Investigation of the current on the wear area of Au/Cr-Au/MWCNT contact pair

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Abstract   A gold coated carbon nanotubes composite was used as a contact material in Micro-Electrical-Mechanical-System (MEMS) switches. The switching contact was tested under typical conditions of MEMS relay applications: load voltage of 4 V, contact force of 1 mN, and load current varied between 20-200 mA. This paper focuses on the wear process over switching lifetime. A fine transfer model has been revised and the dependence of the wear area on the current is discussed. It was shown that the contact was going to fail when the wear area approached the whole contact area, at which point the contact resistance increased sharply to three times the nominal resistance.

Keyword   Carbon nanotubes composite, MEMS switches, Wear, Fine transfer mechanism, Contact resistance

1. Introduction

For Micro-Electrical-Mechanical-System (MEMS) switching devices at low voltages (2-12 V), wear process on electrical contact surfaces can result in device failure. One type of wear processes is the fine transfer mechanism [1-2].

The process of switching an electrical load, even at a low voltage level, is referred to as 'hot switching' for MEMS switches. The typical electrical load for a MEMS switch is 1 mA-100 mA and 4V which is above the softening and melting voltages for the metallic surfaces [1,3-4]. This leads to a transfer mechanism between the two contact surfaces known as 'fine transfer' or molten bridge phenomena. The mechanism of 'fine transfer' without the presence of micro-arcing can be described by the V, T theory [1]:

$$V^2 = 4L\left(T_m^2 - T_0^2\right) \qquad (1)$$

Where V is the potential difference across the electrical contacts, L is the Lorenz constant, T_m is the maximum temperature, and T_0 is the ambient temperature. Eq. (1) is valid for any practical electrical contact provided that: negligible loss of heat from the surface of the hot constriction, and the electrical resistivity and thermal conductivity (ρ, λ respectively) follow the Wiedemann Franze law $\rho\lambda = LT$ [1]. The required voltage to result in the melting and boiling temperatures of Au, which is the commonly used contact material in MEMS, is 0.43 V for melting and 0.88 V for boiling. Both are below the steady

state voltage of a MEMS switch, so during each opening operation, the Au will form a molten bridge, resulting in a wear process.

Furthermore, metallic surfaces used in MEMS relays are often films on Si or other surfaces. If Au is used then the hard (Si) substrate limits the contact area, and even at low force (mNs), the resultant contact pressure can be sufficient to produce cold welding; thus resulting in delamination of the Au films during opening and closing [2]. A proposed solution to both the "fine transfer" and the potential cold welding problems of Au surfaces is to use a sub-layer of structured MultiWalled Carbon Nanotubes (MWCNT) which exhibit high elasticity and provide a compliant layer under the metallic film.

Yunus *et al*. [5] used the gold-coated MWCNT (Au/MWCNT) composite as electrical contact surfaces, and showed that the use of Au/MWCNT composites could provide a stable contact resistance under low load currents (1-10 mA) with a contact force of 1 mN. Chianrabutra *et al* [6-7] further improved the experimental apparatus and showed that the contact resistance remained stable for a large number of switching cycles (between 80 to 120 million switching cycles with current levels of 20 to 50 mA). This demonstrated the feasibility of using the Au/MWCNT surface as a contact material for MEMS switches.

A fine transfer thermal model was proposed by McBride [2] to predict the lifetime of contact pairs of Au-Au/MWCNT. The point of failure of contact was

defined by the rapid increase in the contact resistance to three times the nominal value. The thickness of the Au film was assumed to be uniform (t), and the area of the wear area at failure was assumed to be constant. Thus the total volume of material transferred at the point of failure is $V_{max} = A_r t$, where A_r is the failure area. Thus the volume of material transferred per operation (Δv) [2, 8] is:

$$\Delta v = A_r t / N_f \qquad (2)$$

Where N_f is the total number of switching operations at the point of failure. Using the mechanism of material transferred per operation, a general relationship is given by:

$$\Delta v = kI^2 \qquad (3)$$

Where I is the current, and k is the constant determined by (1) and (2), a value of 3.85×10^{-10} (mm^3/operation) was used for k in [2]. So the total number of switching cycles to failure can be determined by:

$$N_f = V_{max} / kI^2 \qquad (4)$$

It was assumed in [2] that the depletion of the Au/CNT surface would reach a fixed area (so the same V_{max}) for a given contact force and independent of current, and then the contact resistance would increase to a level determined to be failure. The primary effect of increasing the current would be an increase in the transfer rate and therefore the failure area would be reached sooner. However, the work by Chianrabutra et al [7] has shown that on the same Au/MWCNT substrate the wear area at failure is a function of current and not constant. It was proposed then by Chianrabutra that the maximum volume of transferred material (V_{max}) on Au/MWCNT is the sum of the volume due to the fine transfer V_{fine} and the delamination process V_{del}[7], and the fine transfer volume kept constant and the lifetime cycles can be predicted by:

$$N_f = V_{fine} / kI^2 \qquad (5)$$

The predicted switching lifetime using the volume of fine transfer from [2] showed a good match with experimental results in [7]. It should be noticed that the bouncing number was considered in the modelling [7] as it caused extra opening and closing event during cycling.

In this work, we revise the work by Chianrabutra et al [7], and look into details how the wear area evolved with the number of cycles, to understand the mechanism of material transfer.

2. Material preparation

The fabrication of the contact pairs has been detailed in previous studies [6-7]. The contact pair consists of a 2 mm diameter hemisphere stainless steel ball and a substrate. The hemisphere ball (cathode) was coated with a 10 nm Cr adhesion layer and a 500 nm Au layer. The substrate (anode) was 500 nm Au coated on 30 μm MWCNT forest which was grown on silicon substrate. MWCNT was growing using thermal chemical deposition (CVD) at temperature 875°C for 15 minutes to form a MWCNT forest of approximately 30 μm in height, after which a 500 nm Au layer was sputtered onto the MWCNT surface. The coated gold does not form a uniform layer but penetrates into MWCNT forest, making a Au/MWCNT composite.

It should be noted that MWCNT is used for its mechanical properties not its electrical properties. In fact, only lateral conduction is possible between MWCNTs, resulting in a higher contact resistance [6].

3. Experimental method

The experimental apparatus is the same as described in [6-7], and a schematic of the testing system is shown in Figure 1. To simulate the repeated switching behavior of MEMS switches, the Au/MWCNT composite was attached to a PZT cantilever which was actuated by a function generator. The contact force was 1 mN, and the load voltage was 4 V for all experiments presented. A 4-probe micro-ohmmeter was used to measure the contact resistance.

The experiments were performed with load current values of 20, 30, 40, 50 and 200 mA. The contact resistance was measured after the 10th, 100th, 1000th, 10000th and 100000th switching cycles, and then periodically until the contact failed. The testing frequency was 2 Hz for 10th and 100th cycles, and 30 Hz from the 1000th cycles onwards, except 100 Hz for 20 mA. The values of R_c were recorded after the PZT cantilever was stopped for 3 minutes, ensuring the contact was stable. As discussed above, the number of bounces (B_{test}) was considered while counting the total number of switching events (see Eq. (6)). A contact was considered to been failed when the contact resistance increased beyond three times of nominal values. The total number of cycles can be calculated by:

$$N_{total} = \sum_k t_k f_k B_k \qquad (6)$$

Where k denotes the testing period between two pausing times. t, f, B represents the testing time in

seconds, the testing frequency and the number of bounces.

To understand the wear process of Au/MWCNT surfaces, experiments with load current of 50 mA were performed at different positions of same Au/MWCNT substrate, as shown in Figure 2, and each experiment was stopped after a predetermined number of cycles,

The Au/Cr ball and the Au/MWCNT substrate were investigated by SEM and laser profiler Taicaan XYRIS CL4000 after the contact reached the predetermined number of cycles or has been failed.
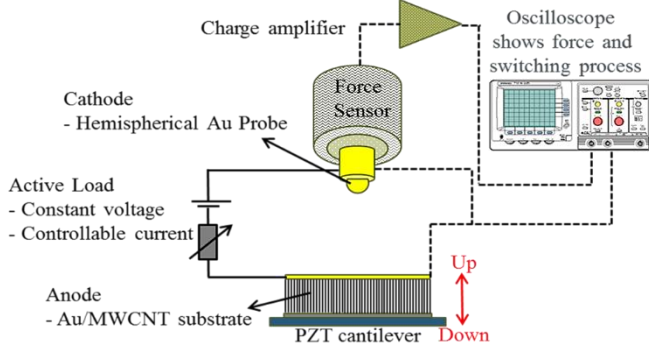

Figure 1. Schematic of experimental setup [7]
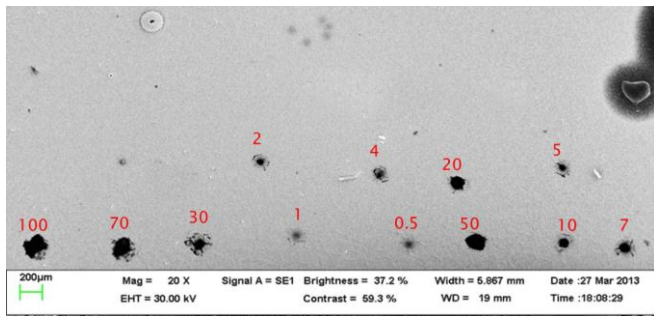
Figure 2 Experimental position of the Au/MWCNT substrate, tested with different number of cycles with load current of 50 mA (after [11]).

4. Results and discussion

A. *Wear area as a function of current load*

Table 1 shows the original contact resistance and the failed resistance. Theoretically, with an increase in the current, the maximum temperature on contact surfaces will increase and therefore the material will become softer, leading to a larger contact area thus smaller contact resistance. On the other hand, the electrical resistivity also increases with temperature, resulting in a larger resistance. The resulting contact resistance will be affected by both factors. Besides, the non-uniform feature of MWCNT under layer also affects the contact resistance as the tests were done at different positions. It was shown in Table 1 that the contact resistance varied with the current, and around the value of 0.3 Ω except for 0.65 Ω

for 200 mA. As the contact resistance would increase sharply at the rising and failure stage [7], the recorded failed contact resistance is not exactly three times of original resistance but higher, around 2.5- 3.5 Ω.

A 3D confocal laser map of the worn Au/MWCNT surface was used to determine the area of the removed material (A_r) from the substrate at the point of failure, and two methods were used to calculate the radius of wear area of contact surfaces, as:

Method 1: using the software associated to Taicaan profiler, BODDIES calculates the volume of removed material on the anode surface automatically [7], and then determine the radius of wear area assuming a circle.

Method 2: using a circle to fit the wear area of image obtained by SEM, this is an approximate method.

Figure 3 shows the results using two methods. Both curves showed a similar trend of radius of wear area that it increased with the current load though the approximate method predicted the radius generally smaller than the software calculated.

Figure 4 plots the maximum temperature calculated using Equ. (1) with the resistances at the initial stage and the failure stage. The measured final contact resistance was replaced by three times of original resistance as too higher resistances come from the MWCNT forest which possibly not obey the classic rule (1). It was shown that the temperatures at the initial stage are quite low for current load of 20-50 mA, suggesting that the material properties are almost the same, and thus the contact area are close. The contact temperature increases with the current as predicted, and it could arrive at 430°C with 200 mA. However, the softening temperature of gold is only 80-100°C [1], at which point the material becomes soft and the contact area increases largely to reduce the contact resistance and retain the softening temperature. So a corrected curve was plotted with the softening temperature 100°C of gold as the maximum temperature. The hardness decreases with the temperature, thus results in the increase of contact area.

One interesting question raised by this work is the wear area at the point of increased contact resistance and thus failure increased with increasing of current. To understand this, the wear process over the lifetime of a contact was investigated, and detailed in Section 4.B.

Table 1 Original and the test-to-failure contact resistances with different load current.

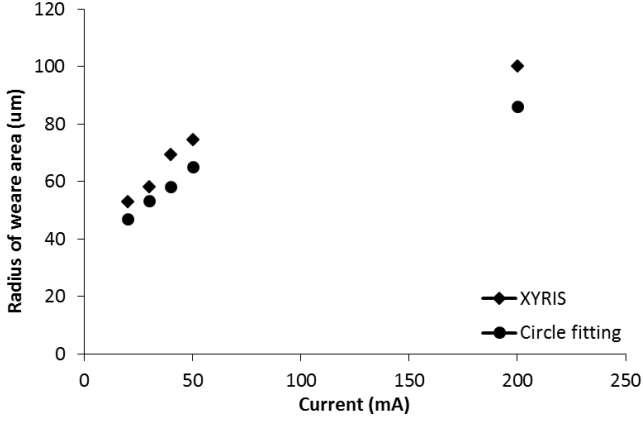| Current (mA)	20	30	40	50	200
R_0 (Ω)	0.38	0.312	0.3006	0.36	0.65
R_f (Ω)	2.458	3.145	3.5	2.5	-

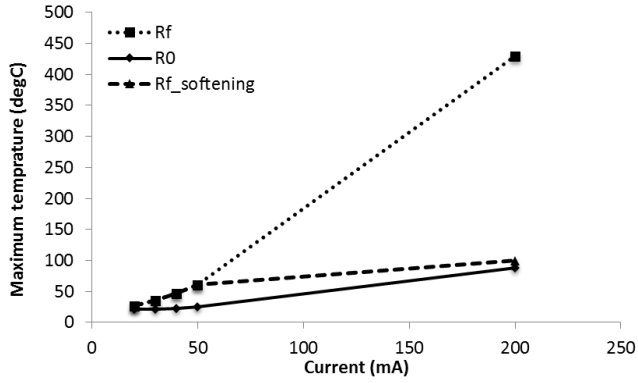

Figure 3 Radius of wear area at failure with current.

Figure 4 The estimated maximum temperature with current for initial stage (R0), failure stage (Rf) and failure stage corrected with softening temperature (Rf_softening).

B. Evolution of wear process of Au-Au/MWCNT contact

The effective radius of wear area was plotted in Figure 5, and the test was conducted with a load current of 50mA. It was shown that the wear area increased with the number of cycles as predicted. It was shown in Figures 6-9 that the material transfer took place over the deformed area. The SEM images (subfigures (b) in Figure 6-Figure 9) suggest that the wear process is a combination of a fine transfer and delamination mechanism. At the early stages, the contact surfaces was permanently deformed as shown in Figure 6 (b) and (c), the depth of crater is about 1 µm. The contact area is observed as a darken area – this area is where the fine transfer mechanism has reduced the thickness of the Au surface with transfer to the ball.

Figure 7 shows the contact surface after 1 million switching cycles. The fine transfer is the combination effect of mechanical and thermal influence. The center of contact zone becomes thinner. The figures (7-9) all show regions where delamination of the surface is occurring. In the case of Figure, 7 this is at the edges of the contact zone. In Figure 8 the delamination is shown in the central region of the zone after the fine transfer has reduced the thickness of the Au layer. Material transfer took place at the center and the vicinity of contact area, until most of the whole contact area been depleted, as can be seen in Figure 9.

The contact resistance over the switching lifetime was plotted in Figure 10. It was shown that whilst the wear area increased with switching cycles, the contact resistance remained stable until 30 million cycles, and then the contact resistance started to increase slightly until 70 million, then it sharply jumped to 4.75 Ω at 100 million cycles.

The contact resistance can be calculated assuming a circle ring as Figure 11 (a) shows [10], and by

$$R_c = 0.868\rho/c \qquad (7)$$

Where c is the radius of circle, also known as contact radius. It was found that the thickness of ring t has little influence on the contact resistance for a given radius until the thickness t becomes less than 0.05% of the contact radius (as Figure 11 (b) shows). The contact resistance increases by about 10% when the thickness of ring is only 10% of the contact radius. So for a given contact radius, the contact resistance would change little during switching cycles whereas the material transfer happened gradually at the center and also the vicinity of contact area.

Additionally, it was found that the contact depth of crater becomes deeper from subfigures (c) in Figure 6-Figure 9, increasing from 1 µm at 15000 cycles, to 3 µm at 1 million cycles, and 4 µm at 2 million cycles onwards. If assuming a smooth ball making contact versus a substrate and with plastic deformation, 1 µm deformation results in a 45 µm radius of contact area, and 3 and 4 µm correspond to 77 and 89 µm radii of contact area. The estimated contact radii values were also plotted in Figure 5 (labeled 'rc'). It was shown that the wear area was much smaller than the contact area at the beginning, and then approached to the contact area at the failure stage. The increased contact radius would reduce the contact resistance whereas the material transfer made a ring of

contact area increased the contact resistance, and the two effects contribute to the real contact resistance. When the wear area almost reached the whole contact area, the contact resistance increased sharply beyond 3 times the nominal values, therefore the contact was considered failed.
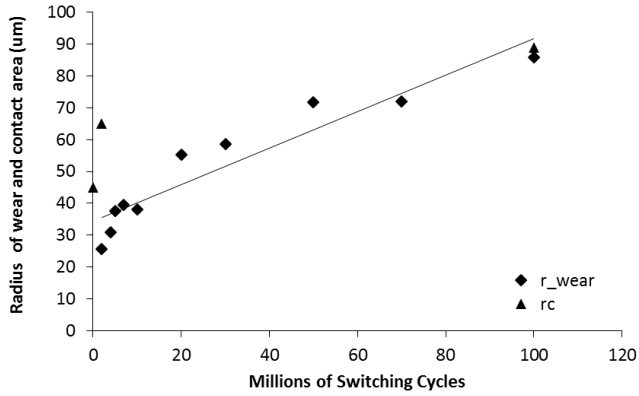

Figure 5 Effective radius of wear area (labelled 'r_wear') with cycles, 30 µm MWCNT with load current of 50 mA, and radius of contact area ('rc') estimated with the depth of crater, assuming plastic deformation.
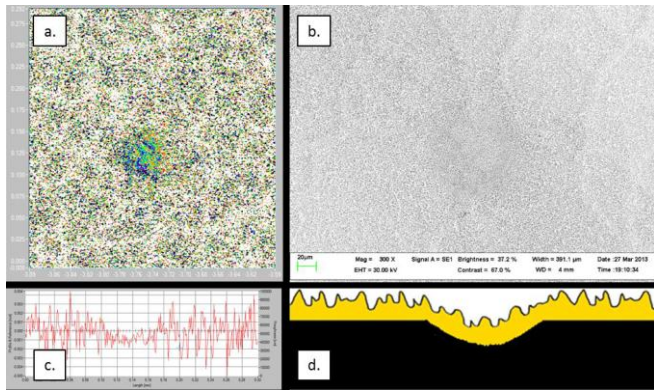

Figure 6 Au/MWCNT surface, with load current of 50mA after 15000 cycles. (a) 3D surface profile, 301X301 data points over area 0.3 x 0.3 mm; (b) SEM image surface; (c) surface profile cross section (dotted line on (a)); (d) drawing of cross section (after [11]).
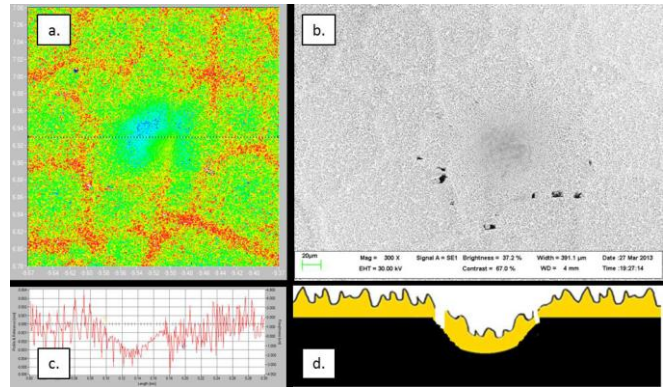

Figure 7 Au/MWCNT surface, with load current of 50mA after 1 million cycles. (a) 3D surface profile, 301X301 data points over area 0.3 x 0.3 mm; (b) SEM image surface; (c) surface profile cross section (dotted line on (a); (d) drawing of cross section (after [11]).
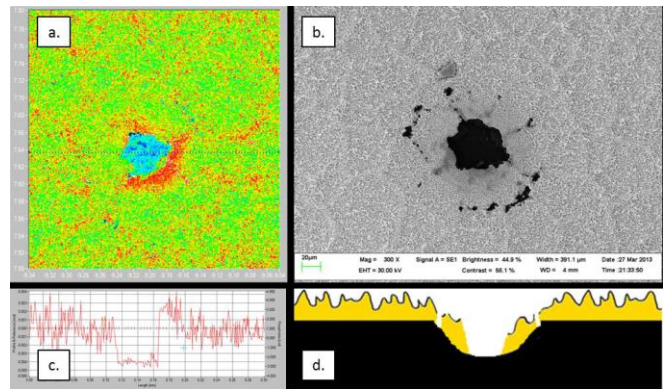

Figure 8 Au/MWCNT surface, with load current of 50mA after 2 million cycles. (a) 3D surface profile, 301X301 data points over area 0.3 x 0.3 mm; (b) SEM image surface; (c) surface profile cross section (dotted line on (a); (d) drawing of cross section (after [11]).
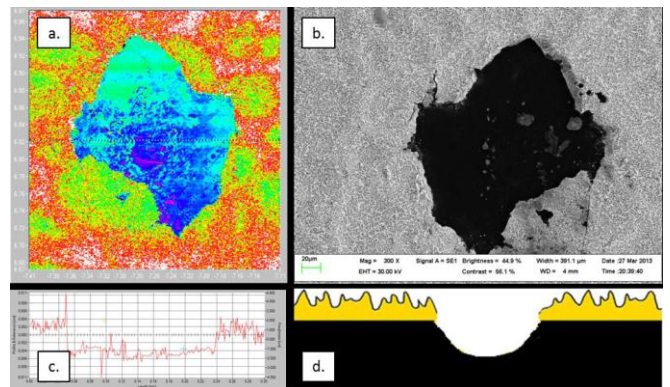

Figure 9 Au/MWCNT surface, with load current of 50mA after 100 million cycles (failed). (a) 3D surface profile, 301X301 data points over area 0.3 x 0.3 mm; (b) SEM image surface; (c) surface profile cross section (dotted line on (a)); (d) drawing of cross section(after
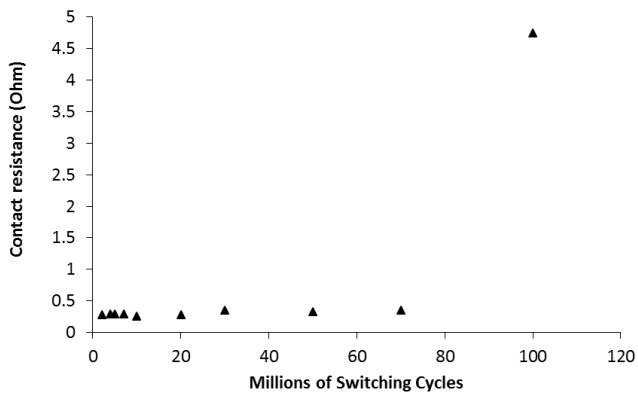
[11]).

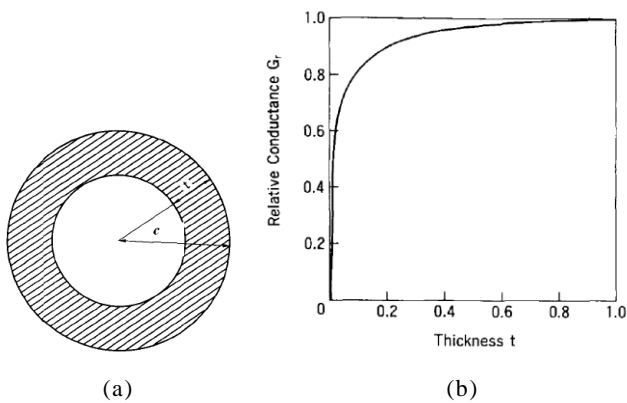Figure 10 Evolution of contact resistance with cycles, 30 μm MWCNT with load current of 50 mA.

(a)   (b)

Figure 11 Contact spot with a form ring (a), and the relative conductance with thickness of ring (b) [10].

5. Conclusions

The Au/MWCNT composite has been used as a surface material in MEMS switches as it could improve the lifetime of electrical contacts. This paper revised the wear process model of fine transfer, looked into details of how wear process occurred and how the wear area evolved. It was shown that the wear area took place over the contact area. When most of the contact area was depleted, the contact resistance increased sharply, causing the failure of electrical contacts.

Higher current results in higher temperature, reducing the material hardness, leads to larger contact area. The influence of current on the contact area is small at the initial stage of switching due to the small contact resistance, and contact resistances are close despite different load current. The effect of current becomes more significant with the increase of contact resistance, i.e. rising stage, higher current causing more contact area. On the other hand, material transfer is happening during switching. And the contact is failed when the contact area is mostly depleted. The steady contact resistance is a function of contact area and wear area, similar contact resistance can be obtained with different contact area.

The MWCNT showed a high elasticity and increased the contact area, resulting in a larger potential wear area compared to Au-Au contact pairs, thus increased the lifetime of electrical contacts.

6. References

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