OUT OF PLANE MOTION OF ASSEMBLED MICROSTRUCTURES USING A SINGLE-MASK SOI PROCESS

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ABSTRACT

We demonstrate out-of-plane motion of microstructures assembled from parts fabricated in a single-mask Silicon-on-Insulator (SOI) process. Compliant microgrippers used during assembly, in-plane electrostatic actuators, sockets and rotation mechanisms are all defined in the same mask. Advantages of this process include high fabrication yield and very quick fabrication time. We further report on three accomplishments: 1) New rigid sockets, 2) compliant, non-electrically-actuated micro-grippers that pick up parts and automatically rotate them 90^o out-of-plane, and 3) out-of-plane rotation of assembled structures using in-plane electrostatic actuators, demonstrating 17^o of static mechanical rotation to date.

Keywords: Microassembly, pick and place, serial assembly, Silicon on Insulator

INTRODUCTION

Complex actuated micromechanical systems capable of out-of-plane motion have numerous applications in fields like optics and micro-robotics. Such systems can be built in complex multi-layer MEMS processes as demonstrated in [1,2]. There is however a tradeoff available between process complexity (difficulty of wafer-level fabrication) and post-process complexity (chip-level operations). Microassembly of MEMS structures using serial pick and place or various parallel directed assembly techniques has been used to integrate electronics with micro-mechanisms [3] and to construct electromechanical structures [4,5]. We propose to use pick and place assembly to create complex mechanical micro-systems which are difficult to realize with conventional fabrication techniques.

Researchers have investigated the forces which dominate assembly at the micro scale [6] and have come up with various grippers to manipulate small parts [7]. Serial pick and place with specially designed actuated micro-manipulators has been demonstrated [8,9]. After a part is picked up, it needs to be rotated by 90^o before being assembled; this is achieved using a robotic arm in these systems. Using this technique, complex assembled structures for applications such as miniaturized scanning electron microscopes and variable optical attenuators [10] have been demonstrated. However, neither of these groups have quantified the mechanical stability of their connectors against actuation forces.

This paper presents a simple single mask SOI fabrication process to create both the microgrippers needed for assembly and the assembled parts. Microgrippers (hereafter referred to as ortho-grippers) are designed to pick up parts and rotate them by 90^o for assembly into sockets. Two designs of sockets are presented that yield strong mechanical joints. Finally out-of-plane motion of assembled parts is demonstrated using in-plane electrostatic actuators.

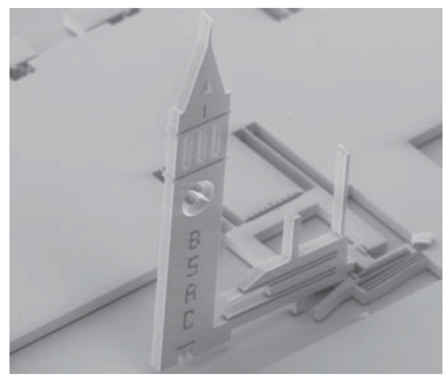

Figure 1: Assembled 645µm tall campanile

FABRICATION

The process consists of a single-mask high-aspect-ratio deep reactive ion etch (DRIE) through the device layer of a custom-made SOI wafer. The wafer consists of a 20µm thick device layer, a 5µm buried oxide layer, and a 300µm handle wafer. Timed HF acid etch and critical point drying steps release the parts from the handle wafer. An entire design cycle consisting of design changes, mask fabrication, part fabrication and assembly of functional devices has been demonstrated in as little as 30 hours.

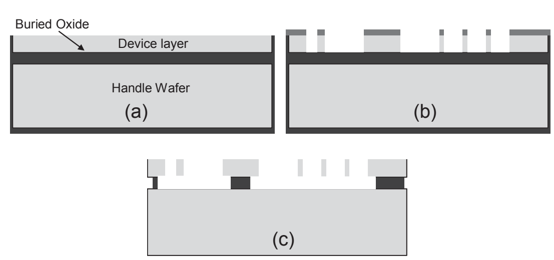

Figure 2: Cross-section of process. SOI Wafer (a) is patterned and etched in a DRIE etcher (b), and released using a timed HF acid etch (c).

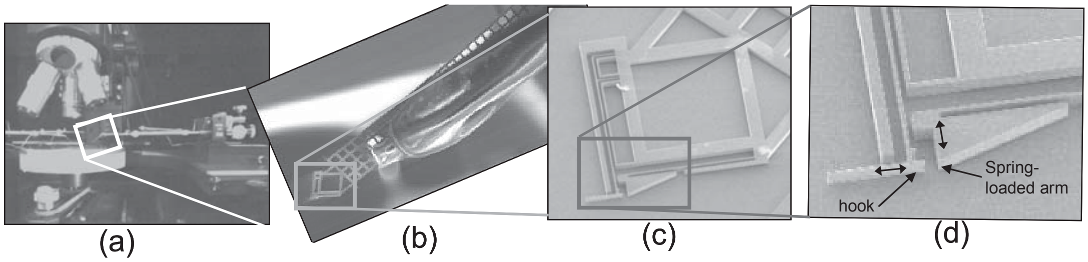

Figure 3: (a) Probe station with 3-axis micromanipulator showing location of probe-mounted ortho-gripper (b) SEM of ortho-gripper mounted on end of probe tip (c) close-up of ortho-gripper end-effector (d) section of ortho-gripper shown schematically in Fig. 4.

ASSEMBLY

Assembly consists of several steps: 1) grasping the part to be assembled using a microgripper, 2) breaking the tether holding the part to the wafer, 3) picking up the part and rotating it 90° out-of-plane, and 4) placing the part into a socket elsewhere on the chip.

Ortho-grippers

The gripping tools described in this section are built using the single-mask process described above. These grippers are equipped with a large (3.8x0.5mm) shaft, to which a standard probe tip is glued using silicone adhesive as shown in Fig. 3(b). As the probe tip is lifted from the surface of the chip, the adhesive force is sufficient to rip apart the tethers holding the microgripper to the chip. The probe tip is then mounted on an X-Y-Z micropositioner as shown in Fig. 3(a).

Ortho-tweezers that grip and rotate microparts using two independently actuated arms have been previously demonstrated [11]. Our novel ortho-grippers, shown in Fig. 3(c), achieve the same motion using spring-loaded actuation in lieu of electrical actuation. This passive design obviates the need for wiring and computer control of the end-effector. The passive rotation capability of the ortho-gripper allows the possibility of automated assembly with 3 axis manipulators with motion and accuracy requirements similar to existing high-speed wire bonders. Previous assembly systems have required more than 3 degrees of freedom [8,9].

The principle of operation of the ortho-gripper is shown in Fig. 4. First, the ortho-gripper is positioned over the part to be assembled. Next, the ortho-gripper is lowered onto the part, pushing the spring-loaded arm onto the top surface. The hook grabs underneath the part. Pushing the part laterally (into the page) breaks the tether attaching it to the chip. Once the tether breaks, the part starts to rotate but is stopped by the substrate. As the part is lifted from the substrate, it continues to rotate until it has reached 90°. It is now ready to be inserted into a socket.

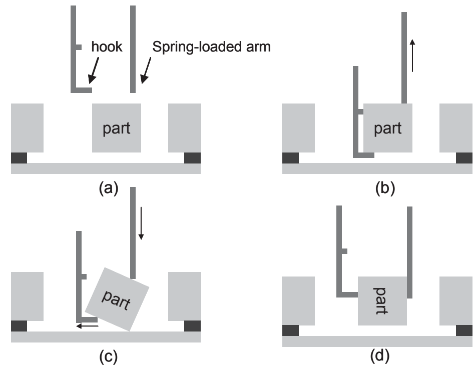

Figure 4: Principle of operation of ortho-gripper

In order to work effectively, the ortho-grippers are designed to meet several criteria: 1) the torque generated by the two springs must always act to continue the rotation motion, 2) the gripping force must be sufficient to grasp the part, yet be low enough to let go after the part is assembled, and 3) the fingers must not slip.

Analysis and observations show that our current designs exhibit finger slippage, but we expect the next generation of ortho-grippers to resolve the slipping problem and increase assembly yield (currently ~30%).

Assembled Parts

The parts are designed to be picked up by the ortho-grippers and assembled into specially designed sockets. The key feature of an assembled part is a square (20µmx20µm) assembly post that is designed to slide into a socket. Additionally, there is a secondary leg that comes into contact with the substrate when the part is about to be inserted into the socket which ensures that the part is horizontal. Once the part is parallel to the substrate, it is slid forward into the socket, passing along a chamfer that guides the part into the socket despite small alignment errors. Finally, the socket latches onto the assembly post and the part is constrained against motion in all six degrees of freedom.

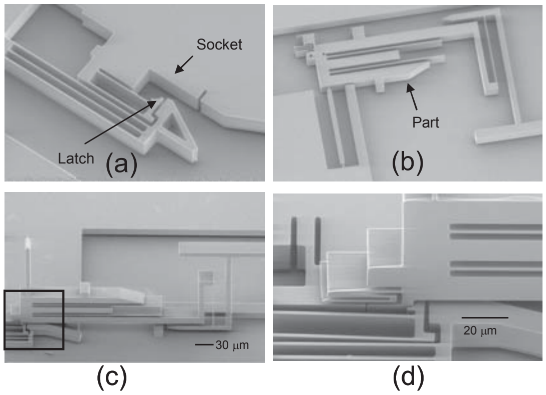

Figure 5: (a) Snaplock socket, (b) part as fabricated (before assembly), (c) assembled part, (d) detail of assembled part

Sockets

The sockets are required to have a low insertion force so that parts can be assembled into them while grasped by the ortho-gripper, yet hold the part firmly while the ortho-gripper is being removed from the part. Most importantly, we would like the assembled parts to be rigid in all directions once assembled to ensure that they can be actuated. Two sockets were designed to meet these constraints.

Snaplock sockets

Silicon latching snap connectors for microassembly were developed in [12]. These connectors demonstrate many of the required characteristics but do not rigidly constrain motion in multiple axes. Our snaplock connector is shown in Fig. 5(a). The latch is forced open during assembly, and closes behind the part after it has been fully inserted. This pushes the part against three flat surfaces: the two sidewalls and either the handle wafer or the device layer, depending on the design of the part. These three surfaces constrain the part's motion in all 6 axes. The latch also provides a spring loading force that ensures that parts are self-centered.

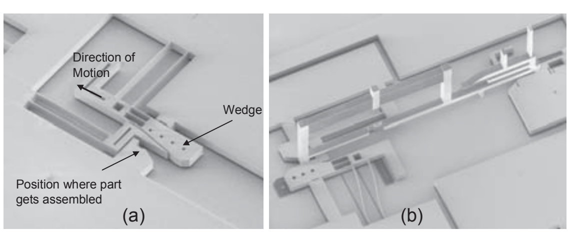

Figure 6: Clamp socket. (a) clamp as fabricated, (b) clamp after assembly. Shadow from gold deposition shows location of wedge before it is engaged.

Clamp sockets

One drawback to our snaplock socket and the socket in [13] is that they do not effectively resist torques applied to the assembled part. In the case of our snaplock socket, this torque forces the flexure open, releasing the part. To combat this problem, the clamp socket in Fig. 6 was designed. After the part is inserted into the socket, the wedge is pushed by a probe, jamming a block against the assembled part. The clamp has also been integrated with other sockets to anchor multiple legs of the same assembled structure. An interesting use of this device would be to provide mechanical stability to a part which is assembled using the connectors in [9].

RESULTS

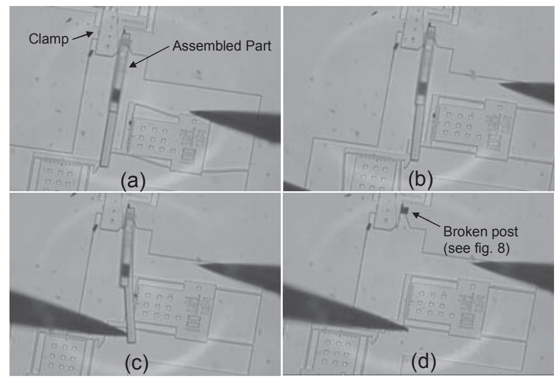

Figure 7: Pullout force test of clamp socket. (a) pulling straight out with 2mN, (b) applying 2mN sideways, (c) pushing directly with probe tip, (d) after part breaks.

Socket performance

The clamping mechanism increases the complexity of the assembly operation since an extra probe is required, but it significantly increases the strength of the connection. We designed a force gauge to test the stability of the assembled part against pullout forces. Both force gauges shown in Fig. 7 can exert a maximum force of 2mN. The assembled structures could withstand the maximum force in x and y directions at a distance of 400µm from the clamp with no adverse effect. Since the test structures could not measure higher forces, the structure was then pushed with a probe tip as shown in Fig. 7(c). The structure showed a stress fracture, breaking without affecting the clamp (Figs 7(d) and 8). Observation of the deflection of the beam before fracture indicates that a force of approximately 5.4mN was applied to it, corresponding to a maximum stress of 1.6GPa at the site of the fracture.

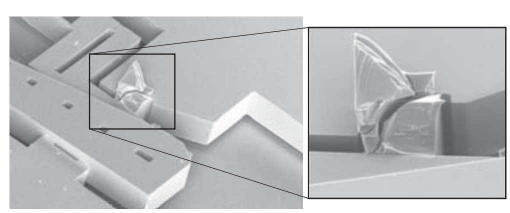

Figure 8: Fragment of assembled part in clamp after stress fracture.

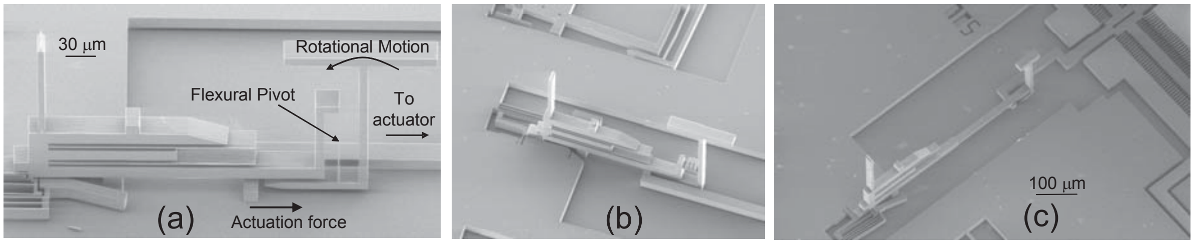

Figure 9: (a) Principle of operation of rotation stage: In-plane force provided by actuators is transformed into rotational motion through a flexural pivot. Actuated rotation stage in (b) achieves 17^o static mechanical rotation. In (c), the interface between the assembled part and an electrostatic comb drive array is visible.

The pullout force of the snaplock socket was measured to be 65 μN. However we believe this number to be an underestimate since one of the flexures on the snaplock used for this test was damaged.

Actuated Mechanisms

One of the long term goals of our microassembly process is to build 2 axis-of-rotation micro-mirrors. Towards this goal, we have tested numerous assembled optical mounts that interface with in-plane electrostatic actuators.

The assembled part in Fig. 9(b) achieved 17^o of static mechanical rotation. Greater rotation was prevented by the pull-in of the electrostatic actuators and we believe that the maximum rotation angle can be increased significantly by minor design modifications. A different rotation stage achieved 4.2^o of static mechanical rotation by applying a force of 7.9μN using in-plane electrostatic actuators. The system was found to resonate at 3.75 kHz and attained a maximum rotation of 5.7^o at resonance.

Future work in this area will include design and testing of a two axis rotation stage followed by assembly of a mirror surface on the rotation stage.

CONCLUSION

The design freedom associated with assembling entire mechanisms out-of-plane expands the design space accessible using simple SOI-based processes. It also enables rotational and vertical-plane motions which are difficult to attain using in-plane structures. We demonstrate novel ortho-grippers, rigid mechanical sockets, and assembled microstructures capable of out-of-plane motion. Future work in our laboratory will optimize the structures for larger angle of rotation, two-axis rotation and vertical motion as well as apply this technique towards building actuated micromirrors and walking micro-robots.

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