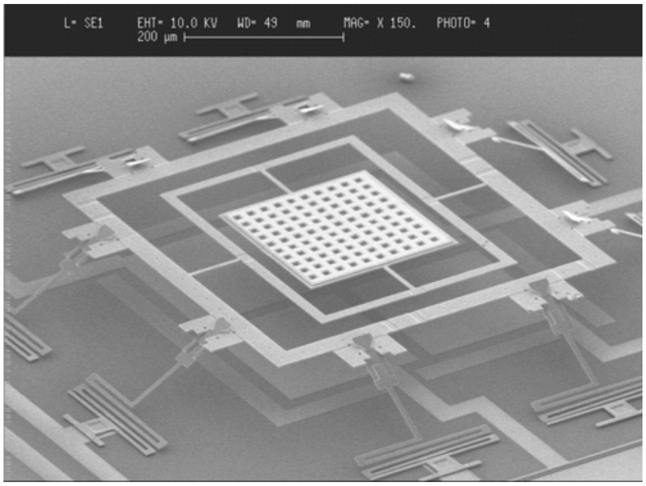


Fig. 13. Fully assembled 2D micro mirror.

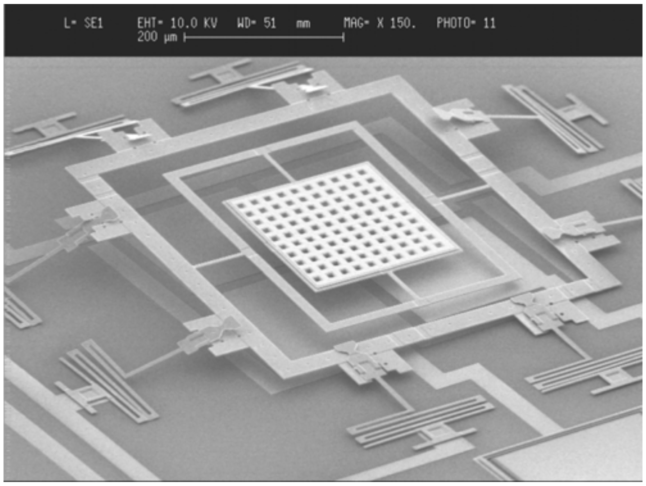


Fig. 14. Partly assembled 2D micro mirror.

The micro mirrors were characterized by measurement microscope, which indicated that they were lifted up to 75-85μm above the substrate after the centrifugal assembly. The micro mirrors were successfully tested to move up and down by voltage between 50-80V AC.

VI. CONCLUSION

Non-contact batch micro-assembly of MUMPs micro structures using centrifugal force was demonstrated. Various MUMPs micro mirrors were rotated about micro hinges autonomously by centrifugal force and vertically locked by latches. Results showed that batch micro assembly by centrifugal force is low-cost and reliable, and give 100% yield when lifting up micro mirrors with 600μmx300μmx4μm dimensions (Type I) without destroying any micro structures. Another kind of dynamic micro mirror (2D mirrors) was assembled successfully using the same process and were actuated using electrostatic force after centrifugal assembly. The assembling process reported in this paper is very low-cost and non-destructive, thus it will provide MOEMS engineers with a quick and convenient way to assemble 3D MOEMS devices.

ACKNOWLEDGMENT

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