Conduction properties of microscopic gold contact surfaces

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ABSTRACT

Electroplated gold surfaces of the type used for MEMS switches were surveyed by atomic force microscopy (AFM) to define the surface topographical features, and by x-ray photoelectron spectroscopy (XPS) to determine the chemical composition of the contact surface. The gold surfaces were contacted with electrochemically sharpened gold and tungsten probes using an interface force microscope (IFM), capable of simultaneously measuring contact currents from 10 fA to 10 mA and forces ranging from 0.01 to 100 μN. Both attractive and repulsive forces were observed, and attractive forces on the probe tip were found to exist at significant distances (greater than 5 nm) from the gold surface. The radius of the probe tip is on the order of a micron, making it a useful model system for a single-asperity contact on an actual MEMS switch-contact surface. The results of these single-contact measurement events are compared with contact measurements made with MEMS switches of various sizes and actuation schemes to understand the origins of contact resistance and switch failure.

Keywords: Contact, MEMS, relay, switch, Au, gold, IFM, microcontact, microrelay, reliability

1. INTRODUCTION

Gold is a useful material for microelectromechanical system (MEMS) switches because gold-gold contacts are capable of exhibiting very low resistances: about 100 mΩ with a 100 μN force under some current and voltage conditions, for example.[1] Further, gold is relatively inert, forming only modest contamination layers and no insulating oxide that must be broken with a large force (or voltage) in order to obtain the desired contact resistance. In general, however, the performance and reliability of MEMS micro contacts are difficult to predict because the contact resistance is a strong function of the surface topography, surface chemistry (contamination), switching current density and voltage, and the number of times the surface has been previously contacted. Under certain conditions arcing can occur, causing sufficient energy to be transferred to the contact surfaces that the switch is destroyed.[2]

Previous work with gold contacts has focused on high-force, high current conditions. For example, with a specialized measurement system, a 120-380 μm radius probe tip sputtered with gold has demonstrated resistances of 100 mΩ over a range of contact forces from a few hundred μN to almost 4000 μN when tested with a planar surface contact.[3] With another specialized system, resistances from about 100 mΩ (100 μN) to 8 mΩ (1000 μN) have been observed with two macroscopic gold contact rivets.[4] Due to the larger size and force range of these systems, it is likely that many asperities were involved in the contact events.

An excellent study by Hyman and Mehregany (1999) used a small (less than 1 μm radius) plated gold contact tip to explore the physical processes involved in gold-gold contacts. This work also focused on lower, but still significant contact forces and currents where the contact resistance was lower than 500 mΩ. Hyman and Mehregany conclude that heat dissipation plays an important role in achieving low contact resistance and that the electrode topography significantly influences both the thermal and electrical properties of the contacts.[1]

In this work, controlled small-scale contact experiments were performed to understand the contaminant layer on gold surfaces, its behavior with voltage, current, and force, and the mechanical changes in the gold surface resulting from tip-substrate currents. Particular attention was focused on the morphology of the gold surface and its interaction with the probe under low current, low force conditions. Under these conditions, insulating surface species are observed to

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dominate electrical and mechanical properties of the tip/substrate interaction. The results of the contact survey and probe experiments are compared to performance data from contacts in MEMS relays.

2. EXPERIMENTAL METHODS

Nominally clean electroplated gold films, of the type used for MEMS switches, were surveyed by atomic force microscopy (AFM) to obtain relatively large-scale topographic information. X-ray photoelectron spectroscopy was used to determine the nature and concentration of contamination species present on the surface .

The films were probed with an interface force microscope (IFM) to measure single-asperity conduction properties. A parabolic electrochemically sharpened gold or tungsten tip, radius approximately 1.2 µm (Fig. 1), was brought into contact with the rough gold film in a controlled vertical sweep. The IFM sensor and associated control electronics are capable of simultaneously measuring contact currents from 10 fA to 10 mA and forces from 0.01 to 100 µN. (For details of the IFM measurement apparatus and methods, see Son, Kim and Houston.[5]) Attractive and repulsive tip/substrate forces are measured. Initial electrical measurements were made by applying a constant voltage to the tip and measuring the resulting tip-substrate contact current. Subsequently, the voltage source was modified to include constant-current control electronics which automatically adjusted the tip voltage down from a pre-set maximum in order to obtain a defined current during the tip-substrate contact event. The constant current source was used so that a high tip voltages could be applied without causing uncontrollably large currents to flow through the contact; in this way, tip/substrate contact resistances could be measured reliably. Constant-current contact measurements were made in air and in a nitrogen ambient with relative humidity less than 10%.

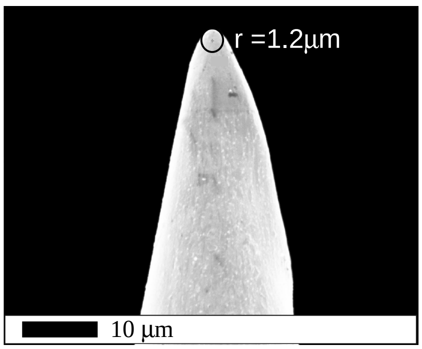

Fig. 1: A scanning electron microscope image of the tungsten IFM probe tip. The nominal tip radius is 1.2 µm.

3. TOPOGRAPHIC AND CHEMICAL PROPERTIES OF GOLD FILMS

Gold films were examined by AFM and found to have a root-mean-square surface roughness of about 30 nm (Fig. 2). When two such rough films come into electrical contact (as in a switch), the actual area of conduction is much smaller than the total surface area since electrical contact occurs exclusively at asperities, or local maxima of the films' surfaces.[6-8] A topographical survey of the gold films' surfaces found that the areal density of distinct asperities varies with distance from a reference plane (Fig. 3). The maximum asperity density of roughly 1 asperity/µm^2 was measured in a plane at a height of about 130 nm from a reference plane containing the rough film's lowest points. Above this plane of maximum asperity density, asperities decrease because there are fewer maxima above successively higher measurement planes. Below the plane of maximum asperity density, the number of distinct asperities decreases as individual asperities merge and form larger features. A map of the asperities in a 10×10 µm electroplated gold contact surface at a height of 160 nm above the reference plane is shown in Fig. 4.

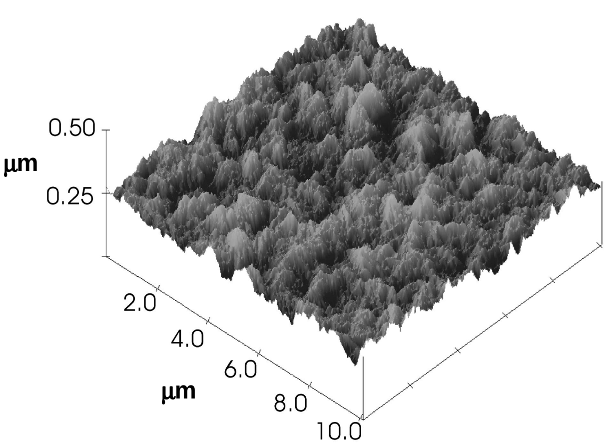

Fig. 2: Atomic force microscope topographic map of gold surface, 10×10 µm area.

Note that although the number of distinct asperities decreases with decreasing measurement plane height, the gold surface area (shown dark in Fig. 4) increases smoothly until it equals the total planar surface area of the contact (Fig. 5). Assuming that the rough surface is contacting a planar surface, and considering the height dependence of both the asperity density and gold contact area, the contact pressure per asperity can be estimated for a given contact force over the 100 µm^2 area, as shown in Fig. 6 (here with a 100 µN contact force).

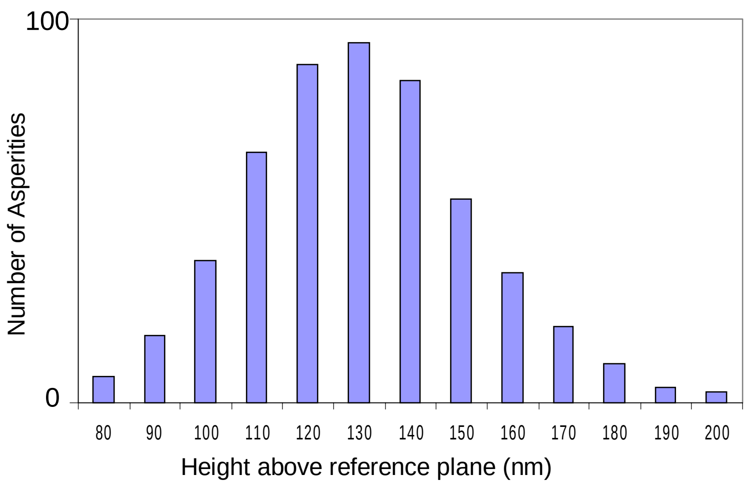

Fig. 3: A histogram of the number of distinct asperities measured at heights between 80 and 200 nm above a reference plane containing the lowest points in a 10×10 µm atomic force microscope topographic survey such as shown in Fig. 2. The number of asperities at each height shown here represent average values for three 10×10 µm surveys of the same electroplated gold film. The maximum asperity density of roughly 1 asperity/µm^2 was measured in a plane at a height of about 130 nm from a reference plane containing the rough film's lowest points.

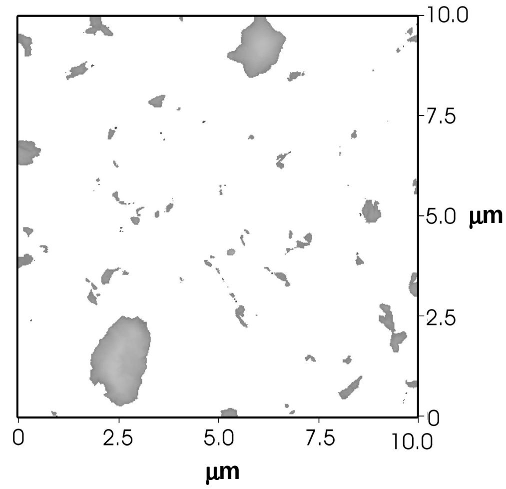

Fig. 4: A map of asperities in the plane 160 nm above a reference plane containing the lowest points in a 10×10 µm AFM survey of an electroplated gold film. Features smaller than about 1500 nm^2 and features on the edge of the map were not included in the count for the asperity histogram shown in Fig. 3.

Not surprisingly, the maximum pressure of approximately 44 GPa occurs at the highest point measured where there are fewest asperities and smallest area. Note that although this simple analysis is useful for bounding the parameters of a rough surface contact, it clearly contains some nonphysical assumptions such as that the highest surface features would yield without changing size, flowing or otherwise disturbing the features below the imaginary planar contact surface. In fact, the contact pressure cannot be greater than the yield stress of the gold film since the contact area will increase to reduce the pressure to below the yield stress (1 GPa for electroplated gold to 20 nm [1]).

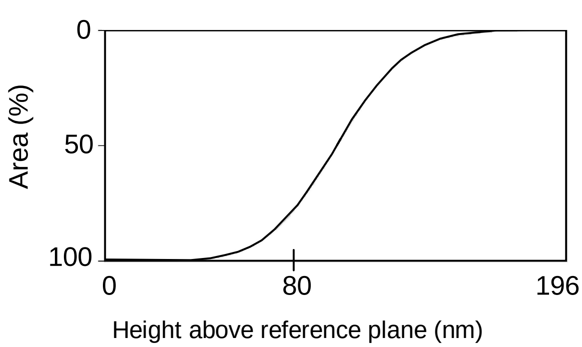

Fig. 5: The percent of 100 µm^2 surface area in a gold film which is above a reference plane containing the lowest point measured. For example, approximately 75% of the film area is higher than 80 nm above the reference plane.

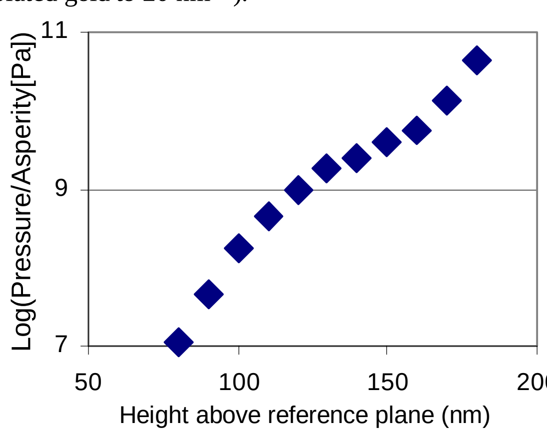

Fig. 6: The calculated average contact pressure per asperity for a 100 µN force over a 100 µm^2 electroplated gold area, given as a function of height above a reference plane containing the lowest measured point. The yield stress of gold to 20 nm is approximately 1 GPa (indicated by horizontal line), so that in reality pressures above 1 GPa would not be observed.

Although the gold surfaces measured were nominally "clean" (water rinsed, dried with nitrogen), XPS measurements taken after the surfaces had been exposed to air revealed that there were other atomic species present on the film to a depth of 10 nm, including carbon, oxygen and sulfur. (Elements present in such typical surface contaminants such as water or hydrocarbons.) Mechanically, the presence of a contamination layer can be inferred from attractive forces between the gold tip and substrate measured sometimes more than 8 nm away from the contact surface (Fig. 7). The contamination layer was observed to be a good insulator under some conditions.

4. IFM CONTACT EXPERIMENTAL RESULTS

4.1 Gold probe tip experiments

Initial IFM experiments were performed using an electrochemically sharpened gold contact tip. Typical experiments were performed in air with a probe speed of about 0.5 nm/sec and a low probe/surface potential of 0.02 V (Fig. 7).

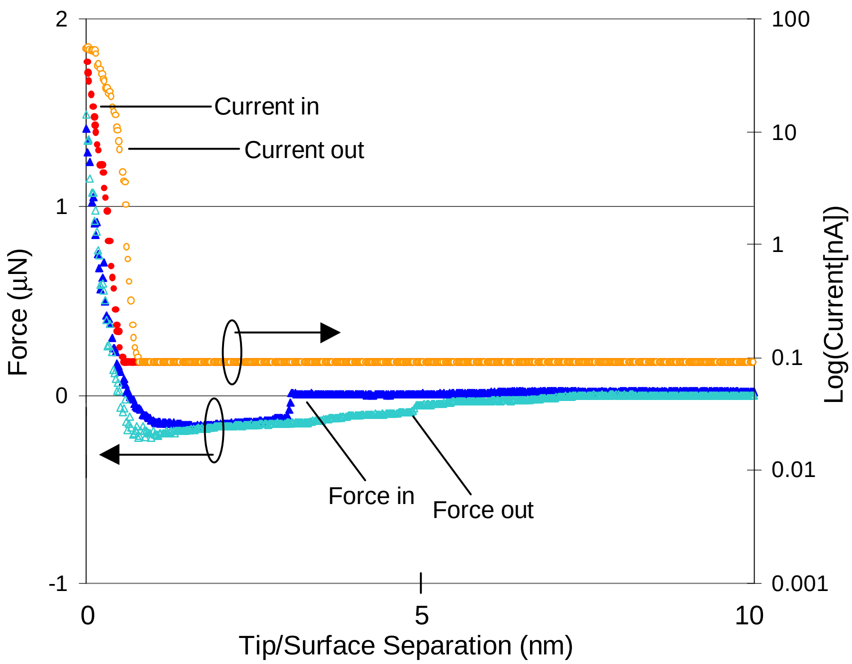

Fig. 7: A force/current profile of a contact event between a gold tip (radius about 1 μm) and a rough, electroplated gold surface. Note that significant attractive forces are present starting at about 3 nm away from the gold surface (taken to start at the point at which the force on the tip becomes positive and repulsive) as the tip approaches the surface, and that these attractive forces remain to almost 7 nm as the tip recedes. Current flow begins almost simultaneously with the onset of repulsive force on the tip.

Contact resistances changed from place to place on the surface of electroplated gold film, possibly because of variability in the surface contamination layer and/or film topography or probe shape. Estimated by the vertical extent of the attractive forces measured by the tip during retraction, the contamination layer could be extended to a distance of up to 8 nm from the film surface, and was often conducting to these distances as well. (In Fig. 7 and 8, the nominal "surface" begins at the point where positive – repulsive – forces are measured on the tip.) Voltage applied to the tip was observed to have the effect of reducing the contact resistance. In fact, without sufficient voltage it was sometimes not possible to make any electrical contact even with forces greater than 10 μN.

4.2 Tungsten probe tip experiments

One of the problems associated with a gold probe tip is that it can deform plastically under relatively low stress and thus change its electrical properties from contact event to event. In order to avoid this problem, a tungsten tip was used in place of the gold tip in some of the experiments reported here. Both tips had nominally the same radius (of about one micron), but with its significantly greater hardness (440 GPa vs. 1 GPa for gold), the geometry of the tungsten tip can safely be assumed to remain constant even after many interactions with the gold surface. At the same time the tungsten tip replaced the gold tip in these experiments, a constant-current source was added to the IFM testing apparatus. Also, for the tungsten-tip experiments the sample chamber was flooded with dry nitrogen, keeping the relative humidity in the chamber consistently less than 10%.

A typical tungsten-gold force-current profile is shown in Fig. 8. Note that, as opposed to Fig. 7, contact resistance is now plotted directly instead of contact current. In the contact event shown in Fig. 8, the initial tip/substrate separation was 50 nm.

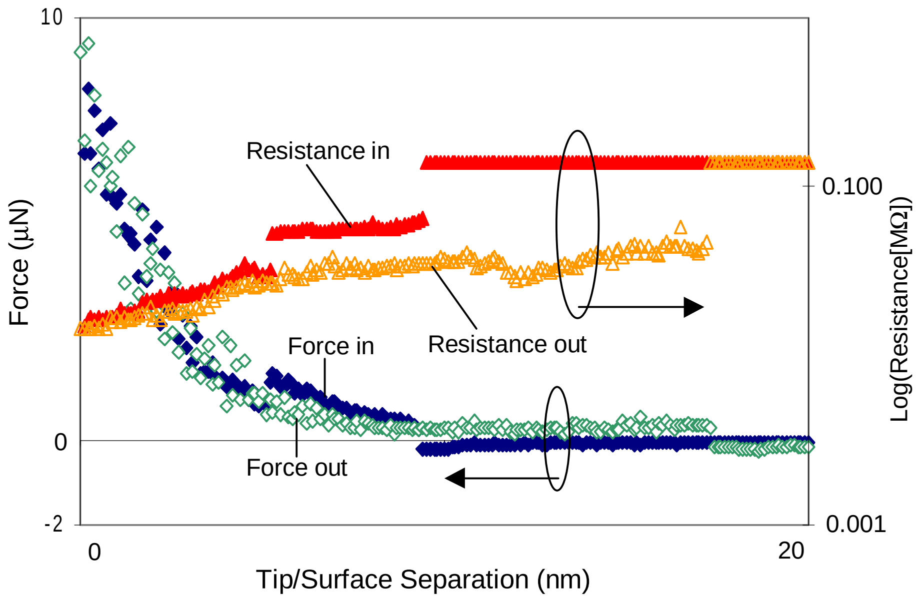

Fig. 8: A force and contact resistance profile of a contact event between a tungsten tip (nominal radius 1.2 µm) and a rough gold electroplated thin film. The minimum contact resistance is about 14 kΩ (at 9.4 µN), and 40 µA of current continues to flow between tip and film as the tip recedes to more than 15 nm away from the point of initial contact.

The current control system was set to operate at 40 µA, so that the tip/substrate bias is reduced from its initial value of 5.6 V as the tip comes into electrical contact with the gold surface in order to maintain 40 µA of current between tip and substrate. The minimum contact resistance measured in this test was 14.3 kΩ, occurring at the maximum contact force of 9.4 µN. In Fig. 8, 40 µA of current begins to flow between the tip and gold substrate at exactly the same time as the force on the tip becomes positive (repulsive). The current then continues to flow as the tip moves in toward the maximum contact force and back again, even after the tip has receded more than 5 nm beyond the initial contact point. Due to the high resistance of this contact, it is hypothesized that the current is being limited by a contamination layer on the gold surface and/or tip. Water vapor or other compounds formed with elements observed by XPS are sources of resistance, and it is possible as well that a thin native oxide on the tungsten tip may be inhibiting current flow.

In order to further examine the mechanical and electrical nature of the contaminant layer, contact experiments were repeated for the same location on the gold film. During a typical contact experiment, the tip starts at a distance of 50 nm from the surface, then approaches the surface while force and resistance measurements are made once every angstrom. The tip reverses direction and begins receding from the surface after the measured force on the tip exceeds a preset repulsive force threshold, often 10 µN.

Consistently, the contact resistance was observed to increase with each successive contact event, as shown in Fig. 9 for a series of 4 µA contacts. Fig. 9 shows a histogram of the number of resistance measurements per contact event that were below a threshold, 2 MΩ (white bars). Due to experimental variability, the actual maximum force the tip experiences from test to test is not constant; the maximum force experienced during each contact event is therefore also shown in Fig. 9 (black bars). For this series of tests, measured maximum forces varied from 8 to 11 µN. The contact consistently degrades with each subsequent contact event until, with the fifth event, no resistance lower than 2 MΩ is measured even with more than 10 µN applied between tip and substrate at 5.6 V.

In general, there was little correlation between maximum measured force and the quality of the contact. In other words, for average contact resistance it did not matter whether the turnaround force was 6 µN or 12 µN. Instead, it did matter whether previous contact measurements had been performed in the same location on the gold film. It is hypothesized that the probe-tip separation which occurs during a contact test allows an insulating contamination layer to accumulate either on the surface or the tip or both. It was observed, for example, that when the tip was simply brought away from the surface as little as 12.5 nm and held in that position with voltage applied for tens of seconds, then the contact resistance increased when the tip was brought back into contact with the surface. The formation of the insulating layer may be facilitated by current conduction between the tip and gold surface.

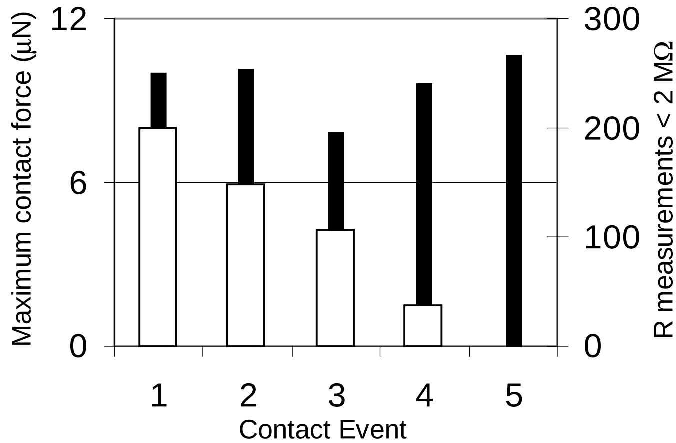

Fig. 9: Five consecutive 4 µA contact events between a tungsten tip and the electroplated gold surface at the same point on the gold surface. For each contact event, the tip receded 50 nm away from the gold surface before approaching. Force and resistance measurements were made once per angstrom as the tip approached and receded. The number of contact resistance measurements below 2 MΩ (white bars) is a rough measure of the quality of the contact. (Setting the contact resistance cut-off at 2 MΩ is arbitrary, but using points other than 2 MΩ gives qualitatively similar results.) The actual maximum force the tip experiences during each event is shown with black bars.

Creep experiments were performed in order to understand the tip/substrate conduction properties under constant force conditions. In a typical creep experiment, the tip is brought into contact with the gold surface to a preset repulsive force level, and the evolution of the position of the tip is observed over time. The constant current control was typically set to operate during the creep experiment so that the tip/substrate contact resistance could be observed.

The results of a typical creep test in which the current control was operating are shown in Fig. 10. The IFM sensor was set to maintain a repulsive contact force of 2 µN on the tip during this test, and the current controller was set to deliver 4 µA.

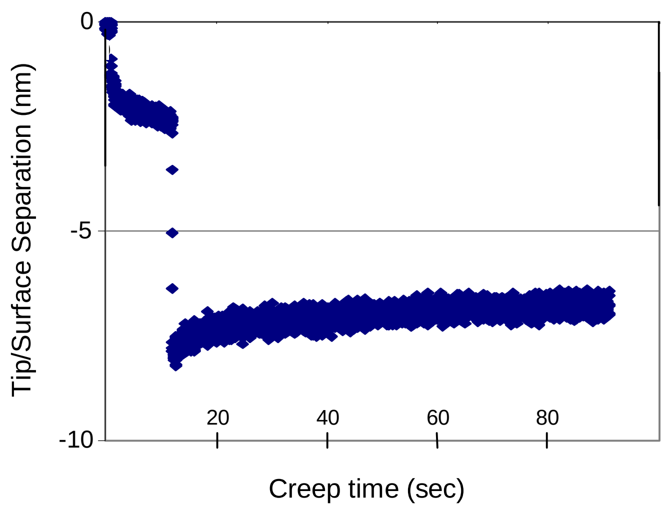

Fig. 10: A creep experiment for a tungsten probe/ gold film contact. The probe/film current was 4 µA, and the tip maintained a constant repulsive force of 2 µN. The maximum contact resistance was measured until 12 sec, when the contact resistance dropped to about 25 kΩ (coinciding with tip movement) and remained constant.

During the first 12 seconds of the test, the maximum electrical contact resistance between the tip an substrate was observed, but after 12 seconds the contact resistance abruptly dropped to 25 kΩ, where it remained relatively constant for the remainder of the experiment. The abrupt drop in contact resistance coincided exactly with the nearly 6 nm reduction in tip/substrate separation. This behavior was consistently observed at the 4 µA current level. During these events, the tip is compressing, displacing or otherwise altering the insulating contamination layer. If the contamination layer compression is in fact responsible for the observed reduction in contact resistance, the creep experiment implies that the thickness of the layer in Fig. 10 is greater than 5-6 nm. In other tests, similarly abrupt tip behavior (coordinated with abrupt reductions in contact resistance) were observed with displacements as small as 0.5 nm. In general, it was found that contact resistance increased following tip-substrate separations, and decreased under constant force/current conditions such as were present in the creep experiments.

The tungsten tip used in this work had a nominal radius of about 1.2 μm, leading to an ideal contact area of about 0.08 μm^2 at a contact depth of 10 nm, assuming a (nonphysical) planar substrate. For a 10 μN force, therefore, the contact pressure is approximately 125 MPa under idealized conditions. Even at these relatively high contact pressures, however, the minimum measured contact resistance was of the order 10 kΩ, implying that the insulating contamination layer dominated the conduction properties of the tungsten/gold contact. Very high-resistance, "quasimetallic" contact has previously been observed with gold-gold contacts in the force range 20-60 μN and with currents between 100 and 50,000 μA. In those tests, gold plated probe tips were used which had similar dimensions to the tungsten tips used for the experiments reported here.[1]

5. GOLD CONTACTS IN MEMS RELAYS

A magnetically-actuated latching micro relay fabricated with gold contacts has been reported to operate with a contact resistance lower than 50 mΩ for contact forces on the order of 100 μN (maximum direct current greater than 500, 000 μA, operating in air).[9] Previous work has demonstrated that gold-gold contacts require at least 60 μN for contact resistances below 100 mΩ [1], so it is probable that these switches rely on one or two asperities to conduct the entire current load. If more than two asperities were supporting the 100 μN of contact force, then the contact pressure would be insufficient to break the insulating contaminant layer to provide the observed low contact resistance. Experiments reported here suggest that asperities being contacted with up to 10 μN of force will be remain resistive due to the contamination layer present on the gold surface, especially after repeated contact events.

In a thermally actuated relay with gold contacts, contact resistances on the order of 100 mΩ have been measured for contact forces of 1,000-10,000 μN with 10,000 μA current loads.[10] Given the previously observed 60 μN minimum force for good electrical contact (of order 100 mΩ), it is likely that the current is being carried by tens or hundreds of asperities in this thermally actuated device. For both the magnetically and thermally actuated relays, the high current densities are thought to play an important role in creating low contact resistance between the gold surfaces.

6. CONCLUSIONS

This work focused on low current (40 μA and below), low force (20 μN and below) contact conditions in order to understand the role of topography and contaminants on gold electrical contact surfaces. Under these contact conditions, it has been observed that an insulating, mechanically strong surface contamination layer is consistently present on the gold film or probe surface even in a dry nitrogen ambient. This layer dominates the electrical and mechanical properties of the probe/surface interaction, leading to increased resistance with repeated contact events and causing significant attractive forces on the tip even to probe/surface separations of up to several nanometers. Voltage on the tip, and tip-surface current both affect the electrical properties of the contamination layer. The layer can be broken down, however, under constant force and current conditions, resulting in rapid probe tip displacement of up to 5 nm. Higher current densities will likely significantly alter the behavior of the gold-gold and gold-tungsten contact. Both higher currents and forces will be examined in subsequent experiments to observe onset of metallic contact conditions in the presence of the insulating contamination layer.

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