

The Contact Resistance Performance of Gold Coated Carbon-Nanotube Surfaces under Low Current Switching

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SUMMARY Multi-Walled CNT (MWCNT) are synthesized on a silicon wafer and sputter coated with a gold film. The planar surfaces are mounted on the tip of a piezo-electric actuator and mated with a gold coated hemispherical surface to form an electrical contact. These switching contacts are tested under conditions typical of MEMS relay applications; 4 V, with a static contact force of 1 mN, at a low current between 20–50 mA. The failure of the switch is identified by the evolution of contact resistance which is monitored throughout the switching cycles. The results show that the contact resistance can be stable for up to 120 million switching cycles, which are 10^6 orders of higher than state-of-the-art pure gold contact. Bouncing behavior was also observed in each switching cycle. The failing mechanism was also studied in relation to the contact surface changes. It was observed that the contact surfaces undergo a transfer process over the switching life time, ultimately leading to switching failure the number of bounces is also related to the fine transfer failure mechanism.

key words: carbon nanotubes, contact surface, MEMS switching surface, fine transfer mechanism, contact resistance

1. Introduction

In MEMS relay devices, a stable contact resistance (R_c) of less than 1–2 Ω is required over millions of switching cycles [1]. To meet this specification a number of materials have been used for the switch contact surfaces, for example palladium alloys, platinum alloys, and gold [1]. Although these materials have low electrical resistivity, they are soft and prone to wear. Silicon carbide and diamond have also been investigated because of high elastic moduli, but these materials have unsuitably high resistivities.

Carbon nanotubes (CNTs) have both good electrical and mechanical properties [2], making them attractive for contact surfaces for a wide range of applications, including MEMS relays. CNTs have two main structures: single-walled nanotubes (SWCNTs) and multi-walled nanotubes (MWCNTs). MWCNTs are relatively easy to grow with controlled a length, diameter and density [3]–[5]. Electrical contact applications of structured (vertically aligned) MWCNTs was first investigated in [6], where the contact resistances of an Au-Au contact pair (Au hemispherical ball and Au substrate) and an Au-MWCNT contact pair (Au hemispherical ball and MWCNT substrate) have been com-

pared. They found that the contact resistance of the Au-MWCNT contact pair was higher ($\sim 108 \Omega$) than that of the Au-Au contact pair ($\sim 0.58 \Omega$) [6]–[9] due to the nonconductive substrate on which MWCNT are grown. The substrate inhibits the current travelling along the MWCNTs; only lateral conduction is possible between the MWCNTs, resulting in higher contact resistance. To improve the performance an Au-coated MWCNT surface (Au/MWCNT) was developed [6]–[15]. Results show that by using the Au/MWCNT surface, $R_c \sim 0.68 \Omega$ and much improved life cycles of the switch (i.e. 70 million cycles for a current of 20 mA) can be achieved with CNTs of 50 μm height, demonstrating great potential for switch contact applications. It was observed that material transfer was always from the Au/MWCNT substrate (anode) to the Au ball (cathode) [11]–[13]. Furthermore, at a current of 20 mA, a fine transfer process dominated [12]–[15]. The fine transfer process is described as a thermal process associated with the softening and melting of asperities during contact opening and is described in detail in [12]. From this work a simplified fine transfer model was defined and used to predict failure at different current levels other than the 20 mA used to define the model. It has since been shown that the wear process is a combination of both fine transfer and a delamination mechanism [12]–[15]. Thus the determination of the failure behavior of Au/MWCNT films has not yet been defined. In this work, four stages of the contact resistance and the bouncing behavior will be introduced to analyze characteristic failure processes. Evolution of contact resistance and the number of bounces are studied throughout the switching cycles, and the failure of the switch is identified by the sharp increase of contact resistance. The paper also re-examines the effect of the fine transfer mechanism based on the thermal model.

2. Material Preparation

The switch consists of two surfaces which are classified according to the direction of the DC electric current. The cathode is a 2 mm diameter stainless steel hemispherical ball sputter coated with a 10 nm thick Cr as adhesion layer followed by a 500 nm thick Au. This Au coated ball has a surface roughness, R_a of 92 nm. The anode is a silicon wafer with vertically aligned MWCNTs on top which has been sputtered coated with a 500 nm thick Au layer. This Au/MWCNT surface has a surface roughness of 1.3 μm . The growth process of the vertically aligned MWCNT is divided into three processes: cleaning, sputtering and growing

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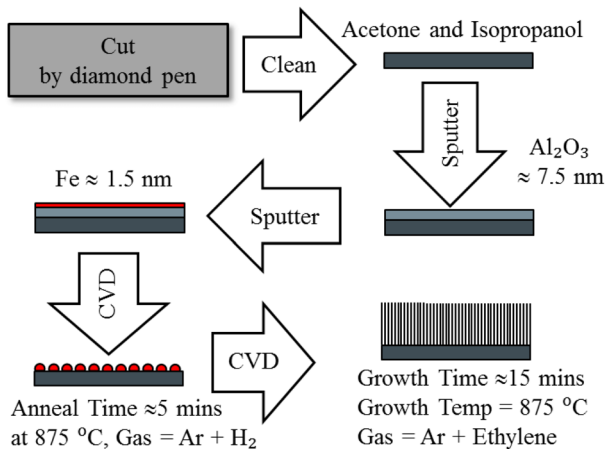


Fig. 1 CNTs growth apparatus and procedure.

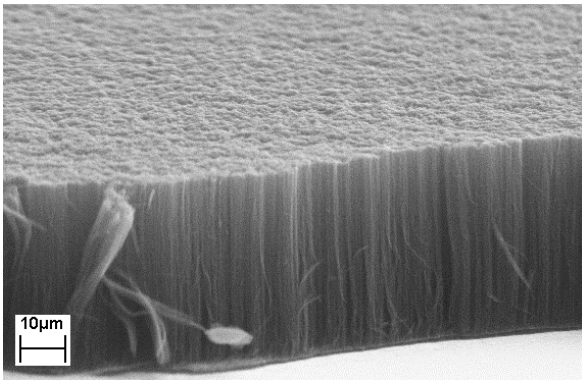


Fig. 2 Dense forest of MWCNT.

as shown in Fig. 1.

The cleaning process consists of submerging and sonicating the silicon wafers (7 mm by 2 mm) for 20 minutes in acetone and isopropanol, respectively. The clean substrate is then coated with 7.5 nm thick Al_2O_3 buffer layer followed by a 1.5 nm thick Fe catalyst layer. The final growth of the MWCNTs is accomplished by chemical vapor deposition (CVD) in a furnace. A mixture of Ar and H_2 gases is introduced into the chamber which is heated to 875°C . At this step, the substrate is annealed at this temperature for 5 minutes. The anneal step is needed to create Fe islands. These islands act as the seeds for MWCNT to grow. After the substrate is annealed, a mixture of ethylene (C_2H_4), H_2 and Ar is passed through the chamber at 875°C for 15 minutes to enable the growth of MWCNTs with height of approximately $30\ \mu\text{m}$. A cross-section SEM image of the obtained MWCNT forest is shown in Fig. 2. It was observed that the MWCNT substrate was well-aligned and uniform across the entire substrate.

Following the growth of MWCNTs, a final step is to sputter 500 nm thick Au layer on the MWCNTs to obtain the Au/MWCNTs surface. The resulting surface has a roughness (R_a) of $1.3\ \mu\text{m}$ and the penetration depth of Au into the MWCNTs is approximately $1\ \mu\text{m}$ as shown in Fig. 3.

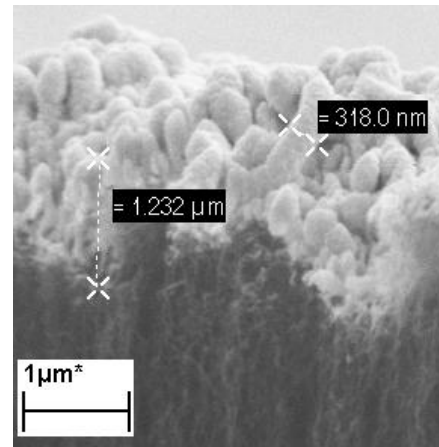


Fig. 3 Au/MWCNT composite contact.

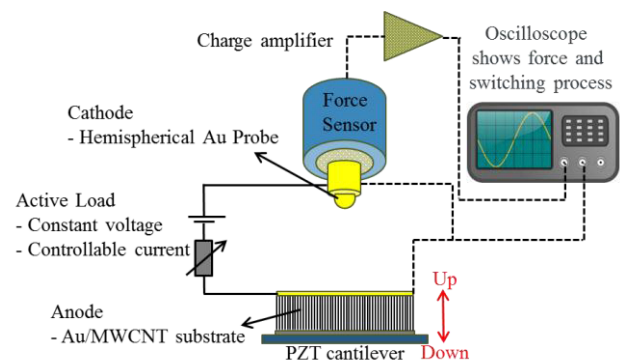


Fig. 4 The schematic of the test configuration.

3. Methodology

To simulate the repeated switching action of a MEMS relay, the Au/MWCNTs substrate is attached to a PZT cantilever. The test platform consists of the PZT with the Au/MWCNT substrate as anode while the Au-coated hemispherical surface at the top is the cathode. The setup configuration is shown in Fig. 4. The platform is mounted on an anti-vibration workstation in a temperature controlled room.

A dynamic contact force of 1 mN is set for the experiment. This dynamic force was measured using a Kistler (type: 9207) force sensor mounted above the ball contact as shown in Fig. 4. The contact force was generated by PZT cantilever which was actuated at frequency of 1 Hz. The data in Fig. 5 shows a typical result of the impact force of the two switching contacts, followed by a stabilization of the 1 mN contact force after 0.2 s.

To measure the contact gap between the contacts, during the open part of a cycle, a laser system was used. This measured the displacement of the PZT cantilever. With no contact, the cantilever could vibrate freely with a maximum displacement of approximately $40\ \mu\text{m}$. When exerting a contact force of 1 mN on the contacts this displacement (i.e. the contact gap) becomes $2\ \mu\text{m}$.

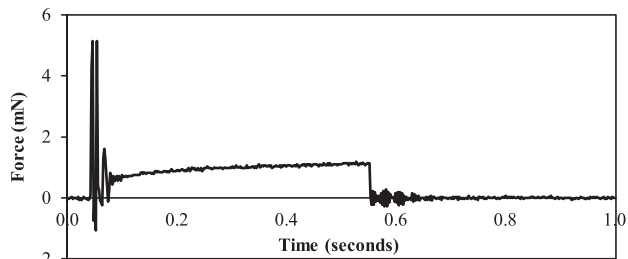


Fig. 5 Measured contact force with 1 Hz activation of PZT actuator.

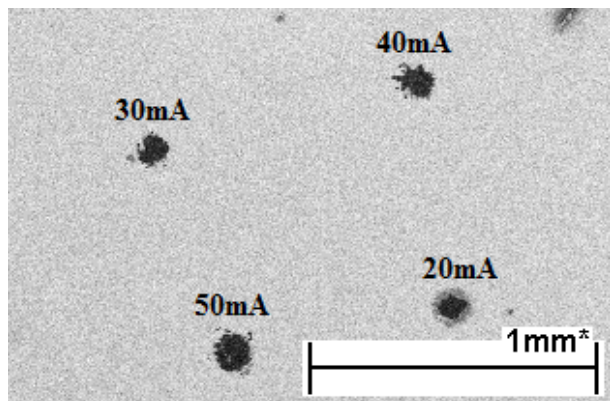


Fig. 6 The location of the experimental positions for the 4 current levels (20, 30, 40 and 50 mA) on the Au/MWCNT substrate.

The experiments were conducted with currents of 20, 30, 40 and 50 mA, a load voltage of 4 V, and a nominal contact force 1 mN. As shown in Fig. 2, the MWCNT forest is uniform over the whole testing substrate. All tests using different current levels were conducted on the same substrate with different positions as shown in Fig. 6. A signal function generator with voltage amplification was used to actuate the PZT cantilever at 20 V at a frequency range of 1100 Hz. Testing is performed as follows:

- Apply voltage to vibrate PZT cantilever by the function generator at testing frequency (f_{test}).
- Record the number of bounces (B_c).
- Measure and record the contact resistance (R_c) and the number of bounces at the 10th, 100th, 1000th, 10000th, and 100,000th cycles, and then every 12 hours until the contact fails. Record time to failure (t_{test}).

For the experiment operated at 20 mA, f_{test} was 30 Hz. For 30–50 mA, the f_{test} was set up at 100 Hz to reduce testing time. Therefore, the numbers of operations (N_{test} , cycles) are derived from;

$$N_{test} = t_{test} \times f_{test} \tag{1}$$

As shown in Fig. 5, the impacting force (1 mN) from the PZT cantilever will be stable after the contact is closed for 0.2 seconds. Therefore, to measure B_c , f_{test} has to be decreased to 1 Hz before counting to get the complete bounce process. The contact resistance R_c is measured using 4-wire measurement method. While measuring R_c , the experiment

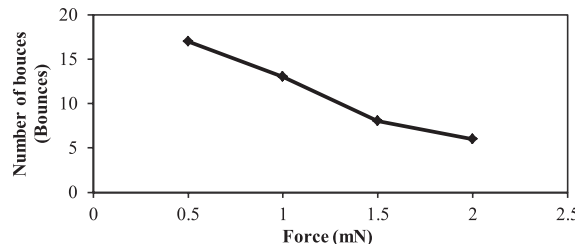


Fig. 7 The number of bouncing versus force for Au-Au/MWCNT, load voltage 4 V and load current 20 mA.

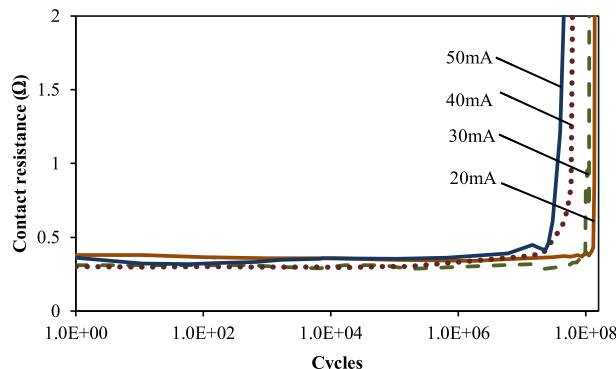


Fig. 8 Contact resistance against number of cycles for Au-Au/MWCNT contact pair with currents of 20–50 mA, 4 V.

is paused for 5 minutes to allow for the resistance to stabilize.

4. Results

4.1 Relationship between Number of Bounces and Force

The bouncing behavior has been observed during a closing process, [13]–[15]. Before investigating the failure behavior, the relationship between the number of bounces and force were studied on a contact sample which consists of a Au ball and an Au/MWCNT surface with 50 μm CNTs in height. The static contact forces varied between 0.5 mN and 2 mN. The number of bounces for each force is shown in Fig. 7, 17 bounces occurred at 0.5 mN and gradually decreased to 6 bounces at 2 mN.

4.2 Contact Resistance against the Number of Cycles

The contact resistance against the number of cycles is shown in Fig. 8. The contact resistance behavior is similar across all values of current and can be described in four stages. The first stage is an unstable stage of R_c . The R_c starts below 0.4 Ω and decreased over the first 5,000 cycles. The second stage where there is gradual low level increase in R_c over millions of switching cycles. In the third stage there is a rapid increase in R_c . The final stage is when the resistance has reached a failure point, this is defined here as three times the nominal resistance, (1.5 Ω).

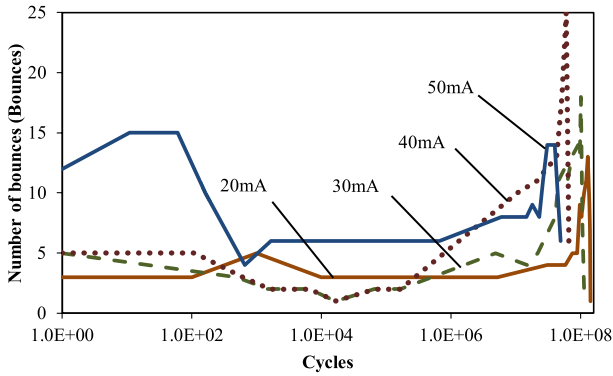


Fig.9 The number of bounce against number of cycles for Au-Au/MWCNT contact pair with currents of 20–50 mA, 4 V.

4.3 The Number of Bounces against the Number of Cycles

The number of bounces against the number of cycles is shown in Fig.9, for the 4 current levels. As with the R_c behavior, the change in bounces can be divided into four stages. The first stage of B_c is an unstable stage. B_c starts at between 3-5 bounces except the experiment operated at 50 mA for which B_c is 12. The bounce process is a complex interaction of components. After performing switching for 5,000 cycles, B_c decreases to 1-4 bounces. This is the stable stage of B_c , which remains stable for millions of cycles, with a gradual increase in the number of bounces for this period. Then the switching contact shifts to the rising stage of B_c . In this stage, B_c rises sharply. Finally, the contact is in the failure stage and B_c shows a reduction, indicating that the contact has failed.

5. Discussion

The data from Fig. 8 and Fig. 9 is used to obtain the numbers of cycles (N_{test}) to failure of the experiment at currents of 20, 30, 40 and 50 mA as shown in Table 1. These are defined as the number of cycles when $R = 1.5 \Omega$.

Figure 10, shows the numbers of cycles to failure (N_{test}) for the 4 current levels used. The data is superimposed for comparison with data from the fine transfer model, and from previous experimental data [12]. The difference in failure cycles and the significant improvement at the higher current levels is a direct consequence of the additional Cr layer under the Au surface on the ball. The fine transfer model in [12] was based on a single (20 mA) data point, thus although the trend is correct there is an offset between the current data and the model.

Since the trends of R_c and B_c with current are similar, the data for 30 mA, 4 V (1 mN) is chosen to show the graph appearance of the four stages of the failure. These four stages; namely unstable, stable, rising and failure stages, are shown in Fig. 11.

The first stage is the unstable stage. In Fig. 12, the decreasing trend of both contact resistance and number of

Table 1 The number of cycles to failure of the experiment.

| Current (mA) | Fine transfer [12] (cycles) | Previous data [12] (cycles) | N_{test} (cycles) |
|--------------|-----------------------------|-----------------------------|---------------------|
| 1 | 2.8E+10 | - | - |
| 10 | 2.8E+08 | - | - |
| 20 | 7.0E+07 | 7.0E+07 | 1.4E+08 |
| 30 | 3.1E+07 | 2.0E+02 | 1.2E+08 |
| 40 | 1.8E+07 | 1.0E+02 | 6.6E+07 |
| 50 | 1.1E+07 | 8.0E+01 | 4.9E+07 |

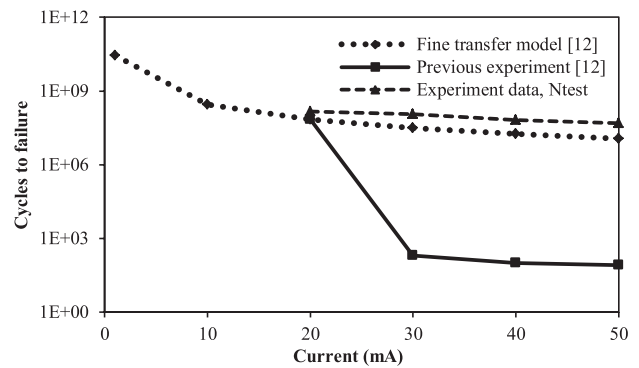


Fig. 10 The number of cycle to failure for a given load current. Dots on solid line resulted from [12]. Dotted line is predicted data from fine transfer model [12]. Dots on dashed line are the N_{test} .

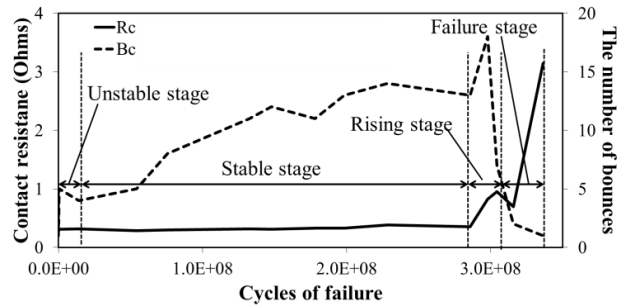


Fig. 11 Four stages of the contact resistance and the number of bounces behavior.

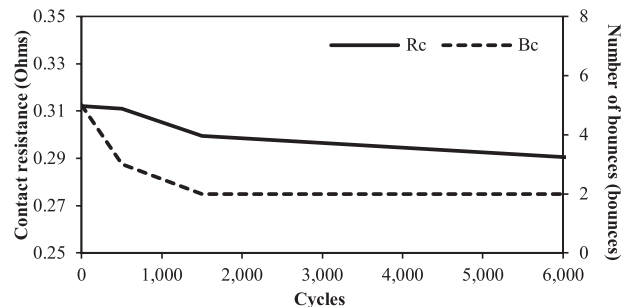


Fig. 12 The unstable stages of the failure behavior.

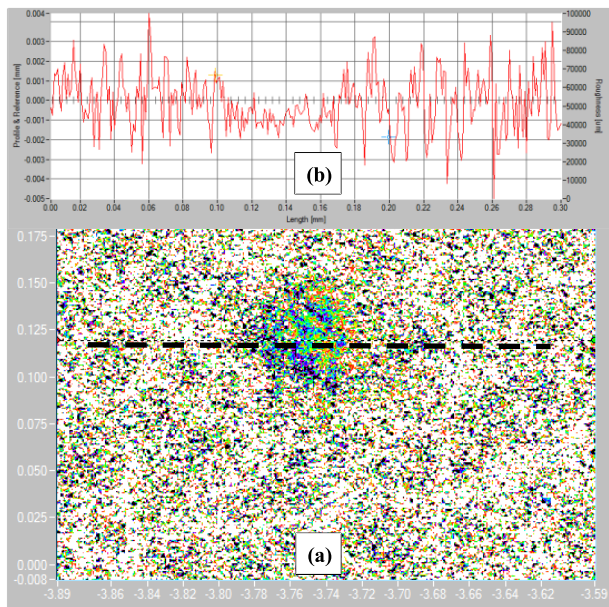


Fig. 13 (a) 3D surface profile of anode surface, 301X301 data points over area 0.3×0.3 mm. of Au-Au/MWCNT; $30\mu\text{m}$ height, (b) Surface profile of Au-Au/MWCNT composite surface.

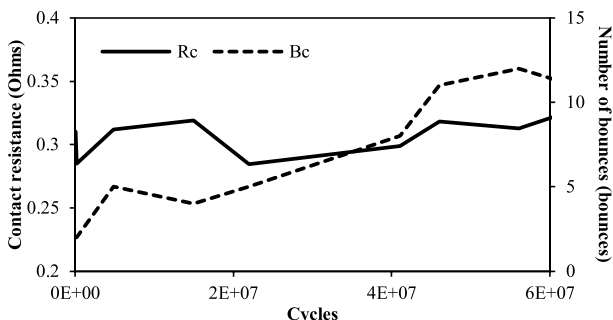


Fig. 14 The stable stage.

bounce is shown. Based on the observation, this permanent deformation process of the Au/MWCNT substrate with $30\mu\text{m}$ MWCNT is completely finished within 5,000 switching cycles.

To investigate the wear-in period further, the Au-Au/MWCNT contact pair was tested for around 5,000 cycles with a current of 30 mA, 4 V (1 mN). After which a laser profiler was used to scan the Au/MWCNT surface (Fig. 13(a)) to investigate the crater of the MWCNT deformation, as shown in Fig. 13(b). It is possible that the MWCNT may have buckled permanently when the contact force was greater than a load threshold, resulting in plastic deformation.

The stable stage is plotted over 60 Million cycles and shows a small increase in the number of bounces, and a stable contact resistance. R_c and B_c are stable within the small ranges ($\pm 0.05 \Omega$ for R_c and 4-8 bounces for B_c) as shown in Fig. 14. At this stage, the fine transfer mechanism is the dominant transfer process. The Au layer is gradually re-

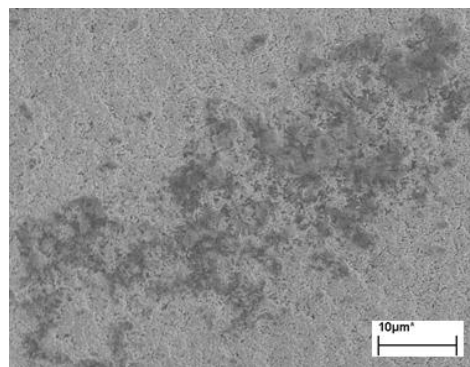


Fig. 15 Au layer transfer at 1 million cycles at 30 mA (yet to fail) on the Au/MWCNT surface, $30\mu\text{m}$ height.

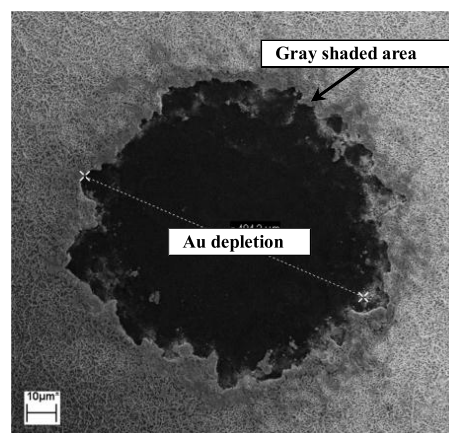


Fig. 16 Material transfer observed at 27th million cycle, at 30 mA (yet to fail) on the Au/MWCNT surface; $30\mu\text{m}$ height.

moved from Au/MWCNT (anode) to Au probe (cathode). This leads to a gradually change in the contact surface. To confirm this, an experiment with Au-Au/MWCNT surface of $30\mu\text{m}$ height, with a current of 30 mA, 4 V (1 mN) was tested for around 1 million cycles. SEM image taken from the contact surface is shown in Fig. 15. It can be observed that Au layer on the Au/MWCNT surface is starting to deplete and transfer to the Au ball.

When the switching contact is in the rising stage, the contact resistance and number of bounces continues to rise, albeit with a steeper gradient. The depleted surface causes the increase in contact resistance due to the decrease in the metallic contact area. Previously the current passes through the Au asperities at the center of the surface. When the center area does not have any Au surface remaining because of the material transfer process, the current density will travel through the area surrounding center until the contact is completely worn out (i.e. contact failure). To illustrate this process, the same experiment was tested to 27 million cycles. Then the SEM was used to examine the contact surface as shown in Fig. 16. The Au layer is completely depleted at the center as shown by the black area. Therefore, the conductive area supporting the current density is significantly reduced and the current starts to move via the area around it depleted

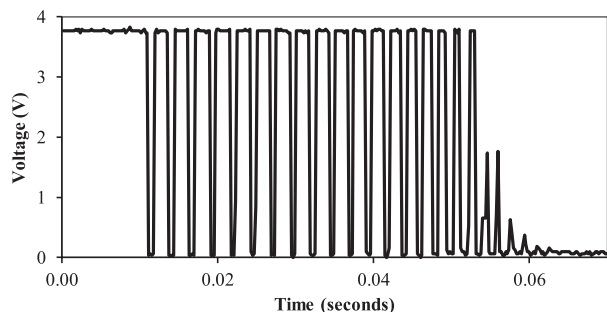


Fig. 17 The bounce process at the highest point on the rising stage.

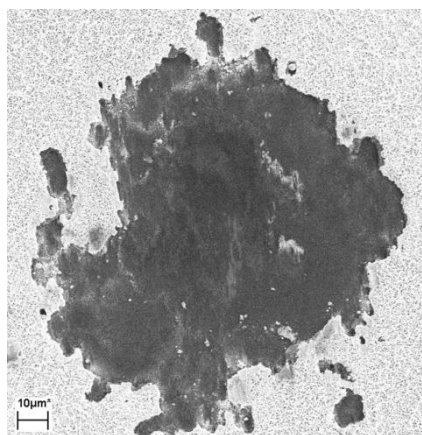


Fig. 18 Au/MWCNT surface at 49 million cycles (failed contact) tested at current of 30 mA.

area. (Grey shaded area).

In Fig. 16, the MWCNT layer is exposed in the black area. It is known that CNTs have high elastic moduli [2], [3] and so the number of bounces should increase with gold removal. The number of bounces increases sharply to the maximum number of bounces when the Au layer nearly completely worn out. The maximum bounce process is shown in Fig. 17.

The final stage is the failure stage of R_c , which shows the contact resistance rising rapidly. In this stage the contact surface is totally depleted as shown in Fig. 18, i.e. the contact area completely touches the MWCNT underneath. The MWCNT surface causes the high contact resistance of this last stage. Therefore, the contact pairs are considered to have failed as the contact resistance is greater a magnitude of three times the nominal value [12], which in this case is about 1.5Ω .

The number of bounces drops rapidly in the failure stage to show that the contact has failed. At this stage, the number of bounces should be equal to the peak amount in the rising stage. However, since the contact surface is almost totally depleted, some bounce events are not recorded as shown in Fig. 19 as the switch touches the non-conductive area which is entirely MWCNT.

In summary, it is possible to use contact resistance and the number of bounces to predict the failure of the switch

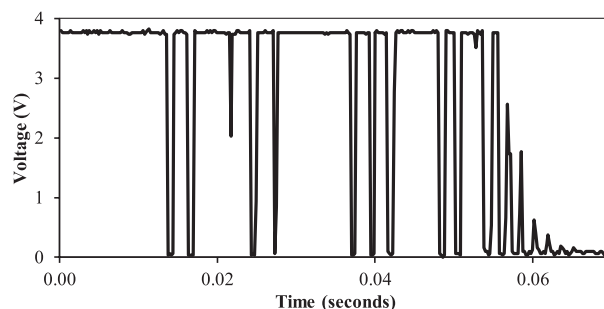


Fig. 19 The bounce process in the failure stage for Au-Au/MWCNT, $30 \mu\text{m}$ height contact pair with current of 30 mA, 4 V (1 mN).

contact. A benefit of the results presented that it allows the trend of B_c to be used predicting when the contact is going to fail, i.e. when contact resistance or the number of bounces increase sharply.

6. Conclusion

It has been shown that a Au ball surface coupled with an Au/MWCNT (gold-coated multi-walled carbon nanotube structure) substrate, can withstand more than 49 million switching cycles at 50 mA (0.2 W), at a low contact force of 1 mN. This is a significant increase in current over previous published work on these surfaces. The contact resistance across the interface is used as the indicator for determining the failure modes of the contact switch. The following conclusions are reached:

- The contact resistance trend is similar to previous studies, and remains stable for over 49 million switching cycles for all current levels between 20 and 50 mA.
- The mechanism of failure previously defined as fine transfer shows that the Au-MWCNT anode surface is losing material to the cathode ball.
- The contact bounce is affected by the changes in the surface and is correlated with the changes in R_c .
- The trend of number of bounces trend can be used to predict the lifetime. If the contact resistance or the number of bounces starts to increase rapidly, the user can predict that the contact is going to fail in the near future.

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Liudi Jiang was awarded her Ph.D. in 2002 by the University of Dundee for research in advanced material physics. Subsequently (2002–2005), she joined the Scottish Microelectronics Centre at the University of Edinburgh as a post-doctoral research fellow for the development of MEMS technologies for harsh environment applications. She was appointed a RCUK Academic Fellow (Roberts Fellow) in 2006 by the Engineering Material group at the University of Southampton, became a lecturer in 2008. Liudi is a member of The Institution of Engineering and Technology, a member of the Institute of Physics, and a Chartered Physicist.



Suan Hui Pu was awarded a Ph.D. in Micro-Electro-Mechanical Systems (MEMS) from Imperial College London in 2010. He earned his MEng in mechanical engineering, also from Imperial College London, in 2006. Suan-Hui has substantial experience in the development of MEMS devices and structures, including design, modelling, process development and characterisation. Prior to joining USMC, Suan-Hui was with Infineon Technologies, working on product yield enhancement in a 200 mm wafer fab.

Hence, he is keen to use his experience to help USMC students settle into their course. He is also happy to answer any queries they may have in relation to earning a degree from the University of Southampton, or about living in the UK.