Contact Resistance, Stiction Force, and Field-Assisted Growth and Migration in MEMS and NEMS Metals

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Abstract – Contact resistance and its evolution are important parameters that determine the useful lifetime of MEMS switches. This work investigates the stiction force and evolution of contact resistance for five different metals (iridium, tungsten, nickel, ruthenium, and platinum). A Pt AFM probe was used as the counter electrode and the contact resistance over 100,000 cycles in nitrogen were recorded. Although this is small number of cycles compared to the desired 1 quadrillion cycles, it reveals a great deal about the contact quality provided that very small changes in the contact resistance are monitored and analyzed. Tungsten showed the largest increase in the contact resistance of 4% that was attributed to its surface anodic oxidation as imaged with AFM. We also used an infrared camera to monitor the contact temperature and noted a small flash of light when the probe touched the surface. Heating and the nano-plasma deposits carbonous materials on the metal contact area increasing contact resistance.

Keywords – MEMS/NEMS switches; contact resistance; stiction force; resistance evolution; contact temperature

I. INTRODUCTION

MEMS/NEMS switches are useful in RF circuits, IC technology, and mostly in harsh conditions where electrical properties of semiconductor switches can change. Metal contact MEMS/NEMS switches have gained attention for their prospective application in space technology, defense application, and RF circuits [1]. To obtain the best performance of these switches, appropriate metals should be used.

The ideal metal contact MEMS/NEMS switches (see Fig. 1 for schematic) should have low contact resistance which should not change over large switching cycles. So, the choice of proper contact metals is important. For high conductivity and inertness, gold is widely used as one of the contact metals in various MEMS/NEMS switches. The contact resistance and their evolution for Au-Au contact and with other metals were studied previously for both hot and cold switching [2-4,7]. Switches with similar and dissimilar metal contacts, degrade their performance due to high contact resistance after $10^5$ – $10^8$ cycles [2-4]. The high contact resistance for these types of switches is attributed to i) material transfer by diffusion and electromigration, ii) growth of carbonous materials, iii) anodic oxidation, iv) stiction (this also contributes to material transfer), and v) contamination by particulates in the switch environment or self-generated vi) pitting, and other physical or electrical damages [2-6]. In most cases it is quite laborious to determine the exact mechanisms of contact deterioration. Here we show that small resistance changes that may occur in contact materials over limited cycles (100,000) of switching can be used to understand contact deterioration. Anodic oxidation and carbonous material growth/deposition are accelerated by the thin water film covering the contact regions that may absorb CO2 and other hydro-carbons from the fabrication or laboratory environment. Carbonous material growth can also be accelerated by the catalytic metals such as Pt, Ni, and Cu while anodic oxidation is largest in other metals such as W as we show below.

In case of hot switching with dissimilar metal contacts, previous works indicated material transfer as the primary reason for contact resistance increase [7-10]. Electrons are emitted from cathode when the separation between two contacts is tens of nanometers. The emitted electrons heat the anode and evaporate metal which transfers to the cathode. In case of soft metals, this phenomenon would be severe. For hard metals, other mechanism for increasing contact resistance can be dominant like thin carbon or oxide based polymer growth in the contact region.

Platinum is used as one of the contact materials in this experiment. Young’s Modulus of Platinum is more than twice of gold but its resistivity is about four times larger than Au. Platinum is a highly inert metal with good conductivity and stability. To investigate the contact resistance and its evolution, switching was done between generally used MEMS metals and a Platinum AFM cantilever.

The stiction force of metals used in MEMS/NEMS switches is also a governing factor for design and fabrication purposes [11]. If the adhesion force is too high, the restoring force needed to turn off the switch will be large. The stiction forces of these tested metals were also measured and reported.

![Schematic of a typical MEMs switch](image-url)

**Fig. 1.** Schematic of a typical MEMs switch.

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II. EXPERIMENTAL PROCEDURE

For the experiment, a cantilever based MEMS switch was used. The tip of the cantilever is platinum. Five different thin films were used and the experiment measured the contact resistance between Pt and these different thin-film metals that included Ir, W, Ni, Ru, and Pt. The 100,000 cycle switching on metal film was done by an Atomic Force Microscope setup. Each thin film was 100 nm thick and were deposited by DC sputtering over a silicon wafer. 10-20nm titanium layers were used as adhesion layer whenever needed. To protect the thin film layers, 2 µm photoresist were used that were removed just before the measurements using acetone and methanol followed by rinsing in DI water and drying by nitrogen flow.

Keithley 236 was used as a voltage source and was connected to the cantilever switch (Fig. 2). The cantilever tip was placed in contact with the thin film in a TT-AFM system. A Labview program was used to perform cyclic Voltammetry up to 100,000 cycles. Voltage was swept from 50 mV to -50 mV in 10mV step with current compliance of 3 µA. The experiment was done in an inert nitrogen environment, while the temperature and humidity were controlled at 25 °C and 20%, respectively.

To measure the stiction force, a Veeco/Bruker AFM setup with a silicon cantilever was used force versus displacement plots were obtained as shown in Fig. 3. In this figure, the cantilever tip is very close to the sample surface at point “a”. As it approaches the surface the measured tip-sample force is given by “b”. At point “b”, the tip interacts with the thin-film surface. After the contact point the force curve follows a diagonal line given by the “b-c” segment. In retraction the force curve goes below the horizontal line “ab” to point “d” dictated by the adhesion force. For each thin film sample, the stiction force was measured at least 6 times in different positions and the average value was reported with standard deviation.

III. RESULTS AND DISCUSSIONS

For iridium, nickel, and platinum, the average resistance change over 100,000 cycles is very small less than 1%. For tungsten, the resistance increased by 3.6% from its initial value in 100,000 cycles. Nickel showed the best performance and its tip-sample resistance was constant at 22.2 KΩ. The average resistances of all the samples as a function of switching cycles are shown in Fig. 4.

From Fig. 4, it can be seen that the average resistance typically increases as a function of switching cycles. In the case of tungsten, the contact resistance went up and was then reduced around 70,000 cycles. The overall increase in the tip-sample resistance is attributed to oxide growth or other depositions discussed before. The reduction in the contact resistance in the case of tungsten is due to the removal or the modification of the anodic tungsten oxide due to mechanical surface forces. A higher resolution dependence of the Ni and W samples are shown in Fig. 5.

As the resistance increases in some metals, there has to be some changes in the contact region. Material transfer from the anode to cathode and formation of anodic oxides or a polymeric layer in the contact region is considered to be among the important reasons for increasing the contact resistance [3,4,7,8]. In the case of polymer layer and oxide layer formations, a higher potential in some cases can be used to break them down and reduce the contact resistance. The I-V plot for dielectric breakdown of the insulating layer (likely anodic oxide) over tungsten is shown in Fig. 6. The voltage in this case was increased in 25 mV steps from 0 V. The contact resistance increased significantly in Pt-W contact followed by the dielectric breakdown of the deposited layers at 2.6 V. The
current versus voltage curve became linear at voltages above 2.6 V and the contact resistance decreased.

We used an IR camera to image the contact temperature as shown in Fig. 8a and noticed that when the tip approached the sample, a light emitting discharge occurred as shown in Fig. 8b. Figs. 8c and 8d show the platinum AFM tip before and after switching experiments respectively. As can be seen in Fig. 8d, a thin layer of carbonous (polymeric) material accumulates around the tip. It appears that the combination of contact heating and plasma generation gives rise to the coating of the Pt tip with a carbonous (polymeric) material. Fig. 9 shows the AFM scan of anodic oxide on a tungsten thin-film sample. The regions with anodic oxides were 2 nm high and had 70-90 nm lateral extensions. These regions can be etched away by applying larger voltages or reversing the polarity of the applied voltage.

IV. CONTACT TEMPERATURE DURING SWITCHING

The average slope of the I-V curve before the dielectric breakdown shown by the dashed line indicates higher contact resistance pointing to the formation of insulating layers between the AFM tip and the tungsten in the contact region.

Stiction forces between the platinum AFM probe and thin-film samples were measured and are shown in Fig. 7. Pt and Ru showed larger stiction forces than iridium, tungsten and nickel. To reduce stiction hydrocarbons (Teflon) or graphene layers can be deposited [12]. Graphene has a honeycomb structure and has very good electrical conductivity, so it can reduce both contact resistance and stiction forces [13].

Pt-Ir had smallest stiction force (25 nN) while Pt-Pt had the largest stiction force (65 nN).
V. CONCLUSION

I-V measurements in the range of +/- 0.1 V with +/-100 nA current compliance was used to study the effect of hot switching between a Pt AFM probe and 5 thin-film metallic samples. I-V values were then analyzed to obtain contact resistance as a function of switching cycles. In iridium and platinum the average resistance changed by less than 2% and in tungsten the resistance increased by 4% from its initial value over 105 cycles. Nickel’s contact resistance changed by less than 0.1% over the same cycles. Next, the voltage range was increased to +/- 5 V to see if Pt-W contact resistance can be restored. The W surface anodic oxide was removed or punctured at 2.6 V and the contact resistance decreased to its pristine value. Stiction force measurements were also performed and found Pt-Ir to have the smallest and Pt-Pt to have the largest stiction forces. We also observed polymer deposition and “micro-plasma” generation in the metal-metal contact regions.

REFERENCES


