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TECHNICAL PAPER

De-tethering of high aspect ratio metallic and polymeric MEMS/NEMS parts for the direct pick-and-place assembly of 3D microsystem

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Abstract We report our study on several de-tethering methods for various high aspect ratio metallic and polymeric MEMS and NEMS parts including 5:1 aspect ratio 50 μm thick metallic (nickel) MEMS parts, 3:1 aspect ratio 1 μm thick sub-micron (350 nm) feature size metallic NEMS actuators, and 10:1 aspect ratio 100 μm thick polymer/metal bi-layer MEMS actuators. Resistive heating was found to be effective for the de-tethering of high aspect ratio metallic MEMS parts. In order to de-tether metallic NEMS parts and polymer/metal bi-layer devices, we performed the milling of tethers using a focused ion beam. Very low current (20 pA) ion beam was found to be effective means of de-tethering the metallic NEMS parts. Relatively larger current (0.3–20 nA) ion beam was found to be good for the polymer/metal bi-layer parts. We demonstrated 3D assembly and complete packaging of the de-tethered high aspect ratio metallic and metal/polymer bilayer MEMS parts.

1 Introduction

Micro-assembly of MEMS devices is indispensable for achieving complex three dimensional structures that cannot be fabricated by direct lithography techniques. True 3D assembled micro systems consisting of various functional MEMS parts are of interest as they may open unforeseen window of opportunities for a wide variety of MEMS applications.

Fold-up assembly of surface micromachined parts using polysilicon microfabricated hinges (Pister et al. 1992) has been one of the most popular approaches to realize 3D assembled microsystems. However, such an assembly technique has limited freedom of 3D assembly as micro parts fabricated on a substrate only folded-up out-of-the plane of the wafer and assembled manually using lock-in mechanism. In addition, choice of materials and choice of fabrication processes are limited as micro parts are fabricated in one substrate.

Tsui et al. (2004) demonstrated complex 3D assembled microstructures by an automated direct pick-and-place assembly of 50 μm thick single crystal silicon structures fabricated by deep reactive ion etching (DRIE) process using a 5 degree of freedom manipulation stage. With accurate design of end-effector, flexures and a suitable micromanipulation set-up, this is a highly repeatable method for assembling 3D silicon MEMS devices.

For the direct pick-and-place assembly, micro parts on a substrate should lie tethered to the substrate to prevent them from floating away after sacrificial layer removal process and must be de-tethered from the substrate for subsequent assembly. The design of the tethers and the mechanism of de-tethering are dependant on the material of the device, dimension of the device and the method of subsequent assembly of the device. Single crystal and polycrystalline silicon are among the most widely used materials in MEMS due to their highly developed micromachining technology. Silicon is a brittle material and hence can be broken with the application of optimum force on the structures using end-effectors of manipulators. Singh et al. (1999) performed transfer and assembly of

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microstructures by breaking polysilicon tethers after cold-welding the polysilicon microstructures to indium solder bumps on the target substrate. Dechev et al. (2004) used solder bonding to break tethers of their polysilicon microgrippers. These micrograppers were used to grip fabricated micro parts and to remove them from the substrate by breaking their tethers. Faheem et al. (2004) incorporated necking features in the tethers to demonstrate pre-assembly release of PolyMUMPS devices.

Polysilicon devices, due to their higher electrical conductivity than the single crystal silicon devices, can be released not only by the stress induced method but also by using thermal techniques. Fedder et al. (1991) demonstrated thermal assembly of polysilicon microstructures by using polysilicon microbridges as fuses. A 100 µs, 0.3 A current pulse was found to be sufficient to sever a tee-bridge polysilicon fuse. Chiu et al. (2006) used two fuse-tether designs to demonstrate de-tethering of polysilicon MEMS devices by applying a current pulse of the order of a few microseconds.

The focus of this paper is to discuss the various de-tethering methods suitable for different types of micro-components like metallic MEMS, metallic NEMS and polymer/metal bi-layer MEMS parts. Unlike single crystal and polycrystalline silicon MEMS devices, stress-based de-tethering method typically does not work for metallic and polymeric MEMS devices as these materials are not brittle. We have identified resistive heating and focused ion beam assisted de-tethering as the suitable candidate for de-tethering of these devices. The assembly of one of such MEMS devices has also been demonstrated.

2 De-tethering of high aspect ratio thick metallic MEMS devices

Metallic MEMS devices are made typically using surface micromachining techniques in which a lithographically patterned photoresist mold is electroplated with metals or metal alloy. Thin (2–10 µm thick) metallic MEMS devices can be de-tethered by applying force using a tungsten probe. But in order to de-tether thick (>20 µm thick) metallic MEMS devices, such mechanical means are not reliable. Since metals are ductile, mechanical stress applied for de-tethering of relatively thick metallic MEMS devices typically results in deformation of the metallic tethers rather than severing of the tethers. Figure 1 shows an optical image of a deformed 50 µm thick metallic tether by mechanical force applied with a tungsten probe.

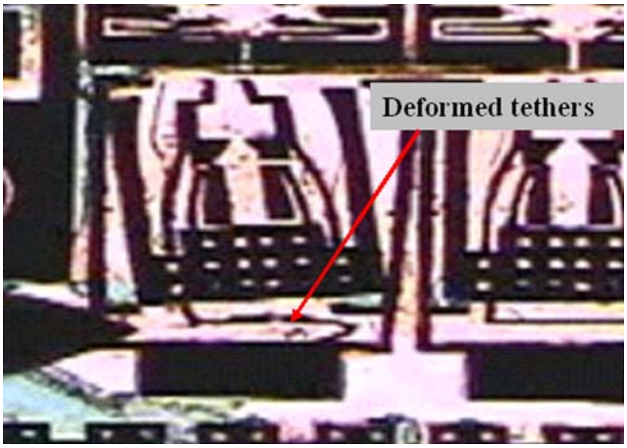


Fig. 1 50 µm thick Nickel micro-component with tether deformed on applying stress

In order to de-tether such thick metallic MEMS parts, we injected high current across the tethers to de-tether 50 µm thick nickel microparts by resistive heating. Figure 2a shows the de-tethering of one such nickel micro-component by applying current using a tungsten probe. Such a de-tethered nickel micro part was picked, rotated and placed by a micro gripper attached to a 5 degree of freedom manipulation stage. Figure 2b shows the 3D micro-assembly of a released high aspect ratio metallic MEMS structure.

3 De-tethering of metallic nems and polymer/metal bilayer MEMS devices

The scaling down of microelectromechanical system (MEMS) technology to nanoelectromechanical systems (NEMS) has been gaining great interest for the past few years. Recently, we reported fabrication and characterization of a sub-micron high aspect ratio (1 µm thick, 350 nm feature size) metallic electrothermal actuators using a combination of electron beam lithography and electroplating techniques (Lee et al. 2005) and an electrothermally actuated metallic sub-micron gripper (Lee et al. 2006). Studies on scaling down of MEMS devices provide opportunity as well as challenges. For the de-tethering of metallic NEMS devices, initially, resistive heating method was tried. But due to the very narrow cross-section (2 µm wide, 1 µm thick) of the tether, even with extremely small amount of applied current along the tethers, most areas of the device of the metallic NEMS were severely damaged by burning. Hence, an alternative method of the de-tethering using focused ion beam milling described in the next section was investigated.

Polymer MEMS devices are gaining prominence these days due to the incompatibility of metals for different applications, primarily those used for biological manipulation. One such polymer widely used in MEMS is SU-8, an epoxy based negative photoresist. SU-8 has a high coefficient of thermal expansion (~52 ppm/°C), cross-links on exposure to UV radiation and becomes structurally

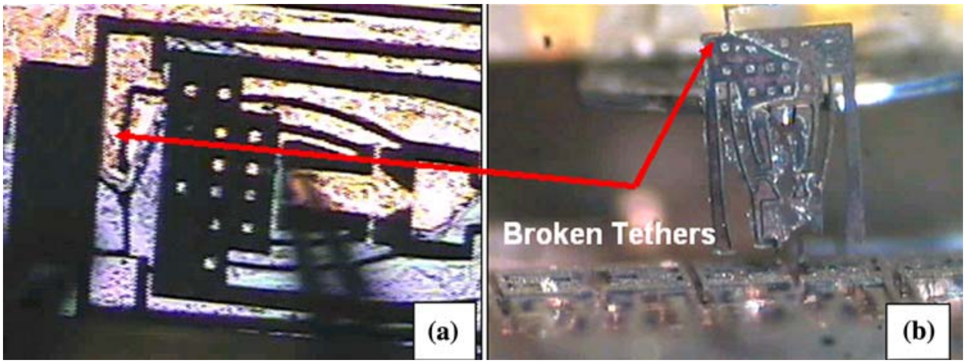


Fig. 2 **a** 50 micro meter thick Nickel micro-component with tethers broken by passing high current;**b** de-tethered micro-component picked and assembled onto a 3-D microsystem

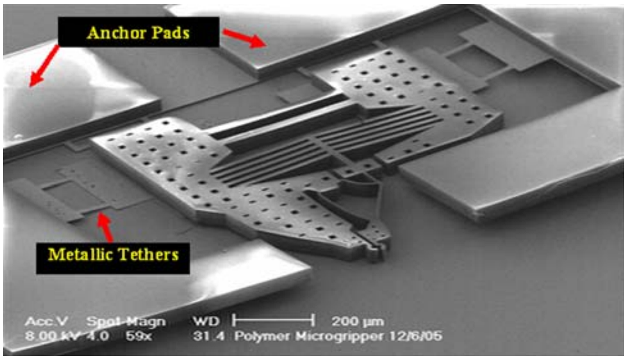


Fig. 3 A partially released polymer gripper tethered to the anchor pads on the substrate using thin metallic tethers

rigid on baking at high temperatures (Lorentz et al. 1998). SU-8 is stable up to 380°C, after which it starts to degrade (Labianca et al. 1995).

Since SU-8 is an insulative polymer, for applications where it needs to be electrically heated, it's mostly integrated with a metallic heater layer. One such application is an electrothermally actuated polymer microgripper as shown in Fig. 3 (Colinjivadi et al. 2006). This consists of a 2 µm thick electroplated gold layer which heats up a 50 µm thick SU-8 layer on application of a voltage ranging from 0.1–1 V. These devices are fabricated on a silicon substrate by a typical surface micromachining process using a 5 µm thick low temperature oxide (LTO) as a sacrificial layer. Using a timed release process in 7:1 buffered oxide etch solution, these devices are partially released such that they lie suspended from huge anchors on the substrate through metallic or polymeric tethers. Figure 3 shows the SEM picture of a polymer/ metal bi-layer gripper which lies tethered to anchor pads on the substrate through thin metallic tethers.

This partially released device was attempted to be detethered similar to the metallic MEMS devices—by passing current through the metallic tethers. The high current required to melt the metal across the tether resulted in the heating up of the SU-8 polymer, causing it to be damaged. Figure 4 shows the effect of passing high current through the tethers on the metal/SU-8 interface. In order to understand the temperature distribution through the polymer when a high current is applied through the metallic tethers, finite element modeling was performed using Ansys. It was observed (Fig. 5) that a temperature of about 1,453°C required to melt the nickel tether raised the temperature in the polymer layer to as much as 500°C which is highly detrimental to the SU-8 polymer.

It is evident from Fig. 3 that the thin metallic tethers are not efficient in effectively suspending the bulky polymer/ metal bi- layer device as they result in sagging of the device. Hence, the preferable method to anchor these devices would be by using tethers made of the same polymer layer as the device. But such thick polymer tethers

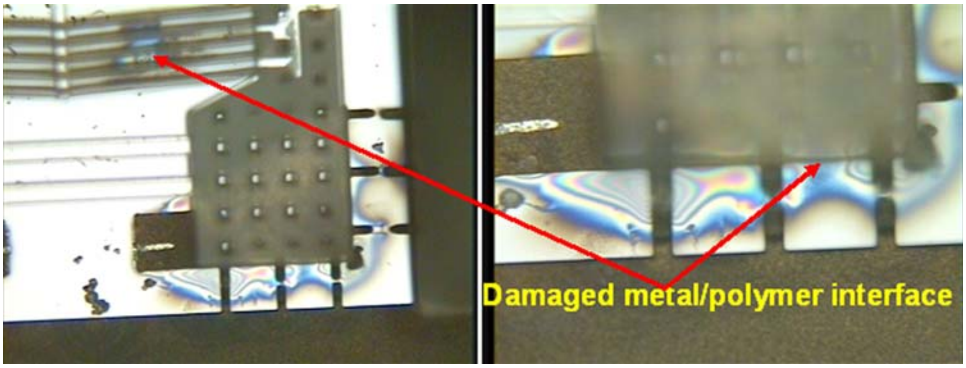


Fig. 4 De-tethering of Polymer/ metal bi-layer devices by passing current

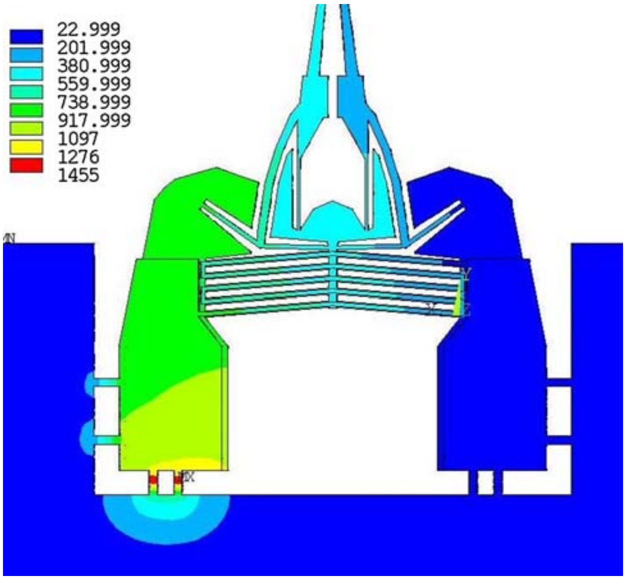


Fig. 5 Finite Element Modeling results showing temperature distribution along the polymer layer

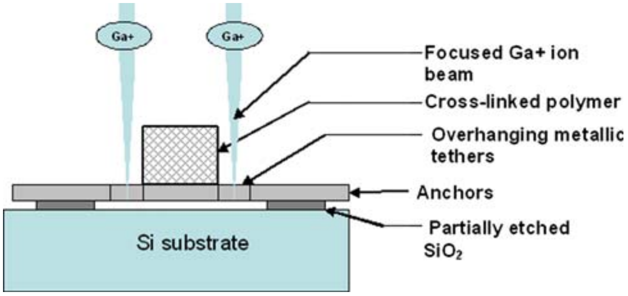


Fig. 6 Focused ion beam milling of metallic tethers to release polymer/metal bi-layer device

cannot be broken by resistive heating or by applying force without compromising the metal/ polymer interface. Hence, the assembly and packaging of such polymer/metal bi-layer devices calls for a de-tethering method that avoids any mechanical or thermal damage to the interface.

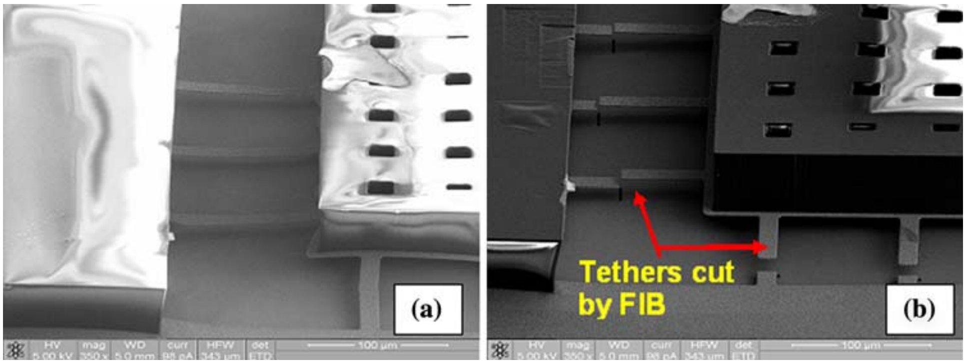
4 Focused ion beam assisted de-tethering

Focused ion beam (FIB) is extensively used for milling of transmission electron microscopy (TEM) samples to obtain their cross-sections and also for nano-patterning and nano machining. Since FIB uses highly focused beam currents ranging from a few pA to nA, most areas of the device are not heated to a high temperature. Since the ion beam diameter is on the order of a few nm, the mechanical impact caused on a MEMS device is also negligible. Considering the advantages of the FIB and the constraints in de-tethering of the polymer/ metal bi-layer devices and metallic NEMS devices, we studied the milling of the metallic and polymeric tethers of these devices using FIB.

Dual column FEI Nova 200 Nanolab FIB system was used for our experiments. The sample was mounted onto the stage and tilted to 52 degrees so that it was oriented normal to the ion beam. The current of the ion-beam was suitably adjusted depending on the material and thickness of the tethers. The beam was focused along the width of the tether for sufficient duration to completely sever it. Depending on the number of tethers holding the microdevice, the time for de-tethering a single device varied. Figure 6 shows the schematic for focused ion beam milling of a polymer/metal bi-layer device. Figure 7 shows SEM pictures of the polymer/metal bi-layer device before and after de-tethering using FIB. We can observe that the FIB induced cuts of the thin metallic tethers were clean without any residue and did not damage the surrounding part of the device.

A typical polymer cannot be distinctly milled or patterned along a thicker cross-section using the FIB as the surrounding polymer bonds might not be strong enough to withstand the localized heating by the Gallium ions of the ion beam. But, SU-8 is a structurally rigid polymer which becomes stronger when hard baked at 140°C to complete its cross-linking. Hence, thick SU-8 tethers could be effectively milled using the FIB. Figure 8a, b shows SEM pictures of 50 and 100 μm thick SU-8 tethers that have been cut completely across their cross-section using the

Fig. 7 **a** Polymer/metal bi-layer device suspended from anchor pads by metallic tethers **b** Complete release of the device by cutting metallic tethers using focused ion beam



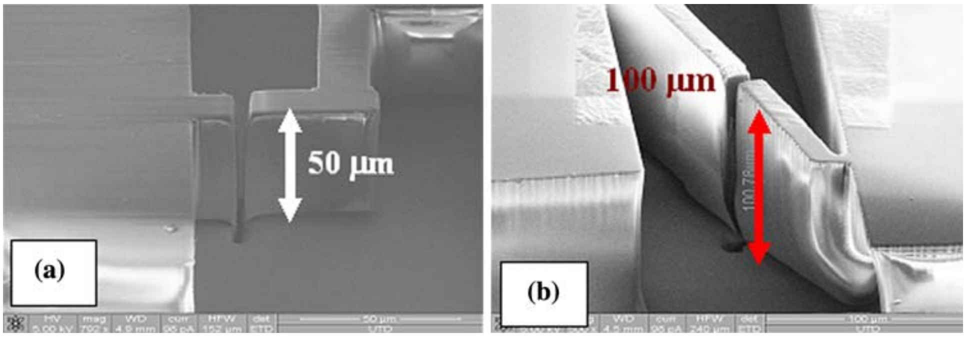


Fig. 8 FIB-assisted de-tethering of **a** 50 µm thick and **b** 100 µm thick high aspect ratio SU-8 tethers

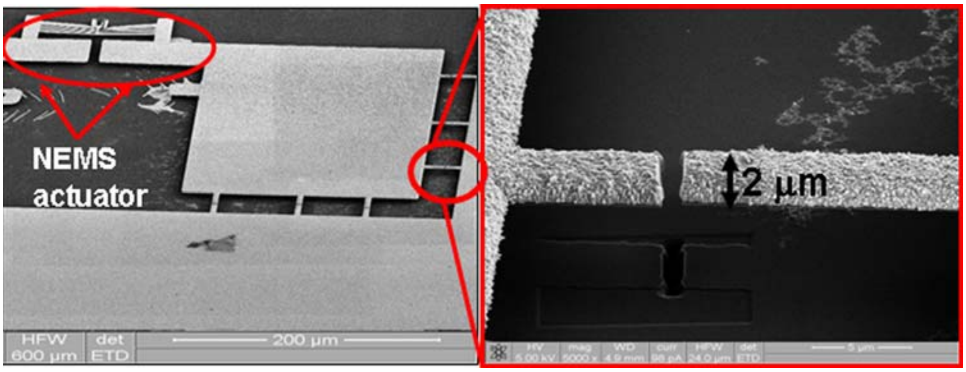


Fig. 9 De-tethering of a metallic NEMS actuator using focused ion beam

FIB. Figure 9a, b shows the SEM picture of a metallic NEMS actuator made of nickel, whose tethers of cross section 2 µm by 1 µm have been cut using the FIB. A low ion beam current of only 20 pA was sufficient to cut the thin tethers supporting the NEMS actuator.

Table 1 summarizes the ion beam current and duration required for cutting tethers used in metallic MEMS/NEMS and polymer/metal bi-layer MEMS devices. The devices de-tethered using FIB were then picked up by gripping the cut tethers for subsequent assembly and packaging. Figure 10 shows an optical microscope image of a completely de-tethered SU-8/gold bi-layer microgripper, which has been assembled onto a ceramic pad for use as a micro end-effector onto a macro biological manipulator.

Table 1 Parameters for FIB assisted de-tethering of MEMS/ NEMS devices

Device	Tether material	Tether dimensions (µm)	FIB current	Time for each cut
Metallic NEMS	Nickel	$W = 2$; $H = 1$	20 pA	30 s
Metal/polymer bi-layer MEMS	Nickel	$W = 10$; $H = 2$	0.3 nA	30 s
	SU-8	$W = 10$; $H = 50$	20 nA	6 min
	SU-8	$W = 10$; $H = 100$	20 nA	12 min

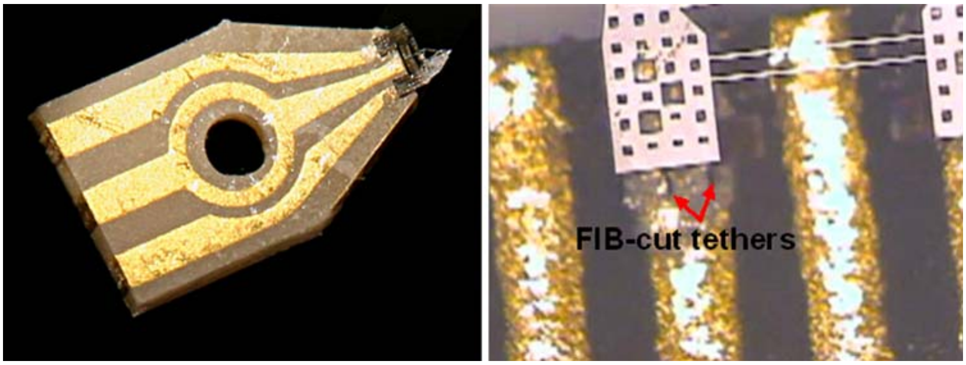


Fig. 10 Assembly of a de-tethered polymer/metal bi-layer gripper onto a ceramic pad

5 Conclusion

We have discussed the various methods of de-tethering employed for different types of MEMS/NEMS components, based on their materials and dimensions. Resistive heating has been identified to be suitable for de-tethering of thick metallic MEMS devices while such a method was found inappropriate for metallic NEMS and polymer/metal bi-layer devices. We have developed a de-tethering process using focused ion beam which enables easy, precise and clean de-tethering of polymer/metal bi-layer MEMS devices and metallic NEMS devices. We have also demonstrated the assembly of such a de-tethered micro-component for use as an end-effector for biological applications. This FIB assisted method has a high percentage, repeatable yield with no damage to the devices and hence, can be employed reliably to de-tether and release high aspect ratio NEMS and polymeric MEMS devices.

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