Cyclic deformation and nano-contact adhesion of MEMS nano-bridges by in-situ TEM nanomechanical testing

A J Lockwood¹, M S Bobji², R J T Bunyan³ and B J Inkson¹

¹ Dept. Engineering Materials, University of Sheffield, Sheffield, S1 3JD, UK
² Dept. of Mechanical Engineering, Indian Institute of Science, Bangalore, India
³ MEMS Division, QinetiQ, Malvern, WR14 3LG, UK

Email: a.lockwood@sheffield.ac.uk

Abstract. MEMS nano-bridges fabricated by FIB have been deformed in-situ in the TEM. The polysilicon bridges show high levels of flexibility but also, at increased indentation depths, residual plastic deformation after fully unloading the bridges. Here, a significant number of cycles were applied to the centre of a bridge by a W-probe. This resulted in the formation of an adhesive contact with the W-probe. On unloading the nano-bridge regained its original shape and then deformed upwards, adhered to the W-probe. A significant high tensile force of \(-17 \mu N\) was required to sever the nano-contact. Analysis of the W-probe and polysilicon nano-bridge indicate that carbon migration along the W-probe and local contact heating due to the associated fatigue cycles were responsible for the adhesive bond, with initial carbon contamination layer on the W-probe of 2nm, thickening during the loading cycles to 25nm.

1. Introduction

The mechanical response of nanoscale structures and nano-contacts, including those used in microelectromechanical systems (MEMS), are not simple to characterise individually because of the difficulty in locally selecting and applying a mechanical load to the area or object of interest. Here, a specifically designed nanomanipulation and nanindentation/nanomechanical test holder has been built for in-situ transmission electron microscope (TEM) studies, which allow a sharp probe to be brought into close proximity and to contact a structure. The holder uses an ultra miniaturised slip-stick coarse positioner and fine piezoelectric tube to manipulate a probe inside the TEM [1]. Fine position (within <2\(\mu\)m) and the final programmable cyclic or single loading indentation process is achieved by using a fine piezoelectric tube with quartered external electrodes [2].

There are many mechanisms documented regarding MEMS failure [3-7]. One in particular is stiction, which is caused by static pull down of components [3, 4]. This is generally seen in devices with low stiffness and very high surface to volume ratios, such as cantilevers or RF switches. Stiction failure is not generally seen in MEMS nano-contacts or devices designed with high stiffness that are able to self release from the attractive forces of their contact pads.

Here we use a W-probe to form a metallic-silicon nano-contact with a polysilicon MEMS nano-bridge typically seen in some MEMS applications [8]. Nano-scale movement of the W-probe is used to cyclically deform the nano-bridge over >3000 cycles.
2. Sample preparation
Polysilicon MEMS cantilevers of micron dimensions were fabricated in a standard 300nm thick process by QinetiQ. For in-situ TEM to be successfully performed, these cantilevers were post patterned and machined by 5keV focused ion beam (FIB) to generate a set of uniform suspended bridge type structures with a minimum feature size ~100nm (Figure 1(a)). The polysilicon nano-bridge investigated here had dimensions of \(x=3040\text{nm}\) and \(z=115\text{nm}\), supported by a leg at either end with dimensions of \(x=180\text{nm}\) and \(z=1220\text{nm}\). The as deposited thickness (y-direction) was 300nm and formed a columnar grain structure with an average grain size of 50–100nm.

![Figure 1.](image)

3. In-situ experimental procedure
The coarse positioner of the in-situ nanomanipulator was used to bring a tungsten tip with an end radius of ~25nm into close proximity (<1µm) of a polysilicon bridge structure. Fine position and precise alignment was performed by altering the applied voltage across the opposing electrodes of the fine piezo tube. A programmed indentation was performed along the z-axis by applying a uniform voltage across all quadrants of the piezoelectric tube with some small degree of \(x, y\)-scan offset to ensure the tip trajectory remained perpendicular to the bridge cross-beam (Figure 1(b)).

3.1. Single loading of a nano-bridge
Two displacement controlled indentations of +250nm at a rate of ~5nms\(^{-1}\) were applied to a polysilicon bridge (Figure 2(a)). The first indentation cycle (shown in light grey) resulted in the bridge deforming by a maximum of +205nm with a relatively elastic response, regaining its original shape and position after unloading. The second indentation cycle (shown in dark grey) showed increased deformation resulting in the bridge displacing by +215nm. The unload curve did not match the loading curve as closely as the first indentation, and the bridge developed a residual plastic deformation of ~+25nm.

3.2. Cyclic loading of a nano-bridge
A third indentation was made on the nano-bridge (Figure 2(b)), and reached a maximum load of ~40µN (Figures 2(b) and 3(a)) before it showed some evidence of plasticity in the load-displacement curve, resulting in a gradual drop in load to ~24µN and final indentation displacement of +235nm (Figure 3(b)). At this point, a large number of sinusoidal cycles were applied to the structure (applied position: +250nm\(\leftrightarrow+150\text{nm}\), 600× at ~1Hz and 2750× at ~2Hz). During the cyclic loading which took over 25 minutes to perform, some piezo drift resulted in an unloading of the bridge from +235nm to +176nm (Figure 3(c)), equivalent to <3nm/min. After this, the bridge was fully unloaded at a rate of ~20nms\(^{-1}\). During unloading of the nano-bridge, the load suddenly dropped by 7µN over 4nm (Figures
2(b) and 3(d)) and changed from compressive to tensile at 103nm displacement from the original beam position. At the point of zero applied load, we can estimate the residual deformation at the centre of the cross-beam to be ~+100nm.

The load applied during the tensile unloading portion of the curve was calculated to reach a maximum tensile value of ~17µN where it was seen that the beam had been pulled past its original position by ~100nm (Figure 3(e)) and distance ~200nm from the zero load position. As the contact fractured, the bridge instantly sprung back to a position of residual plastic deformation of +50nm (Figure 3(f)). This is less than the estimated residual deformation of +100nm before the tensile loading to the beam, and indicates that the applied tensile loading causes microstructural changes in the bridge (Figure 3(f)). No further time dependant recovery was evident after several minutes of zero applied load.

As previously seen [2, 9], the residual plastic deformation present after fully unloading the bridge was evident as a gentle residual curvature along the entire length of the cross-beam, suggesting that the deformation was more actively widespread than just the local contact region (Figure 3(f)). Maximum lateral deformation (x-axis) of the two supporting legs was also measured to be ±56nm, but no residual deformation was seen as they regained their original morphology on unloading.

4. Formation of a probe – nano-bridge bond
The tensile section of unloading was a result of the tip becoming strongly adhered to the beam. This adhesion has only been seen with cyclic loading, and has not been observed in any single loading test. The level of adhesion excludes mechanisms such as van der Waals or electrostatic attraction being proposed as the dominant adhesive force and here we can say that the two objects are mechanically bonded to one another. Throughout the entire sequence the tip did not show any significant penetration into the cross-beam (<4nm), and there was no evidence of delamination of the cross-beam. TEM imaging does however show a significant increase in thickness of the carbon shell around the tip. Initially this carbon rich layer is measured to be <3nm in thickness and fairly uniform throughout, but during cyclic loading, increases up to +25nm.
After separation, no additional carbon was observed on the surface of the cross-beam at the contact point and all the migrated carbon remained attached to the tip. It should also be noted that the W core of the tip did not deform at any point throughout the applied cyclic loading and the only morphology difference was the increased thickness carbon shell.

Figure 3. A sequence of images extracted from a video recording showing the deformation stages during the third indentation and fatigue cycles. (a) The bridge at peak load, (b) after some plastic deformation and load reduction prior to the applied fatigue cycles, (c) the nano-bridge after the applied fatigue cycles, (d) during unloading at the point of zero applied load, (e) maximum tensile load and (f) residual deformation after full separation.

5. Conclusions
A W-probe was brought into contact with a polysilicon MEMS nano-bridge to form a metallic-silicon nano-contact. The probe was used to deform a flexible polysilicon MEMS nano-bridge in both single indentation and programmed cyclic loading modes. During single indentation and unloading, the beam initially behaves elastically with only some minor residual plastic deformation <25 nm. However, during applied cyclic loading over more than 25 minutes, significant carbon migration around the W-probe increased the nano-contact area by a factor of more than 30×, resulting in the tip becoming strongly adhered to the nano-bridge and allowing the probe to pull the cross-beam with a tensile force of –17 µN during unloading past the original bridge position by –100 nm, and –200 nm past the point of estimated residual plastic deformation.

Here we have demonstrated that carbon contamination, which is present on all surfaces exposed to air, can have a significant influence on the performance of MEMS/NEMS structures and their contacts. Applied cyclic loading and the associated heating can lead to significant contact adhesion between MEMS contacts of only a few nanometres in radius.

6. References
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