Investigation of the Benefit of MWCNT Forests for Electrical Contacts

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Introduction

The application of gold coated multiwalled carbon nanotube (MWCNT) composites as a contact material has been investigated in previous studies [1-4], and it was shown that the use of MWCNTs significantly impro ved the lifetime of electrical contacts. It is assumed to be due to the high compliance of MWCNTs, which helps to reduce the mechanical damage to the contact surfaces during switching. However, no study had been undertaken to investigate the effect of the MWCNT layer on the mechanical behavior of the contact. In this study, results obtained from nanoindentation tests are used in a finite element model which has been developed for both Au-Au and Au-Au/MWCNTs contacts. The primary aim of this study is to investigate the effect of MWCNT forests on the mechanical behavior of the contact surfaces, and to describe the mechanism for the increase in the switching lifetime.

Experiments, Modeling and Results

The fabrication process for Au/MWCNT composites has been detailed in previous work, eg. [2-3]. Carbon nanotubes are grown using a thermal chemical vapor deposition (CVD) process on a silicon wafer sputtered with an Al_2O_3 buffer layer and a Fe catalyst layer. Following the growth of the MWCNT, they are sputtered with 500 nm of gold. Figure 1 shows an SEM image of a Au/MWCNT composite, where the MWCNTs have a height of 30 µm, which have been sputtered with 500 nm of Au. It should be noted that due to gaps between nanotubes, the gold will not form a uniform layer on surface, but penetrates into MWCNTs forest.

An experimental rig was developed to study the electrical resistance and lifetime of contact pairs [2-4], and Figure 2 shows a simplified schematic of the testing setup. The contact pair consists of a 2 mm diameter stainless steel ball and a substrate. Two contact pairs were studied: one was an Au-Au (i.e. no MWCNTs); the other was Au-Au/MWCNTs. For both cases, the hemisphere ball was coated with a 10 nm Cr adhesion layer and a 500 nm Au layer. For the Au-Au contact, the substrate was a silicon wafer coated with 10 nm Cr and 500 nm Au, labeled as 'Hard to Hard' in Figure 3. For the Au-Au/MWCNTs contact, the substrate was a 30 µm MWCNT forest coated with 500 nm of Au. The substrate was attached onto a PZT cantilever which is actuated and mimics the switching behavior of a MEMS micro-switch. For all experiments, the load voltage was 4V, the contact force was 1 mN and the testing frequency was 30 Hz. Figure 3 plots the number of cycles to failure under different load currents. It shows that the use of a layer of MWCNTs on the contact surface significantly improved the contact life time.

A numerical model of the contact was developed using commercial Finite Element (FE) software ANSYS 14.5. The model imitates the experimental setup, in which a 2 mm diameter hemispherical ball makes contact with a substrate. In the first model presented, the upper contact is simplified as a hemisphere stainless steel ball only. For the lower contact, two cases were modelled accordingly, one was with 500 nm sputtered gold on a silicon wafer, and the other was with the Au/MWCNT composite. The sputtered gold layer penetrates into the MWCNTs forest and therefore the Au/MWCNT composite cannot be considered a gold layer on top of a MWCNT but rather than a mixed material top layer and pure MWCNTs under layer. This multilayered structure assumption was discussed in a preceding study [6], and has been adopted and further developed in this study. Table 1 shows the material properties used in the FE modeling, which were obtained from experiments using nanoindentation tests [5][1]. Figure 4 shows the FE model for Au-Au/MWCNTs contact, which used the same modeling method as in [6]. Only a quarter of the contact pair was modeled to reduce simulation time; the nodes on the symmetric surface were fixed and therefore unable to move along the normal direction of the surfaces accordingly. A contact pressure equating to 1 mN load was applied uniformly on top surface of the quarter hemisphere. The contact area and contact pressure as a function of contact force for two contact pairs are plotted in Figure 5 (a), (b) respectively. Where a MWCNTs layer is present, the contact area is 68.4 times larger than Au-Au contact, and contact pressure is only 1.5% of Au-Au contact at 1 mN. These results agree with analysis of the SEM images of failed contact pairs shown in Figure 6, which showed that the area of contact wear is much larger with Au/MWCNT composites.

Conclusions

We have shown the Au/MWCNTs composite can improve significantly the lifetime of electrical contact. In the study, with numerical contact modeling, the mechanical behavior of contact pairs has been investigated. The results showed that the Au-Au/MWCNTs can cause a reduction in the contact pressure of 98.5% when compared with Au-Au contacts. It is believed that this decrease in contact pressure, results in a reduction of damage to the contact surfaces which in turn aids the enhancement of switching lifetime.

References

[1] E. M. Yunus, J. W. McBride, and S. M. Spearing, 'The Relationship Between Contact Resistance and Contact Force on Au-Coated Carbon Nanotube Surfaces Under Low Force Conditions', *IEEE Trans. Compon. Packag. Technol.*, vol. 32, pp. 650–657, Sep. 2009.

[2] C. Chianrabutra, L. Jiang, A. P. Lewis, and J. W. McBride, 'Evaluating the Influence of Current on the Wear Processes of Au/Cr-Au/MWCNT Switching Surfaces', in *59th IEEE Holm Conference on Electrical Contacts (HOLM)*, 2013, pp. 1–6.

[3] J. W. McBride, C. Chianrabutra, L. Jiang, and S. H. Pu, 'The contact resistance performance of gold coated carbon-nanotube surfaces under low current switching', in *12th International Session on Electro-Mechanical Devices (IS-EMD2012)*, Chiba, JP, 2012, p. 8pp.

[4] A. P. Lewis, M. P. Down, C. Chianrabutra, L. Jiang, S. M. Spearing, and J. W. McBride, 'The effect on Switching lifetime of chromium adhesion layers in gold-coated electrical contacts under cold and hot switching conditions', in *59th IEEE Holm Conference on Electrical Contacts*, Newport, RI, USA, 2013.

[5] M. P. Down, L. Jiang, and J. W. McBride, 'Mechanical Characterisation and Optimisation of Carbon Nanotube Composite Surfaces for Electrical Contact', in *27th International Conference on Electrical Contacts (ICEC 2014)*, Dresden, Germany.

[6] H. Liu, M. P. Down, J. W. McBride, S. H. Pu, and L. Jiang, 'Mechanical Characterization of a Au Coated Carbon Nanotube Multi-layered Structure', in *60th IEEE Holm Conference on Electrical Contacts (Holm)*.in press.

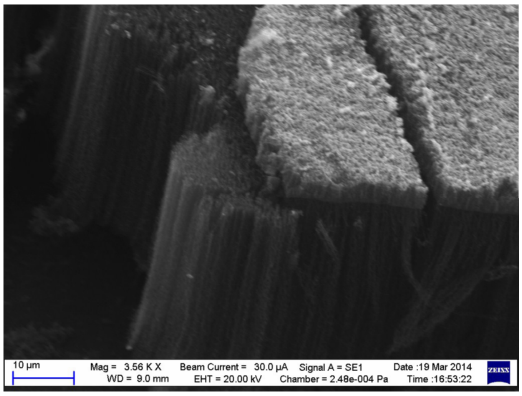


Figure 1: Sample 30 µm CNTs with 300 nm coated-gold: 2-4 µm of Au penetrates into MWCNTs which is on a Si substrate

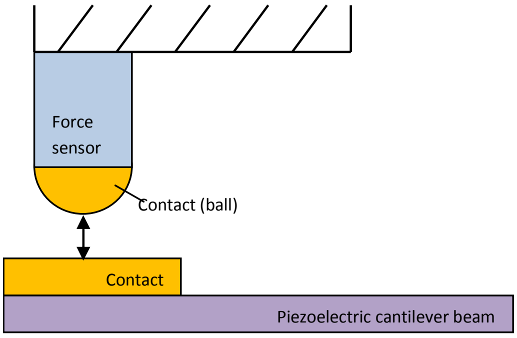


Figure 2: Schematic of experimental setup

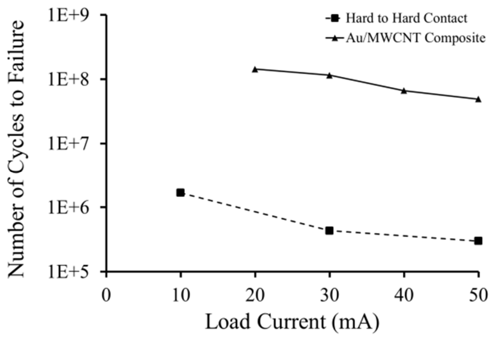


Figure 3: The number of cycles to failure under different load current

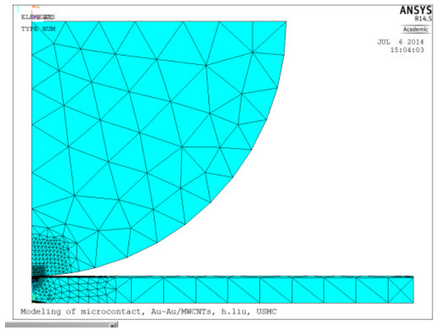
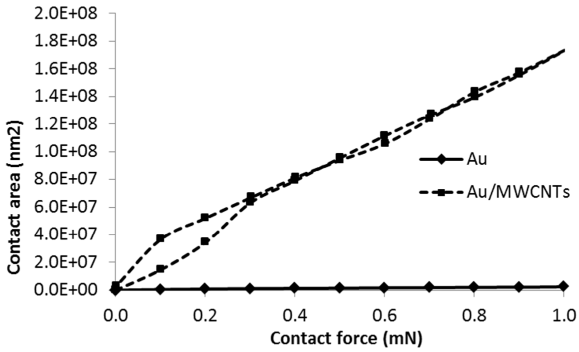
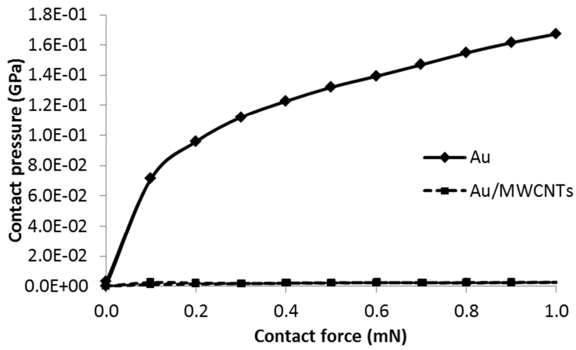


Figure 4 Finite element mesh of the model with quarter sized geometry



(a)



(b)

Figure 5 Simulation results: contact area (a) and contact pressure (b) as a function of contact force

Table 1 Material properties in finite element modeling

Mat/part	Elastic modulus (GPa)	Hardness (GPa)	Poisson's ratio
Silicon	162.5		0.22
Stainless steel	180		0.29
Gold	191.5	1.7 [1]	0.42
Top layer of Au/MWCNTs	1.77	5.78E-3	0.21
Under layer of Au/MWCNTs	7.26E-3		0

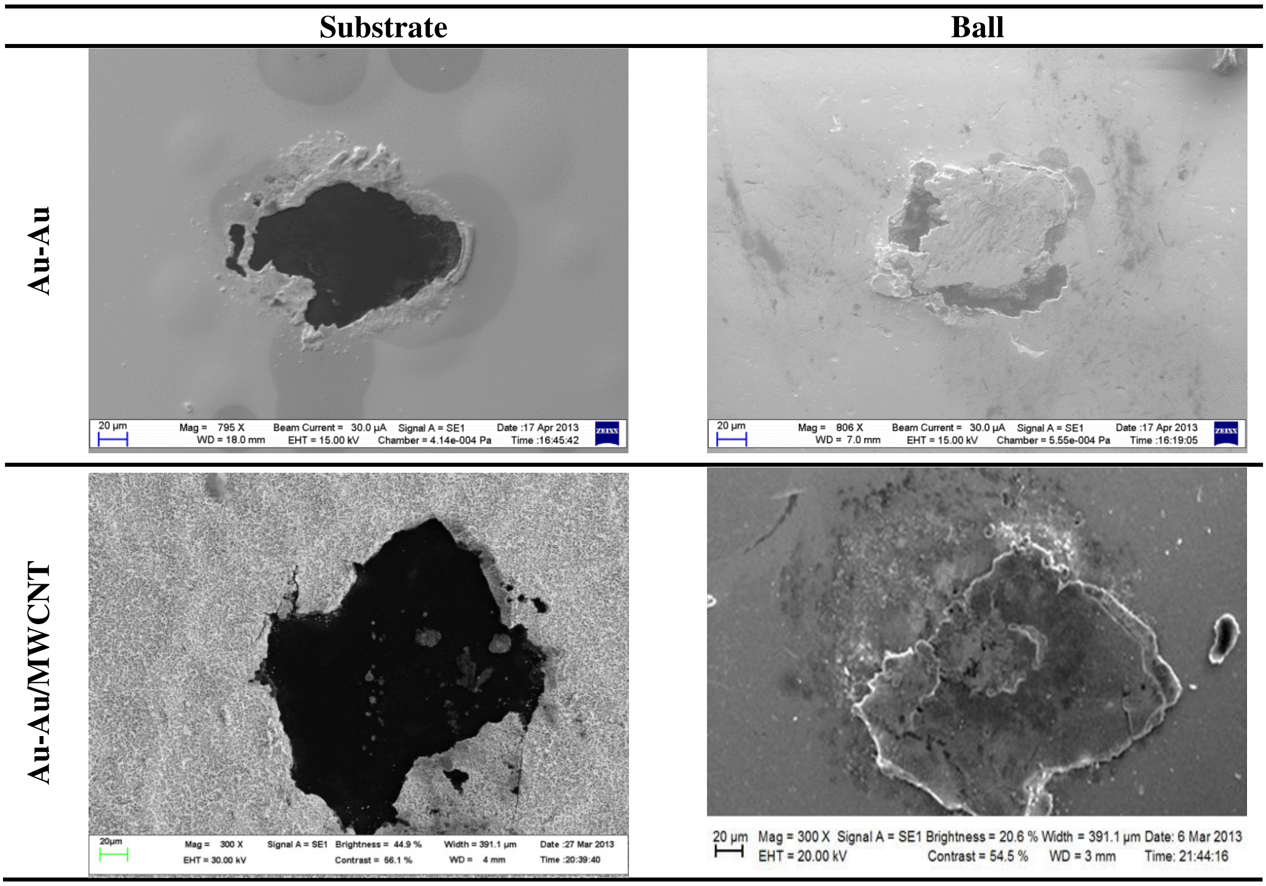


Figure 6: SEM image of ball and substrate surfaces after failure, tested with current of 50 mA and voltage of 4V.