Compliant MEMS Device Actuation and Fracture

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ABSTRACT

Compliant MEMS mechanisms are capable of large out-of-plane displacements induced by in-plane actuation. An attempt to actuate one such compliant MEMS device with a nanoindentation apparatus resulted in the slider fracture. In addition to the easily predictable forces associated with the mechanism's elastic deformation, frictional forces become important at the device level, and need to be accounted for. A lateral force of 1.6 mN was necessary to move the slider disconnected from the compliant MEMS device, which is comparable to the forces required to achieve the planned elastic deflections of the device itself. The high frictional forces are attributed to the slider design and the indenter tip conical geometry imparting large normal forces. Unfortunately, the conical geometry can not be avoided when using probe needles for device actuation, thus the slider design needs to be optimized for the probe geometry.

1. INTRODUCTION

Complaint mechanisms consist of compliant members that transfer force, motion and energy [1]. The use of compliant mechanisms can reduce the cost and improve device performance by eliminating pins, joints and springs. Also, compliant mechanisms require less assembly than traditional mechanisms. Compliant mechanisms' use in MEMS has many advantages, as no assembly is required and devices can be fabricated using standard microelectronics manufacturing techniques.

Some MEMS devices are fabricated by micromachining [2], however most of them can not produce three-dimensional motion. In this paper, we investigate a compliant MEMS device that has potential of achieving accurate three-dimensional motion using bistability. Bistable mechanisms tend to move to their stable positions, which represent local minima of potential energy. The compliant MEMS device considered in this paper has two stable positions. The first stable position is in the plane of fabrication and the second position is out of the fabrication plane (Figure 1) [4].

The device was manufactured using the Multi-User MEMS Processes (MUMPs) [3] with polysilicon as the structural material and silicon dioxide as the sacrificial layers. Silicon nitride was used as the dielectric material between the silicon substrate and the polysilicon.

2. RESULTS AND DISCUSSION

Figure 1 shows two stable positions of the four-bar compliant MEMS device. The device consists of three major parts: two sliders and one compliant spherical four-bar mechanism. Link R2 is the input link, while both R2 and R4 links are attached to the substrate surface by hinges [4]. The sliders are designed to actuate the device and are connected to the link R2. Ideally, when the raising slider is moved to the left, links R2, R3 and R4 will move out of the plane, while moving the lowering slider to the right causes the structure to go back to its original in-plane position.

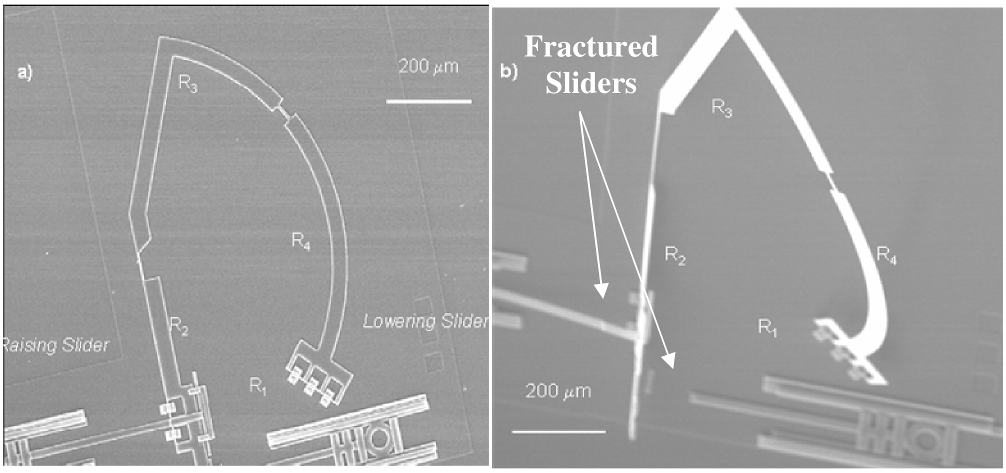

Figure 1. SEM images of a) the first in-plane stable position and b) the second actuated stable position of the compliant MEMS device [4].

When the raising slider was moved by the probe, the whole structure came out of the plane into the second stable position, however, the sliders were broken (Figure 1b). Finite Elements simulations based on the mechanism geometry predict that it should be actuated with less than 1 mN lateral force. In order to obtain the force-displacement characteristics of the compliant MEMS device, we had previously attempted to use the Hysitron Triboeindenter equiped with the Bekovich tip to actuate the device. This attempt was unsuccessfull, as the slider ring fractured during the scratching process, and the raising slider did not move [4]. In this paper we initially tested the slider disconnected from the four-bar mechanism. The experiment was conducted using the Hysitron Triboindenter with a 1 μm tip radius conical indenter operating in the scratch mode. First, the center of the slider hole was located using in-situ topograhical imaging, after which a scratch was performed. The input normal force and the lateral displacement profiles are shown in Figure 2. The slider was moved several times in one direction by repeating the scratching process.

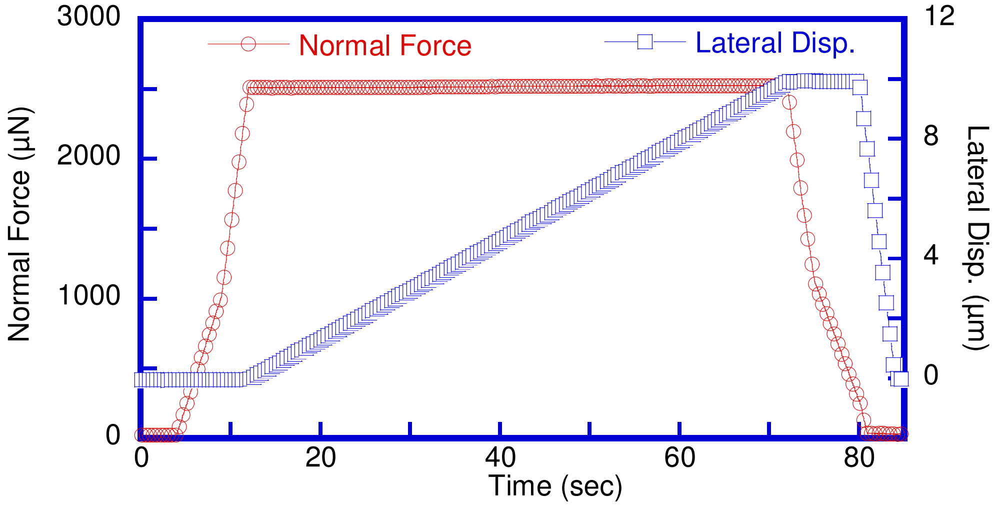

Figure 2. Normal force and lateral displacement profiles for the slider motion scratch test.

Figure 3 shows the normal and lateral forces vs. lateral displacement during a 10th consequent 10 μm scratch. Stick-slip motion is observed when the tip scratches the polysilicon substrate (~0.1 friction coefficient) and later when it moves the slider (0.6-0.9 friction coefficient). A friction coefficient of 0.22 has been measured between diamond-like carbon (DLC) rider and a polysilicon disk at a larger scale [5]. Stick-slip slider motion may be caused by high friction forces in the slider, which was successfully moved in this case (Figure 4). Before and after each scratch test, a topography scan was taken using the Triboindenter scanning mode (in-situ imaging) as shown in Figure 4. During the initial scratch the slider was moved at 2.5 mN lateral force due to stiction, as opposed to the 1.6 mN during the 10th scratch (Figure 3).

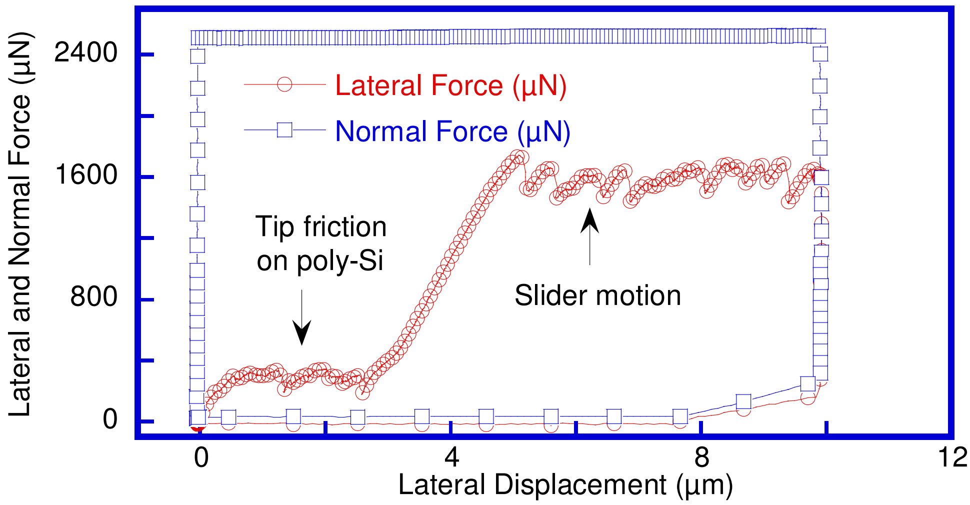

Figure 3. The lateral force vs. lateral displacement of a disconnected slider showing stick-slip motion.

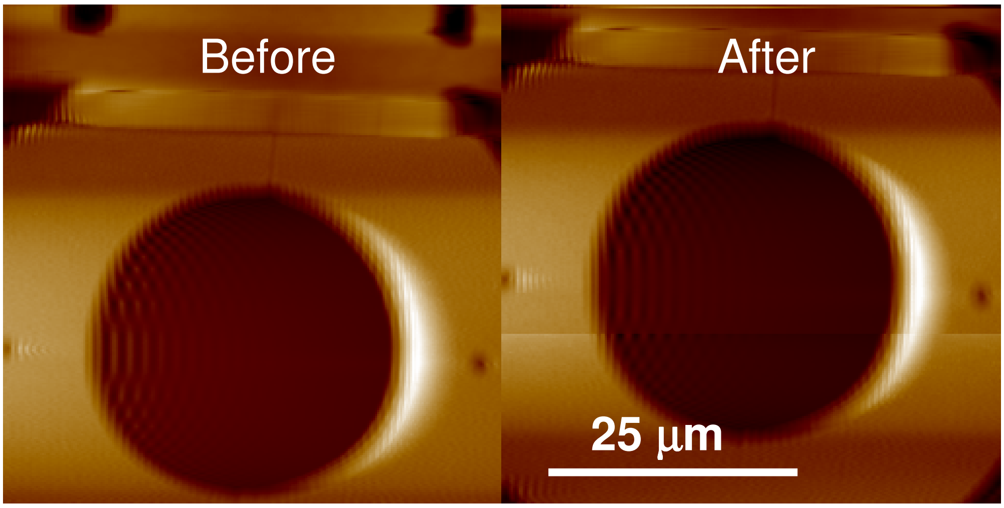

Figure 4. Topography images of the slider ring before and after the scratch.

Figure 5 presents the scratch results obtained from the slider connected to the MEMS device. The scratch exhibits similar stick-slip motion up to 24 seconds, which corresponds to 4 µm lateral displacement, and then the lateral force sign reversal corresponds to the device fracture.

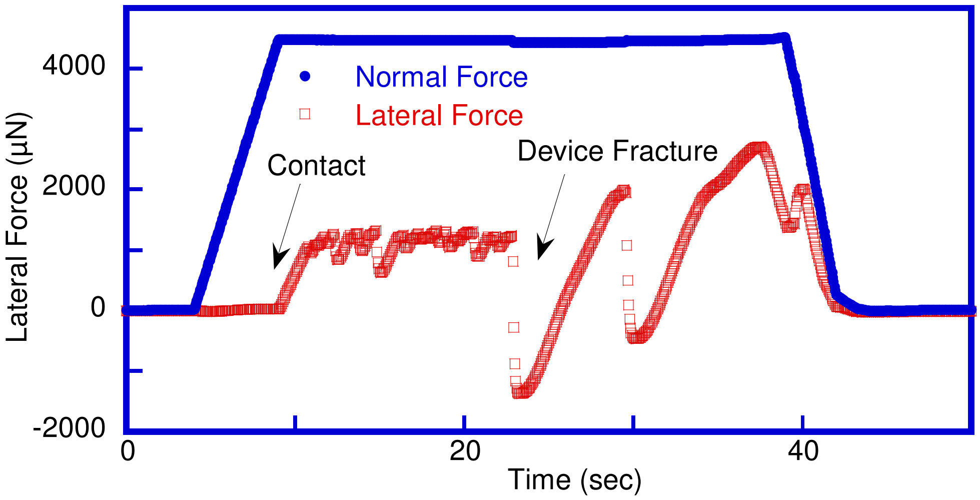

Figure 5. Lateral and normal forces obtained from the slider connected to the MEMS four-bar mechanism.

It is interesting to note that the lateral loading stiffnesses are similar between the disconnected and the connected sliders. Figure 6 shows that the loading stiffnesses of the connected and disconnected sliders are comparable, which originate from the localized contact between the indenter tip side and the edge of the slider ring. Since the compliant MEMS device was not moved, the measured behavior is controlled by the high slider friction.

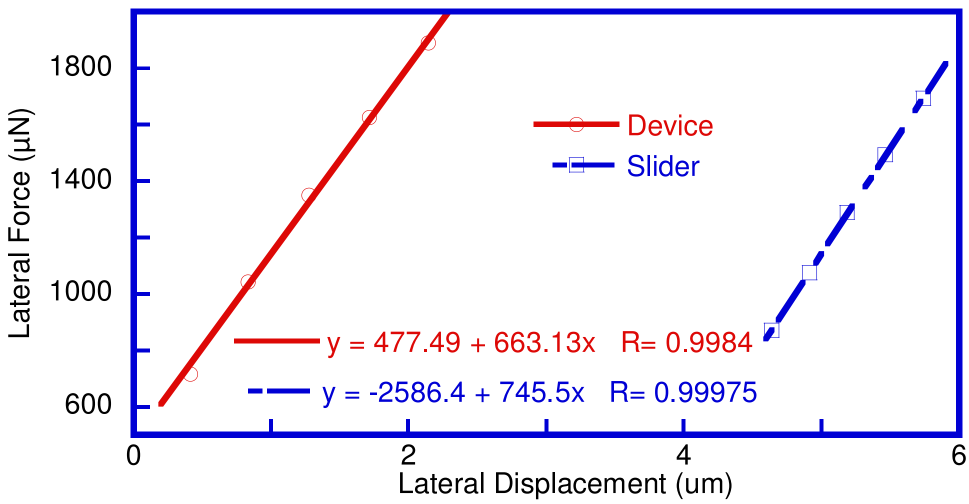

Figure 6. The loading slopes from the slider connected (circles) and disconnected (squares) from the MEMS device.

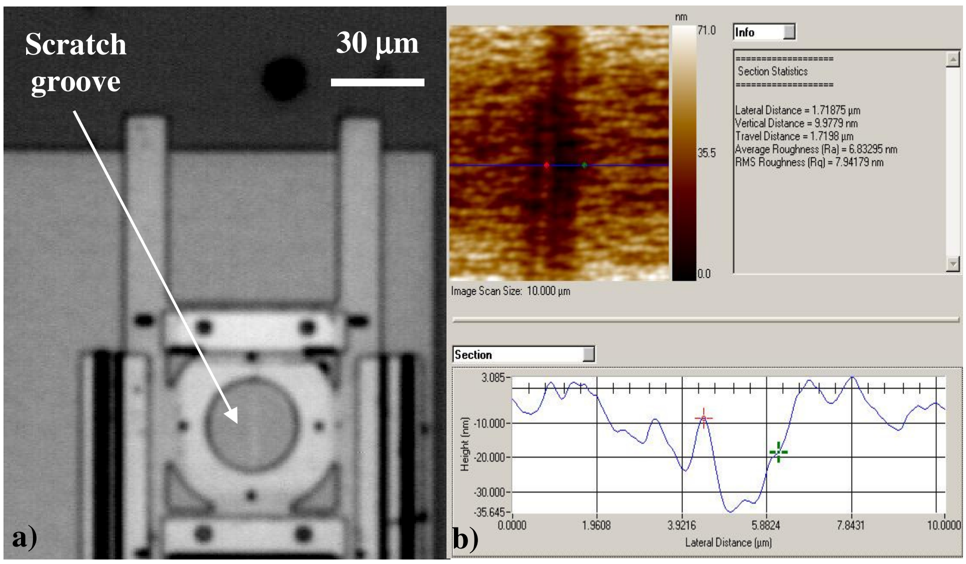

Figure 7. a) Optical image of a scratch groove; b) Topography image and the cross-section profile of the scratch groove.

Closer inspection of the moved slider showed a scratch track left in the middle of the slider ring (Figure 7a). It was initially attributed to the indenter tip scratching the polysilicon substrate. Figure 7b shows the topographical scan of the scratch groove in the polysilicon substrate. The track width is 2 µm, and it is about 10 nm deep. The track profile does not correspond to the indenter tip geometry. One of the possibilities is that the front spacer under the slider (Figure 9) scratches the substrate due to the high normal forces induced by the indenter tip, causing high friction. The spacer width and length is 2 µm, thus the polysilicon substrate and the spacer could be subjected to stresses in excess of 1.4-5 GPa polysilicon fracture strength [6, 7], resulting in the observed scratch groove. Friction between polysilicon surfaces can be quite high, especially if wear is involved [8].

Normal and lateral forces are interdependent because of the conical indenter tip geometry, thus during normal indentation, without scratching there will be a lateral force component originating from the normal force. Similarly, the lateral force will reduce the normal force upon contacting the slider ring, as there will be normal force component acting in the opposite direction from the normal force applied by the indenter.

It would be beneficial to increase the spacers contact area in order to decrease the induced contact pressure on the substrate, and thus reduce friction. The other option would be to use an indenter tip with smaller included angle, or a cylindrical flat punch with the diameter close to that of the slider hole.

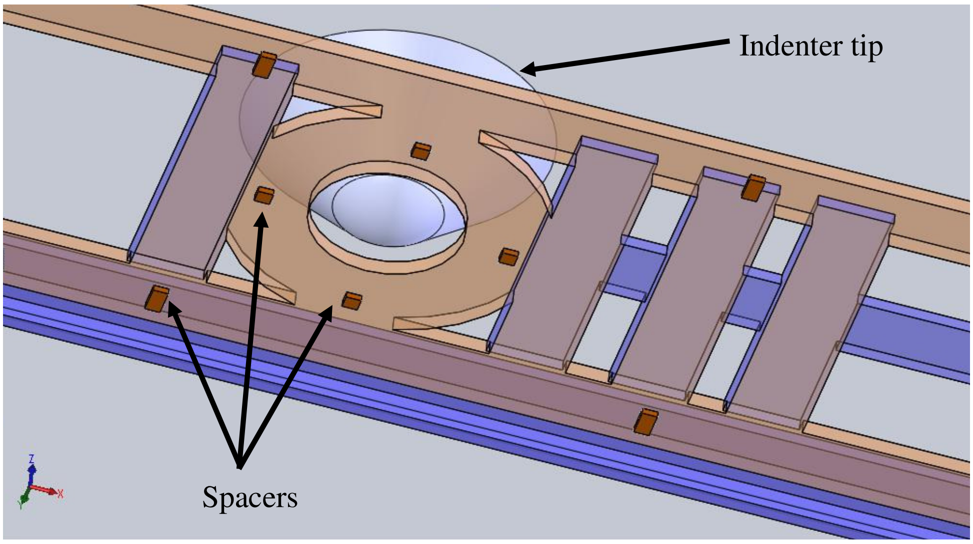

Figure 8. The spacers underneath the slider.

3. CONCLUSIONS

The slider connected to the four-bar compliant MEMS mechanism was scratched using the nanoindenter conical tip. MEMS device could not be successfully actuated using this procedure, and fractured. However, motion of the disconnected slider was achieved initially at the lateral force of 2.5 mN, and later at 1.6 mN, which is over two times higher than the calculated force to cause the elastic deflection of the compliant mechanism between its stable states. The slider’s high frictional forces are possibly caused by the spacers, which scratch the substrate. The friction in the slider should be reduced by increasing the spacers contact area. Using a cylindrical flat punch with the diameter close to the slider hole’s diameter may be also beneficial for actuating these devices.

4. ACKNOWLEDGEMENTS

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