Development of a MEMS Test Platform for Investigating the use of Multi-Walled CNT Composites Electric Contacts

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Abstract

The use of gold-coated multi-walled carbon nanotube (Au/MWCNT) composites have been shown to extend the life of electrical contacts, in previous work [1-3]. Due to the long lifetimes (which are of the order of 10^6 up to 10^8 cycles [4, 5]) the lifetime testing tends to be highly time consuming. In this work we discuss the design and development of an electrostatically actuated MEMS cantilever beam which enables testing at higher frequencies than our previous experimental rig. Following calculations using fundamental cantilever beam equations, a computational model of the designed beam was developed to accurately predict the characteristics of the beam, including the resonant frequency, pull-in voltage and contact force. Where possible the values from the model have been compared with the fabricated MEMS cantilever beam. A MEMS-based electrostatically actuated cantilever beam has been fabricated and incorporated with Au/MWCNT composite surfaces to form a MEMS switch test platform. Initial results show the improved performance over a PZT based test platform.

Introduction

MEMS relay switches offer numerous advantages over PIN diode and FET devices, most notably lower on-resistance, higher isolation and cut-off frequency [6-8]. The latter two advantages are of particular interest for RF MEMS applications. A further advantage for MEMS relays is that they have very high values of off-resistance, which is important for low power applications, especially where power consumption is critical [9]. There two types of MEMS switches: capacitive coupling and metal contacting. For the capacitive coupling switches, their use at low frequencies is limited, however their lifetime is generally not an issue; for example, Yao *et al.* demonstrated the switching of their capacitive shunt switch for 500,000,000 cycles where no mechanical failures were detected [10]. In 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 [11, 12]. A typical electrical load is 4 V, with a load current in the region of 1-10 mA. In previous work, the use of gold-coated multi-walled carbon nanotube (Au/MWCNT) composite surfaces has been discussed as a method for improving the reliability of switch contacts [1-3, 13]. Further to this, the switching surfaces have been demonstrated with load currents up to 200 mA [4]. In this paper we discuss tests using an electrostatically actuated micro-machined gold-coated silicon cantilever beam to contact the Au/MWCNT composite. This experimental setup makes it possible to perform accelerated lifetime tests on contact materials. 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.

Experimental Methodology

A number of experiments have been conducted to investigate the use of Au/MWCNT composites as contact materials for MEMS switches. The focus is on the advantages gained, in particular the improvement in device lifetime. Both dry-switching experiments and hot-switching experiments (10 – 200 mA) have been investigated. For comparison, surfaces without the MWCNTs have also been tested. Further to this, the effect of contact force has been investigated; this work goes some way towards enabling a comparative discussion between new experimental results on a MEMS-type system with previous experimental work [14]. Briefly, in previous work, the contact pair consisted of a fixed gold-coated spherical contact and an Au/MWCNT composite which was adhered to a lead zirconate titanate (PZT) piezoelectrically-actuated cantilever beam [5].

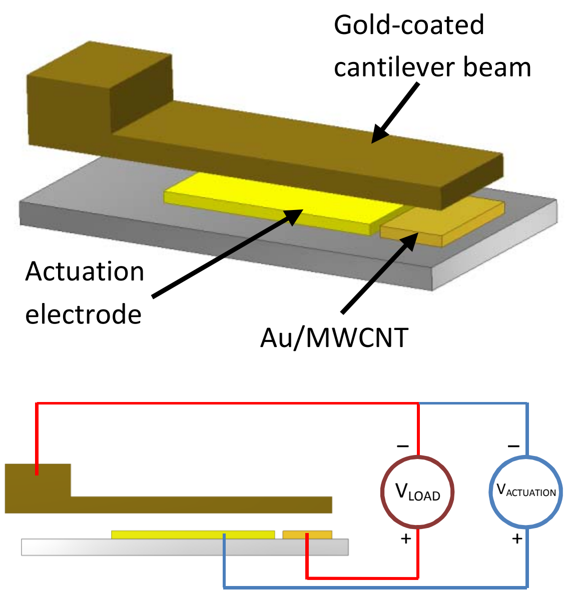

Figure 1: Top: 3D drawing showing experimental setup. Bottom: side view showing electrical connections for load and actuation voltages.

In this work, results from experiments performed on a previously described experimental setup (detailed in [5]), are discussed and compared with results from a new experimental setup (described below); for convenience these will be referred to as the PZT rig and the MEMS rig respectively. In the new experimental setup (the MEMS rig), the Au/MWCNT contact is fixed, and the gold coated sphere has been replaced with a micro-machined gold-coated silicon cantilever beam. A schematic of the experimental setup is given in Figure 1.

Unlike the PZT rig setup, the use of a MEMS cantilever beam enables switching to be performed with a very low contact force (in a range typical for electrostatically actuated MEMS switches). Electrostatically actuated MEMS based switches typically switch in the region of 50 µN to 1000 µN [7, 15]. Further to this, the setup is comparable to that of a typical MEMS switch, with the primary difference being that one of the electrical contacts is an Au/MWCNT composite.

The load voltage for all hot-switching experiments was 4 V, the load current was varied. The cantilever beam was held at 0 V, whereas the load voltage was applied to the Au/MWCNT contact. Using an electrostatic actuation method, the cantilever beam moved towards the Au/MWCNT composite surface; an illustration of the switch closing event is shown in Figure 2.

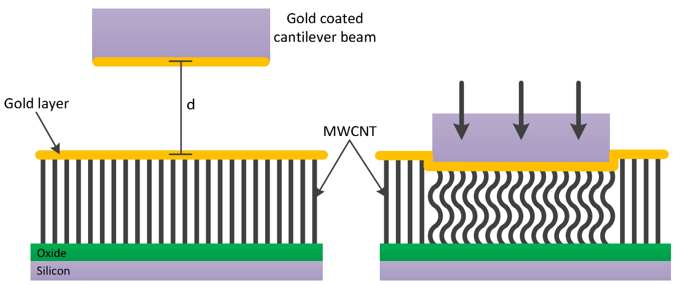

Figure 2: Illustration of closing process between gold coated silicon cantilever beam and an Au/MWCNT composite surface.

Cantilever Beam Design

Using the fundamental equations (1), (2) and (3) concerning the design of cantilever beams, it was possible to design a MEMS cantilever beam [16]. The end deflection (δ) of a fixed-free beam is given by:

$$\delta = \frac{F \times L^3}{8 \times E \times I} \tag{1}$$

where F, L, E and I denote the force, beam length, Young's modulus and moment of inertia respectively. The pull-in voltage (V_p) is given by:

$$V_p = \sqrt{\frac{8 \times k \times d^3}{27 \times \varepsilon \times A}} \tag{2}$$

where k, d, ε and A denote the spring constant of the beam, gap between the beam and actuation electrode, the permittivity and the effective electrode area respectively. The resonant frequency (f) of the beam is given by:

$$f = \frac{\alpha}{L^2}\sqrt{\frac{E \times I}{A \times \rho}} \tag{3}$$

where α is the coefficient for the first modal frequency and ρ is the density.

Practical limitations on the device, such as the contact gap and pull-in voltage were combined with the fundamental equations to obtain the design of the beam; for example, the beam length, width and thickness. It was decided that a first modal resonant frequency in the region of ~200 Hz would be suitable for testing the switch to failure under hot-switching conditions. At 200 Hz, 100,000,000 cycles can be achieved within a week of continuous testing. Whilst comparatively large, a contact gap of 25 µm was chosen to address potential setup issues with regards to bringing the contacting surfaces (the Au/MWCNT composite and the cantilever beam) close together. For a high resonant frequency, the beam should be short and thick; however for a low pull-in voltage the beam should be long and thin. To achieve a balance between the resonant frequency and pull-in voltage the values for length, width and thickness of the beam were chosen to be 10 mm, 2 mm and 20 µm respectively. These values give 1st modal resonant frequency of ~275 Hz. Using the material properties of silicon, the equations estimated that for a contact gap of 25 µm, the actuation voltage would be ~10 V. It should be noted here that the test platform we have designed is the first stage of a full MEMS device where the contact gap and the corresponding beam length would be substantially reduced. The values for the beam dimensions and contact gap were used to define the geometry which was computationally modelled using CoventorWare 2012. Refinement of the mesh resulted in a slight variation of the frequency response of the cantilever beam. With an increase in the mesh scaling factor, the size of the mesh decreased. Whilst smaller meshes result in greater accuracy, the computational time greatly increases. An extrapolation of the data from the simulation predicted a resonant frequency of ~270 Hz.

The contact force of electrostatically actuated MEMS beams tends to be small (tens of µN); this makes it difficult to accurately measure the contact force. Based on the simulations performed in CoventorWare 2012, the contact force is estimated to be ~40 µN at the pull-in voltage. The pull-in voltage was computed to be ~17 V. This is slightly higher than predicted by the simplified equations (1), (2) and (3). The primary reason for the difference is due to the assumption that the actuation force acts along the whole length of the beam, rather than just above the actuation electrode. Whilst the equations can be used for quickly estimating the characteristics of the beam, the use of a computational model, such as CoventorWare 2012, is useful for more accurately describing the beam behaviour.

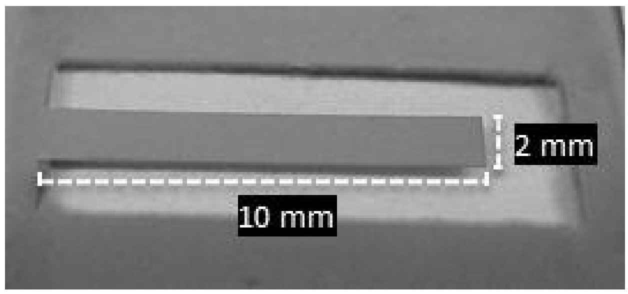

Figure 3: Image of Au-coated MEMS-based electrostatically actuated cantilever beam.

The beam was fabricated using standard lithographic and etching processes a cleanroom. Once the silicon cantilever beam was fabricated it was sputter-coated with 500 nm of gold; to get good adhesion between the gold and silicon, a 10 nm chromium adhesion layer is used. An image of the cantilever beam can be seen in Figure 3.

Using a scanning laser-doppler vibrometry technique with a MSA-400 micro system analyser instrument it was possible to calculate the resonant frequency of a fabricated gold-coated cantilever beam. The results of this analysis are given in Figure 4. They show that the 1st modal resonant frequency was located at 235 Hz. This is close to the 270 Hz predicted by the model. The difference in the two values is attributed to manufacturing processes. During fabrication, precise control of the cantilever beam thickness was difficult. Due to over-etching, the fabricated beam is slightly less than the modelled 20 µm thick. A consequence of this reduced thickness is that the resonant frequency reduces, as described in earlier in equation (3).

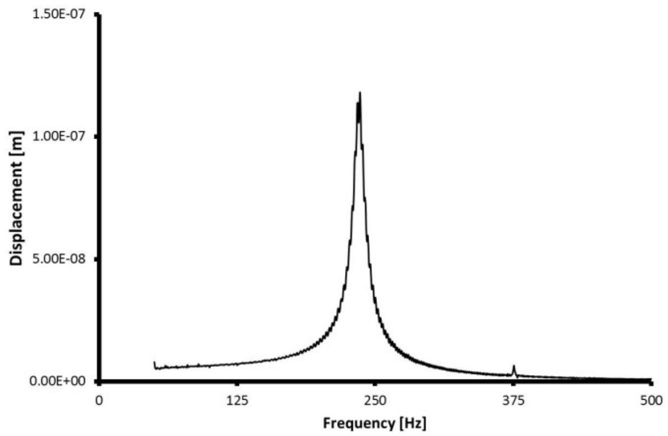

Figure 4: Graph showing displacement of beam over range of frequencies. 1st modal resonant frequency identified as ~235 Hz.

Results

PZT Test Rig: Dry-Switching Versus Hot-Switching

An advantage of MEMS switches, as stated earlier, is their ability to switch high frequency signals (in the GHz - THz range). Switching signals of such AC signals by alternative technologies (such as semiconductor transistors) becomes difficult because the impedance of the transistor (even in the 'off-state') reduces with an increase in frequency. Hence, even with the transistor in the 'off-state', high frequency signals can propagate through the device. In MEMS switches, physical separation of the contacts results in significantly higher isolation, hence enabling switching of higher frequency signals.

In MEMS processing, Cr and Ti are commonly used to promote the adhesion of Au to substrates (e.g. silicon) [17]. The switching lifetime of thin-film Au-contacts with and without a Cr adhesion layer were measured under hot-switching conditions to evaluate the effect of the adhesion layer. On the PZT rig, it was shown that failure between an Au-coated ball and an Au-coated substrate occurred at approximately 600,000 cycles planar when hot-switching with a load current of 50 mA (at 4 V) with 1 mN contact force [17]. The failure was identified by monitoring the contact resistance; upon failure the contact resistance increases significantly (i.e. >3 times the initial value) [18]. The same contact pair was dry-switched for 600,000 cycles to eliminate the influence of electrical failure mechanisms. Following the initial impact between the contacts there is a bouncing process. It should be noted that the number of bouncing events closing processes have been neglected from the calculation of the number of cycles. The bouncing events result in a number of opening and closing events occurring per switching cycle [19].

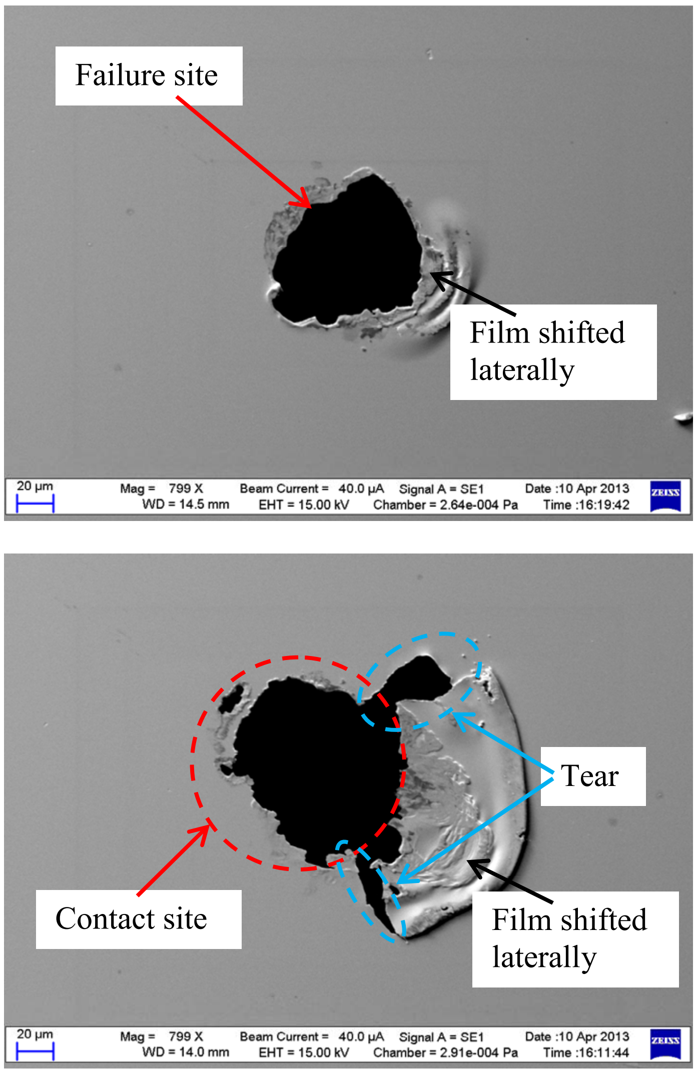

Figure 5: Au-coated silicon substrate after ~600,000 switching cycles, where load current was 50 mA; the contact has failed (top). Au- coated silicon substrate after ~600,000 dry-switching cycles (bottom) [17].

In the SEM image in the top of

Figure 5, shows the failure site for the hot-switching (50 mA) case; in the bottom image, the contact is shown after the same number of switching cycles but with no load current. Comparing the images, it is clear that there is a significant amount of material transfer from the substrate to the Au-coated ball. This transfer occurred in both cases, with and without load current. The lack of an adhesion layer has resulted in lateral movement of the Au film across the surface upon removal of the material from the substrate; this can be seen in both images of

Figure 5. The film appears to ripple around the edges of the failure site. For the no load case, this lateral movement has resulted in a tear of the Au layer, and the Au film has shifted away from the failure site. A consequence of this movement is that it appears that there is greater damage caused in the no load case, however it should be noted that the contact resistance of the no load case at 600,000 cycles was 0.2112 Ω; therefore it had not failed. This suggests that whilst the failure is primarily due to the mechanical impact between the contacts, the electrical interaction accelerates the failure process.

PZT Test Rig: Dry-Switching Versus Hot-Switching (with Cr Adhesion Layer)

It is well-known that Au has a poor adhesion to silicon, therefore a 10 nm Cr adhesion layer was subsequently included on the silicon substrate between the silicon and Au layer. After 600,000 cycles (i.e. the number of cycles at which the Au-Au contact pair failed) it can be seen (in Figure 6 (top)) that whilst some material transfer occurred, premature delamination was prevented. Further to this, comparing the SEM image in the top of

Figure 5 with the image at the top of Figure 6, it can be seen that for the case with the Cr adhesion layer, there is no evidence of the film shifting laterally across the substrate. The contact pair with the Cr adhesion layer was also tested to failure; this occurred after ~10,300,000 switching cycles (SEM image of failure site given in the middle of Figure 6). The material transfer at the edge of the failure site is indicative of the molten metal bridge phenomenon. The centre of the failure site appears to have failed due to a mechanical adhesion mechanism such as delamination [17]. In the bottom of Figure 6, a SEM image a Cr/Au-coated silicon substrate after 10,300,000 dry switching cycles is shown. From this it is clear that the Cr adhesion layer improves the contacts resilience to delamination, though only delays the process rather than eliminates it. At the edge which has been magnified in the bottom image of Figure 6, there are a number of small areas which appears to have experienced local damage. Unlike the damage caused by the molten metal bridge phenomenon (labelled fine transfer in Figure 6 (middle)), the damaged areas appear to be less circular (spot-like), and more irregular.

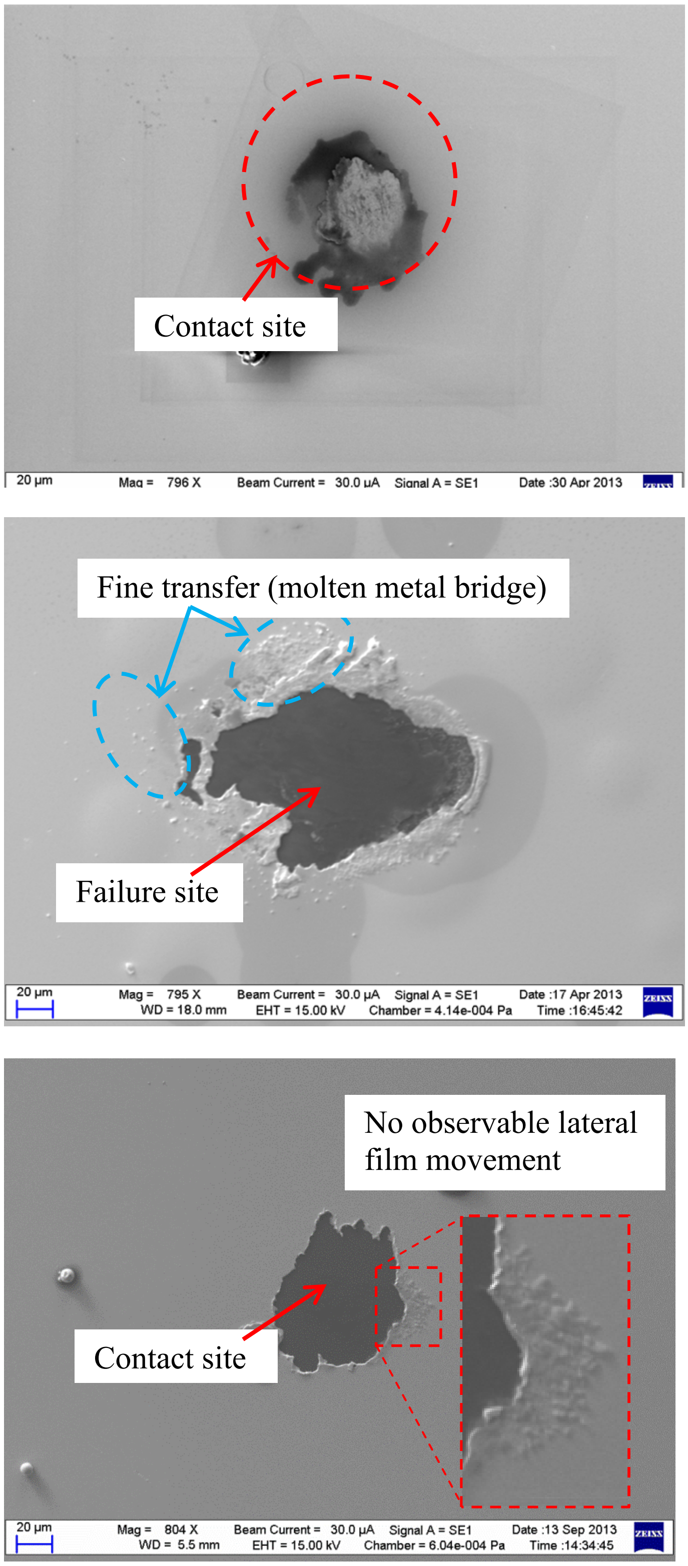

Figure 6: Top: Cr/Au-coated silicon substrate after ~600,000 switching cycles, where load current was 50 mA (top). Middle: Cr/Au-coated silicon substrate after ~10,300,000 switching cycles, where load current was 50 mA; the contact has failed [17]. Bottom: Cr/Au-coated silicon substrate after ~10,300,000 cycles with no load current.

PZT Test Rig: Dry-Switching Versus Hot-Switching (with MWCNT composite)

The use of Au/MWCNT composite surfaces have been shown to improve the lifetime of electrical contact surfaces. Figure 7 (top) shows the resulting surface after ~600,000 switching cycles, where some surface damage is observable; though the contact has not failed. The damage shown in Figure 7 (top) is significantly less than can be seen in

Figure 5 (top). Further to this, the Au/MWCNT composite contact survived ~20,000,000 cycles. Figure 7 (bottom) shows the contact surface after ~20,000,000 cycles i.e. after failure. The inclusion of an Au/MWCNT composite surface enabled a larger number of switching cycles before failure of the contact. The area of the failure site for the Au/MWCNT composite (which is proportional to the contact area) is larger than for the Au and CrAu contacts. This is attributed to the larger compliance of the MWCNT layer which is favourable to deformation. The elastic nature of the MWCNTs acts to restore the MWCNT forest following the deformation which results from the impact, though complete restoration does not happen.

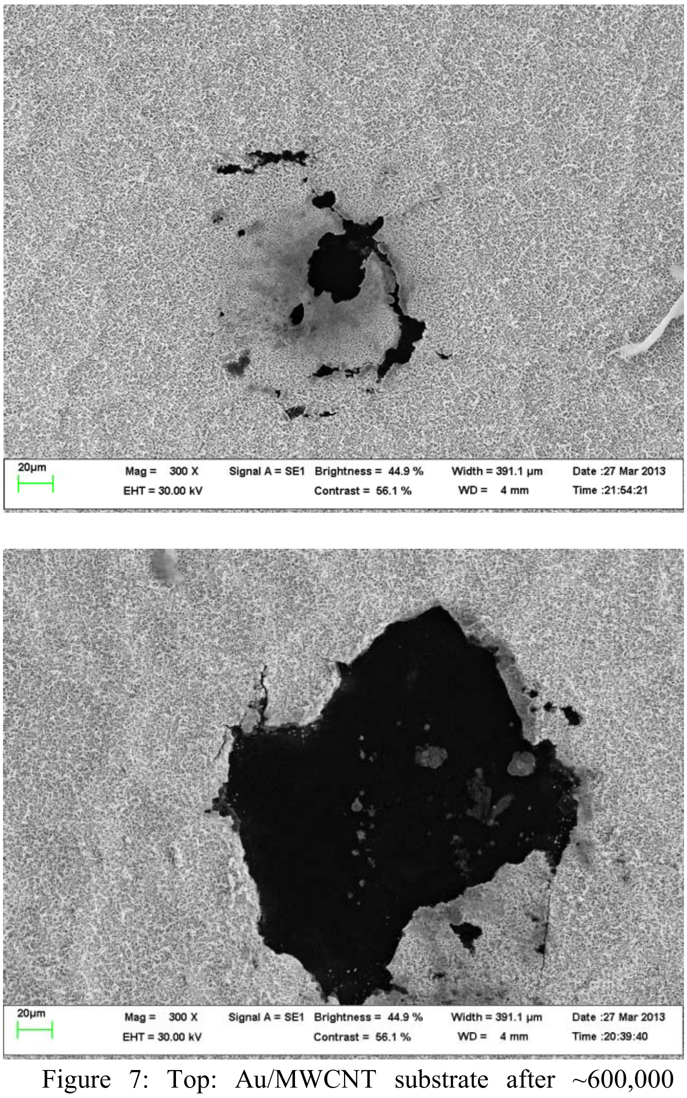

Figure 7: Top: Au/MWCNT substrate after ~600,000 switching cycles where load current was 50 mA. Bottom: Au/MWCNT substrate after ~20,000,000 switching cycles where load current was 50 mA; contact has failed.

MEMS Test Rig

As a step towards the development of a MEMS switch we created the MEMS test rig which is based on a MEMS cantilever, the design considerations for which were discussed earlier. The use of an electrostatically actuated MEMS-based cantilever beam within the test rig enables electrical switching at higher frequencies than possible on the PZT test rig. One of the main limits of the test frequency on the PZT rig is due to the bouncing behaviour, the duration of which is in the region of tens of milliseconds. A typical waveform of switching events showing the bouncing events for a Cr/Au ball and Au/MWCNT composite contact pair performed on the PZT rig, can be seen in Figure 8 (top). After an opening or closing event, the switch must be given sufficient time to settle (i.e. all the bouncing has finished).

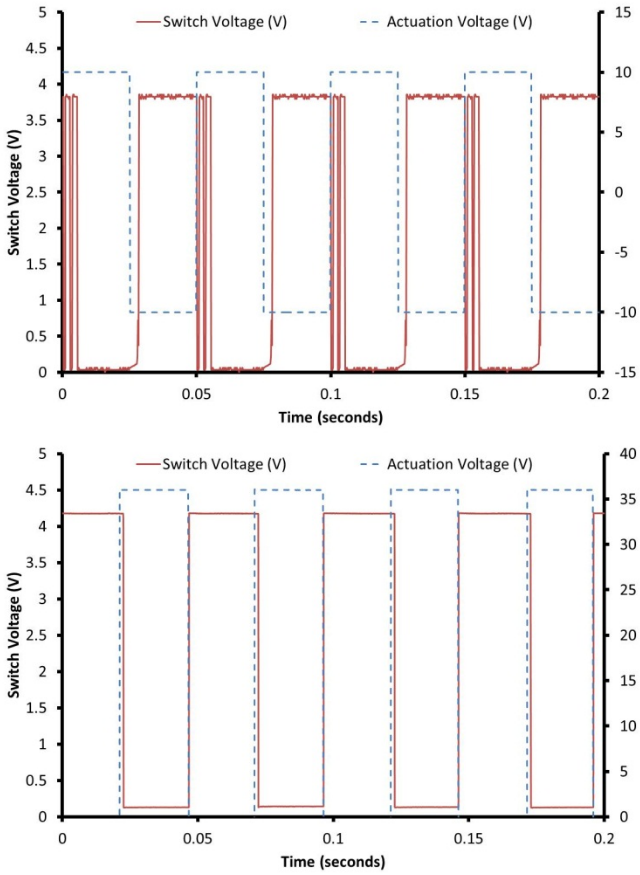

Figure 8: Switching waveforms using PZT rig (top) and MEMS rig (bottom) at 20 Hz. The load voltage was 4 V and the current was 50 mA. The contact force for the PZT rig was measured as 1 mN; based on the simulations described earlier, for the MEMS rig, the contact force is estimated to be ~40 μN.

A typical waveform for the MEMS rig setup is shown in Figure 8 (bottom). The contact pair is a Cr/Au-coated MEMS-based cantilever beam and an Au/MWCNT composite. The switching frequency of the MEMS cantilever beam was tested up to 200 Hz. A graph showing the switching at 200 Hz is shown in Figure 9. It can be seen that as the actuation voltage is applied there is a few milliseconds of delay, after which the contact voltage drops (i.e. the switch closes). Once the actuation voltage is turned off, there is a very short delay before the switch voltage rises (i.e. the switch opens). This delay is attributed to the physical movement of the cantilever beam. During the closing cycle the tip of the beam needs to deflect by the distance defined as the contact gap (25 µm). During the opening cycle, the beam only needs to move away from the contact site by a small distance sufficient to prevent the current flow to be considered open.

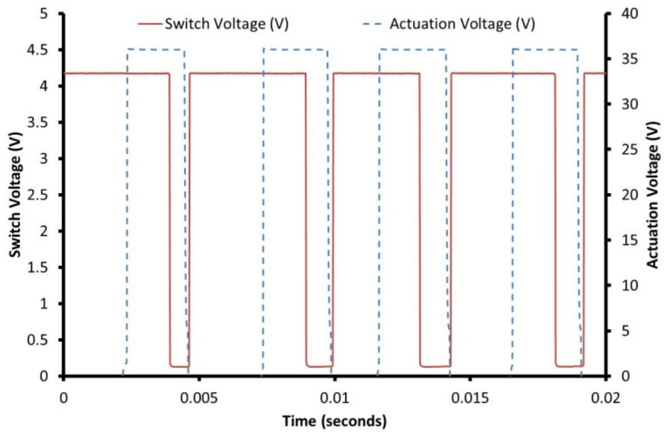

Figure 9: Switching waveform at 200 Hz between Au-coated cantilever beam and Au/MWCNT composite.

The waveform given in Figure 9 shows that during the opening and closing cycles there was no observable electrical bouncing behaviour. This is important for accurately calculating the number of switching events. From an application point of view, bouncing of electrical contacts is undesirable since it shortens the device lifetime. In addition, debouncing circuitry is typically required to improve lifetime.

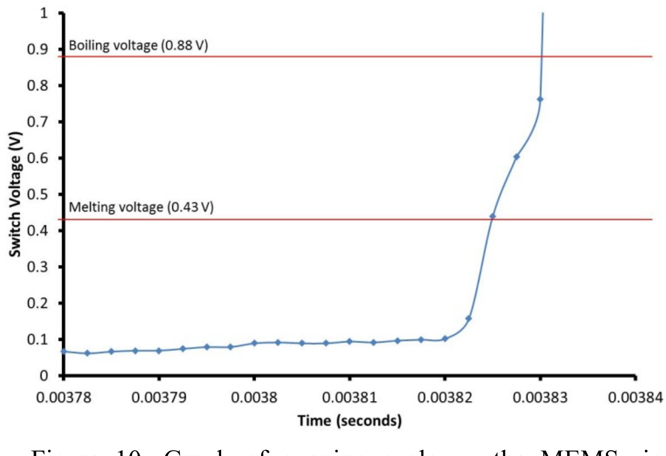

Figure 10: Graph of opening cycle on the MEMS rig (contact pair: CrAu cantilever beam and an Au/MWCNT composite), showing switch voltage increasing through melting and boiling voltage of Au.

During each opening cycle, the potential across the contacts passes through the melting voltage and boiling voltage of the Au; for gold these values are approximately 0.43 V and 0.88 V respectively [11, 20]. In Figure 10, the transient voltage for an opening cycle is shown. The voltage across the switch increases from <0.1 V (where the switch is closed), to 4 V (once fully opened). As the voltage passes through the melting voltage, a molten metal bridge is formed. This is the result of an extrusion of the melted material (i.e. gold for this contact). As the voltage increases to >0.88 V, the gold will boil and therefore the molten metal bridge will be broken. Due to asymmetries in the breaking of the bridge, material will transfer from one contact surface to the other (i.e. a fine transfer mechanism) [20]. In Figure 10, it can be seen that above ~0.88 V, i.e. once the gold has boiled, the switch voltage rapidly increases.

Discussion of Results

There are a number of factors, both electrical and mechanical which cause the failure of the contact. By investigating both dry- and hot-switching, it is possible to monitor the mechanical mechanisms independent of the electrical mechanisms. In the case of hot-switching, during the opening and closing of the switch the voltage sharply increases/decreases. Provided the load voltage is large enough, the potential across the switch contacts will pass through the melting voltage and boiling voltage of the contact material. For the contacts where there were no MWCNT present, referred to as hard-to-hard contacts, the failure was primarily due purely to a mechanical delamination of the Au from the substrate to the Au-coated ball. In the case where there was no Cr adhesion layer, the failure occurred after ~600,000 switching cycles with 50 mA load current; with dry-switching of the same contact material, it was shown that significant delamination occurred within the first 600,000 cycles. This implies that at no or low currents the failure is primarily due to a mechanical mechanism, such as those associated with stiction [21]. However, the effect of load current on the lifetime is not negligible; its effect has been investigated and discussed in previous work [17]. Whilst the addition of a Cr adhesion layer improved the lifetime of the electrical contact, the use of MWCNTs gave a significantly greater improvement. It is believed that during the closing event, the deformation of the MWCNT forests aids the dissipation of the contact impact energy. Further to this, the deformation means that the contact area is larger.

At the start of the experiments on the PZT rig, the switch voltage waveform showed two bounces per cycle, whereas there were no bouncing events observed from the tests with the MEMS rig. This reduction in the number of bounces combined with the small features of the MEMS-based cantilever beam is favourable to the development of a rapid switching test platform. With the MEMS rig, switching tests have been performed at frequencies up to 200 Hz. At 200 Hz, it takes ~28 hours to reach 20 million switching cycles. On the PZT rig setup, which was limited to <30 Hz, this would take ~186 hours.

Conclusions

Results demonstrating the improvement in the switching lifetime enabled by the use of Au/MWCNT composites have been discussed. A MEMS-based electrostatically actuated cantilever beam has been fabricated and incorporated with Au/MWCNT composite surfaces to form a MEMS switch test platform.

The low force electrostatic actuation method used on the MEMS test rig results in no observable electrical bouncing. This is advantageous over the PZT test rig which exhibited a minimum of 2 bounces per cycle and limited the maximum test frequency.

The feasibility of using this system as a rapid switching test platform has been shown. Experiments have demonstrated the ability to perform switching at 200 Hz. High-speed testing will result in the production of a larger set of data to aid the understanding of the failure mechanisms. It will also enable the effect of the test frequency on the failure mechanism to be studied over a wide range of frequencies.

Acknowledgments

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