Micro-Contact Performance Characterization of Carbon Nanotube (CNT)-Au Composite Micro-Contacts

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Abstract—This paper presents the micro-contact performance comparison between contact pairs of Au/Au and composite contact pairs Au/Au-CNT. The Au/Au-CNT micro-contact’s planar-lower contact interface is an Au-CNT composite film with encapsulated CNTs. Micro-contact performance is affected by factors such as applied micro-contact force, temperature, current density, etc. At the micro-contact interface, asperities provide localized points for current flow. Increased temperature at these localized points may soften the contact metal and lead to bridge transfer. Prior work revealed that an Au/CNT contact pair performed poorly compared to an Au/Au contact pair, with two orders of magnitude difference in contact resistance. To maintain micro-contact performance and to reduce thermal effects, a Au/Au-CNT micro-contact was designed and fabricated. This design allows the micro-contact interface to remain Au/Au with the embedded CNTs acting as a thermal conduction conduit below the lower Au contact interface. The upper micro-contact support structure is an Au micromachined fixed-fixed beam with hemisphere-shaped upper contact geometry. The micro-contacts were studied under repeated cycles using an external, calibrated load, resulted in repeatable resistance of approximately 1Ω for nearly 40 million cycles. This research revealed that including a CNT composite film in the lower contact extend the operating life and lower contact resistance as compared to similarly constructed micro-contacts.

Index Terms—Micro-contacts, CNT, Contact Resistance

I. INTRODUCTION

This paper describes the methodology used to explore and characterizes the physics of the evolution of micro-contacts over their lifetime of performance. Using an improved test fixture, with the ability to cycle micro-contact at up to 3kHz, a better understanding how the physics of the micro-contact interface can be achieved. Understanding how micro-contact resistance evolves over time, engineers will be able to enhance micro-contact development time and help predict lifetime performance. Research goals were to create a micro-contact with encapsulated CNTs, then to cycle these contacts and compare to similar Au-Au micro-contacts.

Despite carbon being a key component of frictional polymers, which develop over time and can lead to increased contact resistance [1], Yaglioglu et al. examined the electrical contact properties of CNT coated surfaces [2]. The high Young’s Modulus and potential for low contact resistance of CNTs makes them suitable candidates for micro-switch contacts. The advantage of a micro-contact support structure’s architecture is the ability to fabricate structures with different contact materials. This allows the investigation of the properties and physics of various contact materials and/or structural layer materials to increase or decrease the beam stiffness to account for adhesion. In addition to fabricating entirely Au-Au micro-contact support structures, structures using encapsulated layer materials such as CNTs were fabricated.

II. BACKGROUND

A. Test Stand

The test stand was designed to characterize the performance over the lifetime of a micro-contact. The test stand consists of a nitrogen environment that still allows for manipulation of the micro-contact and connections to be able to monitor the contact throughout testing.

The test stand allows for rapid actuation of a micro-contact with a known force and frequency. A Femto Tools FT-S270 force sensor was used to determine the amount of force applied to the micro-contact test structure. A Thorlabs BPC301 piezo motor and controller was used to apply force to the micro-contact and to actuate the sensor towards the micro-contact support structure. Micro-manipulators were used to align the force sensor with the micro-contact support structure.

Testing in a nitrogen environment reduces the opportunity for oxides and other organic films to develop prematurely and simulates a hermetic environment that a micro-contact would normally perform in.

The micro-test structure fixture is a fabricated device on a wafer that was then is attached to a carrier using crystal bonder. The micro-contact test structure was then wire bonded to the breakouts of the carrier to make it easier to measure the current and voltage across the contact. This also reduces the probability of physically interacting with and changing the surface of the micro-contact test structure and removes the necessity for probes. The wafer was wire bonded to the carrier and placed into the carrier socket which has pins for every wire bond. These pins were wire wrapped separately and the wires were guided outside of the enclosed test fixture. Micro-manipulators are available in the x,y and z axes to allow
for the alignment of the force sensor with micro-contact. A picture of this fixture is shown in Figure 1.

Fig. 1. Test stand, showing major components encased in a nitrogen environment

Using this test stand, two types of tests were performed, the Virgin Contact Test and Cold Switch Test

1) Virgin Contact Testing: The virgin contact test applies a load to the micro-contact and determines the amount of force needed to initiate surface contact. For this research, the virgin contact test was applied for every cycle where a measurement was required. The user set the appropriate step size, time interval, and maximum applied force and then the system incremented the force sensor in the set step size until the force sensor limit was reached. At each increment, voltage, current, and force are recorded.

2) Cold-Switch Testing: Using the information from the virgin contact test, the user may opt to perform a cold-switch test. Cold-switching promotes the mechanical failure of the micro-contact by applying current only when contact is already made and removing current before contact break; thereby reducing the probability of electrical failure modes. For the cold-switch program, the micro-contact is first closed before current is applied. With the contact closed, the desired current level is applied to the micro-contact and the current and voltage is measured. After the measurement of current and voltage, the applied current is then turned off and the micro-contact is opened. These steps are then repeated for the desired number of cycles.

For the cold-switch test (CST), the devices under test were first cycled up to 100 times at 10Hz with measurements taken at every 10 cycles. Following the initial 100 cycles, the devices were actuated up to 1,000 cycles at 100Hz with measurements performed every 100 cycles. Then 10,000 cycles at 1kHz with measurements every 1,000 cycles. In addition, the micro-contact structures were actuated to 100,000 cycles at 3kHz with measurements every 10,000 cycles. Lastly, the devices were actuated into the millions of cycles with measurements at every 100,000 cycles. This total actuation number varied between the different micro-contact structures.

B. Fixed-Fixed Beam Micro-Contact Support Structure

The micro-contact support structure used for this experiment was the fixed-fixed beam micro-contact structure that emulates Holm’s crossed bar experiment on the micro-scale. This design allows a four-wire measurement in which current only flows through the micro-contact at contact. Voltage is then measured across the micro-contact via Au traces connected to the anchor of the beam and micro-contact area.

For this paper all fixed-fixed beams have a width of 250μm and length of 400μm. The beams are designed with a gap of 1μm between the contact bump and contact pad. The contact bump allows for the contact to be made between a plane for the bottom contact and a hemispherical contact on the beam. Figure 2 shows a 3D model of the fixed-fixed beam micro-contact structure. The micro-contact support structure is constructed for a Au-Au micro-contact and utilizes a structural layer to enhance the micro-contact structure’s stiffness and to reduce the risk of stiction, but can be easily modified to investigate other contact materials.

Fig. 2. 3D model of Fixed-Fixed Beam Micro-Contact Support Structure

CNTs were added to the upper hemispherical contact of the device by encapsulating them by sputtering a layer of gold for the contact, applying the CNTs, and electroplating gold over them. The resultant device is not an Au-CNT or alloy type structure; it is an Au structure with encapsulated CNTs. Figure 3 shows an example diagram of a micro-contact support device with CNTs encapsulated in the upper hemispherical contact device cross-section, and the planar/hemispherical contact. The CNTs can, in effect, change the paths of conduction through the beam since the beam is no longer uniform. According to literature, creating a structure with two different materials does not always produce an alloy or composite that has better or even comparable performance to metals do individually. By itself, CNTs are better conductors than gold, both thermally and electrically.

The CNTs were applied by spinning on a mixture of CNTs diluted in isopropyl alcohol. After deposition of the CNTs, a thermal image was taken to demonstrate the thermal conductivity of the CNTs. The thermal image is shown in Figure 4. The more readily identifiable CNT groupings or “clumps” appear as the bright green and red spots, indicating
better thermal conduction than the dark blue nitride coated silicon substrate and Au bottom metal layer. The reason for the CNT clumps appearing in different colors is due to the fact that these clumping of CNTs are not all the same size and thus conduct heat differently. The thermal image was processed in Matlab to calculate the percent coverage by separating the areas with only Au and the area with a Au-CNT film. The final product of this processing is shown in Figure 5. The image analysis revealed a 55% coverage of Au-CNT film.

To intensify the visibility of the larger clumps, another thermal image was taken at a higher temperature, as can be seen in Figure 6. The large CNT groupings or “clumps” appear as the bright green and red spots. The addition of CNTs may not only enhance the thermal conductivity of the micro-contact support structure, which would help maintain lower contact temperatures, but increase resistivity due to the CNTs changing the conducting paths of the electrons. Depending on the application, the higher contact resistance may be a potential drawback to the design.

C. Use of CNTs in micro-contacts

As stated earlier, despite carbon being a key component of frictional polymers, Yaglioglu et al. examined the electrical contact properties of CNT coated surfaces [2]. The high Young’s Modulus and potential for low resistance of CNTs makes them suitable candidates for micro-switch contacts. For instance, Au contacts with a substrate coated with tangled single-walled CNTs were shown to have a resistivity between $1 \times 10^{-4}$ and $1.8 \times 10^{-4} \Omega m$ [2]. Yunus et al. explored two contact pairs with carbon nanotubes: Au to multiwall carbon nanotubes (MWCNTs), where one electrode is Au and the other is MWCNTs, and Au to Au/MWCNT composite in a vertical configuration, where the contact interface is Au on Au [3]. Figure 7 shows an SEM image of the Au/MWCNT composite. This vertical configuration is different than what was done here, as the CNT clumps have no set direction.

As shown in Figure 8, it was found that the Au-Au/MWCNT was the better performer than Au-MWCNT in terms of contact resistance [3]. While the MWCNTs did not improve contact resistance, the modulus of the lower contact was enhanced which could lead to greater reliability. The data was collected with a nanoindentor apparatus which cycled for ten repeated operations with a maximum applied load of 1mN [3]. The hardness of each material is also significantly different, approximately 1TPa for CNT and 1GPa for Au [3]. The CNT structure supporting the Au film allows the Au film to deform elastically under the applied load. In this study, a hard Au coated steel ball is making contact with the softer Au/MWCNT surface. The latter surface deforms to the shape of the steel ball, increasing the apparent contact area. With the Au coated steel ball in contact with the MWCNT surface the conduction...
path is through the lateral connection of the vertically aligned CNTs; leading to a higher contact resistance, as shown in Figure 8. A disadvantage to the mechanical design of the switch was discovered to be excessive bouncing on closure; that is, the contact takes time to settle in the closed position, which leads to poor reliability due to “extra” contacts.

A study was conducted by Choi et al. to explore the current density capability of a CNT array with an average CNT diameter of 1.2 nm, site density of 2 CNT/μm, and the number of CNTs for devices with 1 μm channel width ranged from one to three [4]. It was reported that a high current density of 330 A/cm² at 10 V bias was successfully transmitted through the contact without any noticeable degradation or failure [4]. A reliability test, as seen in Figure 9, with an input current of 1 mA showed repeatable and consistent contact characteristics over a million cycles of operation [4].

D. Contact Resistance Modeling

Contact resistance modeling requires knowledge of the two contact material surfaces and their material properties. Holm initially studied clean contacts and did not consider contact contamination effects on contact resistance. Though it is not initially considered in the determination and description of micro-contact resistance, it can have a major effect [5]. Even though the bases of the cylinders appear to be similar, the contact areas are actually quite different. This is because no surface is perfectly smooth. The two surfaces are covered in asperity peaks or “a-spots”, which are what meet at the interface and become the contact area. These a-spots have been described as “small cold welds providing the only conducting paths for the transfer of electrical current” [6]. A graphical representation of the contacting a-spots and the effective radius of the contacting area can be shown in Figure 10. This effective area is used for making simplified contact resistance calculations.

Holm also investigated contact resistance changes due to plastic and elastic deformation of a-spots, which greatly affect the interface of the contact areas.

Majumder et al. model micro-contact switches with three steps. First determine the contact force available from the mechanical design of the electrostatically actuated micro switch. This contact force will be a function of applied gate voltage.
Second, determine the effective contact area at the interface as a function of contact force. Finally determine the contact resistance as a function of the distribution and sizes of the contact areas [8]. Both Majumder and Holm noted that the surface profile is sensitive to plastic and elastic deformation.

Elastic modeling is accurate for extremely low values of contact force of a few mN where surface asperities retain their physical forms after the contact force is removed. Plastic deformation permanent surface change occurs by the displacement of atoms in asperity peaks whereas neighboring atoms are retained under elastic deformation.

1) Elastic: The a-spot contact area under elastic deformation is given by:

\[ A = \pi r \alpha \]  

where \( A \) is the contact area, \( r \) is the a-spot peak radius of curvature, and \( \alpha \) is the a-spot vertical deformation [9].

For circular areas, 1 and 3 are related to the contact area radius (\( r \)) through the Hertz’s model [10]:

\[ r = \frac{3 F_{ce} R}{4 E'} \]  

The normal contact force \( F_{ce} \) is given by:

\[ F_{ce} = \frac{4}{3} E' \alpha \sqrt{r \alpha} \]  

where \( E' \) is the Hertzian modulus derived from:

\[ \frac{1}{E'} = \frac{1 - v_1^2}{E_1} + \frac{1 - v_2^2}{E_2} \]  

where \( E_1 \) and \( v_1 \) is the elastic modulus and Poisson’s ratio for contact one respectively and \( E_2 \) and \( v_2 \) is the elastic modulus and Poisson’s ratio for contact two respectively [10].

When deformation is no longer reversible and the applied load is approximately three times the yield point, ideal plastic material deformation begins.

2) Plastic: Plastic material deformation is modeled using Abbott and Firestone’s fully plastic contact model, which assumes sufficiently large contact pressure and no material creep [11].

Single a-spot contact area and force are defined using 5 and 6 [10]:

\[ A = 2 \pi R \alpha \] \hspace{1cm}  \[ r = \sqrt{\frac{F_{cp}}{H \pi}} \]  

where \( H \) is the Meyer hardness of the softer material, \( A \) is the contact area, \( R \) is the asperity peak radius of curvature, and \( \alpha \) is the asperity vertical deformation. The effective contact area radius is then related to contact force by:

\[ F_{cp} = HA \]

An area discontinuity at the transition from ideal elastic to ideal plastic behavior is revealed when the elastic and plastic model are used together.

3) Resistance Modeling: The “Classical” contact resistance model using Maxwell’s spreading resistance theory:

\[ R_{con} = \frac{\rho}{2 r_{eff}} \]  

where \( R_{con} \) is the constriction resistance and \( \rho \) is resistivity [5]. When the contaminate film resistance is neglected the Constriction resistance is equal to the contact resistance.

The “classical” macro switch contact resistance is shown in Equations 9 and 10 and shows that the elastic deformation \( R_c \propto F_{ce}^{-\frac{1}{3}} \) and plastic deformation \( R_c \propto F_{ce}^{-\frac{1}{2}} \) [5].

\[ R_{c,DE} = \frac{\rho}{2} \sqrt{\frac{4 E'}{3 F_{ce} R}} \] \hspace{1cm}  \[ R_{c,DP} = \frac{\rho}{2} \sqrt{\frac{H \pi}{F_{ce}}} \]  

where \( R_{c,DE} \) is contact resistance for diffusive electron transport and elastic material deformation and \( R_{c,DP} \) is contact resistance for diffusive electron transport and plastic material deformation.

Figure 11 shows the predicted analytical contact resistance for the fixed-fixed micro-contact structure’s Au-Au micro-contact based on diffusive electron transport and elastic deformation with the assumption of a simplified contact area and no contaminant films.

![Fig. 11. Contact Resistance Prediction for elastic deformation of Au-Au and Au-CNT Material Candidates](image)

III. RESULTS

Each micro-contact support structure was subjected to the following tests as shown in Table I. The tests were repeatable with minimal interruption caused by output errors from the current source. The devices were tested to examine the evolution of contact resistance over 10 million cycles. Measurements were made up to the designated number of cycles by the measurement interval. Between measurements, the micro-contact was cycled at the actuation rate and force. This system has proven to be an effective test fixture for cycling micro-contacts at relatively fast cycle rates to examine the evolution of micro-contact resistance. Finally the last micro-contact, with the CNT composite film in the lower contact, was tested to 40 million cycles.
### TABLE I

**AUTOMATED MICRO-CONTACT TESTS PERFORMED BY MICRO-CONTACT TEST FIXTURE**

<table>
<thead>
<tr>
<th>Number of Cycles</th>
<th>Measurement Interval</th>
<th>Actuation Rate (Hz)</th>
<th>Actuation Force (μN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>10th</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td>1000</td>
<td>100th</td>
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<td>1000</td>
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</tr>
<tr>
<td>100000</td>
<td>10000th</td>
<td>3000</td>
<td>100</td>
</tr>
</tbody>
</table>

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**A. Au-Au contact material**

1) **Virgin Contact Test:** Figure 12 shows a comparison of the measured micro-contact resistance for the Virgin Contact Test (VCT) of an Au-Au contact fixed-fixed micro-contact support structure. The predicted values of micro-contact resistance are based on Holm’s contact resistance for plastic deformation and elastic deformation with diffusive electron transport. The initial contact resistance nearly matches the plastic deformation resistance model with less than $40 \mu N$ applied. After $40 \mu N$ the measured contact resistance begins to deviate from the model. Variations between the modeled micro-contact resistance and measured results can be explained by the accuracy, precision, and performance of the test taking equipment.

2) **Cold Switch Test:** For the cold-switch test (CST), the device under test was cycled as stated in Section II-A2. This device’s final set of actuation were to $10$ million cycles with measurements at every $100,000$ cycles.

3) **Micro-Contact Resistance Evolution:** Results of these tests are shown in Figure 13. The contact resistance showed an initial increase, maxing out at $17.87 \Omega$. Then, most likely due to a wearing in period, contact resistance decreased at around $8M$ cycles. As the cycling of the micro-contact continued, the contact resistance started to increase, potentially due the growth of a contaminate film. This increase resistance remained until testing was ended at $10M$ cycles.

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**B. CNT film in upper hemispherical contact**

1) **Virgin Contact Test:** Figure 14 shows a comparison of the measured micro-contact resistance for an Au contact with CNTs encapsulated film in the upper hemispherical planar contact of a fixed-fixed micro-contact support structure. Similarly as seen in Figure 12, with less than $40 \mu N$ of force applied, initial contact resistance mimics the plastic deformation resistance model.

2) **Cold Switch Test:** For the cold-switch test (CST), the device under test was cycled as stated in Section II-A2. The final set of actuation for this device was to $10$ million cycles with measurements at every $100,000$ cycles to match the Au-Au micro-contact.

3) **Micro-Contact Resistance Evolution:** Results of these tests are shown in Figure 15. This contact showed an initial high resistance at $1.22 \Omega$ then a wearing in period until resistance dropped to below $1 \Omega$ where it remained until testing was stopped at $10M$ cycles.

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**C. CNT composite film in lower planar contact**

1) **Virgin Contact Test:** Figure 16 plots a comparison of the measured micro-contact resistance for a Au contact with CNTs...
Fig. 15. Resistance Values for Fixed-Fixed Au-CNT in the beam in the Micro-Contact Support Structure

Fig. 16. Contact Resistance of Au-Au Beam with CNT encapsulated into the lower contact pad, until around 50μN the results followed the model

encapsulated into the lower contact pad fixed-fixed micro-contact support structure. Similarly to what was seen in Figure 12 and Figure 14, the initial contact resistance with less than 50μN applied is close to the plastic deformation resistance model. After the first 50μN, contact resistance begins to deviate from the model. As stated with the first micro-contact, this deviation is attributed to the measurement equipment.

2) Cold Switch Test: For the CST, the devices under test were first cycled same as the other beams, only this time, the device was actuated to failure, which for this contact was to 40M cycles with measurements at every 100,000 cycles. This increase was that we wanted to actuate the switch to failure to see what failure modes would surface. This should have promoted the the failure of the micro-contact support structure due to mechanical reasons.

3) Micro-Contact Resistance Evolution: Results of these tests are shown in Figure 17. This contact showed an initial increase in contact resistance from starting at 0.19Ω, to maxing out at 1.1Ω, followed by a warming in period. Finally the fixed-fixed micro-contact with CNTs encapsulated into the lower contact was cycled 36.9 million times, at which point the closed contact resistance was 1.21Ω. At the 37 million cycle mark, which was the next data collection point, the contact failed to close.

Fig. 17. Resistance Values for Fixed-Fixed Au-CNT in the lower contact in the Micro-Contact Support Structure

IV. ANALYSIS

A. Plastic deformation of Beam

Fig. 18. Fixed-Fixed Micro Contact support structure with CNTs encapsulated in in upper hemispherical planar contact

Figure 18 shows the CST data collected for the fixed-fixed Au micro-contact support structure with the CNT film in the hemispherical upper contact. Looking at the figure, the force
The beam itself was approximately 2.7 μm thick. For plastic deformation, the applied force must meet and surpass the yield stress of the material, which is the lowest value for stress to cause permanent deformation. According to Volinksy et al, the yield stress for Au films decreases with a rise in material temperature, which can increase due to the flow of current through the micro-contact and the beam supporting structure. His team also reports that for a 2.7 μm thick Au film, the yield stress of the support structure was shown to be about 400 MPa (or 400 N/mm²) at room temperature and become 250 MPa (or 160 N/mm²) at 120 °C [12]. Considering that the max applied force to the beam was 200 μN in order to achieve near 100 μN of contact force, it is likely that the yield stress threshold of the support structure was passed causing the beam to be plastically deformed.

B. Micro-contact Resistance

![Fig. 21. Resistance Values for Functional Fixed-Fixed Au and AU-CNT encapsulated Micro-Contact Support Structure](image)

Figure 21 shows the life cycle data for three different style beams, one Au-Au, the other CNTs composite film in the upper and lower contact. The fixed-fixed Au micro-contact support structure experienced steadily increasing contact resistance as the number of actuations increased. This particular micro-contact was cycled nearly 10.2 million times, at which point the closed contact resistance was 14.43 Ω. However, the CNT composite film in either the lower or upper contact did not display this rise in resistance. The Micro contact support structure with CNTs in the upper contact was also cycled to nearly 10.2 million times, at which point the closed contact resistance was 1.1 Ω. Finally, the fixed-fixed micro-contact with CNTs composite film in the lower contact was cycled to approximately 36.9 million times, at which point the closed contact resistance was 2.121 Ω. At the next test point, 37 million cycles, the contact failed to close. This failure to close is most likely due the the build-up of an insulating film.

The most promising results were with the CNT composite film in the lower contact. This beam had a much lower and consistence resistance until failure compared to a similarly constructed Au-Au beam. This could be because the CNT are providing a highly conductive thermal layer to diffuse the heat to allow for a longer life and help prevent catastrophic plastic deformation to occur. The CNT film might also allow some current to flow through the CNT, reducing overall resistance. The CNT in the lower contact also had fewer surface defects due to the CNTs encapsulation in the lower contact rather than in upper contact, thus not causing the voids seen in Figure 19.

After testing, the CNT encapsulated into the lower contact was pulled back for examination on what caused the micro-contact not to close. The SEM image of the contact area (Figure 22) was taken to reveal a large area of film developed on the lower contact pad. Other contacts in this sample were also examine to revealed that this film was unique to this micro-contact. To further evaluate this contaminate film, an energy dispersive spectroscopy (EDS) measurement was taken, the results are shown in Figure

![Fig. 19. Zygo Intensity Map showing Contour of Micro-Contact Support Structure](image)

![Fig. 20. Zygo 3D Image of Fixed-Fixed Au Micro-Contact Support Structure](image)
23. This return of carbon in the EDS measurement, like the film, was unique to this micro-contact.

The amount of carbon present in the film on the lower contact was 20% of the return on the spot EDS measurement (≈ 1μm in diameter). This possibly uncovered an issue with the encapsulated CNTs, where after wearing through the thin encapsulation Au layer, the exposed CNTs accelerated the growth of an insulating carbon film. This rapid rise of resistance is similar to what was seen in literature in the presence of frictional polymers [13]. Frictional polymers are organic films, that develop on commonly used contact materials when there are low levels of organic vapors or compounds evident in the operating environment of the contact [13]. It appears that the breakdown of the encapsulating layer, which exposed some carbon contamination, led to a growth of a frictional polymer.

V. Conclusion

Improvements in micro-contacts can provide benefits in many areas of technology. These benefits may include greater RF bandwidths and performance, lower power consumption, and enhanced performance. This research shows the advantage of CNT composite film use in micro-contact to extend the operating life and lower contact resistance as compared to similarly constructed Au-Au micro-contacts. Additionally the results from encapsulating a CNT composite film in the lower contact provided the best results among those designs tested. This paper reported the contact resistance evolution results of thin film, sputtered and evaporated gold, with CNTs encapsulated, micro-contacts dynamically tested up to 3kHz.

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