Lifetime Testing of a Developmental MEMS Switch Incorporating Au/MWCNT Composite Contacts

Adam P. Lewis[1], M. P. Down[1], C. Chianrabutra[1], L. Jiang[1], S. M. Spearing[1] and J. W. McBride[1, 2]
[1] Electromechanical Engineering, University of Southampton, Southampton UK, SO17 1BJ
[2] University of Southampton Malaysia Campus, No. 3 Persiaran Canselor 1, Kota Ilmu, EduCity @ Iskandar, 79200, Nusajaya, Johor, Malaysia
{a.p.lewis, mpd2g12, cc12g10, l.jiang, s.m.spearing, jwm}@soton.ac.uk

Abstract

Microelectromechanical systems (MEMS) have many advantages including: low power operation and small size. Compared with competitive technologies (such as PIN diodes and FETs) metal-contacting MEMS switches exhibit low on-resistance, good isolation and excellent high frequency performance, making them attractive for RF applications, e.g. telecommunications. The lifetime of metal-contacting MEMS switches is limited due to electrical and mechanical interactions between the contacting surfaces. Contact degradation results in an increase in contact resistance and ultimately device failure. A potential solution to significantly increase device lifetime is to use Au/MWCNT composites for one or more of the electrical contacts. The compliance of the composite renders a larger contact area, and dissipates the impact energy from the contact force more effectively. In previous work, the advantages of Au/MWCNT composites for switching applications have been described. In this work we discuss the first implementation of a MEMS device utilising the Au/MWCNT composite technology. As well as demonstrating an application of the Au/MWCNT composite technology, the MEMS device serves as a platform which has been used to further investigate the failure mechanisms. The results are compared to an established methodology. A discussion on the effect of the effect of low contact forces (typical within MEMS) is given.

1 Introduction

There are a number of advantages of MEMS relay switches over PIN diode and FET devices, most notably lower on-resistance, higher isolation and cut-off frequency [1-3]; the latter being of particular interest for RF MEMS applications. Further to this, MEMS relays have high values of off-resistance, which is important for low power applications, especially where power consumption is critical [4]. Commonly, two types of MEMS switches are investigated: capacitive coupling and metal contacting. For the capacitive coupling switches, their use at low frequencies is limited, however they exhibit high lifetimes; for example, Yao et al. demonstrated the switching of their capacitive shunt switch for 500,000,000 cycles where no mechanical failures were detected [5]. With metal-contacting switches an ohmic contact is formed which means that transmission of DC to high frequency signals is possible. Due to electromechanical mechanisms occurring during the opening and closing processes of a metal contacting MEMS switch, the contact surfaces suffer from degradation which over a number of cycles causes the switch to fail [6, 7]. A typical electrical load is 4 V, with a load current in the region of 1-50 mA. In previous work, the use of gold-coated multi-walled carbon nanotube (Au/MWCNT) composite surfaces to improve improving the reliability of switch contacts has been discussed [8-11]. Further to this, the switching surfaces have been demonstrated with load currents up to 200 mA [12]. In this paper we discuss tests using an electrostatically actuated micro-machined gold-coated silicon cantilever beam to contact the Au/MWCNT composite. The MEMS cantilever beam is a developmental device, created for both investigating the contact mechanics of low force electrical contacts and as a prototype to inform the development of MEMS device incorporating Au/MWCNT composite contacts. We report experimental results performed on a MEMS switch incorporating an Au/MWCNT contact. This is the first demonstration of a MEMS switching device which incorporates the Au/MWCNT composite. The MEMS switch has been tested to failure. The use of electrostatic actuation results in a relatively low contact force. Previous work on Au/MWCNT electrical contacts has focussed on higher contact forces [13]. In the previous work a piezoelectric PZT (lead-zirconate titanate) actuator was used which resulted in a contact force of 1 mN [12, 14]. Due to its low power consumption, ease of manufacture and high speed, electrostatic actuation is often the preferred actuation method for MEMS switches. A typical contact force for an electrostatically actuated MEMS switch is in the region of 50 – 200 μN [2]. To give insight into the effect of the lower contact force used by our electrostatically actuated MEMS switch on the performance and failure mechanisms with Au/MWCNT contacts, the results from the MEMS switch are compared with previous results discussed in [12, 13]. This previous work investigated Au to Au/MWCNT contacts but at a higher force of 1 mN. The applied voltage and load current for both cases are 4 V and 50 mA respectively.

2 Fabrication of the Contact Pairs

The electrical contact pair consists of an Au-coated cantilever beam and an Au/MWCNT composite. These contacts are separated by a contact gap of <25 µm in a specifically designed test rig.

2.1 Au-coated Cantilever Beam

The cantilever beam was fabricated in the Southampton Nanofabrication Centre using standard lithographic and etching processes. Briefly, a photoresist was patterned onto a 150 mm diameter silicon wafer to define the cantilever beams. Inductively coupled plasma etching was used to etch 20 µm into the silicon wafer. Following this, a photoresist was patterned onto the back of the wafer to define holes. These holes were etched through the wafer to release the cantilevers. Following the fabrication of the silicon cantilever beam it was sputter-coated with 10 nm and 500 nm of Cr and Au respectively. The Cr layer is required as an adhesion layer between the gold and silicon [15]. The dimensions were selected based on a trade-off between frequency and pull in voltage; further to this, practical considerations such as handling and alignment of the beams was taken into consideration. As the beam length increases, both the pull-in voltage and resonant frequency decrease. As the bean thickness is increased, the pull-in voltage and resonant frequency increase. A large pull-in voltage is undesirable since it means that a high voltage will be required to actuate the beam. An image of the cantilever beam can be seen in **Figure** 1; it has a width, length and thickness of 2 mm, 10 mm and 20 µm respectively. A detailed description and justification of the design of the cantilever beam, focussing on the width, length and thickness is given in [16]. Computational modelling of the cantilever beam predicted a contact force of up to 40 µN and a pull-in voltage of 17 V. The first modal resonant frequency of the beam was measured as 235 Hz [16]. A high frequency is desirable since it enables testing to high cycle numbers (>50 million cycles) within a short period of time (<1 week).

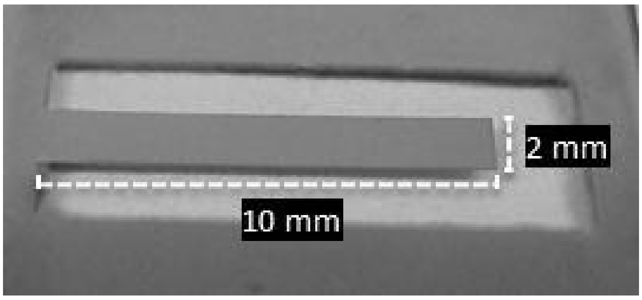

Figure 1: Image of Au-coated MEMS-based electrostatically actuated cantilever beam.

2.2 Au/MWCNT Composite

The vertically aligned MWCNT forests are grown using a thermal CVD method. A range of MWCNT heights from 10 µm to 100 µm is achieved by varying the growth time. Following the growth of the MWCNT forests, 500 nm of Au is sputter coated onto the samples. A detailed description of the fabrication process for the Au/MWCNT composites is given in [13]. In the work presented here the MWCNT forest height is fixed at 30 µm.

3 Experimental Setup and Test Conditions

3.1 Experimental Setup

The Au coated cantilever beam is electrostatically actuated and therefore requires an actuation electrode close to the beam surface. To position the beam close to the actuation electrode, the cantilever beam was mounted on a spacer; an illustration of the spacer stage can be seen in the top of **Figure 2A.**

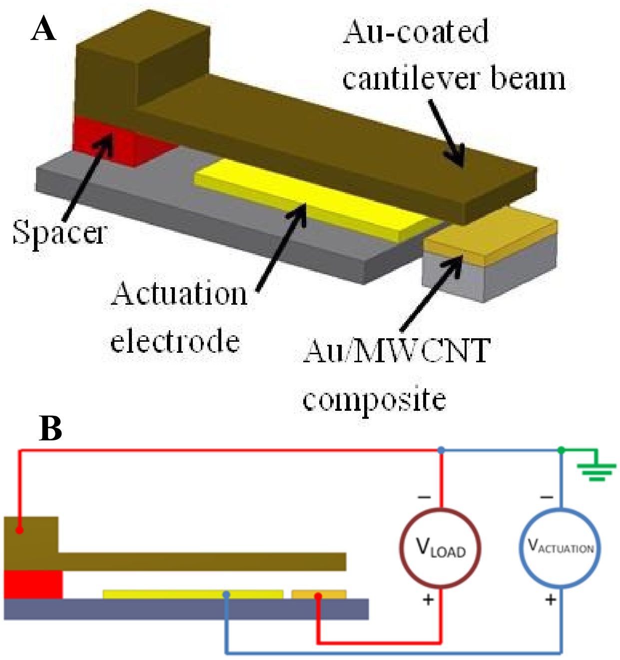

Figure 2A: 3D drawing showing experimental setup. **B:** side view showing electrical connections for load and actuation voltages.

Throughout the experiment the Au-coated cantilever beam was held at 0 V as shown in **Figure 2B**. An actuation voltage of 36 V was applied to the actuation electrode to pull the cantilever beam into the Au/MWCNT contact. The Au/MWCNT composite was held at 4 V, as the tip of the cantilever beam touches the Au/MWCNT composite, the potential across the contact pair dropped towards 0 V. The voltage across the contact pair when switched will not reach 0 V due to the contact resistance of the contact pair. Using a current limiting resistor in series with the switch, the current flow through the contact surfaces when the switch is closed was limited to 50 mA. For continuous switching of the contact pair, the applied actuation voltage had a square waveform with a frequency of 100 Hz and amplitude of 36 V.

A schematic illustrating the closing process of the cantilever beam into the Au/MWCNT is given in **Figure 3**. It should be noted that the MWCNT forest is used for its mechanical properties, namely high elasticity rather than its electrical properties. The high elasticity of the composite results is the spreading of the applied mechanical load during the closing process. The spreading of the mechanical load reduces the damage to the contact surface. Provided the elasticity is sufficiently large relative to the contact force the composite will conform to the impacting contact.

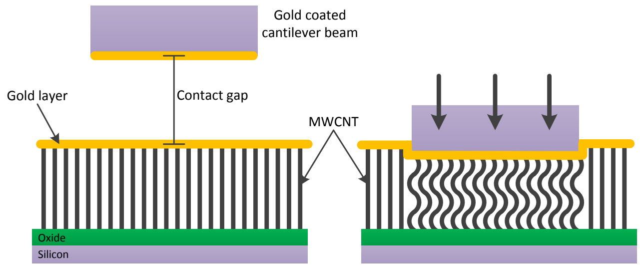

Figure 3: Illustration of closing process between gold coated silicon cantilever beam and an Au/MWCNT composite surface.

3.2 Testing Methodology

The Au-coated silicon cantilever beam and Au/MWCNT composite contact pair were tested with a load voltage and current of 4 V and 50 mA respectively until failure. Upon failure, the contact resistance sharply increases. Failure is defined as when the contact resistance increases to >3 times the nominal contact resistance value [12]. The contact force is estimated to be between 5 µN – 40 µN based on results from a computational model [16]. The MEMS switch was actuated at a frequency of 100 Hz. The contact resistance is measured throughout using an ART Reflex 51 system from Applied Relay Testing Ltd. The values measured with this system were verified at numerous intervals using a Keithley 580 4-point probe micro-ohmmeter. In addition, the voltage across the switch during the opening and closing events is monitored throughout the experiment to verify that the switch successfully opened and closed. To monitor the change in voltage across the contact pair during the switch opening and closing processes, an oscilloscope was connected across the contact pair. The data from the oscilloscope gives information regarding the switching dynamics. For example, it shows if the molten metal bridge phenomenon occurs on an opening event [17]. Further to this, it can be used to evaluate if any contact bouncing occurs on the closing event.

4 Results and Discussion

4.1 Contact Resistance

The contact resistance was measured throughout the lifetime of the switch. Further to this, the effect of the actuation voltage was investigated prior to starting the lifetime switching experiment.

4.1.1 Contact Resistance versus Actuation Voltage

At the start of the experiment, the effect of the actuation voltage on the contact resistance was investigated. As discussed earlier, the pull-in voltage was estimated to be ~17 V, based on a computational model [16]. The voltage was increased from 0 V to 36 V and the contact resistance was monitored. The results from this can be seen in **Figure 4**. As the actuation voltage increases, the cantilever beam moves towards the Au/MWCNT composite surface. At 24 V the beam makes sufficient contact with the composite surface and the contact resistance drops to 5.4 Ω. As the actuation voltage is further increased, the contact force increases and it can be seen in Figure 4 that the contact resistance decreases accordingly. For actuation voltages above 32 V, the contact resistance is stable at ~3.5 Ω. The actuation voltage used for the switching experiment was 36 V.

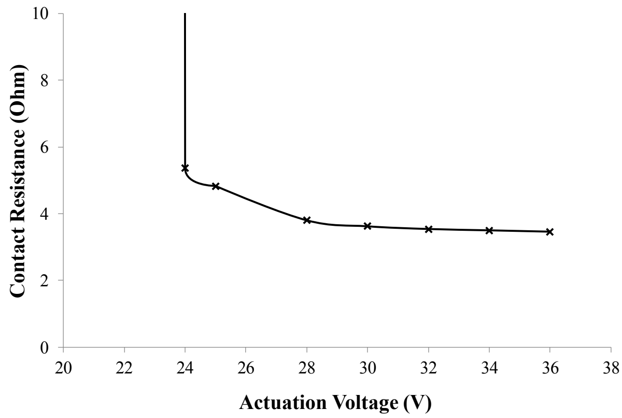

Figure 4: Graph showing actuation voltage versus the contact resistance.

4.1.2 Contact Resistance versus Number of Cycles

With the testing conditions described in Section 3.2, the Au-coated cantilever beam and Au/MWCNT composite contact pair survived hot switching to 44.4 million cycles. The change in contact resistance over the lifetime of the contact pair can be seen in **Figure 5**.

In Figure 5, it is possible to identify four stages of switch performance over the switching lifetime; these are the initial stage, stable stage, rising stage and failure stage. Details on these stages have been described in [13]. At the start of the experiment the contact resistance was 3.5 Ω; this dropped to 3 Ω by 5,000 cycles. Until 32 million switching events the contact resistance remained at around 3 Ω. After 32 million cycles, the contact resistance becomes unstable and starts to rise. After 44.4 million cycles the voltage across the switching during the opening and closing events remained at the open circuit voltage of 4 V indicating that the contact resistance had significantly increased (i.e. the switch had failed).

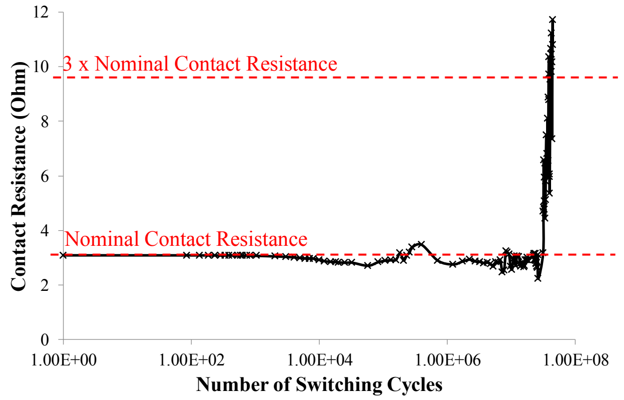

Figure 5: Contact resistance versus number of switching cycles for the Au-coated silicon beam and Au/MWCNT contact pair. Hot switching at 50 mA, at estimated force of between 5 and 40 µN.

Compared with previous results, between the Au-ball and Au/MWCNT composite mounted on a PZT actuator [12], the nominal contact resistance of the MEMS switch presented here is higher, i.e. 3 Ω compared with 0.4 Ω. This is attributed to the lower contact force and reduced contact area. The contact resistance versus number of cycles for the Au-ball and Au/MWCNT contact pair is shown in **Figure 6**. This contact pair survived 48.9 million cycles. The trend and number of cycles to failure is comparable with the electrostatically actuated MEMS switch. It should be noted however that there were no bouncing events observed for the electrostatically actuated MEMS switch, however the results on the PZT rig, showed an average of 6 bouncing events which occurred after each closing event. Each bouncing event can be considered an additional opening and closing event of the switch and so should be considered when calculating the number of switching cycles to failure [12, 13]. With the number of bounces taken into consideration, the number of switching events to failure for the Au-ball and Au/MWCNT composite on the PZT test rig becomes 135 million cycles.

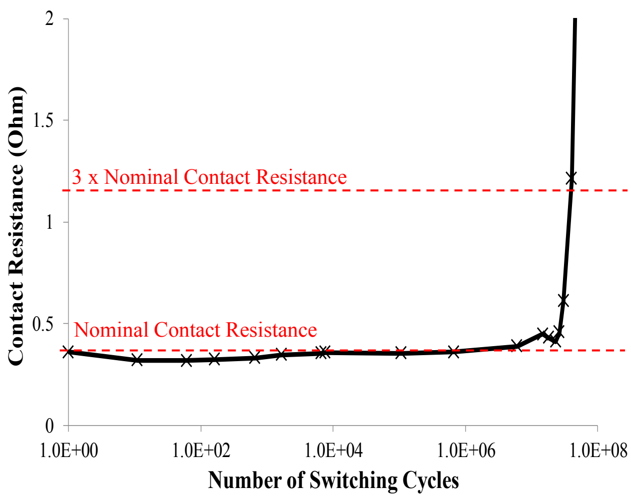

Figure 6: Contact resistance versus number of switching cycles for the Au-coated ball and Au/MWCNT contact pair (using PZT test rig – contact force 1 mN). Hot switching at 50 mA.

4.2 Failed Contact Surfaces

Figure 7A shows an image of the Au/MWCNT composite tested with the MEMS switch after failure. It shows that within the contact area, the Au layer on top of the MWCNT forest has changed. This would suggest that Au is transferring between the Au/MWCNT composite and the Au-coated beam. A likely method for this transfer would be the fine transfer mechanism [17]. The depth profile in **Figure 7B** shows that the depth of the failure site is about 1 µm lower than the plane of the composite surface. This is in agreement with experiments performed on the PZT test rig with the same contact pair of Au film to Au/MWCNT; where the Au transfer is from Au/MWCNT to Au film [13]. The depth of film transferred on the PZT test rig (shown in **Figure 8**) was measured as 2 µm [12].

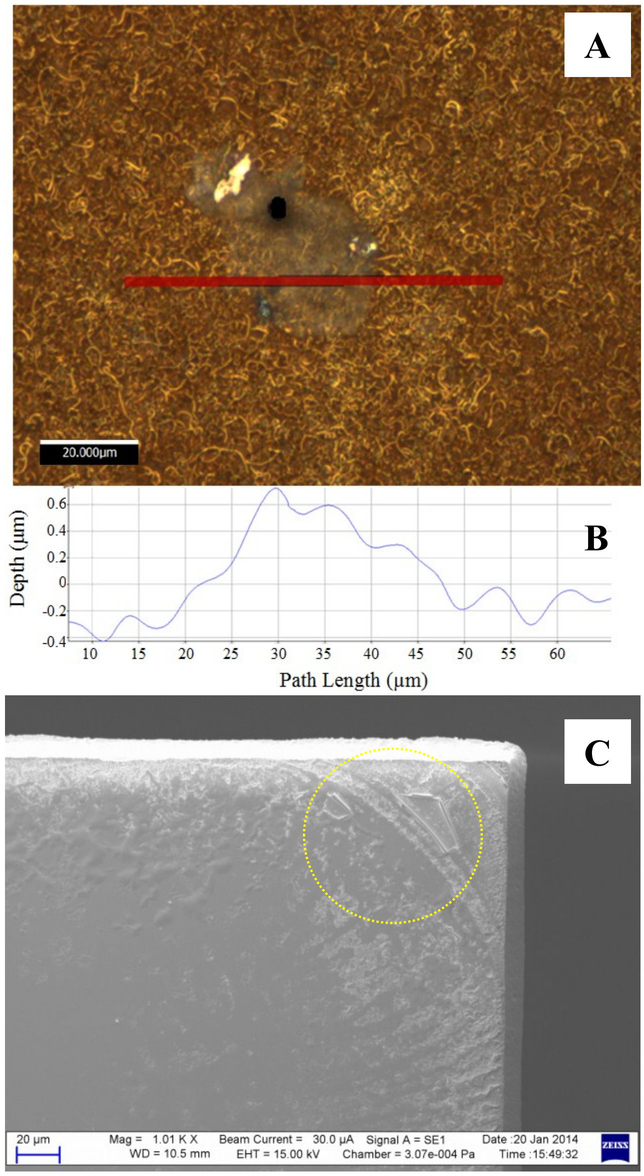

Figure 7A: Image of failure site on Au/MWCNT composite tested with MEMS cantilever beam. **B:** Surface profile showing depth of failure site (~1 µm). **C:** SEM image of cantilever beam tip.

Due to the low contact force the MEMS switch exerts on the composite surface, as the Au layer becomes smoother because of the fine transfer, the contact resistance will increase. With a larger contact force, it would be expected that a contact area would be larger and the centre of the contact would be smoother. The increase in contact resistance begins at ~30 million cycles, at which point it should be noted that an increase in the duration of the molten metal bridge was observed by monitoring the opening transients on the oscilloscope. The duration of the molten metal bridge is defined as the time taken from the initial rise in voltage across the switch to the open circuit voltage (i.e. 4 V). The duration of the transient increased from ~ 50 µs to 300 µs from the period of 30 million cycles to 40 million cycles. This increase in duration indicates an increase in the energy used by the molten metal bridge phenomenon. It is therefore assumed that the amount of material transferred is related to the duration of the molten metal bridge.
The tip of the cantilever beam can be seen in **Figure 7C**. Due to a slight misalignment of the cantilever beam to the Au/MWCNT composite, the cantilever beam makes electrical contact near a corner of the tip. From the image in Figure 7C it is unclear if there is any material transferred to the cantilever beam however an area of comparable size to the failure site can be seen on the cantilever tip. One possible explanation is that the fine transfer of Au from the Au/MWCNT composite has resulted in the build-up of a thin film on the beam surface which in turn may have induced stress into the Au film causing the resulting rolls of gold film visible on the cantilever beam [18, 19]. Further investigations are on-going to verify this.

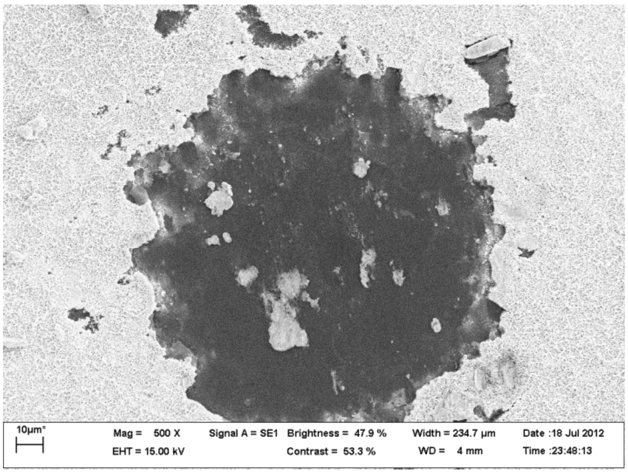

Figure 8: SEM image of failure site on Au/MWCNT composite tested with PZT test rig [12].

With the higher contact force, it can be seen in **Figures 8** and **9** that the contact area is significantly larger. Further to this, it is also possible to see that a larger volume of material has transferred from the Au/MWCNT composite to the Au ball. A consequence of the lower force exhibited by the electrostatically actuated MEMS switch is a smaller contact area and contact force. Therefore it would be expected at the area and depth of a failed contact surface should be less than for the higher force case, as can be seen by comparing Figures 7A and 8.

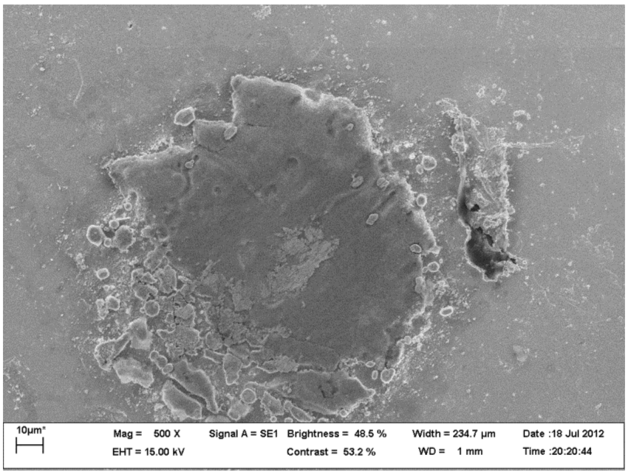

Figure 9: SEM image showing material transferred to Au-coated ball from failure site (shown in Figure 8).

5 Conclusions

We present the first lifetime test of a MEMS switch incorporating an Au/MWCNT composites contact surface.
It was shown that the contact resistance throughout the lifetime of the switch remained stable at around 3 Ω (with a load voltage and current of 4 V and 50 mA respectively) until 32 million cycles, after which it began to increase. After 46 million cycles the contact resistance significantly increased, such that the switch was deemed failed.
The MEMS switch is actuated using an electrostatic actuation method which results in a low contact force; assumed to be in the region of 5-40 µN based on results from computational models. Electrostatic actuation methods are often preferred for MEMS switches [2] and therefore this work is a step towards the development of Au/MWCNT composites into MEMS devices. The effect of the low contact force has been compared with work on Au/MWCNT composites at higher force (1 mN). The resulting area of the failure site at lower contact forces is significantly smaller. Further to this, the damage inflicted to the surface is reduced. One disadvantages of using a lower contact force is that the contact area is reduced, which means that the switch lifetime is reduced. A consequence of the reduced contact area is that the nominal contact resistance is larger. However, it should be noted that the MEMS switch survived 44.4 million hot switching cycles (4 V, 50 mA). This result is comparable with the 48.9 million hot switching cycles achieved by the PZT test rig. The MEMS switch described in this paper showed no signs of bouncing following switching events. This has the advantage that no additional damage occurs during the switching process. Further to this, from an application point of view, the switch could be used without the requirement of debounce circuitry, which results in a simpler device with reduced size and cost. Since the PZT test rig setup exhibited bouncing following each closing event, the actual number of opening and closing processes the contacts experience is larger than the actuated 48.9 million events.

6 Acknowledgements

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