Accelerated Testing of Multi-Walled CNT Composite Electrical Contacts for MEMS Switches

Adam P. Lewis[1,*], John W. McBride[1, 2], Suan Hui Pu[2] and Liudi Jiang[1]
[1]Faculty of Engineering and the Environment, University of Southampton, Southampton, SO17 1EN, UK
[2]University of Southampton Malaysia Campus, Nusajaya, 79200, Johor, Malaysia
[*]a.p.lewis@soton.ac.uk

Abstract

The use of gold-coated multi-walled carbon nanotube (Au/MWCNT) bilayer composite surfaces has been discussed in previous work as a method for improving the reliability of switch contacts [1, 2]. A consequence of large lifetimes means that testing to failure is time consuming. To address this we developed a MEMS-based test platform which enables testing at high frequency [3]. The MEMS devices were developed in a two stage process. In this paper the results obtained from the first stage design for a MEMS-based test platform device are discussed. Further to this, an overview of the design of the second stage device is given. Using the first-stage device, at a current of 50 mA (at 4 V), the composite yielded a lifetime in excess of 44 million hot-switching cycles [4]. At a lower load current of 10 mA, the contact maintained a stable contact for >500 million hot-switching cycles. As well as monitoring the contact resistance, SEM images of the surface before and after testing are presented. The first stage MEMS-based developmental device is a step towards a smaller integrated and packaged high-lifetime metal-contacting MEMS switch. An overview of the considerations for the redesign is given with a discussion on the predicted performance and improvement for accelerated switch testing.

Introduction

The advantages of MEMS relay switches over PIN diode and FET devices are well known; most notably lower on-resistance, higher isolation and cut-off frequency [5-8]. MEMS relays have very high values of off-resistance, which is important for low power applications, especially where power consumption is of concern [9]. There are two common implementations of MEMS switches: capacitively coupled and metal-contacting. The use of capacitive switches at low frequencies is limited, however they tend to be capable of surviving high numbers (>500,000,000) of switching cycles without showing any signs of mechanical failure [10]. For the second implementation, metal-contacting switches, the electrical contacts are mechanically brought into contact; there is no dielectric layer present on the contacts which means that the transmission of DC to high frequency signals is possible. Due to the mechanical switch opening and closing process the contact surfaces suffer degradation which over consecutive opening and closing processes, causes the switch to fail [2]. In this paper we discuss hot-switching tests (4V, 10 mA and 50 mA) performed on the MEMS-based platform in which an electrostatically actuated micro-machined gold-coated silicon cantilever beam repeatedly makes contact with an Au/MWCNT composite.

Experimental Methodology

The fabrication of the contact pairs and the experimental methodology has been described in detail in previous work [3, 4], a brief overview is given here. The contact pair consists of an Au/MWCNT composite and an Au-coated cantilever beam.

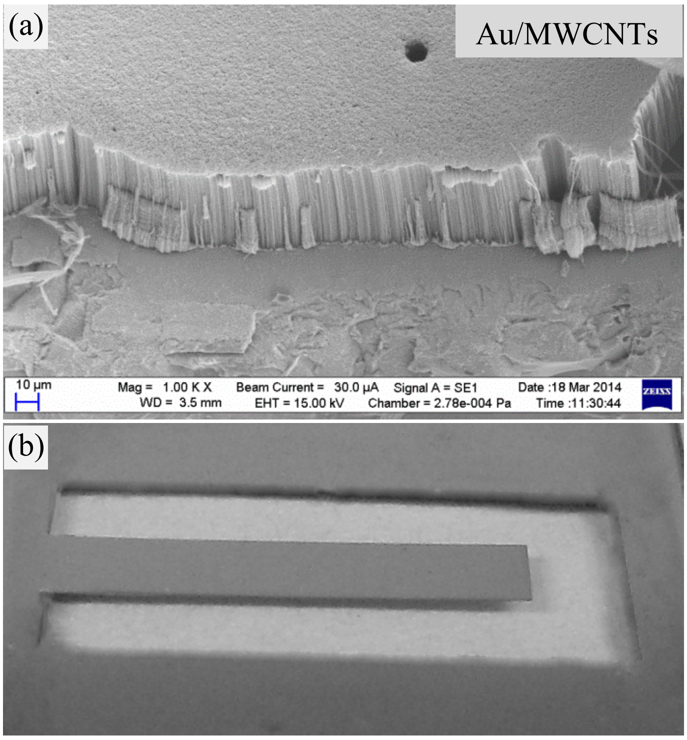


Figure 1(a): Tilted SEM image of Au/MWCNT composite, (MWCNT height: ~30 µm). (b): Image of Au-coated electrostatically actuated cantilever beam (beam length, width and thickness: 10 mm, 2 mm and 20 µm respectively).

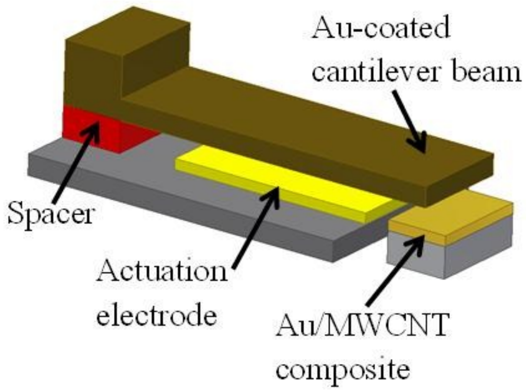
The forest of MWCNTs (30 µm in height) was grown on an oxidized silicon chip using a chemical vapor deposition process. Following the growth, the forest is sputter coated with 500 nm of gold, resulting in the Au/MWCNT composite. A SEM image of the composite can be seen in Figure 1a.

The Au-coated cantilever beam was created using inductively coupled plasma (ICP) etching of silicon. After patterning the cantilever beam on a silicon wafer in photoresist, the silicon is etched by ICP to the required depth (i.e. the cantilever beam thickness of ~20 µm). The underside of the wafer is patterned with photoresist which defines holes through the wafer to the cantilever beam. The underside of the silicon wafer is ICP etched until the beam is released. The final step is to sputter coat the cantilever beam with a 10 nm layer of chromium and a 500 nm layer of gold. The chromium layer is an adhesion layer to promote the adhesion of the gold to the silicon [11]. An image of the Au-coated cantilever beam is given in Figure 1b.

Following the fabrication of the contact pair the Au-coated cantilever beam is suspended on a spacer (>25 µm) above an actuation electrode as shown in Figure 2. Au-MWCNT composite is then placed <3 µm from the tip of the Au-coated cantilever beam. The application of a voltage on the actuation electrode induces an electrostatic force on the cantilever beam which moves the beam into contact with the Au-MWCNT composite. With the actuation voltage removed, the stiffness of the cantilever beam provides a restoring force which moves the beam away from the Au/MWCNT. The resonant frequency of the beam was measured as 235 Hz, which was in good agreement with the model which predicted ~270 Hz [3].

For all experiments described here, the load voltage was 4 V and from computational modelling the contact force is estimated to be ~5-10 µN [3]. The experiment was run with two values of load current, these values were 10 mA and 50 mA. Throughout the course of the experiments the voltages across the switch and the current limiting resistor, R_x in Figure 2b, were monitored. The voltage across the current limiting resistor is proportional to the current flow through the resistor and hence through the switch contacts. Dividing the voltage dropped across the switch contacts by the current through them (and by accounting for the lead resistances) it was possible to calculate and monitor the contact resistance throughout the course of the experiments.

(a)



(b)

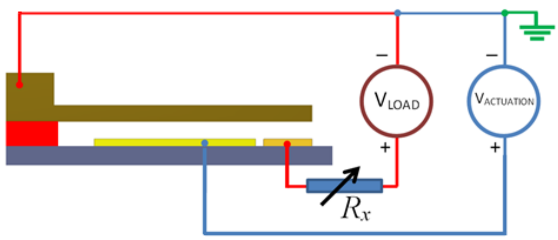


Figure 2(a): Illustration of experimental setup. (b) Side view showing electrical load and actuation voltage connections.

Accelerated Testing: Development of the Cantilever Beam Design

The development of the MEMS switch was intended as a two-stage process whereby the first stage was used to guide the second. The experiments discussed in the results section were performed on the MEMS cantilever beam described above (first stage device). The resonant frequency of that beam was 235 Hz and the tests were performed at 100 Hz, well below the resonant frequency. As a consequence it took a long time to complete the testing. Long testing durations are undesirable for practical reasons. To perform switching at higher frequencies the resonant frequency of the cantilever beam used in the switch must be increased. The following parameters were considered for the second-stage cantilever beam design:

- beam thickness,
- beam length,
- gap between beam and actuation electrode.

Provided that the beam width << length the beam width does not significantly affect the resonant frequency of the beam; often when discussing the analysis of cantilever beams, parameters such as spring constant are normalized to the beam width [6]. The diagram in Figure 3 illustrates the dimensions of the beam considered with respect to the actuation electrode and the sample. The beam thickness may be increased or the beam length can be reduced in order to increase the resonant frequency. Both changes result in an increase in the beam stiffness. A consequence of a higher value of beam stiffness is that a larger actuation voltage will be required to actuate the beam. In the redesign the beam thickness was 10 µm, and the nominal beam length and width were set to 1.7 mm and 100 µm respectively. In order to control the actuation voltage it was decided to set the actuation gap to ~5 µm. With the given dimensions the expected resonant frequency and pull-in voltage were estimated (using analytical calculations) to be 4.8 kHz and 11.3 V respectively. The cantilever beam was modelled and simulated in CoventorWare which yielded a resonant frequency of 4.3 kHz and a pull-in voltage of 12 V. The second mode of resonance was computed to be 27 kHz which is significantly greater than the first mode of resonance. This is an important consideration since if the modes are two close together in the frequency domain the mechanics of the beam may be affected by the second mode of resonance. The first modal resonant frequency gives a maximum value to operate the switch at. With a resonant frequency of ~4.3 kHz, the beam could be operated at 4 kHz which would mean that the test time for 500 million cycles is brought down to 1.5 days. This is a significant reduction (40 times) in the test duration compared with the test discussed in the next section which switched at 100 Hz.

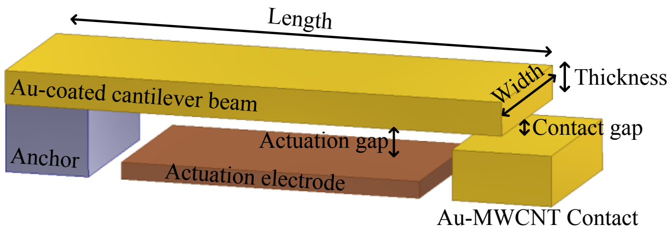


Figure 3: Illustration of the beam dimensions considered.

Results and Discussion

1. Contact Resistance

It is known that the lifetime is linked to the load current and hence the lower load current was expected to give a larger lifetime [1]. Figure 4 shows the change in contact resistance with the increasing number of switching cycles. With a load current of 10 mA the contact pair had a relatively stable contact resistance of ~4.8 Ω for over 500 million hot-switched cycles. This contact resistance is slightly higher than desirable but is still useful. A typical MEMS switching device capable of DC-high frequency performance was discussed by Majumbder *et al.* [12]. The switch was micro-machined in silicon, the contact material was a platinum-group metal. The contact resistance of a single switch was 3 Ω [12]. This was reduced by switching 8 contacts in parallel; the contact resistance (including interconnects) was less than 1 Ω at DC and low frequencies [12, 13]. Majumbder *et al.* stated that the lifetime of the switch when subjected to hot-switching (with voltage of 1 V) was about 10^7 cycles. The largest lifetimes for these devices were observed where they were packaged in TO-8 cans thereby confirming that packaging is an important aspect for improving device lifetime [13].

It should be noted that the contact pair did not fail at 500 million cycles however the experiment was stopped after 500 million cycles for a number of reasons. From a practical viewpoint, testing to large numbers of cycles is time consuming (e.g. with a switching frequency of 100 Hz, it would take 58 days of continuous switching to reach 500 million cycles) hence in this paper we discuss the design of cantilever beams for accelerated testing. From an application viewpoint, 500 million is a large number of cycles especially considering that the contacts are hot-switched. Where comparable MEMS switches have been quoted with similar lifetimes they tend to either switch very low or zero current (i.e. cold switching) [6, 7, 12-14]. The commercial surface-mounted compact SPDT MEMS switch (usable up to 10 GHz) developed by Omron Corp. has a size of 5.2 mm x 3.0 mm x 1.8 mm (L x W x H) [14]. The mechanical and electrical life expectancy is stated as a minimum of 100 million operations (tested at 0.5 mA, 0.5 V); the maximum rated load is 0.5 mA at 0.5 V [14]. The RedRock™ device developed by Coto Technology is stated to have a life expectancy of 10^8, however this is with no load [15, 16]. The device is capable of hot-switching though details on the effect of hot-switching on the expected lifetime are not given. The dimensions of the device are~ 2.185 mm x 1.125 mm x 0.94 mm (L x W x H), making it smaller than the Omron device [14, 15]; however it should be noted that this is an example of a reed switch rather than a MEMS switch, therefore the size of the actuation system is neglected by the datasheet. The contact material used for the RedRock™ relay is ruthenium which has a melting voltage of 0.795 V [13]. For comparison, the melting voltage for gold is 0.43 V [17]. With the absence of current during switching the damage to the contact surface is primarily mechanical. In cases where MEMS switches are tested with hot-switching, the lifetime becomes significantly reduced from 100s of millions of cycles to <10 million [7, 18-20].

With a load current of 50 mA, the Au/MWCNT to Au-coated cantilever beam contact pair failed after 44.4 million cycles [4]. The nominal contact resistance during the operational lifetime was ~3 Ω. The shorter lifetime compared with the lower current experiment was expected given that the load current is known to be a significant contributor to the electrical contact failure mechanism for hot-switched contacts [1].

In previous work where Au/MWCNT composites were tested as electrical contacts, to simulate MEMS switching behavior a number of lifetime experiments were performed on a PZT-based test rig which brought the Au/MWCNT composite into contact with a gold-coated ball with a contact force of 1 mN [1, 21]. A contact force of 1 mN is considered to be in the upper limit of what is typical for MEMS switches, depending on the actuation method. However if the actuation method is electrostatic actuation which is often preferred for MEMS switches, a contact force of < 200 µN is typical [6, 12]. From computational modelling, the contact force of the MEMS-based cantilever beam is estimated to be ~5-10 µN. Therefore the results presented here give evidence for the performance of the Au/MWCNT composite at contact forces more closely related to typical MEMS switches. In order to compare the switch failures with the lower force MEMS-based system to understand the failure mechanisms, it is important to evaluate the effect of the lower contact force. We propose that a decrease in the contact force will result in a decrease in the extent of the deformation of the Au/MWCNT composite. This will in turn result in a decrease in the available contact area and may consequently reduce the switching lifetime. It is generally accepted that the contact force should be large enough to yield a stable contact resistance without being unnecessarily large thereby resulting in additional damage to the contact surfaces [22, 23].

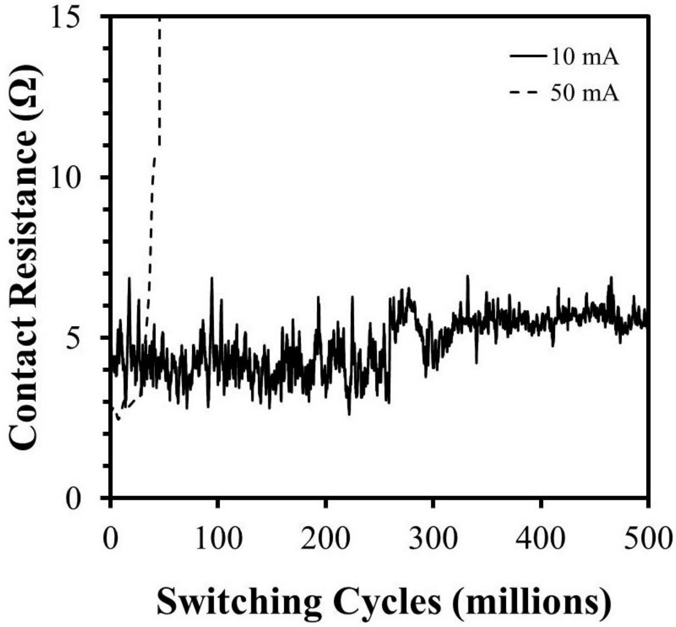


Figure 4: Graph showing contact resistance throughout switching lifetime for electrical contact pair of Au-coated cantilever beam to Au/MWCNT composite with load currents of 10 mA and 50 mA.

2. Surface Analysis

In addition to monitoring the contact resistance, the contact surfaces were analyzed using a scanning electron microscope (SEM). Before initializing the 10 mA experiment both of the contact surfaces were scanned by SEM, an image of the Au/MWCNT composite can be seen in

Figure 5a and a SEM image of the tip of the Au-coated cantilever beam surface is given in Figure 6 a.

Figure 5b shows the SEM image of the Au/MWCNT contact after 500 million hot-switching cycles. No obvious damage was observed. Figure 5 shows SEM images of the Au coated cantilever beam surface before (a) and after (b) testing. It also suggests there was no obvious damage observed on the contacting surface. Further detailed characterization of the contacting surface using a high resolution laser profilometer will be included in future work.

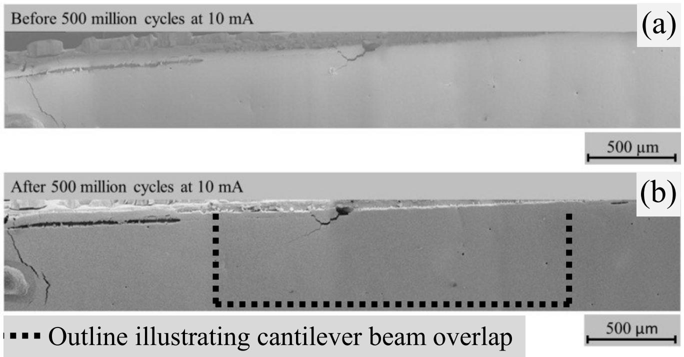


Figure 5: SEM images of Au/MWCNT contact before testing (a) and after testing at 10 mA, 4 V for 500 million cycles (b). *Note: due to the large contact area, the SEM images are composed of a number of SEM images stitched together.*

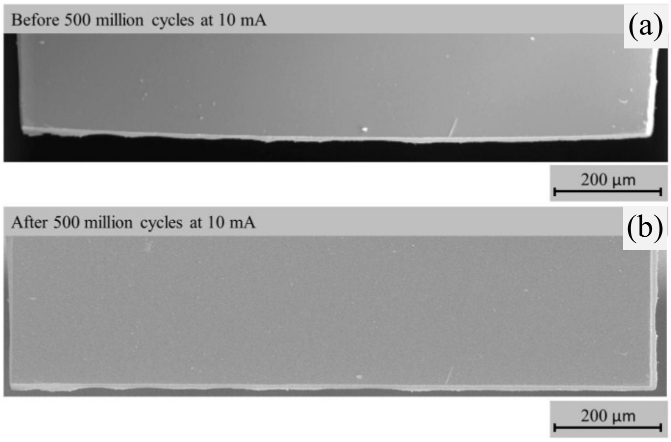


Figure 6: SEM images of the tip of the Au-coated cantilever beam contact before testing (a) and after testing at 10 mA, 4 V for 500 million cycles (b). *Note: due to the large contact area, the SEM images are composed of a number of SEM images stitched together.*

Conclusions

The MEMS-based test rig is a developmental device which enables accelerated testing of electrical contacts at a contact force typical of MEMS switches. We present new results demonstrating the use of Au/MWCNT composite electrical contacts within a MEMS-based switch setup. With a load current of 10 mA at 4 V, the contacts survived over 500 million hot-switching cycles. At a higher current of 50 mA the contact pair failed after 44.4 million cycles. After 500 million switching cycles at 10 mA, SEM analysis of the surfaces showed that there was no observable damage. Further analysis is required to confirm these observations. These results demonstrate that the Au/MWCNT composites are a useful material for MEMS switches with high lifetimes.

The incorporation of the redesigned cantilever beams will enable testing at significantly higher frequencies which will result in the generation of experimental data to further the understanding of the Au/MWCNT composite failure mechanisms.

Acknowledgements

This work was supported by the Innovative Electronics Manufacturing Research Centre (IeMRC) and Engineering and Physical Sciences Research Council (EPSRC) under grant number: EP/H03014X/1. The authors would also like to acknowledge the support given by Applied Relay Testing Ltd. particularly in the form of the loaning of test equipment.

References

[1] 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*, Newport, RI, 2013, pp. 344-349.

[2] J. W. McBride, "The Wear Processes of Gold Coated Multi-walled Carbon Nanotube Surfaces used as Electrical Contacts for Micro-electro-mechanical Switching," *Nanoscience and Nanotechnology Letters,* vol. 2, pp. 357-361, 2010.

[3] A. P. Lewis, C. Chianrabutra, L. Jiang, S. H. Pu, and J. W. McBride, "Development of a MEMS Test Platform for Investigating the use of Multi-Walled CNT Composites Electric Contacts," in *Engineering and Packing Technology Conference (EPTC 2013)*, Singapore, 2013.

[4] A. P. Lewis, M. P. Down, C. Chianrabutra, L. Jiang, S. M. Spearing, and J. W. McBride, "Lifetime Testing of a Developmental MEMS Switch Incorporating Au/MWCNT Composite Contacts," presented at the The 27th International Conference on Electrical Contacts (ICEC 2014), Dresden, 2014.

[5] G. M. Rebeiz and J. B. Muldavin, "RF MEMS switches and switch circuits," *Microwave Magazine, IEEE,* vol. 2, pp. 59-71, 2001.

[6] G. M. Rebeiz, *RF MEMS: Theory, Design, and Technology*: Wiley, 2004.

[7] J. J. Yao, "RF MEMS from a device perspective," *Journal of Micromechanics and Microengineering,* vol. 10, p. R9, 2000.

[8] B. F. Toler, R. A. Coutu Jnr, and J. W. McBride, "A review of micro-contact physics for microelectromechanical systems (MEMS) metal contact switches," *Journal of Micromechanics and Microengineering,* vol. 23, p. 103001, 2013.

[9] S. Lucyszyn, S. Pranonsatit, J. Y. Choi, R. W. Moseley, E. M. Yeatman, and A. S. Holmes, "Novel RF MEMS Switches," in *Asia-Pacific Microwave Conference (APMC 2007)*, 2007, pp. 1-4.

[10] Z. J. Yao, S. Chen, S. Eshelman, D. Denniston, and C. Goldsmith, "Micromachined low-loss microwave switches," *Journal of Microelectromechanical Systems,* vol. 8, pp. 129-134, 1999.

[11] 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, 2013, pp. 49-55.

[12] S. Majumder, J. Lampen, R. Morrison, and J. Maciel. (July 2013). *An Electrostatically Actuated Broadband MEMS Switch*. Available:

http://www.radantmems.com/radantmems.data/Library/Finalsensorsexp2paperREVSR.pdf

[13] J. Maciel, S. Majumder, R. Morrison, and J. Lampen, "Lifetime characteristics of ohmic MEMS switches," pp. 9-14, 2004.

[14] Omron Corporation. (July 2013). *Surface-mounted MEMS Switch (2SMES-01) Datasheet*. Available: http://www.omron.com/ecb/products/pdf/en-2smes-01.pdf

[15] Coto Technology Inc. (2013, July 2013). *RedRock^{TM} MEMS-based Reed Switch Datasheet*. Available: http://www.cotorelay.com/datasheets/Coto%20Technology%20RedRock%20Switch.pdf

[16] S. Day and T. Christenson, "A High Aspect Ratio Microfabricated Reed Switch Capable of Hot Switching," in *59th IEEE Holm Conference on Electrical Contacts*, Newport, RI, 2013, pp. 336-343.

[17] F. Llewellyn-Jones, *The Physics of Electrical Contacts*: Clarendon Press, 1957.

[18] E. A. Sovero, R. Mihailovich, D. S. Deakin, J. A. Higgins, J. J. Yao, J. F. DeNatale, and J. H. Hong, "Monolithic GaAs PHEMT MMICs integrated with high performance MEMS microrelays," in *Microwave and Optoelectronics Conference, 1999. SBMO/IEEE MTT-S, APS and LEOS - IMOC '99. International*, 1999, pp. 257-260 vol. 1.

[19] D. Hyman, A. Schmitz, B. Warneke, T. Y. Hsu, J. Lam, J. Brown, J. Schaffner, A. Walston, R. Y. Loo, G. L. Tangonan, M. Mehregany, and J. Lee, "GaAs-compatible surface-micromachined RF MEMS switches," *Electronics Letters,* vol. 35, pp. 224-226, 1999.

[20] D. Hyman, J. Lam, B. Warneke, A. Schmitz, T. Y. Hsu, J. Brown, J. Schaffner, A. Walston, R. Y. Loo, M. Mehregany, and J. Lee, "Surface-micromachined RF MEMs switches on GaAs substrates," *International Journal of RF and Microwave Computer-Aided Engineering,* vol. 9, pp. 348-361, 1999.

[21] J. W. McBride, L. Jiang, and C. Chianrabutra, "Fine Transfer in Electrical Switching Contacts Using Gold Coated Carbon-Nanotubes," in *Joint Conference of 26th International Conference on Electrical Contacts and 4th International Conference on Reliability of Electric Products and Electric Contacts*, Beijing, 2012, pp. 353-358.

[22] Z. Yang and N. C. S. University, *Contact Material Optimization and Contact Physics in Metal-contact Microelectromechanical Systems (MEMS) Switches*: North Carolina State University, 2008.

[23] H. Qiu, H. Wang, and F. Ke, "Instability of Contact Resistance in MEMS and NEMS DC Switches under Low Force: the Role of Alien Films on the Contact Surface," *Sensors,* vol. 13, pp. 16360-16371, 2013.