AN SPM-BASED CONTACT TESTER FOR STUDY OF MICROCONTACTS

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ABSTRACT

In this paper, we report on an SPM (Scanning Probe Microscope)-based contact tester. The tester is designed for contact material selection and micro-contact studies, with a special focus on metal-contact MEMS switch applications. It uses a silicon force sensor with an integrated contact bump and a mating silicon pillar to simulate switch operation. After coating the sensor and the pillar with contact materials, a wide range of contact metals and metal pairs can be evaluated. The tester provides accurate force measurement with a resolution of 1 μ N. Both force and resistance can be measured simultaneously during the contact tests. A custom-built test chamber is used to introduce both the plasma and the UV-ozone to the contact area for contact cleaning and surface modification. After having tested Au, Ru, Ir contact pairs, it is found that the Au-Ru dissimilar contact pair with O₂ plasma cleaning can provide low contact adhesion and low resistance.

INTRODUCTION

Contact material selection is critical for the performance and reliability of metal-contact RF MEMS switches. The selection of contact materials requires the study of contact force, resistance, adhesion, power handling, reliability, as well as thin film preparation, contact surface treatment, and operational ambient. It can be extremely time-consuming to evaluate a wide range of materials if such tests are performed in MEMS switches.

To improve the efficiency in material selections, and also to directly measure contact adhesion, contact force, and contact resistance, our group previously used an SPM-based contact tester for contact studies. The setup used a custom built cantilever with an integrated contact bump and a planar mating surface to simulate contact operation in microswitches. The cantilever served as a force sensor, i.e. the contact force between the bump and the surface is equal to the cantilever deflection multiplied by the cantilever stiffness. After coating various contact materials on both the cantilever and the mating surface for contact studies, the contact tests were performed in an SPM system. The tester was successfully used to study several contact metals and metal alloys [1], contact failure mechanisms [2] and the rate-dependent pull-off force of micro-contacts [3].

Despite its versatility, our previous setup has some limitations. By using a cantilever structure as a force sensor, we encounter sliding effects during the contact tests. The higher the loading force, the larger deflection at the end of the cantilever and, therefore, the larger the sliding. Also, the measured resistance in our previous setup always included the sheet resistance components of the metal films on the cantilever and testing pads. For instance, using the previous setup, the measured resistance for a Au-Au contact at 250 μ N was 0.85 Ω , which is about one order of magnitude higher than the constriction resistance of pure Au-Au contacts. The third limitation is that our previous setup lacked surface cleaning capabilities. Most samples had been exposed to room-air before contact tests were started, allowing surface films or contamination to form on the contacts. Contamination failures were commonly observed during our previous contact tests. On

the other hand, clean contact tests are reported within hermetic-packaged MEMS switches [4]. In order to mimic metal contact operation within a packaged switch, it is highly desirable to create a clean environment for contact tests.

In this paper, we report on a new SPM-based contact tester. The new system has been improved in three ways: 1) more accurate force measurement; 2) better resistance measurement; and 3) the capability for both plasma and UV-ozone treatments. The improvements in the new tester help us to obtain high quality resistance and force data.

CONTACT TESTER SYSTEM

Figure 1: A photograph of the SPM-based contact tester with the vacuum chamber and plasma source.

Figure 1 shows the chamber setup of our SPM-based contact tester. There are three parts in this system: 1) the SPM module which is used for both test control and force measurement; 2) The test chamber which is a custom-built vacuum chamber providing a controlled environment for the contact test and allowing us to introduce plasma and/or UV-ozone cleaning to the contact area; and 3) The MKS-AX7670 remote plasma source used to clean the contacts with plasmas containing Ar, O₂, N₂ and NF₃.

We changed the force sensor structure from a cantilever to a fixed-fixed beam. For the fixed-fixed beam structure, the contact bump is located in the middle of the beam (Figure 2 a). The deflection of the bump, and hence the force, is determined by shining the laser beam on one of the two optical paddles located on either side of the contact tip (Figure 2 b). By using a fixed-fixed beam structure, the sliding effect during contact tests can be significantly reduced. Also, compared with a cantilever structure with the same length, the fixed-fixed beam can provide more rotation at the optical lever paddle for a given deflection at the bump, which helps to improve the force measurement dynamic range.

Figure 2: (a) An SEM image of a force sensor with the fixed-fixed beam structure. The optical lever paddles are necessary to deflect the laser beam in the SPM; (b) the deflection of the laser beam is monitored by an optical level system; (c) Test layout for contact resistance measurement.

In addition, we included two trenches on the force sensor for better contact resistance measurements. The trenches are located between a current sourcing pad ($I+$) and a voltage sensing pad ($V+$), as shown in Figure 2(c). These trenches are micro-fabricated with intentional undercuts. Because of the undercuts, electrical isolation is created between the current sourcing pad and the voltage sensing pad, even after a blanket coating of a contact metal, allowing us to perform 4-wire contact resistance measurements.

Table 1: Comparison between old and new force sensors.

Force Sensor	New	Old
Structure	Fixed-Fixed	Cantilever
Dimension (μm)	120x20x4.5	180x50x30
Stiffness (N/m)	2500	15000
Force Resolution (μN)	1	12.5
Contact Sliding	Minimum	Yes
Measured Resistance (Ω) (Au-Au at 250 μN)	0.15	0.85

Table 1 shows a comparison of old and new force sensors. The new sensor provides better resistance and force measurements along with minimal sliding.

CONTACT TESTS/EXPERIMENTS

Here we demonstrate the capabilities of the contact tester in contact surface cleaning; contact resistance vs. force

characterization; and contact cycling testing.

All contact materials reported in this paper, Gold (Au), Ruthenium (Ru) and Iridium (Ir), are thin films prepared by sputtering. The thin films have been deposited on both the force sensors and pillars with a nominal thickness of 300nm. To reduce the sheet resistance components from the pillar side, a layer of 500nm of plated gold was electroplated on the pillars prior to deposition of contact materials. Au contact materials were prepared with 20nm Cr as an adhesion layer; no adhesion layers were added for Ir or Ru thin films. The resistivity for sputtered Au, Ru and Ir thin films are 3.46 $\mu\Omega\cdot\text{cm}$, 13.8 $\mu\Omega\cdot\text{cm}$ and 18.9 $\mu\Omega\cdot\text{cm}$, respectively. All materials were tested within 72 hours of deposition.

Contact Cleaning Experiments:

With capabilities for plasma and UV-Ozone treatments, the tester provides a platform for contact cleaning and surface modification studies. In this paper we show the results of three treatments – O_2 plasma, Ar plasma and UV/Ozone – on contact resistance of Ru-Ru contacts.

Figure 3: Measured contact resistance of Ru-Ru contacts, at a loading force of 100 μN , after three different cleaning procedures: 10-minute Ar plasma, 10-minute O_2 plasma, and 10-minute UV-Ozone.

The MKS AX7670 is used to generate Ar and O_2 plasmas. The Ar plasma is generated at 1.7Torr. The O_2 plasma is generated at 4Torr with a mixture of Ar and O_2 at a ratio of Ar: O_2 =3:5. In order to introduce UV-Ozone to the contact area, we use a deuterium lamp HAMAMTSU L7292. The cut-off wavelength of the HAMAMTSU L7292 is 115nm. The lamp is mounted on the vacuum chamber through a vacuum side flange, and radiates UV light to the contact area. While doing UV-ozone cleaning, the chamber is filled with O_2 at a pressure of 50Torr when the lamp is on. The UV light can directly break the contaminant molecule bonds. At the same time, the UV light can be absorbed by O_2 which creates atomic oxygen and ozone [5]. Oxygen radicals and ozone can accelerate the removal of organic layers on the metal surfaces.

Figure 3 shows the contact resistances of Ru-Ru contacts (seven samples for each condition), after a 10-minute O_2 plasma treatment, a 10-minute Ar plasma treatment and a 10-minute UV-ozone treatment. At a loading of 100 μN , the lowest resistance was observed after 10 minutes of O_2 plasma treatment, and the UV-Ozone treatment was also effective, in contrast to the Ar plasma treatment, which was not. The results indicate that O radicals are essential for Ru contacts cleaning.

Figure 4: Contact resistance and pull off force of a Au-Au contact during an in-situ plasma treatment test. The contact was cycled at 1Hz, with a loading force of 100 μN . The Ar plasma was on for five minutes (0-5min), and then the O_2 plasma fifteen minutes (5-20min), followed by another five minutes Ar plasma (20-25min).

However, the O_2 plasma treatment can increase the resistance of Au-Au contacts. Figure 4 shows an *in-situ* plasma test result of a Au-Au contact. The contact was cycled within the chamber, at 1Hz, with a loading force of 100 μN . The plasma was turned on during the cycling test and the resistance and force were measured simultaneously. It shows that the Ar plasma had little effect on the pull-off force or the contact resistance. However, the O_2 plasma rapidly caused the pull-off force to decrease below the detectable level, and the contact resistance increased gradually during the period when the O_2 plasma was on. When after 15 minutes, the O_2 plasma was turned off and the Ar plasma was turned on, the resistance started to drop, while the pull-off force did not recover within 5 minutes. The drop of adhesion for the Au-Au contact, as well as the increase of the resistance during the O_2 plasma treatment, could be due to the formation of layers of Au_2O_3 layer on the contact surfaces [6].

Resistance vs. Force Curves:

With good measurements of both resistance and force, we can compare resistance vs. contact force data for different contact materials with a special focus on the low force region ($< 500\mu\text{N}$). This is the force region of greatest interest for most MEMS switch applications.

Figure 5: Resistance vs. contact force for five different metal contact pairs.

Before the tests, both the Ru and Ir surfaces were cleaned using an O_2 plasma for 10 minutes. To collect the resistance vs. force data, the contacts were cycled at 1Hz in a low-voltage, low-current hot-switching mode. The resistance was measured using a 0.2V voltage source in series with a 22 Ω current-limiting resistor and with the contact. All contacts were cycled to a maximum load of 500 μN for at least 50 cycles before the data was collected.

As shown in Figure 5, the Au-Au contact yielded the lowest contact resistance. It is due to the low resistivity and low hardness (creating a larger contact area) of Au thin films. Hard metal contact pairs, such as Ru-Ru and Ir-Ir, have higher resistance compared to Au-Au. Dissimilar metal contact pairs, i.e. Au-Ru and Au-Ir, have intermediate contact resistance.

Contact Cycling Tests:

Contact cycling tests are important for contact material evaluation. They show evolution features of contact resistance and contact adhesion for each material pair, which can help to reveal potential reliability issues of these metal combinations during real switch applications. This tester can perform cycling tests at a rate of 800Hz, and measure contact resistance and force at 1Hz after a certain number of cycles.

Figure 6: Resistance vs. number of cycles for different metal contact pairs; the maximum loading force for each cycling test is labeled in the graph.

Figure 6 shows resistance vs. number of cycles of different metal contact pairs. Current was only applied during the contact cycles resistance data was obtained. The resistances plotted here are the average values of three samples tested under the same conditions. Without strict ambient control, the resistance usually increased after cycling test, except for the Au-Au contacts. Upon inspection, contaminants were observed, in particular in the presence of Ru and Ir surfaces. Susceptibility to the contaminants is related to the surface reactivity of the metals. The Au surfaces are known to be relatively inert to contamination, but Ru and Ir are not. Compared to the Ru-Ru contacts, the Ir-Ir contacts show a much higher contamination rate. The resistance of the Ir-Ir contacts doubled within 500 cycles of testing, which makes Ir less promising for use as a contact material.

To create a clean test ambient, we added a nitrogen tube with flowing nitrogen from a liquid source introduced immediately adjacent to the contact area. It was found that such an arrangement is an efficient way to reduce the contamination.

Figure 7 shows the results of cycling tests of three Au-Au contacts and three Au-Ru contacts in a clean nitrogen ambient. The loading forces for all tests were controlled to be 100 μN .

Figure 7: Resistance and pull-off force vs. number of cycles for pure sputtered Au-Au (a) and Au-Ru (b), with a maximum loading of $100\mu\text{N}$ and zero current.

For Au-Au contacts, a clear drop of contact resistance and a simultaneous increase of contact adhesion (pull-off force) are observed during the cycling tests. The maximum adhesion force is seen to be three times the contact force, clearly demonstrating the very large amount of contact separation force necessary for reliable operation of a MEMS switch using unhardened gold for contacts.

For Au-Ru contacts, the drop of resistance and the increase of adhesion are also observed. However, the pull-off forces for Au-Ru contacts are below $100\mu\text{N}$, much lower than those for Au-Au contacts. Also noted is that, after 10^6 cycles of testing the Au-Ru contacts, the Au bumps were plastically deformed and there was no severe contact wear (Figure 8). These preliminary results suggest that a Au-Ru contact may be a good candidate for switch applications, especially when the available loading force is low ($<150\mu\text{N}$).

CONCLUSIONS

A new SPM-based tester with accurate force and resistance measurements and plasma treatment capabilities has been built for contact studies. In this paper, we demonstrate its capabilities in contact surface cleaning; contact resistance vs. force characterization; and contact cycling testing. It is found that: O_2 plasma and UV-Ozone treatments are effective methods for cleaning Ru contact surfaces; The O_2 plasma treatment can modify gold surfaces by significantly reducing the contact adhesion between Au-Au contacts, and slightly increasing the contact resistance. Without strict ambient control, most cycling tests experienced contamination issues, especially with the presence of

Ru and Ir surfaces. The Ir-Ir contacts show higher contamination rates than Ru-Ru contacts during the cycling tests. By introducing flowing nitrogen close to the contact area, the contamination problem has been greatly reduced. In a clean ambient, Au-Ru contacts show the decrease of resistance and increase of adhesion after the cycling tests. With less contact adhesion and minimum contact wear, Au-Ru contacts show better potentials than Au-Au contacts for use as contact materials, especially in low force applications.

Figure 8: An SEM micrograph of a Au contact bump after 10^6 cycles Au-Ru contact test, with a maximum loading of $100\mu\text{N}$.

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