An Experimental Investigation of Hot Switching Contact Damage in RF MEMS Switches

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Abstract

RF MEMS switches have been shown to have better performance than their solid state counterparts on account of their low insertion loss and high isolation. Despite their superiority, these switches suffer from several reliability issues which limit their lifetime when compared with p-i-n diodes and GaAs FET switches. One of the major reliability issues is the reduction in lifetime of these switches when switched under hot switching conditions i.e. when a DC voltage or RF signal is applied across the contact while it is switching from an off to on position or vice versa. In this work, contact damage in Ruthenium-on-Ruthenium microcontacts has been investigated under hot switching conditions. Using an AFM based test setup, developed at Northeastern University for the purpose of contact testing, a large number of experiments were performed to observe and understand the mechanisms that lead to microcontact damage and ultimately its failure. The structure used was a clamped-clamped beam structure with a contact bump at its center. A flat topped mating pillar formed the other end of the contact and this pillar was mounted on a piezoactuator whose expansion and contraction, leading to contacts closing and opening, replicated switching cycles.

It was observed that material transfer was the primary cause for contact failure in DC hot switching. When the applied hot switching voltage exceeded 2.5 V, the direction of material transfer appeared to be polarity dependent and is always found to be from the anode to the cathode. This gives rise to the formation of a pit at the anode and a mound on the cathode. Prolonged material transfer leads to contact erosion until at one point the contact resistance becomes too high leading to contact failure.

It was determined, through models and experiments, that the mechanisms leading to contact erosion operate when the electrodes are separated by either a few Å or are barely
touching. For leading edge hot switching, i.e. hot switching during the make phase of the contact, the damage mechanism was found to be associated with very low current and was prominent even when a current limiting resistance up to 1 Meg\(\Omega\) was placed in series with the contact.

For both leading and trailing edge hot switching, when a hot switching voltage of 3.5 V is applied and a 50 \(\Omega\) resistance is placed in series, the amounts of material transfer observed at a cycling frequency of 500 Hz were found to be almost identical. However, leading and trailing edge hot switching were also found to be different under other conditions such as when a high external resistance of 5 k\(\Omega\) is placed in series. Also, for trailing edge hot switching, when contacts are separated extremely slowly, two different mechanisms – one polarity dependent and one polarity independent – were found to exist. These mechanisms were found to operate before the contacts fully come apart, probably when a molten metal bridge is formed between them.

By examining microcontacts under a variety of hot switching conditions, ranging from different voltages, different polarities and different approach and separation rates, it was concluded that hot switching damage is an extremely complex phenomenon for microcontacts. It consists of a number of different mechanisms all occurring simultaneously in different degrees depending on the exact hot switching conditions. Even a small hot switching voltage of 0.25 V can cause damage that is significant when compared with pure cold switching i.e. when a voltage is applied only when the contact is fully closed. However, hot switching also gave rise to lower contact resistance compared with cold switching. Under bipolar hot switching, microcontacts were able to last up to more than 100 million cycles while still maintaining a contact resistance of less than 1 \(\Omega\).
To the pursuit of knowledge and those who have devoted their lives and careers to it.
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Chapter 1 - Introduction

1.1. Overview of RF MEMS switches and their applications

Micro-electromechanical Systems (MEMS), also known as Microsystems in Europe are miniature devices that are fabricated using process technology derived from the semiconductor IC industry. MEMS transducers have expanded in their applications and from being a mere research interest in the 1970s it has grown to be a nearly $9 billion industry [1].

RF MEMS switches refer to micro-electromechanical switching devices with applications in the RF communications industry. Currently, the RF industry overwhelmingly uses solid state switches. While solid state switches do offer advantages, MEMS switches are exceedingly useful in two very important aspects – high isolation and low on-resistance. The predecessor to RF MEMS switches in terms of similar performance was electro-mechanical relays. However, these being bulky and expensive to manufacture, were never considered seriously in the RF industry. With the advent of MEMS and with miniaturization of the geometry, MEMS switches provided a realistic alternative for the RF industry [2,3].

The first major progress in the development of RF MEMS switches was accomplished by Northeastern University in collaboration with Analog Devices [4,5]. Radant MEMS, a startup that designed RF MEMS switches, spun out of this collaboration. Following that, several companies including IBM and Motorola started pursuing this area in a major way. However, the most successful of all has been the switch manufactured by Omron Corp. which has shown remarkable performance and reliability. Radant MEMS too, has manufactured and commercialized a high performance switch with high reliability and lifetime. The lifetime of the switch exceeds several hundred billion cycles [6,7].
Functionally, RF MEMS switch is almost identical to an electromechanical relay. Thus, it must have an actuation mechanism and should have an electrical signal transmission area. The actuation mechanism can be one out of the following: electrostatic, electromagnetic, piezoelectric or thermal. The electrical signal transmission is done either via a metal-to-metal contact or a capacitive contact. In an RF circuit, the switches may be placed in series or in shunt configuration to isolate one part of the circuit from another.

The primary competitor of RF MEMS switches are the p-i-n diodes and the GaAs FET switches [8]. A p-i-n diode is made up of a p-doped and an n-doped region similar to a conventional diode. However, it also has an intrinsic i-region where both p and n charges reside [9]. This allows the p-i-n diode to behave differently from other diodes. Basically, it acts as a conventional rectifier diode at low frequencies, but at higher frequencies it will behave as a
resistor whose resistance can be controlled by the amount of DC current passing through it. Depending on the thickness of the i-region, p-i-n diodes can be designed such that a few mA of DC current can result in very low resistance at RF frequencies. However, the use of DC current as the control for these switches results in them having a high insertion loss.

Figure 1.2 – Cross section of a P-I-N diode [10]

In MESFET switches, such as the GaAs devices, the RF signal flows from Source to Drain while the gate voltage acts as the control voltage. A major disadvantage in FET switches is leakage current which prevents it from offering adequate isolation and lowers the off-resistance of such switches.

Figure 1.3 – Cross section of a GaAs FET switch [11]
The Figure of Merit in all RF switches is given by the following expression:

\[
FOM = \frac{1}{2\pi R_{on} C_{off}}
\]

The unit of the Figure of Merit is that of Frequency i.e. Hz and is referred to as the cutoff frequency. The table below compares the properties of the different kinds of the RF switches developed over the last decade [12]:

<table>
<thead>
<tr>
<th>Device</th>
<th>Figure of Merit</th>
<th>Switching speed</th>
<th>Power dissipated</th>
</tr>
</thead>
<tbody>
<tr>
<td>PIN Diode</td>
<td>800-1600 GHz</td>
<td>&lt; 1 µs</td>
<td>High</td>
</tr>
<tr>
<td>GaAs FET</td>
<td>700 GHz</td>
<td>&lt; 1 µs</td>
<td>Low</td>
</tr>
<tr>
<td>RF MEMS</td>
<td>10-20 THz</td>
<td>5 - 50 µs</td>
<td>Low</td>
</tr>
</tbody>
</table>

Table 1: Comparison of Switch technologies on the basis of Figure of Merit

Apart from a high figure of merit, what sets RF MEMS switches apart is their extremely high linearity. In any RF circuits, IP3 is an important parameter, and hence a high value of IP3 is essential. Also, power consumption in both electrostatic and piezoelectric MEMS switches is almost zero. The actuation voltages, however, are high (up to 80 V for electrostatic and up to 20 V for piezoelectric switches). Therefore, an up-converter may need to be added to the actuation circuit in case the battery of consumer electronics is not able to supply that magnitude, in which case the power consumption of the up-converter will have to be taken into account.

RF MEMS, in the past have been suggested to be extremely viable alternatives for phased arrays in radars, as well as in cell phone front ends. However, of late, SiGe technology has seen
advances while SOI and SOS transistors too have seen tremendous development which have resulted in extremely inexpensive solid-state switches being manufactured with great power handling capabilities and high IP3 value. Thus, both these areas, which were earlier thought to be potential markets for RF MEMS, are not viable any longer. However, there are other application areas where RF MEMS has a clear advantage over semiconductor technology [13]. These are:

1) Automated Testing Equipments or ATEs used for characterizing RF ICs. ATEs require both DC and RF signals to pass through and metal-to-metal direct contact MEMS switches can be extremely useful in this regard.

2) Spectrum analyzers and signal analyzers which require high linearity and also high isolation between different ports. Currently, they often use electromechanical relays to achieve these and scaling down to RF MEMS can only prove beneficial.

3) Wideband receivers and transmitters in defense systems which contain switched filter banks (made up of SPDT switches) mostly use the lossy p-i-n diode switches. RF MEMS can be a viable alternative for these.

4) Satellite switch matrices which require a huge number of switches and therefore moving to RF MEMS will result in reduction of the bulkiness of such systems and also lead to better performing networks [14].
As mentioned earlier, the greatest advantages of RF MEMS are low loss, high linearity and high isolation. However, the disadvantages include lower durability particularly of the contact type switches (although, with better understanding of contact metallurgy, high performance switches that last up to hundreds of billions of cycles are now being designed). Also, RF MEMS switches are more expensive and that is one area where solid-state switches have a head-start as of now.

Some of the RF systems building blocks where MEMS switches can replace solid state switches are shown below:
Figure 1.5 – Satellite switching network with MEMS applications highlighted [14]

Figure 1.6 – Transceiver system with MEMS applications highlighted [14]
1.2. Electrical contacts for MEMS switches

As mentioned before, MEMS switches can be classified into two categories based on how they conduct the electrical signal. These are: a) Capacitive and b) Direct contact. In capacitive switches, a dielectric separates the surfaces of the metal electrodes. RF MEMS capacitive type switches have been designed to have insertion of <0.1 dB at tens of GHz and isolation of tens of dB. However, one drawback of capacitive switches is its inability to conduct DC signals. Sometimes, even in RF circuits, conducting DC voltages is essential, particularly as biasing voltages in devices. Also, there is a reliability issue with capacitive switches which is dielectric charging that can be affected by environmental conditions such as humidity [15].

Metal contact RF MEMS switches have received a lot of attention in the communications industry lately since these switches have low on resistance, high isolation and are suitable for signals with frequency ranging from DC to the millimeter wave frequencies (100 GHz) [16]. Some of the best RF MEMS switches, particularly the ones that have so far been successfully commercialized are the metal contact type. The reliability of these switches is in a large part related to the reliability of their electrical contacts. Much like in electromechanical relays, therefore, the study of electrical contacts has grown to be a separate area of research by itself. There are several different parameters of the electrical contacts that require close investigation. As such, not a whole lot of work has been done so far in accurately trying to understand the behavior of these contacts.

While studying contact metallurgy, a lot of thrust was placed on the electrical resistance of these metal contacts, since low power consumption was one of the selling points of RF MEMS switches. A lot of the very first switches designed and manufactured, therefore used Au
as the contact material [17]. The main advantages of Au were its high conductivity and also extremely low affinity to organics. Low affinity to organic contamination meant that these switches had an increased lifetime and suffered little in terms of increase of resistance due to surface contamination. However, Au is a soft metal. This property prevents it from being the ideal contact material. Softness of Au leads to high adhesion between the contact surfaces [18,19,20]. In his work on study of contacts, Lei Chen determined that high adhesion even during cold switching, makes Au switches prone to failure by sticking. This failure to open is one of the primary modes of failure in MEMS switches after they have cycled for a large number of cycles [21]. Both hot and cold welding (associated with hot switching and cold switching respectively) have been reported to cause contact damage [22,23,24]. In order to reduce adhesion between contact surfaces, the two electrodes of a contact have been coated with different materials. Such contacts, however, have been shown to suffer from high resistance caused by carbon build-up [25,26].

Carbon contamination and frictional polymer on the surface causes contacts to lose their conductivity [21,27,28]. However, Au has better reliability in this area because of the reasons discussed before. Contamination, though, can be reasonably prevented by hermetic packaging. This factor led researchers to concentrate more on high adhesion and to design switches which do not fail by stiction. For instance, low force switches suffer from much less adhesion and subsequent failure than high force ones.

While determining reliability of switches, it is their reliability in cold switching conditions that is mostly discussed. Hot switching is a relatively unexplored area and while it has been known that they cause great damage to the microswitch contacts (much like in electromechanical switches), not a great deal of literature is available on them. The difference
Significant work has been published that studies the performance of the electric contacts coated with different materials. For contact material, different alloys of Au have been investigated that can improve the hardness of the contacts while retaining the conductive properties of Au. Contact materials such as Pt and Ir have been tested by the predecessors of this author [29,30,31]. While some of these materials have been promising they still do suffer from high resistance after millions of cycles. Clean Ru switches, which have undergone oxygen plasma clean and have a layer of oxide on it, have on the other hand shown excellent performance particularly under cold switching conditions. Having been limited by the switching rate in SPM-based contact tester, these contacts in the past hadn’t been tested for more than a million cycles. But in this work, the author reports tests that lasted much longer without sufficient degradation of the contact performance. It should be noted, however, that these tests have been conducted under a constant \( \text{N}_2 \) flow which means that the atmosphere around the contact is extremely pure.

In larger electromechanical relays, one technique to avoid build-up of contamination between contacts is to introduce scrubbing [32,33]. In micro-contacts, however, sliding is discouraged because of the extremely thin layer of contact material present which can get removed quickly. The absence of sliding thus makes micro-contacts susceptible to surface contamination build-up, particularly during cold switching.

1.3. **Hot switching in MEMS switches**

Although adhesion and carbon contamination can degrade the performance of electrical contacts
in MEMS switches, it is hot switching that causes the most significant damage to metal contacts. In RF circuits, it is entirely possible that a voltage may be applied across the switch while it transitions from off to on state or vice versa. Hot switching refers to the application of an RF signal or DC voltage across the switch contacts during this transition process. Although it is possible to incorporate logic so as to avoid hot switching, it is important for switches to be able to withstand hot switching without extensive damage.

It has been observed that hot switching leads to significantly more damage and reduced lifetime than pure cold switching. Although hot switching was not fully explored in MEMS switches until recently, switch designers have nevertheless attempted to design switches and contacts such that hot switching damage can be reduced. One of the more novel methods proposed in this regard was the ball grid array dimple design by Linda Chow et al [34]. Their switches were able to sustain more than 100 million hot switching cycles at an RF power of 1.25 W. They attributed the success of their design to a reduced contact area.

In macrorelays, it is well-established that arcing, which is a direct effect of a high voltage across contacts having a small separation, occurs both when the contacts come together as well as when they begin to come apart and is possibly the most significant cause of contact damage. Arcing can cause several detrimental effects on the contact. On the one hand, such arcing can lead to contact erosion since it will melt the contact material on either side of the arc while on the other hand, arcing and the consequent high temperatures associated with it can also cause the formation of oxides, nitrides, sulphides, carbonates and carbonaceous compounds by triggering reactions with gases adsorbed by the contact material from the ambient air [33]. For microcontacts, though, contact damage leading to failure can occur at voltages much below arclike conditions as explored in this thesis.
Hot switching damage in microcontacts has been analyzed from various perspectives by different research groups. When MEMS relays were still at their inception stage in the late 90s, their electrical contacts were studied as a part of the overall study of the reliability of the switches. It was deduced early on that in the absence of the high voltages associated with contact damage in macrorelays, the damage mechanisms for the MEMS relays are different. In some of the earliest work on MEMS relays, “Microrelay design, performance and systems”, Kruglick noted that Paschen effects and arcing are irrelevant in MEMS relays [35].

Detailed investigation of damage mechanisms and damage characteristics in the MEMS switches was not undertaken until a few years back. There were two most prominent theories that were proposed to explain the lifetime reduction of the contacts under hot switching:

1) Micro-arcs appear between the contacts just prior to closing and immediately after breaking of contact. These micro-arcs decompose any organics available either in the ambient or on the surface of these contacts, causing carbonaceous contamination to appear on the surface of the contacts. The appearance of such carbon contamination was documented separately by at least 2 different research groups [36,37,38]. In [38], contact damage was associated with current transients due to parasitic inductances in the circuit which can be compensated by adding a capacitive quenching circuit.

2) Material transfer between contacts leading to erosion of contacts finally leading to high contact resistance. The phenomenon of material transfer was well known among macro sized electromechanical relays and it is also fairly well understood. However, in MEMS contacts these are not well understood. The two proposed theories in this regard are field emission and field evaporation which have been suggested by two different research groups [39,40,41]. The
field emission theory proposes that at small distances, tunneling of electrons from cathode to anode leads to a rise in temperature at the anode. If the energy in the electrons is high enough to raise the temperature of the hottest area of the anode to boiling point, then material from anode will evaporate and deposit on to the cathode. Field evaporation on the other hand suggests that the electric field between the contacts at small separations can lead to surface atoms being pulled out of its lattice when the electric field is greater than a threshold value. Field evaporation also leads to material transfer from anode to cathode.

Field emission and tunneling of electrons has been studied in the past at lower voltages. In their work in [42], Wallash and Levit suggested that at very small separations between electrodes Fowler Nordheim current leads to small breakdown voltages, thereby giving us what he calls the modified Paschen curve.

Another possible cause of material transfer is the formation of a metal vapor when asperities come into contact and then evaporate due to the sudden release of capacitive energy. The metal vapor then gets ionized and the positively charged ions are attracted towards the cathode leading to mass transfer. During trailing edge, there is a possible formation of a metal bridge [43,44] due to adhesion which subsequently evaporates due to the high associated temperature forming a metal vapor that ionizes and finally gets deposited on to the cathode. This phenomenon is similar to what is observed in macro-relay contacts and is known as arc erosion of contact material [45,46].

There is also the possibility of material transfer due to electromigration which can be caused due to very high current density. Such electromigration can be accelerated due to the formation of a molten bridge [47]. Thermal effects, such as Thomson effect where the flow of
current causes a thermal gradient in a molten bridge which then leads to material being transferred towards the cooler electrode, can also lead to material transfer [32].

The combination of all these phenomena makes it difficult to predict quantitatively how much material transfer can occur at a given voltage. The aim of the author, in the course of his thesis work, is to attempt to address the significance of each phenomenon and to establish evidence of each.
Chapter 2 - Experimental setup

2.1. AFM based test setup

Fabrication of RF MEMS switches can be expensive due to a variety of reasons. Since the focus of this work is the study of the electrical contacts, fabrication of actual switches is unnecessary. For testing various different contact materials without having to fabricate an entire batch of chips with a particular contact material, it is much more convenient to use test structures on which the contact material can be deposited after the structures have been completely fabricated and released. That way, several contact materials can be tested from chips derived from a single wafer. In actual switches, since the contacts lie underneath the structure, it is impossible to coat the contact with whatever material one wishes to. Coating of the contact material, therefore, cannot be a final step and instead has to be done before release.

Also, in order to have the flexibility of studying the performance of the contacts under varying amount of contact forces, it is necessary that a suitably adaptive method is designed. If the tests were done on actual switches, then the study of the contacts could only be done within the range of contact forces for which the particular switch had been designed. Figure 2.1 shows the picture and the overall schematic of the SPM based test setup for study of contacts.
For study of contacts, various research groups have in the past used contact test setups. The three most popular test facilities are – 1) Customized AFM setup, 2) Nano-indenter, 3) Pico-indenter [24,48,49,50,51]. However, with all these systems, there is a compromise between accuracy and speed of testing. Cycling the contacts for more than $10^6$ cycles requires that cycling of the contacts be performed at a fast enough rate so that the test does not prolong to days. Among several systems implemented purely for testing of contact material, some that stand out are those by Ma et al [24], Yunus [51] and Kwon [49]. However, lifetime tests lasting up to millions of cycles could not be conducted with these systems and thus long term tests on reliability of contacts and contact evolution were not performed.

Figure 2.2 shows the simplified test setup while Figure 2.3 shows the entire test setup.
Lei Chen, for his work on contact evolution [21], had used a cantilever beam with a contact bump at its tip which formed one end of the contact. The other end was a flat surface. However, by using such a cantilever structure as a force sensor, sliding effects were encountered during the contact tests. Also, the measured resistance in this previous setup included the sheet resistance components of the metal films on the cantilever and testing pads. A better test setup would incorporate a four wire measurement such that the effect of sheet resistance and other
resistances on the contact resistance measurement can be minimized.

The structures fabricated and used for the tests performed during this work were designed by a previous graduate student working in this group [31]. Lei Chen and Nikhil Joshi, students under Professors Nick McGruer and George Adams, have also used this identical setup [30].

Fig 2.4 shows a typical force sensor and the mating pillar. The clamped-clamped beam structure of the force sensor is fabricated from silicon and later coated with the required contact material. The dimensions of the two different structures used for the various tests are presented in Table 2 and then coated with a metal film. The stiffness of these force sensors with these dimensions were found to be approximately 3380 N/m for the long beams and 8300 N/m for the short beams using finite element analysis. The paddles on the force sensor are wider than the rest of the beam and are used to reflect the laser from the source to a mirror which further reflects it to the force sensor. By adjusting the mirror one can focus the laser right at the center of the photo detector. When the mating pillar, during actuation, comes into contact with the force sensor, it pushes it upward which causes the laser beam to move upward. On the other hand, when the contacts are coming apart, the laser beam moves downward and may even go below its original starting position if there is adhesion.

The pillar side of the contact is slightly raised from the rest of the chip so that proper contact is made only between the contact bump and the pillar and not anywhere else on the chip. Also, the clamped-clamped beam housing the contact bump ensures there is no scrubbing or sliding between the contact surfaces.
Table 2: Dimensions of the force sensor structures used

<table>
<thead>
<tr>
<th>Feature</th>
<th>Short Structure</th>
<th>Long Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Length</td>
<td>90</td>
<td>120</td>
</tr>
<tr>
<td>Paddle Width</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Paddle Length</td>
<td>35</td>
<td>40</td>
</tr>
<tr>
<td>Middle Spacing</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>End Spacing</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Beam Width</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Beam Thickness</td>
<td>4.5</td>
<td>4.5</td>
</tr>
</tbody>
</table>

Figure 2.4 – a) SEM micrograph of Force sensor, b) SEM micrograph of the mating pillar, c) Schematic of the force sensor
The relationship between the A-B voltage from the photodetector of the AFM and the displacement of an AFM tip was found by using a calibrating sample with a known step height. This information can then be combined with the result of a finite element model for the force structures which can relate the displacement with the corresponding force experienced by the structure. The results of the Finite Element Analysis concluded that the conversion factor for transforming the A-B voltage into force is approximately 153.8 µN/V for the large structures and for the smaller structures it is 266.67 µN/V.

2.2. Contact preparation and testing procedure

2.2.1. Contact preparation

Before the start of a test, the microchips to be tested ideally need to undergo an oxygen-plasma clean. The purpose of the plasma clean is two-fold: a) to remove any organic surface contaminants from the samples under test, b) to create a protective oxide layer on top of the contacts that ensure longer durability of these contacts. In the past, it has been proven that ruthenium oxidizes to RuO_2 when exposed to O_2 plasma for an appropriate amount of time [52]. Ruthenium oxide has also been shown to be stable and conductive [53]. Based on these findings and other work by [54,55], it can be stated that a thin oxide layer will be present on the contact surfaces at the start of any test.

Initially (up to June 2012), for samples tested within 48 hours of deposition, the test was performed without performing the oxygen plasma clean; samples tested between 2 and 5 days of deposition were plasma cleaned for 3 minutes; samples tested 5 or more days after deposition were cleaned for 5 minutes. This procedure applies to tests where contact damage and material
transfer were characterized as a function of the number of hot switching cycles. Later, to maintain more consistency between sample surfaces, all tests were performed within 72 hours of deposition and cleaned for 3 minutes. It is important to note that the ex-situ plasma cleaning presented above was found empirically to not affect the results of the test contacts at least for the hot switched samples that underwent material transfer.

The system used for the oxygen plasma clean was an MKS-AX7670. The following steps describe a typical plasma cleaning procedure:

1) The cooling water supply is turned on. The water passes through a filter before passing through pipes that enter and leave the plasma chamber.

2) The vacuum chamber of the plasma system, at this stage, is at atmospheric pressure and one of its outlets is open. The chamber is manually lifted and the samples that need to be cleaned are placed inside the chamber.

3) The plasma system is turned on by switching on the power switch. There is a display screen on the plasma system which displays various messages depending on system conditions. When the screen says ‘READY’, the user would know that the next steps can be carried out.

4) The vacuum pump is turned on. At this stage, the vacuum chamber of the plasma is still disconnected from the pump via the main valve. This valve should not be opened until the user is ready to close the chamber by shutting the open outlet with an O-ring and KF flange.

5) The main valve is gradually opened after the chamber is closed.

6) The pressure in the chamber will now begin to drop. If the pump is functioning properly, this drop in pressure (monitored with a pressure sensor) occurs very rapidly within 4-5 seconds.
7) When the pressure is around 200 mTorr, the Ar supply is turned on at a flow rate of 0.5 sl/m. The software used for controlling the gas supplies is Smartrak.

8) The pressure in the chamber should now start to increase. Once there is a steady pressure of 1200-1300 mTorr, the voltage to fire the plasma can be turned on. The voltage supplied is a DC voltage of 24 V. This is pure Argon plasma with no Oxygen in it.

9) Oxygen at a flow rate of 0.15 sl/m is now started. It takes about 6-7 seconds for the software to trigger the Oxygen supply.

10) When the oxygen starts flowing into the chamber, the plasma changes its color. From being a dim purple color, the plasma transforms into a bright purple color.

11) In steps of 0.05 sl/m, the Oxygen flow rate is ramped up to 0.5 sl/m

12) In steps of 0.05 sl/m, the Argon flow rate is now ramped down to 0.3 sl/m.

13) At a ratio of 5:3 of $O_2$:Ar the plasma clean is done.

14) At the end of the clean, the DC voltage supply which supplies current to the plasma is turned off.

15) The main valve is then shut closed thus cutting off the vacuum pump from the plasma chamber.

16) The Argon and Oxygen supplies are then turned off.

17) The chamber is now purged with atmospheric air by slowly pulling out the gate of one of the outlets of the chamber. There are a total of 4 hoses with KF flange. One is connected to the vacuum pump, one is connected to the pressure sensor. Out of the remaining two hoses, opening
either one can purge the chamber and bring it back to atmospheric pressure.

18) The chips can now be taken out by manually lifting the plasma chamber. The user should also remember to shut down the main power supply to the plasma system.

### 2.2.2. Contact testing procedure

Setting up of an experiment, after the oxygen plasma treatment of the contacts, begins with placing the chips on their respective holders. For the force sensors, the AFM tip holder itself acts as the tool where the chip is mounted. However, for the pillars, a specially designed metal plate structure has been made with help from the Machine shop. The holder has a center region carved at an inclination of 120. This is the angle which the AFM tip makes with the horizontal axis when it is placed on the holder. To match this angle, the opposite pillar must be placed at the same angle too. The piezoelectric actuator is mounted on top of the metal plate and on top of that the chip for the pillar is placed. Two metallic springs are placed on either end of the pillar performing the dual responsibilities of providing mechanical support for the pillar as well as electrical connectivity. Wires are soldered to both the metallic springs to provide connectivity to the external devices (DAQ).

Mounting and perfect alignment of the pillar is particularly difficult. A pair of tweezers is used for the mounting process and care must be taken while sliding the pillar underneath the springs and on top of the piezoelectric actuator. The pillar chip must lie flat on top of the actuator. Any inclination at any angle will cause misalignment resulting in imperfect contact. Also, the user has to make sure that he doesn’t scratch the surface of the chip since even a minor scratch can introduce particles that are hard to get rid of. It is also necessary to wear gloves.
during mounting to avoid contamination from skin contact.

After mounting both the force sensor chip and the pillar chip, the following steps must be taken. A lot of these steps are identical to what one does during a normal AFM scanning process. However, in this case the AFM tip is replaced by the force sensor chip.

1) The AFM laser spot is focused on the right paddle of the force sensor. Out of the three force sensors, generally the sensor in the middle was used.

2) Turn on the SPM scanning software and set the SPM to contact mode. The reference can be set at 0.2 V.

3) Make sure that the laser spot as detected by the photo-detector is exactly at the center where the x-axis meets the y-axis. The laser spot can be adjusted by turning “Check PD” on and then manipulating the mirror which reflects the laser after it has been reflected by the paddle.

4) The pillar holder is placed where samples for AFM scanning are usually placed. Also, one must remember to connect all the wires from pillar, force sensor and the piezoelectric actuator to the external equipment.

5) Make sure that the pillar lies approximately below the force sensors and can be seen through the backside window that has been etched to make this visibility possible.

6) Start moving the pillar upwards with the coarse adjustment screw. This can be done up until the pillar and force sensor are roughly at the same focal length. At this stage the x and y axes of the pillar holder may be adjusted so that the pillar is right underneath the force sensor under measurement.

7) Turn on ‘Check PD’ and make sure the laser alignment is still ok. The laser will remain on
during the course of the experiment.

8) Turn ‘Retract off’ so that AFM’s own piezoelectric device can now be controlled by the control system of the AFM. Now, click ‘Approach on’. One should remember that the reference voltage for the AFM has been set at 0.2 V while the initial voltage is at 0 V.

9) The stepper motor now turns on and gradually pushes the pillar upwards in steps of a few nm. When the pillar just barely touches the force sensor, and the AFM voltage increases to 0.2 V, the control system ensures that the stepper motor turns itself off.

10) Now we apply 40 V on to the piezoelectric actuator (PI 022). Since the AFM control system is still on and its job is to keep the A-B voltage fixed at 0.2 V, any expansion of the external piezo will result in shrinking of the AFM’s piezo such that the A-B voltage does not alter.

11) Now we go to the ‘Advanced’ tab of the SPM software and turn the control system off by putting the tip on hold.

12) The voltage that was hitherto applied to the external piezoelectric actuator will now be turned off resulting in its shrinking. However, since the control system is off, AFM’s piezo will not expand back. This will result in the pillar de-engaging from the force sensor and contact.

13) At this stage, if we apply a voltage across the contact and external series resistor, the entire voltage should appear across the contact. If it does not that would mean the pillar chip is making contact with the force sensor chip at some point other than the actual intended contact spots i.e. the bump. Usually this would mean that the AFM stage where the pillar has been placed needs to be brought back down, the pillar holder removed, and the pillar readjusted. Sometimes it could also mean that the piezoelectric actuator itself is not working anymore. That implies that when
40 V was applied across the piezo, it in fact did not expand. The lifetime of the piezos, however, is at least 10 billion as per the specifications. It is, therefore, very uncommon to find the piezo not working. Changing the piezo should be the last resort after verifying without a shadow of doubt that the alignment is indeed perfect.

14) After the pillar and the contact bump have de-engaged, a ramp-hold-ramp voltage a voltage of about 50 V amplitude is applied.

15) It should be ensured that contact between the electrodes synchronize with the increase in A-B voltage. Presence of electrical contact is monitored by observing the voltage across the contact and the external resistor. At electrical contact, most of the voltage drop will be across the 50 $\Omega$ external resistor. Also, we know that mechanical contact is monitored by observing the A-B voltage. Thus is mechanical and electrical contact synchronize perfectly, the test setup is working as it should.

16) The Test program software, built with LabVIEW, lets the user monitor the number of switching cycles undertaken. All other details, including ramping rate, contact resistance, and required contact force is available on the screen.

17) A new addition to the test program is a control system which controls the voltage applied to AFM’s piezo. By increasing and decreasing this voltage, any piezo drift, in either direction, can be compensated for. For allowing the program to control the voltage on AFM’s piezo, the user needs to be on the “Advanced” tab of the SPM software and turn on ‘External Z-control’.

18) The program will run unless stopped. When force control is on, the program also stops by itself if the AFM’s piezo has drifted too far away and the required contact force cannot be reached even by applying the maximum voltage to the piezo. Also, if the contact resistance
becomes too high, indicating failure of the contact, the test program will stop.

19) For tests where an extremely slow approach/separation rate is used, a separate program is used for actuating the piezo. This program is built such that the voltage to the piezo can be gradually increased, decreased or kept constant.

The author acknowledges the major contribution by Ryan Hennessy who designed the software for the test setup and made it easy for the author to conduct tests under various conditions. This enabled a detailed study of microcontact behavior.

2.3. **Electrical circuits for contact testing**

2.3.1. **Contact resistance measurement circuit**

As mentioned before, the measurement of contact resistance is done using a four-probe measurement setup. Since constant data acquisition during the course of a test is of paramount importance, the test setup needed to be interfaced with a computer. LabVIEW was used as the data acquisition (DAQ) software. As far as supplying voltage and current to the samples is concerned, there can be two approaches to it: a) Using an external power supply, b) Using the LabVIEW DAQ. There are two voltages here that need to be supplied: 1) the voltage applied to the switch and the external resistor in series; 2) the voltage applied to the piezoelectric actuator. In the HERMIT program, students in the past have used external power supplies for generating these voltages. The current source for the contacts used to be generated with a DC power supply while the voltage to the piezoelectric actuator was supplied with a function generator. The author himself, for some preliminary investigation on the contacts, used this same setup. However, for most conditions of leading edge and trailing edge hot switching tests, as well as for pure cold
switching tests, where contact voltages for the off state and on state segments of a cycle are different, an external non-programmable power source was inadequate. Even with a programmable power source, synchronizing it with a separate voltage source for the piezoelectric actuator, is impossible. Such synchronization, of course, is necessary so that the ramping voltage applied to the piezoelectric actuator is applied at the same time as the leading edge hot switching voltage is applied to the contacts. For trailing edge, the contact voltage is removed as soon as the ramping voltage is brought down to zero. Only for pure hot switching tests is the contact voltage applied constantly.

These voltages, therefore, were required to be generated using a DAQ and had to be generated programmatically. NI PCI-6251 DAQ board was used for interfacing the LabVIEW software with the contact test-setup. One issue with using the DAQ to directly supply voltages to the contact was that the internal circuit of the DAQ limits the current that can be generated. This would limit the study of contact behavior only under low power conditions. It was necessary, therefore, to interface the DAQ with the test setup using a driver circuit consisting of a buffer amplifier with a voltage gain of 1 as shown in Figure 2.5.
The buffer amplifier circuit, used for supplying current to the contacts, consists of the input voltage buffer, four different current-limiting input resistances. Also, TVS diodes and capacitors are included for protection.

As mentioned, the buffer amplifier was necessary so as to enable the circuit to drive high currents up to 1 A. Bypass capacitors were added from the positive and negative voltage supply rail to the ground. These bypass capacitors have the function of controlling and restricting any high and low frequency oscillations in the power supply.

Figure 2.5 shows the overall schematic of the amplifier circuit. The four resistors chosen as current controlling resistors are $5 \, \Omega$, $10 \, \Omega$, $20 \, \Omega$, and $50 \, \Omega$. In standard RF circuits, the load impedance is usually $50 \, \Omega$. For this purpose, most tests done in order to investigate contact properties are done with $50 \, \Omega$ in series. It should be noted, though, that the characteristic impedance of the interconnects between the resistance, to contact to ground can cause the voltage appearing across the contact to fluctuate particularly during opening and closing of the contact.
switch at a high frequency. This is due to the characteristic impedance of a transmission line not matching the load impedance [56] leading to reflection and re-reflection of the wave. Thus, it was decided that a 50 Ω terminator, as shown in Figure 2.2, needs to be used. By using a terminator, whose resistance was equal to the characteristic impedance of the co-axial cable connecting it to the contact, this problem was addressed. Thus, instead of using a 50 Ω resistor before the contact, the resistor was used after the contact.

The signal, therefore travels through the contact structure and then to the mating pillar and finally through the terminating resistor. The other ends of the structure and the pillar are connected to voltage measuring probes which are then connected to the DAQ break-out box through a BNC. Since, it is important to protect the DAQ from current spikes or over-voltages, a protection circuit consisting of a parallel combination of TVS (transient-voltage-suppression diode) diodes and a capacitor was included. This protection circuit also contains a series resistance. The TVS diode will limit the voltage to a safe limit of +/- 10 V [57]. This circuit was originally designed as the test setup for the Northeastern University Microswitch, by Brandon Jalbert [58].

An interface circuit was also required for the piezoelectric actuator and will be discussed in detail later. The maximum voltage that can be supplied by the DAQ is +/- 10 V. This is insufficient if one has to generate any significant expansion of the actuator. A voltage of 50 V can result in an expansion of approximately 1.1 µm for the piezo used i.e. PL 022.31 [59]. Thus, yet another amplifier, this one with voltage gain, is required for applying the requisite voltage to the actuator.

The DAQ is connected to the test setup in two different ways. The two amplifier circuits,
which are on a PCB, are connected using a National Instruments GPI bus. The pin diagram for this GPI bus is provided by National Instruments. For measuring the contact voltage, a BNC cable is used to connect the leads from the contact measurement circuit to the break-out box from the DAQ. The break-out box of the DAQ has several channels for providing both input and output signals. For our setup, the break-out box was used solely for the purpose of measuring signals. The measurement of voltages and the issues encountered while doing so will be discussed later.

2.3.2. **Piezo-actuator amplifier circuit**

The circuit for the piezo-actuator was originally developed to supply voltage to the gate of the RF MEMS switch developed at Northeastern University [58]. Figure 2.6 shows the power amplifier circuit board for the piezo-actuator. The part number for this power amplifier is PA85 from Texas Instruments. The amplifier is connected in a non-inverting mode with feedback resistors. TVS diodes and capacitors are included for overvoltage protection of the DAQ similar to the protection provided in the main amplifier circuit described in the previous section. The amplifier is capable of handling supply voltages of 450 V single ended or ±225 V differential. A current limiting resistance of 30 Ω, as recommended by the manufacturers was added to limit the current to 39 mA [60]. This is the maximum suggested current limiting resistance value. The amplifier was designed for a gain of 21. Since the DAQ can output a maximum voltage ±10 V, therefore the maximum available voltage from the output of the power amplifier was ±210 V unless limited by the supply voltages. Also, the manufacturers recommended a phase compensation impedance. This consisted of 330 Ω (R_C) and 10 pF (C_C) in series [60]. To prevent the amplifier from getting damaged, 200 V rated unidirectional TVS diodes were placed on the
positive and negative rails. These will help avoid overvoltage and also protect against voltage reversals.

Here too the effect of oscillations caused by the power supplies was accounted for. In order to control the oscillations, a 200 V rated 1 µF and another 0.1 µF bypass capacitors were placed in parallel from positive and negative supply voltages to ground.

![Amplifier for piezo-actuator](image)

*Figure 2.6 – Amplifier for piezo-actuator*

### 2.4. Measurement of voltages with LabVIEW DAQ

An integral part of the test setup jointly designed by this author is its ability to acquire data continuously through the period of a complete test. As mentioned before, some of these tests can run for $10^7$ cycles at 500 Hz, which required seamless integration of the DAQ board, the interface circuits, the switch contacts and the LabVIEW software. In LabVIEW, creation of channels is required before data can be acquired. Some of the issues that need to be addressed in
order to enable accurate Data acquisition are a) Avoiding ground loops, b) Determining ground reference setting of the Analog input of the DAQ, c) Avoiding ghosting. Each of these issues will be subsequently addressed and described in detail. Among these issues, the formation of ground loops is especially important since apart from the interface amplifier circuits, certain low level currents in the hundreds of nA regime need to be monitored by including an additional transimpedance amplifier. While the necessity, application and construction of this circuit will be described in detail later, the issue of ground loop which is common to the system as a whole is being addressed below.

2.4.1. Avoiding ground loops

During any low level current and voltage measurements, ground loops can introduce avoidable noise in a signal. Ground loops arise when there is more than one connection to ground. For example, in our setup, the DAQ has its own ground which is connected to the earth ground through the computer; the op-amps both for the main amplifier circuit connected to the switch as well as the amplifier circuit for the piezoelectric actuator have two grounds. Now, if these different grounds are connected to the same ground bus, a loop can be formed causing a small amount of voltage drop between the grounds. While for larger voltages such ground loops may introduce insignificant amounts of noise, for smaller voltages and currents which may be present in the circuit, such noise can prove to be significant. The current caused due to the presence of such ground loop will result in a voltage drop in series with the source voltage. If the current through the ground bus is I and the resistance from one ground connection to another is R then the voltage drop through the ground bus → \( V_G = IR \). A schematic of this is shown in Figure 2.7.
In order to avoid the ground loop issue, the remedy is to have independent power sources for all the instruments used in the setup. All the grounds of these power sources and other circuits should then be connected to a single node which goes to a common ground. For our setup, since the DAQ is already grounded through the ground of the computer, this was chosen as the common ground node.

2.4.2. **Ground reference setting**

In a DAQ, the analog input channels used for acquiring the signals are marked as AI. The circuit for analog input ground-reference settings is designed to be able to choose between differential, referenced single-ended, and non-referenced single-ended input modes. It is possible for each individual AI channel used for measuring voltages to use a different mode. For most of the signals measured by us, the signals were sent to the DAQ through a breakout board with BNC inputs. For our setup it was important to choose the right setting for each individual channel.

*Figure 2.7 – Creation of ground loop [61]*

\[
V_{IN} = V_G + V_C.
\]

where \( V_G = I R \), and

- \( R \): Resistance of input LO connection (typically around 100 mΩ)
- \( I \): Current passing through input LO connection due to ground voltages (\( V_G \)) in the ground bus (magnitude may be amperes)
- \( V_S \): Source voltage (desired signal)
- \( V_C \): May exceed \( V_S \) by orders of magnitude.
Both in the breakout board as well as in the LabVIEW program, the reference setting needed to be mentioned. For our setup, since the applied voltages are also being applied by the DAQ whose signals are referenced to DAQ ground (referred to as AI GND), the voltages too are ground-referenced. The only exception to this is the voltage across the resistor which is a differential voltage. However, strictly speaking the differential voltage across the resistor is also a ground referenced one since the voltages at the two ends of the resistor are each independently referred to the earth ground and not floating voltages.

In the differential mode, the voltage is measured between a pair of input nodes. In the LabVIEW DAQ, certain pins are paired to each other and in the differential mode, the voltage for these pins will have to be measured in pairs. Thus, when the interconnections on the PCB are designed so as to measure the voltage across resistor, it has to be ensured that the correct pair of pins on the DAQ’s GPI-bus is connected to the ends of the resistor. An arbitrary pair cannot be chosen since there are only specific pairs that are meant to measure such differential voltages. For instance, for differential measurements, AI 0 and AI 8 are the positive and negative inputs of differential analog input channel 0. Similarly, the following signal pairs also form differential input channels: <AI 1, AI 9>, <AI 2, AI 10>, <AI 3, AI 11>, <AI 4, AI 12>, <AI 5, AI 13>, <AI 6, AI 14>, <AI 7, AI 15>, <AI 16, AI 24> and so on. In our setup, the <AI 16, AI 24> pair was chosen for measuring voltage across the one of the four resistances. However, if the 50 Ω terminator is used as the external resistance, then one of the channels on the breakout board is used as the input.

2.4.3. **Ghosting**

If the scanned channel of a DAQ is connected to a source with high impedance, then the settling
time for the DAQ increases. This is because the ADC has a small internal capacitance which charges or discharges as the multiplexer selects different channels of the ADC. The multiplexer in between the source and input switches from one channel to another depending on the order in which the LabVIEW program commands it to as shown in Figure 2.8. The source impedance, will combine with the capacitor that is being charged to form a low pass filter whose time constant increases with increases in the source impedance. The schematic of the circuit is shown below:

![Figure 2.8 – Schematic of the DAQ input [62]](image)

When the multiplexer is at channel ai0 for example, it charges to a particular value. Subsequently, the multiplexer switches to the next channel that it needs to scan, say ai1. At this point the capacitor will charge from the voltage it was at the moment of disengagement from the previous channel and up to the voltage on the new channel. Note that the new voltage may be greater or less than the old voltage. If source resistance RX is too large, then the capacitor C will take too much time to be either charged or discharged to the voltage corresponding to the new
channel. Instead it might contain some residual voltage from the previous channel scanned and that will be clearly evident. This shadow effect due to the time constant associated with the charging and discharging of the capacitor is sometimes called ghosting. An example of ghosting is shown below. Here, we assume R1 is too large whereas R0 is reasonably small. If the channels are scanned independently and not as part of a common program, then the values read are accurate (Figure 2.9 and 2.10). If, however they are both scanned concurrently, then a shadow effect from channel ai1 is evident on the reading of channel ai0 (Figure 2.11).

![Figure 2.9 – Independent input at channel ai0](image)

![Figure 2.10 – Independent input at channel ai1](image)
We will face this same problem if channel ai1 is disconnected while the program is asking it to be scanned (Figure 2.12). In that case, because of the infinite source impedance, the capacitor will not charge or discharge from its previous value from channel ai0.

Having realized the root cause of ghosting, several remedies can be suggested. These are recommended by National Instruments and were strictly adhered to while writing the code for the data acquisition as well as making the circuit connections:
i) Use of low impedance sources is always recommended since this can reduce the time constant for the low pass filter.

ii) Scanning rate should be made only as fast as required for capturing accurate data. Too high of a scanning rate leading to more data points may not be a good idea since that would give the capacitor less time to settle in between transitioning from one channel to another.

iii) It is advisable to choose wisely the order in which the channels are scanned. Two channels whose voltages have similar values can be placed one after another whereas the channel with a voltage of a different range can be placed afterwards. It is also a good idea to place the channels in either ascending or descending order of the magnitude of voltages they measure.

### 2.4.4. A-B voltage from the AFM photodetector

Another issue that had to be addressed before accurate data could be acquired was the A-B voltage of the AFM photodetector. The A-B voltage is the signal that the photodetector of the AFM generates when the AFM tip scans the surface of a sample. A change in the position of the AFM tip corresponds to a shift in the laser point which is then detected by the photodetector and interpreted as a change in voltage.

In the context of the contact testing structures, A-B voltage is directly related to the contact force as explained earlier, since the A-B voltage changes as a result of the pillar striking against the clamped-clamped structures with the contact bump. Under a normal circumstances, the change in A-B voltage should be easy to detect and interpreted in terms of contact force. However, in our setup, the laser point, apart from shining on the paddle of the force structure, also shines on the pillar when it is very close to the force structure. The reflected signal from the pillar interferes with the signal from the structure and can either prove to be constructive
interference or destructive depending on where the pillar is positioned. This led to the following A-B signal shown in the figure below.

![A-B voltage with ripples indicating constructive and destructive interference between reflected laser spots from the pillar and force structure](image)

As seen in Figure 2.13, there is a ripple right before contact force starts increasing and right after the contact force has gone back to 0 μN. This ripples are due to constructive interference which increases the A-B voltage thus giving an illusion of increase in contact force, and then decreasing the A-B voltage which again makes us think the pillar has come out of contact.

To work around this problem, the resolution was to focus the laser as well as possible. It was observed that by manipulating the focus of the laser, the ripples can become greater or less in magnitude. At a particular focus, the ripple would be least significant which corresponds to the point where the focus is the best and almost the entire laser beam strikes against the paddle of the force structure and very little of it spills on to the pillar. Given below is the A-B voltage corresponding to a properly focused laser.
As seen from Figure 2.14, on properly focusing the laser beam, the ripple is practically removed thereby enabling us to capture accurate contact force data.

2.5. Calculation of contact resistance

The purpose of monitoring the contact and resistor voltages with the DAQ is to enable us to estimate the contact resistance during the course of cycling of the contacts. Along with monitoring the contact force, monitoring contact resistance is of utmost importance in order to characterize the behavior of the contacts through many cycles. While measurement of contact force is done directly by calibrating the A-B voltage from the photodetector, monitoring the contact resistance is done indirectly by using the four-probe approach as shown in Figure 2.15.
Because of fabrication issues as well as the design of the chips, the contact resistance calculated using the measured contact voltage was not entirely accurate. Given below is the design of the chip with the force structures.

As seen from the design shown in Figure 2.16, there are three structures on each chip. This design was chosen to enable more no of samples to test per chip. However, when current flows through the contacts, the two other structures give an alternate path for the current to flow. This needs to be factored into an electrical model of the chip in order to arrive at an accurate value of the contact resistance.

The second issue, essentially a fabrication deficiency, has to do with isolation trenches. On the chip, the isolation trenches are built in between the two areas where measurement probes
are placed. These two areas are the inner rectangle and outer periphery. The reason behind building the trenches is as follows: at the time of electrical contact and flow of current, it has to be ensured that the path of current flow can only be through the structures so that the contact resistance is the only resistance encountered by the current. In the absence of trenches, the sheet resistance of the chip may become significant.

The isolation trenches are 1 µm deep and are etched all the way through the Silicon Dioxide layer of the SOI (refer to the fabrication steps in the appendix). After release of the structures, the contact material is deposited by sputtering whereby the entire chip gets coated with the contact material. Sometimes, the presence of a small particle in the trench ensures that the trenches do not end up being isolation layers, since the contact material gets deposited on these particles too and gives the current an alternate path to flow much like the alternate paths through the untested structures. While considerable effort was put into ensuring that the particles are completely removed by refining the cleaning process and trying an ultrasonic clean, there always remained some additional unwanted particles in the trenches. This gave rise to what we called the “Shunt path” for the current and had to be characterized and included in the electrical model of the contact system.

To study the presence of the shunt resistance, a four wire measurement to characterize the surface current on the chip was made. The test was done as follows: Using a probe station, two probes were placed on either side of the trenches (inner and outer). Using Keithley 237 Source Measure Unit in its four probe mode (also known as Remote operation), a current was supplied between these two probes. A third probe was placed next to the first source probe. The fourth probe was navigated throughout the entire area of the inner portion of the chip to measure the voltage at each of these points with respect to the third probe. This is a standard four-probe
measuring approach and the aim was to determine where current flows.

In the presence of the force structures, current should be flowing in the direction of the structures since they provide the path of least resistance. However, if the structures are removed, current should flow towards the particle in the trench that has been coated with contact material, since that offers the path of least resistance. The figures below show both these cases and tell us how the shunt path has a tangible effect on flow of current.

Figure 2.17 a) Voltage profile of the inner area of the chip with test structures present, b) Voltage profile of the inner area of the chip with test structures absent

Figure 2.17 a) and b) clearly show that in the presence of the test structures, the current flows in a particular direction whereas in their absence it flows in a different direction. However, ideally one would expect zero current flow in the absence if the test structures and zero potential drop across the tested area.
It was also found that the direction of flow of current may vary from one chip to another and there is no consistency as to where the shunt path is located.

Keeping all of the above discussed factors in mind, an overall electrical model was developed to accurately estimate the contact resistance. The value as measured with the four-probe setup had to be further modified to reach the correct value.

Given below is the electrical circuit model of the overall system. For now, any parasitic inductance or capacitance in the circuit has been ignored. However, a more accurate model will include all of those. Since for the time being the purpose of this model is only to analyze the effective resistance of the electrical contact, the circuit parasitics may be ignored without loss of accuracy.

The probes in this circuit indicate where the voltages for the four-probe measurement are being measured.

Figure 2.18 – Effective circuit diagram taking into account shunt resistances

In Figure 2.18, Rint1, Rint2, Rint3 = Resistance in the interconnects

$R_{str} = $ Resistance of the structure due to sheet resistance of the deposited film.
\( R_{\text{shunt}} \) = Resistance of the shunt path.

\( R_{\text{ext}} \) = External current controlling resistor in series with contact.

\( R_{\text{contact}} \) = Actual contact resistance.

\( R_{\text{pillar}} \) = Resistance of the pillar due to sheet resistance of the deposited film.

Effective measured resistance =

\[
\frac{R_{\text{str}}^2}{4} \left( \frac{R_{\text{shunt}} \times R_{\text{str}}}{R_{\text{shunt}} + R_{\text{str}}/2} \right) + R_{\text{contact}} + R_{\text{pillar}}
\]
Chapter 3 - Hot and cold switching – baseline tests and empirical results

The primary objective of this thesis is to understand and characterize the damage in the micro-contact of a MEMS switch while also determining the damage mechanisms. To this end, the primary tests undertaken and described in this chapter have looked at switch behavior under different conditions – viz. different current and voltage values. The test results that are described here are both qualitative and quantitative. While qualitative data consists of images under a Hitachi SEM, the quantitative data looks at the volume contact material transferred. A large part of the damage characteristics of the contacts consist of material transfer from one electrode to another. Therefore, a volumetric analysis was important in order to quantify the damage. Also, the contact resistance was monitored using the experimental setup in order to ensure that the contacts did not completely fail at any point. Contact force was set at 400 μN for all tests.

Volumetric measurements were taken using the same AFM but in its conventional scanning mode. Using the tapping mode of scanning, high resolution images were captured and the data points thus captured were used to determine the volume of material added or subtracted. By comparing the damaged area of the contact to the surface fit of the undamaged area of the contact, the volume of material added to or subtracted from the contact could me calculated [63].

3.1. Hot switching damage – a complex phenomenon

Hot switching damage can be a result of a variety of different mechanisms that are at play. Over the last several years, a number of different mechanisms that lead to material transfer and contact damage have been proposed [38,39,40,41,64,65]. Notable among these theories are field
emission, field evaporation, capacitance and inductance in the switch leading to voltage overshoots, and also formation of a metal bridge which was experimentally observed in Au microcontacts [65]. This thesis describes how complex the hot switching damage in contacts is and how it cannot be explained by any simple model. While one or more of the mechanisms discussed by other groups may well contribute to damage to the contact, there are almost certainly a number of events occurring simultaneously. It can be stated that the contact damage observed is due phenomena occurring in three domains that are coupled to one another – a) Electrical, b) Thermal and c) Mechanical. The investigation presented in this thesis attempts to address the phenomena due to these three domains.

To add to the complexity, not all mechanisms operate with the same intensity under all conditions. There are certain voltage regimes where one mechanism gets precedence on another. Also, as mentioned before, thermal mechanisms can become more prominent only at the trailing edge and not at the leading edge. While these voltage regimes are discussed in detail later, it is pertinent to show some of the types of observed contact damage and how the nature of the damage can vary depending on the conditions in which the hot switching cycles took place.
Figure 3.1 shows the hot switching damage on a contact under a variety of conditions. While usually the damage observed is polarity dependent, as seen in 3.1 (d, f, g and h), sometimes the damage may not follow this rule. It has been observed that at low voltages, polarity independent material transfer and contact damage is often seen. Furthermore, at 0.5 V, a
lot of contact damage is observed with contact material scattered in the form of debris all over the contact bump both at the anode as well as the cathode end of the contact. As we go to higher voltages, at 2.5 V and above the polarity dependent material transfer becomes most significant. Although for both leading and trailing edge hot switching material is transferred from the anode to the cathode, the surfaces of the contacts under these two conditions often look different from each other. For contact material erosion/deposition in the case of leading edge hot switching, the surface tends to have a lot more scattered debris and also spherical particles which look like molten and resolidified material. Trailing edge contact damage seems a lot more uniform. Quantitatively, however, for a contact approach/separation rate of 4400 um/s, the volume of material transferred from the anode to the cathode is almost the same [66]. This result should ideally dictate that for a bipolar test, where the polarity of the contact is reversed every cycle, almost zero material transfer should be observed. However, it was found that if the testing is continued for tens of millions of cycles, it leads to material transfer away from the contact bump thereby indicating that another mechanism, possibly thermal, is also at play. This mechanism, though, is overshadowed by the polarity dependent mechanism when unipolar hot switching voltage is applied.

Keeping all of the above observations in mind, the picture that evolves is that hot switching damage is an extremely complex phenomenon and not something that can be easily explained using a single model or explanation. In the course of this discussion, each mechanism will be looked at in detail and will be investigated in isolation as much as possible by defining conditions where one mechanism is allowed to dominate more than the others.
3.2. Comparison between mechanical, cold and hot switching

In RF MEMS switches, as indeed in relays of macroscopic dimensions, hot switching causes damage to the electrical contacts particularly through contact erosion. As discussed earlier, hot switching is the phenomenon where a voltage (DC or RF) is applied across the contact of a switch while the switch is transitioning from open to or the other way around. Also, while hot switching has been extensively studied for macrorelays, it is yet to be explored to the same extent for microswitches. It is likely, that some of the mechanisms responsible for extensive hot switching damage in microswitches are not significant in macrorelays due to the difference in size.

The author tested several switches under both hot and cold switching conditions to investigate the difference between the damage to a typical hot switched contact and a cold switched one. Cold switching damage is usually caused by mechanical wear and frictional polymer formation on the surface of the contact. For softer metals (e.g. Au), contacts can even weld together and fail to open as discussed earlier. On testing several contacts, it was observed that while under cold switching conditions, the Ruthenium contacts were able to easily withstand power levels of up to 6 W, under hot switching conditions, a hot switching voltage of 3.5 V (corresponding to 0.25 W) followed by an on-state power level of 0.3 W. For a most tests discussed in this section, the voltage levels used are 3.5 V hot switching and 3.9 V on-state with a 50 Ω resistance (corresponding to 77.5 mA on-state current). An on-state power level of 0.3 W also matches well with typical voltages that contacts are subjected to in switching matrices and other applications [67]. For most tests, the external current limiting resistor was fixed at 50 Ω. The applied force on the contacts was approximately 400 µN. Being able to conduct tests where the contacts last up to 1,000,000 cycles enables us to monitor the damage progressively. There
have, however, been, a large number of tests which were done under conditions different from those mentioned above and for the discussion on those tests, the conditions will be mentioned separately.

As seen in Figure 3.2, for pure mechanical switching, test results show very little contact damage. For pure cold switching, test results show more contact damage as compared to mechanical switching. The damage done to the contacts does not have clear polarity dependence. The hot switching tests show a much larger amount of contact damage while also exhibiting a clear polarity dependence of material transfer in the direction of the electric field, from anode to cathode. The volume calculations for each hot switching electrode are shown at the bottom of the corresponding micrograph. In both hot switching tests the measurements of material missing from the anode and added to the cathode are approximately equal. Furthermore, the amount of material transferred for the two polarities is approximately equal. Both of these results are typical and serve as a validation of the volume calculation method; conservation of mass is observed from one electrode to the other in a given test.
Figure 3.2 – Contact damage for various types of switching cycled at 500 Hz for $5 \times 10^7$ cycles: a) Mechanical switching – contact bump, b) Mechanical switching – Pillar, c) Cold switching with 77.5 mA on-state current – contact bump as anode, d) Cold switching with 77.5 mA on-state current – Pillar as cathode, e) Cold switching with 77.5 mA on-state current – contact bump as cathode, f) Cold switching with 77.5 mA on-state current – Pillar as anode, g) Hot switching with 3.53 V hot switching voltage and 77.5 mA on-state current – contact bump as anode, h) Hot switching with 3.53 V hot switching voltage and 77.5 mA on-state current – Pillar as cathode, h) Hot switching with 3.53 V hot switching voltage and 77.5 mA on-state current – contact bump as cathode, i) Hot switching with 3.53 hot switching voltage and 77.5 mA on-state current – Pillar as anode
Although cold switching has lower physical damage than hot switching, the contact resistance associated with cold switching is usually high as shown in Figure 3.3. One explanation for this is that hot switching leads to contacts melting and welding leading to greater contact area and better conduction.

![Contact resistance of four different contacts under hot and cold switching](image)

**Figure 3.3 – Contact resistance of four different contacts under hot and cold switching**

Based on the tests in Figure 3.2, it is clear that there are damage mechanisms associated with mechanical switching, additional damage mechanisms associated with cold switching, and even more additional damage mechanisms associated with hot switching. Results similar to these have been reported before [30,39,41] and these tests serve as a baseline for investigating the contact damage reported and discussed in the rest of this chapter. It is also pertinent to note that, as seen by comparing Figure 3.2 (f) to (g) and Figure 3.2 (h) to (i), one can observe the conformity of the contacts. The pit formed in the anode is almost the same shape and size as the mound formed on the cathode.
3.3. Hot switching damage variation for various hot switching voltages

To understand hot switching mechanisms, tests were conducted for both leading and trailing edge hot switching with the contact bump as both anode and cathode, under hot switching voltages ranging from 0.5 V all the way up to 5.0 V. The picture emerging from these tests showed the complexity of hot switching contact damage as discussed in section 3.1. The images in Figure 3.4 – 3.7 are representative of the qualitative contact damage under these conditions.
Figure 3.4 – Leading edge hot switching voltage dependent contact damage with contact bump as anode and switch is cycled at 500 Hz – a) Leading edge hot switching voltage of 0.25 V and on-state current of 77.5 mA, b) Leading edge hot switching voltage of 0.5 V and on-state current of 77.5 mA, c) Leading edge hot switching voltage of 0.5 V and on-state current of 77.5 mA, d) Leading edge hot switching voltage of 1.0 V and on-state current of 77.5 mA, e) Leading edge hot switching voltage of 1.0 V and on-state current of 77.5 mA, f) Leading edge hot switching voltage of 2.0 V and on-state current of 77.5 mA, g) Leading edge hot switching voltage of 2.0 V and on-state current of 77.5 mA, h) Leading edge hot switching voltage of 2.5 V and on-state current of 77.5 mA, i) Leading edge hot switching voltage of 3.5 V and on-state current of 77.5 mA
In Figure 3.4, different types of leading edge hot switching contact damage at several voltages are shown when the contact is the anode. It should be noted that even 0.25 V of hot switching voltage can cause much greater contact damage than pure cold switching or 0 V of hot switching voltage. At 0.5 V, there seems to be contact damage that is much more severe than either 0.25 V or 1.0 V. This could possibly point to contact damage related to the softening voltage of Ru which is around 0.4 V. At 1.0 V and 2.0 V, the contact damage is typically related to material transfer, although there is no clear trend to which direction the material gets transferred.

Similar tests, comparing leading edge hot switching contact damage at different voltages, were also conducted with the contact bump being the cathode. Figure 3.5 represents these tests.
Figure 3.5 – Leading edge hot switching voltage dependent contact damage with contact bump as cathode and switch is cycled at 500 Hz – a) Leading edge hot switching voltage of 0.25 V and on-state current of 77.5 mA, b) Leading edge hot switching voltage of 0.5 V and on-state current of 77.5 mA, c) Leading edge hot switching voltage of 1.0 V and on-state current of 77.5 mA, d) Leading edge hot switching voltage of 1.0 V and on-state current of 77.5 mA, e) Leading edge hot switching voltage of 1.5 V and on-state current of 77.5 mA, f) Leading edge hot switching voltage of 3.5 V and on-state current of 77.5 mA

As seen in the figure above, some of the trends when contact bump is the cathode are similar to what is observed when it is the anode. Once again, 0.25 V leads to some amount of contact damage while at 0.5 V, the contact damage is much more significant. The damage at 1.0 V is slightly less than that at 0.5 V although there is no clear polarity dependence on the direction of transfer of material.

Similar tests with the contact bump as anode and cathode were also performed for trailing edge hot switching as shown in Figures 3.6 and 3.7. Again, at 0.5 V, material seems to be scattered all over the contact bump indicating that a similar damage mechanism is present for both leading and trailing edge at this voltage. At 2.0 V, with contact bump as anode, material transfer is observed both towards and away from the contact bump. At 3.0 V and above, material transfer is polarity dependent and from anode to cathode. More tests to confirm this observation have been performed and described in this thesis, particularly at 3.5 V of hot switching voltage.
Figure 3.6 – Trailing edge hot switching voltage dependent contact damage with contact bump as anode and switch is cycled at 500 Hz – a) Trailing edge hot switching voltage of 0.5 V and on-state current of 77.5 mA, b) Trailing edge hot switching voltage of 1.0 V and on-state current of 77.5 mA, c) Trailing edge hot switching voltage of 1.0 V and on-state current of 77.5 mA, d) Trailing edge hot switching voltage of 2.0 V and on-state current of 77.5 mA, e) Trailing edge hot switching voltage of 2.0 V and on-state current of 77.5 mA, f) Trailing edge hot switching voltage of 3.0 V and on-state current of 77.5 mA

Figure 3.7 – Trailing edge hot switching voltage dependent contact damage with contact bump as cathode and switch is cycled at 500 Hz – a) Trailing edge hot switching voltage of 0.5 V and on-state current of 77.5 mA, b) Trailing edge hot switching voltage of 0.5 V and on-state current of 77.5 mA, c) Trailing edge hot switching voltage of 5.0 V and on-state current of 77.5 mA

From the images in Figure 3.4-3.7, one can make several conclusions regarding the effect of hot switching voltage on the nature of the contact damage in MEMS switches. It is evident
that at a hot switching voltage of 0.5 V, there is significant damage to the contact irrespective of the polarity or whether hot switching occurs at the leading or trailing edge of a cycle. At a voltage of 0.25 V, the damage to a contact is much less, but larger than for cold switching (0V) and above 0.5 V again it reduces. One explanation of this enormous damage particularly at 0.5 V is that the softening voltage of Ru is around 0.4 V. Thus, this softening can lead to the material around the contact spot getting deformed and then displaced and scattered. From 1.0 V to around 2.5 V, the contact damage is independent of polarity and can lead to material transfer both away and on to the anode. This points to a mechanism that is random and it is entirely possible that if material transfer occurs in a particular direction within the first few cycles, then this mechanism tends to force the material transfer to persist in that same direction. It is also possible that for these low voltages, we in fact observe material transfer in both directions but for a given test, we end up getting more material transfer in one direction as opposed to the other which is more of a statistical phenomenon and not indicative of how this mechanism operates. Above 2.5 V, we always see material transfer strictly in the direction of conventional current.

When contact erosion became significant (3.5 V hot switching voltage), failure in the switch was caused by high contact resistance after about 1 million cycles or so. High contact resistance was due to absence of Ru on one of the electrodes which resulted in a Ru to Si contact. Prior to reaching high resistance, the contact would start showing signs of failure by making intermittent contact. Eventually, the contact resistance would rise permanently to a value or greater than 5000 $\Omega$. It should also be noted that when the contact bump is the cathode and the pillar is the anode, the switch would typically last much longer since contact erosion takes place from the pillar which has 300 nm of Au below the 600 nm of Ru resulting in contact lifetime being increased.
3.4. Leading and trailing edge hot switching – similarity and difference

To compare leading edge hot switching with trailing edge hot switching for the case of material transfer in the direction of current flow, two sets of tests were performed to explore the progression of contact damage with cycling: one set with the contact bump as the anode, and another set with the contact bump as the cathode. Each set of six tests comprises three leading edge hot switching tests terminated after $10^4$, $10^5$, and $10^6$ cycles, respectively, and three trailing edge hot switching tests terminated at the same intervals. Figures 3.8 and 3.9 represent the micrographs of the contacts after they have been tested Figure 3.8 and is a set of seven tests in which the contact bump was the anode, and Figure 3.9 shows a set of seven tests in which the contact bump was the cathode. All of the contacts were cycled at 500 Hz with a 50 Ω series resistor, 3.5 V hot switching voltage, and an on-state current $I = 77.5$ mA.
Figure 3.8 – Leading edge vs trailing edge hot switching progression tests cycled at 500 Hz, 3.54 V hot switching voltage, and 77.5 mA on-state current with contact bump as anode – Note that (e) and (g) represents two different types of damage observed for leading edge hot switching under identical conditions.
Figure 3.9 – Leading edge vs trailing edge hot switching progression tests cycled at 500 Hz, 3.54V hot switching voltage, and on state current of 77.5mA with contact bump as cathode – Note that (e) and (g) represents two different types of damage observed for leading edge hot switching under identical conditions.

Qualitatively, for both leading and trailing edge hot switching tests the damage area grows with cycling and material transfer is from anode to cathode. Figure 3.10 is a plot of the measured volume transfer as a function of the number of switching cycles. Each point on the plot represents the average of the volume calculations from at least three separate tests.
Quantitatively, this plot provides a few interesting results. First, the amount of volume transferred due to leading edge hot switching is roughly equal to that due to trailing edge hot switching under these conditions. Second, the rate of material transfer decreases somewhat as the number of cycles increases. Third, the amount of material transfer averages about 500 nm$^3$/cycle for the first $10^6$ cycles for both leading and trailing edge hot switching. This result indicates that the material transfer mechanisms change only modestly as the contact surfaces are damaged and reshaped with cycling. Also, there is a significant amount of variation in the amount of material transferred from test to test for a given set of test conditions, as indicated by the error bars.

**Figure 3.10** – Volume analysis for leading edge vs trailing edge hot switching progression tests; each point represents the average of at least three separate tests. The error bars represent the maximum and minimum volume measurement for each condition. Error bars with long rounded caps correspond to trailing edge tests and error bars with square caps correspond to leading edge tests.
Figures 3.8, 3.9 and 3.10 suggest that there could be similarities between the material transfer mechanisms on the leading edge and on the trailing edge. However, it should be noted that the damage mechanisms on the leading and trailing edges are probably not exactly necessarily the same. Evidence of this can be found when comparing the qualitative damage of leading edge tests to trailing edge tests. Generally, trailing edge contact damage was smoother than leading edge contact damage. This is readily apparent when comparing Fig 3.8(e) to 3.8(f) and Fig 3.9(e) to 3.9(f). However, by comparing 3.8(e) to 3.8(g) and 3.9(e) to 3.9(g), we observe that leading edge hot switching damage itself is not always qualitatively consistent. Sometimes the damage area has a lot of scattered debris while at other times it is relatively smoother.

Leading and trailing edge hot switching damage were found to be quantitatively different under a different set of conditions. Contacts were tested with a high external impedance leading to low steady state current tests were carried out under identical conditions for both leading and trailing edge hot switching. With an external impedance of 5 kΩ and voltage of 3.5 V, contacts were cycles for $10^6$ cycles with leading and trailing edge hot switching. The results, represented in Figure 3.11 below, showed that leading edge hot switching caused more damage than trailing edge. For all these tests again, the DAQ channel measuring contact voltage was removed so that when the contacts are open, the voltage across the contact is 3.5 V.
Figure 3.11 – Comparison of contact damage at 3.5 V and 5kΩ external resistance between leading and trailing edge hot switching after $10^6$ cycles.

From Figure 3.11, it can be concluded that limiting the current through the contact leads to reduced contact damage in the case of trailing edge hot switching. Furthermore, in 3.11c), we observe material transfer from cathode to anode which indicates a mechanism that can behave opposite to the most commonly observed anode to cathode material transfer mechanism. This is a strong indication of different mechanisms operating for the leading and trailing edge hot switching.
3.5. Current variation tests

Tests investigating the role of hot switching voltage and the on-state current were performed on 12 contacts. Contacts were cycled at a hot switching potential of 3.54 V while varying the on state current from 0.78 mA to 387 mA using series resistors of 5k Ω, 50 Ω, and 10 Ω. Again, these contacts were cycled at 500 Hz for $5 \times 10^5$ cycles. All of the contacts presented in Figure 3.12 show polarity dependence of material transfer from the anode to the cathode. Quantitatively, there does not seem to be a strong relationship between the on-state current and material transfer in these contacts for either polarity.
Figure 3.12 – Contacts cycled at 500 Hz for $5 \times 10^7$ cycles – a) 3.5 V hot switching voltage and 3.9 on-state voltage with 5 kΩ external resistance and contact bump as anode, b) 3.5 V hot switching voltage and 3.9 on-state voltage with 5 kΩ external resistance and contact bump as cathode, c) 3.5 V hot switching voltage and 3.9 on-state voltage with 50 Ω external resistance and contact bump as anode, d) 3.5 V hot switching voltage and 3.9 on-state voltage with 50 Ω external resistance and contact bump as cathode, e) 3.5 V hot switching voltage and 3.9 on-state voltage with 10 Ω external resistance and contact bump as anode, f) 3.5 V hot switching voltage and 3.9 on-state voltage with 10 Ω external resistance and contact bump as cathode

The tests presented in Figure 3.12 suggest that for a hot switching voltage of 3.5 V, the contact damage is independent of the current in the circuit when the switch is closed. More tests were conducted to understand the effect of different external resistances on leading edge hot switching and to investigate possible mechanisms. These will be discussed subsequently in section 4.4. It is likely that the mechanism in question is associated with low current and occurs
at the point of initial contact when the contact voltage is high enough to cause melting and even boiling of the material.

3.6. High power cold switching

Another significant reliability issue for MEMS switches is its power handling capabilities. Some early work conducted for this thesis attempted to study the evolution of the MEMS contact over the course of its lifetime purely under high power cold switched conditions. Several tests for low to moderately high power operations were performed that suggested that at higher power the contact resistance tends to be lower.

![Figure 3.13 – Contact resistance vs cycles for moderate to high power](image)

The data shown in Figure 3.13 were taken in an early part of the author’s work. The data suggests that, in general, increasing current through the contact results in lower resistance. The resistance of the contact also initially tends to decrease with more cycling before going back up again. Such behavior has been observed in MEMS contacts [17]. A possible explanation for this
is the presence of insulating films on the contact surfaces initially. The film gets removed after
tens of thousands of cycles. Later on, formation of frictional polymer on the surface of the
contact causes the resistance to rise again [28].

While it would have been interesting to test the power handling capabilities of the
contacts at higher powers than 5W, the limitations of the test system did not allow those tests to
be conducted. Because of a high current passing through the contacts, the structure would
thermally expand and bend causing the laser point to shift thereby providing incorrect values for
the contact force. In fact, beyond 5W, the structure would bend enough for the contact force to
appear below zero.

3.7. Adhesion

An important cause of failure reported for hot switched microcontacts is failure to open as a
result of adhesion. In Au coated switches in particular, adhesion was observed even with cold
switching. In [21,22,31] failure to open was reported as one of the primary reliability issue. For
hot switching, when the electrodes initially come into contact, the high temperature associated
with the contact voltage may cause contacts to weld together with increase in contact area. While
coming apart, the welding can lead to high adhesion force.

The adhesion force can increase with increasing number of cycles since, with more
cycling, asperities will flatten out leading to more contact area. Material transfer might also lead
to more contact area and result in higher adhesion. This is because the sidewalls of the pits and
mounds, formed as a result of material transfer, could add to the area of contact.
In this work, the Ru contacts tested were found to exhibit very little adhesion force however. While initially trailing edge hot switching was thought to exhibit higher adhesion than leading edge hot switching, it was later concluded that at the trailing edge, as the contacts begin to open, the heat generated causes the structure to bend downwards leading to the appearance of adhesion. For leading edge hot switching where heating and false adhesion was absent, the observed adhesion was usually between 10 – 15 µN. At most up to 40 – 50 µN of adhesion was observed. However, adhesion never led to complete failure of the contact. The contacts never stuck closed and even if a real microswitch with reasonable pull-off force is considered, the observed adhesion would not lead to contacts being stuck closed. Figure 3.14 below shows the highest adhesion force observed due to leading edge hot switching for Ru contacts.

![Figure 3.14 – Highest adhesion observed for leading edge hot switching](image)
Chapter 4 - Study of mechanisms for hot switching material transfer

4.1. Observation and investigation of pre-contact current

In [39,40], a group from CEA, France reported for the first time the presence of small currents of a fraction of a µA just before the contacts closed completely. The hot switching voltage that was applied across the contacts was 5 V. They attributed these currents to Fowler Nordheim tunneling.

For monitoring transient currents at the time of contact closing, a transimpedance amplifier was used. A cycling frequency of 1 Hz which corresponds to a contact approach rate of 8.8 µm/s was chosen to enable detailed monitoring of the transient currents. Of particular interest in microcontacts is the presence of a small current before the contacts have closed completely, while the contact voltage is still large.

The results shown in Figure 4.1 correspond to transient currents observed at hot switching voltages of 1 V, 3 V, 5 V and 10 V respectively as the contacts are brought together. The data presented in Figure 4.1 were acquired by cycling the same contact at various hot switching voltages. It should be noted that the measured current is different at each cycle, and the results below reflect reasonably typical behavior, but also the variation of the currents from cycle to cycle. The transimpedance amplifier limited the maximum current to 7µA.
Figure 4.1 shows that even at a hot switching voltage of 1 V, a transient current is still present. For Fowler Nordheim tunneling into the vacuum (or N₂), the applied voltage has to be greater than the work function of the metal. The work function of clean Ruthenium is 4.7 eV. If a ruthenium oxide layer is present, as a result of the oxygen plasma process that the samples are made to undergo before testing, the work function will increase to that of ruthenium oxide, at 5.1 eV. The material transfer process, though, may disrupt the ruthenium oxide layer after thousands of cycles of hot switching. Other contaminants may also appear on the contact surfaces. In any event, the presence of current both below and above the work function seems to suggest that both Fowler Nordheim tunneling (for voltages greater than about 5 V) and direct tunneling of electrons (for voltages less than about 5 V) may contribute to the observed transient currents.

Beyond this observation, direct tunneling between two Ru surfaces should vary by several orders of magnitude as the separation is decreased by even 1 nm, meaning that the
current measurements in Figure 4.1 appear to be inconsistent with tunneling theory [68,69]. Tunneling theory has been discussed in further detail in Section 4.2. One possible explanation is that the contact pair makes physical contact through a contamination layer which conducts poorly until the force increases sufficiently. A second explanation is that we are observing a material transfer process in action, and this is changing the separation during the measurement.

In the course of the investigation of the pre-contact currents, it was found that perhaps they had very little role to play in material transfer or hot switching contact damage. It was observed, that if a clean Ru contact, freshly deposited with, was tested within 1 day of the sputter deposition process, then the pre-contact current disappears. The test is conducted after the contact is treated with oxygen plasma. If the same contact was left in the AFM test bench overnight, then the following day, the current starts to appear again. Figure 4.2 shows two graphs of corresponding to a ‘dirty’ and a ‘clean’ contact. The graphs shown correspond to the same contact except that for the ‘dirty’ case, the contact was left in the AFM overnight.

![Figure 4.2 – Pre-contact current in a) Dirty contact tested 2 days after deposition of contact material, b) Clean contact tested immediately after deposition of contact material](image)

It should be noted here that material transfer observed at a hot switching voltage of 3.5 V takes place in Ru contacts irrespective of how many days have passed between when the Ru is sputtered on the test structures and when the contacts are tested. The fact that the absence of the
pre-contact current does not lead to absence of material transfer proves indicates that the pre-
contact current may not be responsible for material transfer.

Also, if the pre-contact current is related to material transfer, then such material transfer
should be observed if one is able to sustain the current without allowing the contacts to close. In
order to replicate this scenario, several tests were conducted on contacts such that the pillar was
allowed to approach the contact slowly until approximately 1 µA of current was observed. The
approach rate of the contacts was set at 2.2 nm/s. The moment there was current in the order of
hundreds of nA or a couple of µA observed, the piezoactuator was paused and the contacts were
held at a constant separation. The current was very unstable, typically varying from nearly zero
to several µA. Although there was some amount of drift in the AFM piezo which would often
cause the contacts not stay at a constant separation for a long time, the author was fairly
successful in sustaining the pre-contact current for 4-5 seconds. If the AFM piezo caused the
contacts to close or to drift away (so as to make the current disappear), the drift would be
compensated for. Figure 4.3 is a representation of the sustained pre-contact current.

Figure 4.3 – Pre-contact current allowed to sustain without making the contacts close (figure zoomed in on a typical region)
After sustaining the current for around 40 minutes, the contacts were inspected under an SEM. For all 3 contacts tested in this manner, there was no significant damage observed. Figure 4.4 gives two examples of contacts that were tested under these conditions and were completely undamaged.

![Contacts undamaged from the sustained pre-contact current](image)

This current is probably due to the electrodes making actual physical contact through a thin layer of contamination which then results in tunneling through that insulating layer. The insulating layer here is probably made out of carbonaceous compounds from atmosphere adsorbed by the contact surface when the contact is kept in the AFM for more than two days.

4.2. **Analysis of the role of field emission and field evaporation in material transfer**

Various groups have suggested field emission and field evaporation as the possible mechanisms behind material transfer [39,40,64,41]. While conclusive evidence of the role of either theory is yet to be established, it is important to study both these theories more closely in order to speculate the role of each in material transfer.

The authors in [39] suggest that the electric field between the contacts results in Fowler
Nordheim tunneling from the cathode to the anode thereby releasing a large amount of energy on to the anode causing the anode material to evaporate and deposit on the cathode. As described above in section 4.1, these tests were repeated by our group at 5 V as well. The observed pre-contact current was found not to have a direct correlation with material transfer.

For Ru, the work function is 4.7 eV. Therefore, Fowler Nordheim tunneling is unable to explain the material transfer at 3.5 V of hot switching voltage as observed in this work. If field emission is to be significant at this voltage, the mechanism in question has to be direct tunneling. Under this scenario, the separation between the contacts has to be small enough to allow direct tunneling. As described below, this implies that the asperities must be separated by less than 0.5 nm for significant tunneling currents to flow. Under such circumstances, the picture of direct tunneling leading to material transfer will look somewhat as shown in Figure 4.5, with the gap predicted to be on the order of 0.1-0.2 nm, or just 1 to 3 times the size of a Ru atom.

![Diagram](image-url)

**Figure 4.5 – Proposed mechanism of direct tunneling leading to polarity dependent material transfer: Direct tunneling between highest tip of the asperities followed by evaporation of contact material resulting from the high local temperature.**
It is necessary to understand direct tunneling and field emission in detail in order to get an idea of the amount of current one can expect due to these effects. Tunneling can occur primarily across two different kinds of barriers – square and triangular. A perfectly square barrier can only lead to direct tunneling of electrons from cathode to anode at small enough separations. In a triangular barrier, however, we can get both Fowler Nordheim and direct tunneling depending on the applied potential difference between the electrodes. Figure 4.6 shows the rough schematic for both Fowler Nordheim and direct tunneling.

![Figure 4.6 – Fowler Nordheim and Direct tunneling mechanisms for tunneling of electrons from cathode to anode – a) Tunneling from cathode to anode due to trapezoidal barrier, b) Tunneling from cathode to vacuum due to triangular barrier](image)

\[
J_{FN} = \frac{q^3E^2}{16\pi^2(h/2\pi)\Phi} \exp\left(-\frac{4\sqrt{2m^*\Phi^{3/2}}}{3(h/2\pi)qE}\right)
\]

\[
J_{DT} = AE^2 \exp\left(-\frac{B[1 - (1 - \frac{V}{\Phi})^{3/2}]}{E}\right)
\]

In the above 2 equations, \( J_{FN} \) and \( J_{DT} \) refer to the current density due to Fowler Nordheim and direct tunneling, respectively.
emission (due to square barrier) and direct tunneling (due to triangular barrier) respectively. $E$ is the electric field, $m^*$ is the effective mass of the electrons, $\Phi$ is the work function, $h$ is Planck’s constant, $V$ is the voltage between the electrodes while $A$ and $B$ are constants that are related to charge in an electron, work function, effective mass of an electron and Planck’s constant [68,70].

Using these equations, and assuming different contact area for ballistic transportation of electrons, one can estimate the order of the magnitude of current that can theoretically be present.

![Figure 4.7 – Tunneling current as a function of contact separation for a) Square barrier and b) Triangular barrier](image)

It is evident from Figure 4.7 current of a few $\mu$A can be achieved with tunneling in both square and triangular barriers when the contact area is from 1 to 10 nm$^2$. It is theoretically possible to achieve approximately 2 $\mu$A of current with direct tunneling through a square potential barrier at a separation of 4 Å and to achieve about 1 $\mu$A current with direct tunneling through a triangular barrier at a separation of 3 Å between the contacts. At a rate of 4400 $\mu$m/s, the time required to close a separation of 3 Å is about 69 ns. Assuming 1 $\mu$A current, the number of electrons required to achieve this current flow in 50 ns is $3.125 \times 10^5$. If each electron has 3.5 eV of energy, the total available energy would be $3.5 \times 1.6 \times 10^{-19} \times 3.125 \times 10^5 = 1.75 \times 10^{-13}$ J of energy. Considering the following thermal properties of Ru as shown in Table 3, the amount of energy required to evaporate 500 nm$^3$ of Ru can be evaluated.
Specific heat | 0.024 kJ/mole-K  
Melting temperature | 2607 K  
Specific heat of fusion | 23.7 kJ/mole  
Boiling temperature | 4423 K  
Specific heat of evaporation | 567 kJ/mole

Table 3: Thermal properties of Ruthenium

From these values, it was found that $5.72 \times 10^{-14}$ J of energy is needed to evaporate 500 nm$^3$ of Ru. Thus the energy available from emission is enough to cause this evaporation. In [63], however, it was shown that if the emission is modeled as a heat flux, and if heat conduction away from the hottest point of the contact is taken into account, the net power available from the emission be sufficient to lead to evaporation if a flux radius of 1 nm is concerned. That would, however, require a current of around 1 mA. However, the non-idealities of the system are difficult to accurately model and some amount of evaporation may still be happening even if the amount evaporated is less than 500 nm$^3$.

The phenomenon of Field evaporation, shown in Figure 4.8, leading to material transfer has been used to advantage by several groups to deposit patterns and fabricate nanoscale devices. [71,72,73,74] shows different instances of field deposition being used. Although, such a phenomenon could well give rise to some material transfer for our microcontacts, there are two pieces of evidence which go against it. Field evaporation also seems unlikely to be prominent at large separations for these contacts. The minimum threshold electric field required for field
evaporation in Ru is 42 V/nm. This would imply about 0.08 nm separation between the contacts in order to get field evaporation when the voltage between the contacts is 3.5 V, assuming no field enhancement. However, the presence of a sharp asperity on one surface can lead to some amount of field enhancement which might make it possible to get field evaporation at lower electric fields. It should be noted at the same time, that at really small separations, such enhancement becomes less and less unlikely.

Figure 4.8 – Field evaporation between contacts with small separation: Positive Ru ions are pulled from anode on to the cathode leading to material transfer.

![Diagram](image)

It is interesting to note, that for an average material transfer of 500 nm³ to take place because of field evaporation, the corresponding current associated with such transfer can be calculated using the atomic weight and density of Ru. Given that the atomic weight of Ruthenium is 175 and its density is 12.45 g/cm³, it would require about 22000 ions to be pulled out per cycle on average in order to get the kind of material transfer observed. This many ions correspond to only 1.4 nA of current for 5 µs [75,76].

At a small separation between the contacts, the threshold voltage required for field evaporation can be reduced [77]. This can be explained as follows. When the contacts are far apart, the binding energy of an atom required to remove it from the surface of a contact electrode
is large. Also, the energies associated with atom-anode and atom-cathode interaction as a function of distance from the surface of an electrode do not overlap as shown in Figure 4.9.

![Figure 4.9](image)

Figure 4.9 – Atom-anode and atom-cathode interactions as a function of distance. The two interaction profiles do not overlap [77].

However, as the separation becomes smaller, these two interaction profiles start overlapping which leads to a double-well structure. This results in a reduction of the binding energy that an atom needs to overcome in order to move from one electrode to another. This can be thought of as the field evaporation equivalent of direct tunneling in electrons where a small contact separation can lead to electrons tunneling even at very low potentials. Figure 4.10 shows this phenomenon.

![Figure 4.10](image)

Figure 4.10 – At small separations, the two interaction profiles to overlap. The sum of the two profiles has a double-well structure with a small activation barrier [77].
4.3. Polarity independent material transfer - bipolar hot switching tests

In Figure 4.11, material transfer is shown for the contact bump positive (anode), the contact bump negative (cathode) and the contact bump alternating between cathode and anode on each switching cycle (bipolar). Tests were conducted for both leading and trailing edge hot switching. As shown here, we find that the material transfer is always from anode to cathode for unipolar hot switching [66]. For bipolar hot switching the material transfer in the two directions nearly cancels, resulting in far less net material transfer for the same number of cycles.

Note that ‘HS’ refers to hot switching. For all figures, ‘Anode’ refers to the contact bump being the positive end of the electrode, and ‘Cathode’ refers to the contact bump being the negative end of the electrode, while ‘Bipolar’ refers to the contact bump changing its polarity each cycle i.e. one cycle of ‘Anode’ followed by one cycle of ‘Cathode’.
Subsequently, much longer tests were conducted with bipolar hot switching to see if a smaller net transfer of material would occur despite the near cancellation because of the bipolar testing. Two tests were conducted up to $40 \times 10^6$ cycles (one each for leading and trailing edge) while one test lasting to $1.2 \times 10^8$ cycles was performed and the contacts examined. Over the course of the test it was noted that the contact resistance remained fairly low, showing that despite the material transfer, the contacts were still able to sustain their performance. Figure 4.12 shows the images of the contacts after the tests were concluded, while Figure 4.13 shows the electrical resistance of the contact over the course of the test that lasted 120 million cycles. The corresponding image of the contact is shown in Figure 4.12(c).
As shown in Figure 4.11, the net amount of material transfer in the bipolar case is much less than for dc hot switching. This is not surprising since it is expected that material will
transfer from the anode to the cathode, which for the bipolar case means that material will transfer back and forth between the two electrodes. It has earlier been discussed in Chapter 3 that the magnitude of material transfer was approximately independent of polarity of the force sensor and pillar, implying that the amount of material transferred in the two directions will be nearly equal.

Also shown in Figure 4.12 is that there is a net transfer of material in the bipolar case, from the force sensor to the pillar. The observation that the volume of material transferred is independent of the polarity of the force sensor and pillar might seem to imply that a mechanism, different from the one responsible for the anode to cathode transfer of material, exists in the bipolar case. On the other hand, the net transfer is small, so it could be a result of small differences between the operations of the mechanism in the two directions. It is also possible that any melted or evaporated asperity on either of the contacts might have a bias toward transferring material to the cooler side, resulting in material transfer from bump to pillar as observed in the bipolar experiments.

4.4. Hot switching damage at low current

If there is a critical value of current responsible for hot switching contact damage, then ideally this damage can be reduced or ultimately completely eliminated if the current is limited to a small value. However, while for trailing edge hot switching this may be true, at the leading edge, the inherent capacitance of the system will limit how much we can reduce the current at a given voltage. This is true whether the switch is part of a transmission line or a lumped element in a circuit, or a test chip as in this work. At initial contact, the presence of such capacitance can
cause release of energy in the form of a current overshoot. In our test setup, a first order model considering the SiO₂ isolation layer between the device and handle sides of the chip predicts a capacitance of approximately 35 pF. In order to analyze the effect of this added capacitance, a SPICE model was used. With a switching frequency of 500 Hz, data showed the contact resistance dropping from infinity to around 1 ohm within 10 µs. Simulating a switch with behavior similar to a Ru-Ru contact in our test setup, the final SPICE model was set up as shown in Fig 4.14.

Figure 4.14 – SPICE model of the equivalent circuit for the test setup considering the capacitance in the chip

R3 shown above is the external in series resistor that was varied in order to analyze its effect on circuit response. Using various values for this resistance, the following results were found about the transient response in the circuit at the moment of contact.
Figure 4.15 – Transient current response for an external resistance of a) 50 \( \Omega \), b) 500 \( \Omega \), c) 5 k\( \Omega \), d) 20 k\( \Omega \), e) 1 Meg\( \Omega \) and f) 10 Meg\( \Omega \). Note that for 1 and 10 Meg\( \Omega \) the second current spike is smaller than the first since the capacitance cannot charge up to its full value when RC constant becomes higher.

As shown in Figure 4.15, it was concluded from the SPICE model that a current overshoot was not significant for an external in-series resistance of 1 k\( \Omega \) and below with an applied voltage of 3.5 V. From 10 k\( \Omega \) or so, a current overshoot was observed which became extremely significant (with respect to steady state current) at 100 k\( \Omega \) and even up to 1 Meg\( \Omega \). Beyond that, for higher resistances of 10 Meg\( \Omega \) and above, only on the first cycle was a current
overshoot observed. From the second cycle onwards, the capacitance did not get enough time to charge up so that it can discharge when the contacts come together. The current overshoot for 1 MegΩ could reach up to 125 µA which means if contact damage is caused by a current less than that value, the mechanism would not be prevented by having a large resistance.

In a 50 Ω transmission line, however, from the simulation it is evident that the capacitance does not have any significant effect and does not lead to any large current spike. Therefore, typically, the capacitance does not have a role to play in the observed contact damage.

Experimentally, several tests were performed with external resistances of widely different values from 50 Ω to 1 GigΩ. One important aspect of testing with external resistances that are of high values (in the kΩ range and above), was that the effective resistance of the DAQ channel measuring the contact voltage became comparable to the external resistance. This results in a lower off-state hot switching voltage appearing across the contact and a higher voltage appearing across the external resistance. The effective resistance of the DAQ channel is around 50 kΩ and is a result of a tiny current being injected through the channel capacitance for measuring the voltage. In order to ensure that the DAQ does not have an effect on the hot switching voltage across the contact, the contact voltage was not measured when high resistance tests were performed. In Figure 4.16, the images corresponding to contact damage at different values of external resistance has been shown. It is clear that up to a resistance of 1 MegΩ, the contact damage is significant. This correlates well with the simulation which predicts a current spike up to an external resistance value of 1 MegΩ. The micrographs also suggest that the current that causes contact damage is probably within 0.15 – 0.2 mA but not too low since 10 MegΩ does not lead to much damage at all.
Figure 4.16 – Contact damage with 3.5 V hot switching voltage after $10^6$ cycles for leading edge hot switched tests with different external resistances: a) Leading edge hot switching with 3.5 V hot switching voltage, 3.9 V on state voltage, 50 Ω external resistance and contact bump as anode, b) Leading edge hot switching with 3.5 V hot switching voltage, 3.9 V on state voltage, 500 Ω external resistance and contact bump as anode, c) Leading edge hot switching with 3.5 V hot switching voltage, 3.9 V on state voltage, 5k Ω external resistance and contact bump as anode, d) Leading edge hot switching with 3.5 V hot switching voltage, 3.9 V on state voltage, 20 k Ω external resistance and contact bump as anode, e) Leading edge hot switching with 3.5 V hot switching voltage, 3.9 V on state voltage, 1 Meg Ω external resistance and contact bump as anode, f) Leading edge hot switching with 3.5 V hot switching voltage, 3.9 V on state voltage, 10 Meg Ω external resistance and contact bump as anode.

Figure 4.16 shows the contact damage with different external resistances. The observed trend suggests that it is possible that the contact damage may be related to the capacitance in the
system for high impedance tests. It also indicates that the magnitude of current associated with this damage is in the order of 100 µA or so given that a 1 MegaΩ resistance shows significant damage as well. For extremely high R such as 10 MegaΩ, the capacitance does not charge up to allow current flow when contact occurs. For external resistances less than, however, 20 kΩ, the capacitance does not have a significant role to play. In most RF circuits, considering a characteristic impedance of 50 Ω, the capacitance should not have an effect on the contact damage.

4.5. Slow approach and separation of contacts

Tests were performed to study the effect of slow approach and separation of contacts at a hot switching voltage of 3.5 V and 5 V. The tests were run for about 40-45 minutes at an approach/separation rate of 8.8 nm/s. For these tests, the actuation voltage applied to the piezo-actuator was ramped up from 0 to 50 V in 125s. Voltage was applied separately with a source measure unit. Figures 4.17 – 4.19 show the results that emerged from these tests.

Figure 4.17 – Leading edge hot switching tests at 3.5 V hot switching voltage, 50 Ω resistor, with contacts approached at 8.8 nm/s: a) Contact bump is anode, b) Contact bump is cathode

Figure 4.17 represents tests where a hot switching voltage was applied only at the leading edge. Here, the hot switching voltage applied is 3.5 V with an external resistance of 50 Ω. With
an approach rate of 8.8 nm/s, 40 – 50 switching cycles were performed. On examining the contacts after cycling, no observable damage to these contacts was detected either for the case where the contact bump was the anode, or when it was the cathode. By reducing the ramping rate by a factor of 500,000, effectively the contacts spend time in close proximity for an amount of time that is increased by the same factor. Thus, the damage from 40 – 50 cycles should be equivalent to 20,000,000 cycles at the normal switching speed (when ramp rate is 4400 µm/s) unless contact damage occurs exactly at the point of contact or just before in which case the amount of time spent in proximity becomes irrelevant. The material transfer under these conditions is insignificant which tends to point towards a mechanism that is independent of the time spent in close proximity.

Figure 4.18 shows the result of tests done under the same hot switching voltage of 3.5 V and ramp rate of 8.8 nm/s, but this time the voltage was applied at the trailing edge while the contacts separated. The contacts were again cycled 40 – 50 times and for different polarities. Trailing edge tests were also performed at a hot switching voltage of 5.0 V as shown in Figure 4.19. Surprisingly, the results for the two hot switching voltages were quite different.
From Figures 4.18 and 4.19, it can be concluded that the material transferred for slow trailing edge hot switching is polarity dependent when the voltage applied is 3.5 V. However,
between 3.5 V to 5.0 V there is a change in the dominant mechanism for material transfer. At 5.0 V, irrespective of the polarity of the material transfer, material is always transferred away from the contact bump. Also, at 3.5 V, the material transferred away from the contact bump when the contact bump is the anode looks to be greater than the material transferred on to the bump when it is the cathode. This appears to suggest that there are two mechanisms occurring simultaneously which either reinforce or oppose each other. One mechanism is possibly related to the temperature difference between the contact and the pillar purely on account of the mass difference. The other is a polarity dependent mechanism which could be electromigration or the Thomson effect.

While separating, the electrodes stayed together for a time beyond the neutral point of the force structure (where the contact force is zero). Therefore, the pillar had to be pulled down below this neutral point in order to let the electrodes completely separate. Although this behavior was initially thought to be due to adhesion, further investigation proved Joule heating at the contact causes the force structure to bend towards the pillar causing them to stay in contact longer [63]. This behavior would let the trailing edge hot switching mechanism operate longer than it otherwise would, particularly if the material transfer occurs when a metal bridge is formed and not after the contacts separate. Therefore, it would not be fair to compare leading edge hot switching results at this rate with the trailing edge since the differences would be, at least partially, an artifact of the testing system. However, it is valid to compare the results of 3.5 V hot switching with 5.0 V hot switching which demonstrated a change in the way conflicting damage mechanisms operate for trailing edge.

Yet another set of experiments for trailing edge hot switching was conducted where the contacts were not allowed to come apart. Here instead, the contacts were allowed to slowly
approach separation. The current through the contact decreased with an increase in resistance but was never allowed to go below 75-80 mA. Essentially therefore, any mechanism that depends upon an electric field between open contacts is taken out of the equation when the contacts are cycled in this manner. At 80 mA of current, the contact voltage is approximately 1 V which is high enough for melting but may be just less than boiling. This possibly leads to formation of a molten bridge. These tests were also conducted for 40 – 50 cycles. The results are shown below in Figure 4.20.

![Contacts do not come apart](image1.png) ![Contacts do not come apart](image2.png)

*Figure 4.20 – Slow tests at an approach/separation rate of 8.8 nm/s, at a voltage of 5V and external resistance of with contacts not being allowed to come apart: a) Contact bump is anode, b) Contact bump is cathode*

The results from Figure 4.20 strongly suggest that the material transfer mechanism is independent of polarity and is probably the same as that observed in Figure 4.17 (b & c) and 4.18 (b & c) where the contacts were allowed to come apart. This mechanism results in transfer of material from the force measurement structure to the pillar. As discussed before, this is probably a thermal mechanism where a molten bridge is formed whose hottest point is closer to the contact bump irrespective of the direction of flow of current.
4.6. Thermal effects and electromigration

Thermal effects are always associated with any electrical contact. At a high enough contact voltage melting and evaporation can occur. Further, the resultant metal vapor can ionize leading to material transfer as the positive ions are attracted towards the cathode. Also, in the event of formation of a metal bridge between the contacts, the bridge can also rupture at its hottest point which can be determined by joule heating or Thomson effect. Since the rupture point will be biased towards the hotter electrode, this will lead to material transfer as well.

The theoretical value for melting voltage of a contact depends on its thermal conductivity, electrical resistivity and melting temperature [32,78]. The relationship between contact voltage and temperature has been discussed extensively and is shown to be [32,79,80]:

\[ V^2 = 8 \int_{T_0}^{T_m} \lambda \rho dT \]

\( \lambda \) and \( \rho \) are the thermal conductivity and electrical resistivity respectively. \( T_m \) is the temperature at the contact spot while \( T_0 \) is the temperature at a location that is far away from the contact spot (ambient temperature). Also, the Wiedemann-Franz law states that the product \( \lambda \rho \) is proportional to absolute temperature \( T \). If the proportionality constant is \( L \) or Lorentz number given by [81], then

\[ \lambda \rho = LT \]

The final relationship between temperature and voltage is [32]:

\[ T_m^2 = T_0^2 + \frac{V^2}{4L} \]
The temperature of the contact spot varies as the square of the voltage which indicates that the temperature can quickly reach the boiling point. The boiling point of Ru is 4423 K and its melting point is around 2607 K. Since the melting voltage of Ru is around 0.8 V which indicates that the boiling voltage is around 1.4 V.

Melting can occur for both leading and trailing edge hot switching. However, for leading edge hot switching, melting will lead to contacts sinking into each other thereby increasing the contact area which leads to lower contact resistance and lower voltage across the contact. At the trailing edge, we can have one of two things. One possibility is that the contacts can pull apart completely after initial adhesion. A second possibility is that as the contact area gets smaller the contact voltage approaches the melting voltage. At this stage, a metal bridge will be formed while the contacts continue to pull apart. This causes the temperature of the bridge to continue increasing beyond the melting point. When the temperature is high enough, the molten bridge that was formed can evaporate and ionize leading to the positively charged ions getting attracted towards the cathode thereby resulting in material transfer from the anode on to the cathode.

For ionization of a vapor of Ru metal, a high temperature is required. The relationship between ionization fraction of volume of vapor to its temperature is given by Saha equation:

\[
\frac{N_{i}^{i+1}}{N_{i}^{i}} = \frac{Z_{i}^{i+1} 2}{Z_{i}^{i} n_{e} h^3 (2\pi m_{e} kT)^{3/2} e^{\frac{\chi_{i}}{kT}}} \]

Here, \(N_{i}\) refers to the number of atoms in the \(i^{th}\) ionization state of the atom, \(Z_{i}\) refers to the partition function for the \(i^{th}\) ionization state, \(m_{e}\) is the mass of an electron, \(h\) is Planck’s constant, \(n_{e}\) is the electron number density, \(k\) is Boltzmann’s constant, \(T\) is the absolute temperature of the system, while \(\chi_{i}\) is the ionization energy in eV. Using this equation for
Hydrogen, we get an ionization fraction of 0.8 at a temperature of 10,000 K [82]. This is much lower than the temperature that would be predicted by equating ionization energy with kinetic energy of a molecule ($\frac{3}{2}kT$) at a given temperature. For Hydrogen, this would have given an ionization temperature of 163,200 K. For Ruthenium, equating ionization energy with kinetic energy would give an ionization temperature of 88,272 K. Scaling this temperature down by the same factor as for Hydrogen would give us an approximate ionization temperature of 5,000 K which is only slightly greater than the boiling temperature. The probability of a metal vapor of Ruthenium to be ionized, leading to material transfer towards the cathode, is therefore extremely high.

Electromigration also cannot be discounted in the context of hot switching in microcontacts. Electromigration refers to mass transport in a conductor that occurs as a result of high current densities [47,83]. At current densities above $10^4$ A/mm2, electromigration can become significant. If we consider a current of 75 mA, then the radius of the bridge needs to be 1 µm. For the microcontacts being tested here, the contact spot(s), just before opening, is an order of magnitude (or more) smaller than this thereby giving an even higher current density and hence the probability of electromigration occurring increases by an order or more.

Due to the electric field of a conductor, electrons are pulled towards the cathode, while the ions are pulled towards the anode. However, the energy transferred to the ions from collision with electrons as well as the electrostatic pull of the electrons will result in the ions also experiencing a pull towards to cathode. Thus, there are two opposing forces acting on the ions. The drift velocity of the ions due to electromigration is given in literature by the following equation [47,83]:

$$v = \frac{e}{m} \frac{d}{dt}$$
Here, \( V \) is the velocity of ion transport; \( Z^*e \) is the effective charge in the ion taking into account electrostatic force due to applied electric field, as well as the influence of the electrons; \( \rho \) is the resistivity of the contact material, \( D \) is the diffusion coefficient of the ions, \( K \) is Boltzmann’s constant and \( T \) is the absolute temperature of the contact spot.

Usually, electromigration in metals occurs in the direction of flow of electrons i.e. cathode to anode which implies \( Z^* \) is \(< 0 \). In a fluid, however, since the ions have additional thermal energy, they may be prone to move towards the cathode. Anode to cathode material transfer has been reported in Al, Ag, In and other metals, particularly in the molten state [47,84,85].

The flow of current in an electrical contact leads to joule heating of the contacts. At the time of contact opening, if a metal bridge is formed and the temperature does not reach evaporation point, then the bridge will eventually break at its hottest point. Due to the thermal asymmetry between the two electrodes, this hottest point will be biased away from the pillar, which on account of its greater mass is the better heat sink [63]. As a result of this, there will be asymmetric transfer of material towards the pillar irrespective of the polarity of the applied voltage. This effect, therefore, will be polarity independent and will always lead to material transfer away from the contact bump. It is possible that the material transfer observed with bipolar hot switching is due to this mechanism. The thermal effect also explains why the material is always transferred from the contact bump during the slow tests at 5 V, and in case of 3.5 V there is less material transferred on to the contact bump when it is the cathode than what is transferred away from it when it is anode.
The Thomson effect is another thermal mechanism that should be discussed in the context of material transfer. In an electrical contact, a temperature gradient will occur as a result of the voltage across the contact and the flow of current [32,86] in addition to the temperature gradient due to Joule heating discussed earlier. The temperature gradient may be from anode to cathode or the other way around depending on the sign of the Thomson coefficient. A positive Thomson coefficient leads to the cathode being hotter. This is exhibited in metals such as Cu and Ag. A negative Thomson effect, exhibited in Pt, Ni and Bi, leads to the anode being hotter [87]. However, when Pt was investigated, it was found that depending on its state (solid or liquid), its Thomson coefficient can change signs [32]. While data pertaining to Thomson coefficient for Ru is not yet available, some of the results obtained in the course of this thesis can be discussed in with the Thomson effect in mind. In the event of a molten bridge being formed while the contacts start to separate, the molten bridge will break at the point of the highest temperature and therefore will lead to material being transferred from the hotter to the cooler electrode.

4.7. Summary of hot switching damage mechanisms

From the results and discussion in chapters 3 and 4, it can be concluded that hot switching damage in microswitch contacts can be due to a number of different mechanisms. Among the likely mechanisms are – a) Mechanical transfer through adhesion, cold welding or softening of contact as observed in low voltage hot switching; b) Field Evaporation; c) Field emission leading to heating, melting and evaporation; d) Electromigration with and without melting which can also manifest itself through surface diffusion; e) Ionization of metal vapor; f) Formation of metal bridge where Thomson effect and thermal asymmetry can cause the hottest point of the bridge to
be biased towards one of the electrodes. Having discussed each of these mechanisms separately, it is pertinent to look at a hot switching cycle holistically and understand how the mechanisms are likely to operate in the course of a cycle.

4.7.1. Hot switching mechanisms at the leading edge

For leading edge hot switching, as the contacts approach each other, field emission through either Fowler Nordheim tunneling (for voltages above the work function) or direct tunneling (for voltages below the work function) will occur. Depending on the material properties of the contact as well as the tunneling current, some amount of melting or even evaporation might occur due to field emission. Both for Fowler Nordheim tunneling through a triangular barrier as well as direct tunneling through a trapezoidal barrier, a separation on the order of a few Å is necessary in order to achieve a current level of approximately 1 µA considering a contact area of around 5 nm$^2$. At smaller separations, the current increases exponentially and can reach approximately 1 mA at 1 Å [68] which could lead to evaporation. Material transfer due to this mechanism will be from anode to cathode.

Electric field between the contacts can cause surface diffusion of the ions towards the apex of the anode. Furthermore, if tunneling current causes heating at the anode, this can lead to melting which can further promote surface diffusion towards the apex of the contact. The process of surface diffusion is similar to electromigration where ions are pulled by the electric field between the contacts. Ultimately a liquid cone may form at this tip which can be long enough to touch the other electrode thereby depositing material on to it. This was speculated to be a material transfer mechanism in AFM/STM tips in [77].
Field evaporation might also become prominent at such small separations leading to material transfer once again from anode to cathode. Conventional field evaporation theory such as that presented in [88], considers a threshold electric field for evaporation, using first principles such as the image-hump model, at which atoms are able to break the barrier potential between them and the contact surface. However, at small separations (4 – 6 Å), when the interaction profiles of the anode and the cathode combine, the atoms can essentially tunnel from one surface to another at smaller electric fields which can be 30-40% lower than the value at large separations [77]. Thus, if the usual electric field required for evaporation for Ru is 4.1 V/Å, then at small separations, it can be approximately 2.5 V/Å. At less than 4 Å, the required electric field can be less than 50% of the 4.1 V/Å value. Therefore, for a voltage of 3.5 V as applied to most of the contacts tested as part of this work, the required separation for field evaporation can be approximately 1.5 Å. This phenomenon leading to material transfer at low voltages is also observed in STM tips when the sample is held close to it.

At the moment of initial contact, when the contact voltage is highest, melting or potentially boiling of the contact surface can take place leading to formation of a metal cloud which, depending on its temperature may get ionized thus leading to material transport towards the cathode where the ions will get attracted. Electromigration and surface diffusion, as a consequence of the high current density can also occur at this point. If the contact voltage is large enough to melt but not cause evaporation, it is likely that the contacts will ‘sink’ into each other thereby causing an increase in contact area and lower resistance thereby quickly bringing down the contact voltage [32].
4.7.2. Hot switching mechanisms at the trailing edge

At the time of contact opening, the sequence of events could be different, although some or all of the same mechanisms might still be active. When the contacts start separating, the contact voltage starts to rise as the resistance increases. At the melting voltage, which is 0.8 V for Ru, a molten bridge will form between the contacts. The hottest point of this molten bridge will determine the point at which this bridge will break. The hottest point can depend upon several factors. If we consider joule heating, the contact bump will be the hotter of the two electrodes on account of the fact that the pillar has more mass and is a better heat sink. This will shift the hottest point of the molten metal bridge towards the anode. However, other mechanisms are also active. One is the Thomson effect. Depending on the sign of the Thomson coefficient for the contact material when it is at its molten state, the Thomson effect will lead to a thermal gradient from either anode to cathode or the other way around [89]. While data on the Thomson coefficient of Ruthenium is not available, it is possible that it will cause the hottest point to shift toward the anode [32] causing material transfer from anode to cathode.

Another polarity dependent mechanism leading to material transfer is electromigration. While electromigration is generally associated with solids, it can also be present in a molten bridge [47,86]. In a molten bridge, electron diffusion can lead to ion transport which will ultimately cause the molten bridge to break while transporting material to one of the electrodes. Although conventionally electromigration leads to material transfer from the anode to the cathode, the opposite has also been observed for metals such as Ag.

It was found that at a very slow separation rate of 8.8 nm/s, a voltage of 5 V and an external resistance of 50 Ω, material transfer always occurred from contact bump to pillar
irrespective of which of these was the anode. This would imply that the thermal effect took precedence over any polarity dependent effect that might also be present. At 3.5 V and an external impedance of 50 Ω, however, material transfer was polarity dependent and thus the thermal effects were effectively offset by the polarity dependent mechanism which could be Thomson effect or electromigration. It was noted that although material transferred in both directions, but there was much more from the bump to pillar, implying that the two mechanisms were active simultaneously.

While the role of the molten bridge may be important for trailing edge hot switching, the other field dependent mechanisms can also occur once the molten bridge has broken. These include field emission and field evaporation. When the bridge ruptures at its hottest point, the material on either end of the rupture point will re-solidify. Subsequently, field emission and field evaporation can occur between the resultant asperities for a short duration before the separation between the contacts increase further.

Furthermore, there is also the possibility of a portion of the molten bridge evaporating when the contact voltage is close to boiling voltage, which for Ru can be estimated to be around 1.2 V given that contact temperature is proportional to the square of the contact voltage and that the melting voltage of Ru is 0.8 V. Boiling of the bridge can lead to formation of a metal vapor which could get ionized at a sufficiently high temperature that would lead to material being deposited on the cathode. This mechanism is similar to what can happen at the leading edge.

It was also observed that at an external impedance of 5 kΩ, trailing edge hot switching gave rise to less contact damage than leading edge hot switching. This can perhaps be explained by the fact that at the trailing edge when the melting voltage is reached, the contact resistance
would be about 1 kΩ if the total applied voltage is 3.5V. The resultant contact area under the circumstances would be about 0.36 Å (if resistivity of Ru is 7.1 µΩ-cm and $= \frac{\rho}{2a}$) which is less than an atom’s size.

### 4.7.3. Evidence of multiple mechanisms

The presence of multiple mechanisms operating simultaneously, leading to hot switching damage, is clear from various results obtained in this work. For instance, at a hot switching voltage of 0.5 V, material is displaced due to softening and as such does not lead to transfer of material. The presence of a polarity dependent mechanism together with a polarity independent thermal mechanism is clear from the results of bipolar hot switching as well as those where contacts are cycled extremely slowly. Also, at the leading edge, contacts can weld together due to high temperature and then when they come apart, this can cause material to be scattered. At the trailing edge, the material transfer and contact erosion appears a lot smoother possibly due to the formation of an intermediate molten bridge.

The results discussed in Chapters 3 and 4, can be used as evidence for presence of multiple mechanisms during hot switching. While the evidence available is complex, a careful analysis can help relate the data already presented with possible mechanisms. Given below are two tables – one showing how different test results can be associated with certain mechanisms, and another showing how some of the possible mechanisms could be associated with images of the damaged contacts.
<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Experiments</th>
<th>Pure Cold switching</th>
<th>Hot switching at 0.5 V and 4400 µm/s</th>
<th>Leading and Trailing edge Hot switching at 3.5 V, 50 kΩ and 4400 µm/s</th>
<th>Leading edge Hot switching at 3.5 V, &gt;5 kΩ and 4400 µm/s</th>
<th>Trailing edge Hot switching at 3.5 V, 50 Ω and slow pull-off</th>
<th>Trailing edge Hot switching at 3.5 V, 50 Ω and slow pull-off</th>
<th>Bipolar hot switching at 3.5 V, 50 Ω and 4400 µm/s</th>
<th>Trailing edge Hot switching at 5 V, 50 Ω and no pull-off</th>
<th>Sustained Pre-contact current</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical transfer</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polarity dependent material</td>
<td></td>
<td>Some damage observed. Little heating expected.</td>
<td>Material displacement observed. Melting not expected.</td>
<td>Directional material transfer dominant. No evidence.</td>
<td>Directional material transfer dominant. No evidence.</td>
<td>Damage comparable to cold switching. May be mechanical transfer</td>
<td>Expect mechanical transfer to be small</td>
<td>Expect mechanical transfer to be small</td>
<td>Expect mechanical transfer to be small</td>
<td>No evidence of contact damage</td>
</tr>
<tr>
<td>Thermal material transfer</td>
<td></td>
<td>Not directional</td>
<td>Not directional</td>
<td>Polarity driven material transfer</td>
<td>Polarity driven material transfer</td>
<td>Not able to offset polarity dependent material transfer</td>
<td>Thermally-directed</td>
<td>Major fraction of material transfer</td>
<td>Thermally-directed</td>
<td>No evidence of contact damage</td>
</tr>
<tr>
<td>Thomson Effect</td>
<td></td>
<td>Not directional</td>
<td>Not directional</td>
<td>Candidate for field-oriented directional transfer</td>
<td>Candidate for field-oriented directional transfer</td>
<td>Not directional</td>
<td>Asymmetric directional transfer. This may be one mechanism</td>
<td>Not polarity dependent</td>
<td>Could be active</td>
<td>Not polarity dependent</td>
</tr>
<tr>
<td>Field Evaporation or Field</td>
<td></td>
<td>No field</td>
<td>Not directional</td>
<td>Candidate for field-oriented directional transfer</td>
<td>Candidate for field-oriented directional transfer</td>
<td>Not directional</td>
<td>Asymmetric directional transfer. This may be one mechanism</td>
<td>Not polarity dependent</td>
<td>Could be active</td>
<td>Not polarity dependent</td>
</tr>
<tr>
<td>Emission/ Evaporation</td>
<td></td>
<td>Field very low</td>
<td>Field very low</td>
<td>Candidate for field-oriented directional transfer</td>
<td>Candidate for field-oriented directional transfer</td>
<td>Not directional</td>
<td>Asymmetric directional transfer. This may be one mechanism</td>
<td>Not polarity dependent</td>
<td>Could be active</td>
<td>Not polarity dependent</td>
</tr>
<tr>
<td>Ionization of metal vapor</td>
<td></td>
<td>No field</td>
<td>No field, temperature not high enough for melting</td>
<td>Candidate for field-oriented directional transfer</td>
<td>Temperature not high enough for melting</td>
<td>Not directional</td>
<td>Asymmetric directional transfer. This may be one mechanism</td>
<td>Not polarity dependent</td>
<td>Could be active</td>
<td>Not polarity dependent</td>
</tr>
<tr>
<td>Electro-migration</td>
<td></td>
<td>Solid state electro-migration possible</td>
<td>Solid state electro-migration possible</td>
<td>Candidate for field-oriented directional transfer</td>
<td>Solid state electro-migration possible</td>
<td>Solid state electro-migration possible</td>
<td>Asymmetric directional transfer. This may be one mechanism</td>
<td>Not polarity dependent</td>
<td>Could be active</td>
<td>Not polarity dependent</td>
</tr>
<tr>
<td>Surface Diffusion</td>
<td></td>
<td>No Electric field</td>
<td>No clear evidence</td>
<td>Candidate for field-oriented directional transfer</td>
<td>No clear evidence</td>
<td>No clear evidence</td>
<td>Asymmetric directional transfer. This may be one mechanism</td>
<td>Not polarity dependent</td>
<td>Could be active</td>
<td>Not polarity dependent</td>
</tr>
</tbody>
</table>

Table 4: Contact damage associated with different material transfer mechanisms

- **Evidence for mechanism under these conditions**
- **No evidence for or against mechanism**
- **Evidence against mechanism under these conditions**
Table 5: Figures associated with different material transfer mechanisms

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Figure number(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical transfer, cold adhesion</td>
<td>Figures 3.4 to 3.7 (0.25 V and 0.5 V tests)</td>
</tr>
<tr>
<td>Field Evaporation</td>
<td>Figures 3.9, 3.10, 3.12 and 4.16</td>
</tr>
<tr>
<td>Field emission leading to heating, melting and evaporation</td>
<td>Figures 3.9, 3.10, 3.12 and 4.16</td>
</tr>
<tr>
<td>Electromigration (molten or solid) and surface diffusion</td>
<td>Figures 3.11, 4.18, 4.19 and 4.20</td>
</tr>
<tr>
<td>Ionization of metal vapor</td>
<td>Figures 3.9, 3.10 and 3.12</td>
</tr>
<tr>
<td>Thermal bias due to Thomson effect</td>
<td>Figures 4.18, 4.19 and 4.20</td>
</tr>
<tr>
<td>Thermal asymmetry due to geometry</td>
<td>Figures 4.12 and 4.20</td>
</tr>
</tbody>
</table>

In summary, then, it is important to note that contact damage due to hot switching can occur due to a number of different mechanisms. The results of hot switching tests at different voltages demonstrate the presence of multiple contact damage mechanisms. The mechanisms operate at very short separations or when the contacts are just touching. While there are some similarities between leading and trailing edge hot switching (similar amount of material transfer at a switching speed of 4400 µm/s), there could be effects which are present in one and not the other. It is also noted that pre-contact currents, observed in ‘dirty’ contacts [39,40,76] do not cause material transfer.
Chapter 5 - Hot switching phenomena not leading to contact damage

5.1. Observation and analysis of large current spikes

To monitor in detail the current behavior before closing and after opening of the contact, a 50 Ω external resistor was placed in series with the contact in addition to the built-in testing system 5 Ω series resistor, as shown in Figure 5.1(a). The voltage across this added resistor was measured with an oscilloscope with an acquisition rate of (500 MS/s); current in the circuit was calculated using Ohm’s law.

Several current monitoring tests were conducted at various applied voltages and frequencies for both leading edge and trailing edge hot switching. Figure 5.1 illustrates an example of typical current behavior observed before closing and after opening of a contact cycled at 500 Hz with 55 Ω total series resistance and hot switching potential 3 V. There are several properties of note presented in this figure. First, the magnitude and anatomy of the spikes is remarkably similar. It is important to note that the plotted data came from two different cycles and that not all the current spikes observed look identical to the ones presented; there was some variation in magnitude, duration, and periodicity observed. The similarities in the current spikes suggest that the same underlying mechanism is causing both.
It was initially conjectured that these spikes are related to the observed material transfer as well. However, these spikes stopped appearing once the coaxial cable connected across the contact, for measuring the contact voltage with an oscilloscope, was disconnected. This indicated that the spikes could have been a result of the capacitance in the coaxial cable interacting with asperities on the contact surfaces blowing them out [75]. Contacts were tested up to 500,000 cycles after removing the coaxial cable and the material transfer compared qualitatively with contacts cycled the same number of times with the cable connected. The amount of material transfer appeared to be the same in both cases, indicating that the larger spikes did not contribute to the anode-to-cathode material transfer.

Figure 5.1 shown earlier tells us about the observed large current spikes just before closure and immediately after contacts open. The effect of circuit parasitics, which have been
known to cause spikes in currents, needed to be studied closely to examine their role in contact damage. A few basic experiments were done to better understand the spikes.

**Figure 5.2 – Realistic circuit for the test setup**

The figure above (Figure 5.2) is the effective circuit for the test setup. The circuit shows the parasitic inductance and capacitance in the interconnections. Between the switch and the external 50 Ω resistor though, there is no parasitic because of the use of a transmission line terminator for the co-ax cable.

The first modification done to this circuit was removing the DAQ that was reading the voltage across switch. Since the DAQ can introduce currents (although not as high as the spikes seen), this was seen as a logical first step. It was then observed that the spikes almost disappeared. They are still occasionally seen but even those are of much shorter duration than that noticed earlier with the DAQ on.
Figure 5.3 above shows circuit without the DAQ being connected across the contact. Figure 5.4 shows the nature of the leading and trailing edge behavior of the current following the removal of the DAQ. Note that at the trailing edge the current level is lower. This is seen often and is associated with increase in resistance when the contacts are coming apart.

Figure 5.4 – Current spikes in the absence of a DAQ across the contact
Following the results observed in the figure above, a few more tests were performed. The co-axial cable used for measuring contact voltage was now connected to the contact without the other end being connected to the DAQ break-out box. This was done to test the effect of the parasitic capacitance to ground of the co-axial cable. It was observed that the spikes are now back. By calculating the approximate capacitance of the cable alone to be around 1 nF, the author decided to connect just a 1 nF capacitor in parallel with the contact. This caused the spikes to reappear. The final results can be summarized in Figure 5.5 below.
To check if the spikes themselves were responsible for the material transfer, two different contacts were cycled up to 500,000 cycles with and without the DAQ being connected. The images, shown in Figure 5.6, revealed that in both cases the material transfer was comparable thereby definitively proving that the spikes had nothing to do with material transfer. However, keeping in mind the fact the spikes are not regular and thus cannot be related to any mechanical phenomena such as resonant frequency of the structures, and also the fact that at lower voltages these spikes are not observed, it is clear that the spikes are being triggered by circumstances related to hot switching even if they are not responsible for material transfer. The images of the cycled contacts under the two different conditions are shown below:
Figure 5.6 – a) Contact after 500,000 cycles with no DAQ connected, b) Contact after 500,000 cycles with DAQ in parallel

5.2. Current transients in RF hot switching

The source and load capacitance in an RF system can be estimated by using a typical value of standing wave ratio. These capacitances, along with the effective capacitance of the RF MEMS switch, can cause current transients at the time of closing of the contact. An analysis of these current transients was necessary to conclude if they can have an effect on contact damage. Although no experimental work has been done so far under RF conditions, an analytical study of such a system was necessary for an insight into its behavior.

Figure 5.7 shows the effective circuit under RF conditions.
The values of source and load capacitances as well as the effective inductance and capacitance of the switch were used from Gabriel Rebeiz’s textbook for RF MEMS [3] and correspond to values that lead to a Standing wave ratio observed in a realistic RF circuit. As an example, the switch characteristics used for simulating the switch resistance in the circuit were derived from data available on the NEU-Radant MEMS switch.

Given the Force vs Resistance data and the Force vs time for a typical switch, the resistance vs time curve was derived as shown in Figure 5.8. This curve can be simulated on Spice by having several ideal switches in parallel. After this simulation, the current transients are studied for various values of dF/dt i.e. the switch closure rate. Expectedly, the switch closure rate has a significant effect on the magnitude of the current transients. Another factor that influences the magnitude of the current transients is the phase of the input RF signal at which the switch closes. Figure 5.9 shows the current transient at different values of dF/dt.
Figure 5.8 – Force vs time, Force vs Resistance and Resistance vs time for contacts with different material

Figure 5.9 – Current transient in an RF microswitch vs dF/dt of the switch – the black vertical line represents the dF/dt of a standard

The data above tells us that at realistic values of dF/dt, only Au-Au contacts show any significant current transient which implies that these high values of current transients are not available for causing damage in RF circuits.
Another somewhat pertinent result was obtained through this circuit model. It was observed, as shown in Figure 5.10 that the current transient in an RF system depends on phase angle at which contact is made.

![Figure 5.10 – Current transient vs phase angle at which contact is closed – it should be noted that the current overshoot as a function of phase is plotted at an unrealistic value of dF/dt so as to amplify its magnitude](image)

For Ru-Ru contacts the current transients are very low for all phase angles and all values of dF/dt; Also, the plot for current transient against phase angle was with respect to the highest value of current transient at a dF/dt of 100x103 N/s which is unrealistic for these switches.
Chapter 6 - Conclusion and future work

In this thesis, contact damage in Ruthenium-on-Ruthenium microcontacts as a result of hot switching has been discussed. While it was known that hot switching leads to a reduction in the lifetime of microswitch contacts, the damage mechanisms causing it was poorly understood. Using an AFM-based test setup a large number of experiments were performed, under different hot switching conditions, to observe and characterize these mechanisms. For these tests, a clamped-clamped beam structure with a bump at its center was used as one side of the contact. The other side was a pillar which was placed on a piezoactuator whose expansion and contraction caused the contacts to meet and then come apart thereby replicating switching cycles in a microswitch.

Material transfer, leading to removal of contact material from one side of the contact, subsequently causing contact resistance to increase, was found to be the primary cause for contact failure in DC hot switching. Both leading and trailing edge hot switching, at a hot switching voltage of 3.5 V, were found to quantitatively lead to similar amounts of material transfer when an external resistance of 50 Ω was used in series with the contact, at a cycling frequency of 500 Hz. However, with a 5 kΩ resistor, leading edge hot switching was found to be much more damaging than trailing edge hot switching. Material transfer in bipolar hot switching was found to be several orders of magnitude lower than DC hot switching. It was observed that some amount of material transfer is still unavoidable with bipolar hot switching at a cycling frequency of 500 Hz and a hot switching voltage and external resistance of 3.5 V and 50 Ω respectively. The mechanism leading to such material transfer was speculated to be thermal since any field dependent mechanism should be effectively neutralized. Both leading and trailing edge bipolar hot switching was found to lead to material transfer away from the contact bump. The
contact resistance for a bipolar hot switched test, however, was found to remain low for the entire course of the test up to 120 million cycles.

Multiple mechanisms were found to operate and lead to contact damage during both leading and trailing edge hot switching. At low hot switching voltages, below 2.0 V, it was found that there was no regular pattern to the direction in which material was transferred with respect to the polarity of the applied voltage. At 0.5 V, it was found that there was a significant increase in contact damage compared to cold switching or at 0.25 V, although this damage also was not polarity dependent and may not lead to contact erosion but rather its displacement. From 0.5 V to 1.0 V, however, contact damage decreased while at higher contact voltages of 2.5 V and above, polarity dependent material transfer becomes prominent. Under these conditions, material transfer is almost always from the anode to the cathode. A large number of damage mechanisms were discussed in relation to material transfer. While some of these mechanisms operate when the contacts are separated but in very close proximity (in the order to several Å), other mechanisms operate when the contacts are barely in contact or are connected through a molten metal bridge. The mechanisms could be either electric field dependent (such as field emission, field evaporation, Thomson effect and electromigration) or could be thermally induced (such as joule heating leading to a geometry dependent thermal gradient between the contacts). Each of these mechanisms was found to be potentially damaging for the contacts leading to at least some amount of material transfer. When contacts are separated extremely slowly at the rate of several nm/s, an applied hot switching voltage of 3.5 V causes the polarity dependent mechanism to play a greater role than the polarity independent mechanism (possibly thermal). At 5 V, however, the polarity independent mechanism was dominant and lead to material transfer away from the contact bump.
For future investigation, this thesis opens the door for several different avenues that could be pursued. Given the large number of mechanisms at play, the effect of each mechanism can only be understood if several different contact materials with different properties could be tested under a given set of hot switching conditions. For example, if contact damage occurs as a result of the boiling of contact material when asperities come into initial contact, a material with a higher boiling point should be more resistant to such damage. Thus, different contact materials can be tested under the same hot switching voltage to find out if the one with the highest boiling point has the least damage. Similarly, contact materials should be tested for properties such as work function which dictates the amount of tunneling current between the contacts, and Thomson coefficient, which will determine the contribution of the Thomson effect in material transfer. Understanding the contribution of each mechanism on contact erosion can pave the way to finding an exact hot switching specification for a microswitch made out of a specific contact material or a combination of materials.

The thermal mechanism of material transfer may be amplified in a real microswitch since the difference in thermal properties between the structure and the substrate is greater. Thus, it will also be interesting to observe more closely the effects of different hot switching conditions on a real microswitch and how it matches with the results obtained in this work.
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